مؤتمر الخليج الثالث عشر للمياه

المياه في دول مجلس التعاون: التحديات والحلول المبتكرة

The 13th Gulf Water Conference

Water in the GCC : Challenges and Innovative Solutions

12 -14 March 2019 - State of Kuwait ١٢-١٤ مارس ٢٠١٩ - دولة الكويت

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Water in the GCC: Challenges and Innovative Solutions

State of Kuwait, 12-14 March, 2019

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Preface

Despite the extreme scarcity of water resources in the region, the GCC countries have done well in providing water for their ever-increasing population and rapidly expanding economic base and activities. However, the GCC countries are faced with major challenges manifested by increasing financial, economic and environmental costs associated with providing water supplies. These challenges are expected to grow with time under the current policies and management approaches driven by many external and internal drivers, which include rapid population growth, changing consumption patterns, low management efficiencies, and the expected impacts of climate change.

In the municipal sector, to meet escalating water demands under the current rapid population and urbanization rates and changing consumption patterns the GCC has to resort to desalination which is financially and energy-intensive and is associated with many environmental externalities including greenhouse gases emissions. These challenges are exacerbated by two factors, the first is the relatively high subsidies of water supply that impact the financial sustainability of the sector, and the second is that the GCC are still importers of desalination technology. In the wastewater sector, although the GCC countries have been providing commendable rates for sanitation services and are operating modern treatment facilities, reuse of treated wastewater is not fully developed, which represents a major lost opportunity under the prevailing water scarcity conditions.

Moreover, despite the fact that GCC countries are among the poorest in the world in renewable water resources, the agricultural sector consumes more than 85% of the total water uses, and is the main cause for the mining and quality deterioration of groundwater resources in the region. Water uses in the agricultural sector are exaggerated due to low irrigation efficiencies, cultivating high water consuming crops, unrestricted abstraction rights, and absence of water metering and tariffs. Finally, the industrial sector has been expanding rapidly due to GCC economic diversification policies, and its water consumption as well as its wastewater discharge is increasing at an alarming rate.

The current water policies addressing these challenges in the GCC countries will require major shifts if we want to have a sustainable water sector to continue to serve the socio-economic development needs of the region. What is needed is to mainstream innovation in the water sector at strategy, management, and operation levels. In this context, investments in technological and non-technological (financial, institutional, management) innovation will be essential. Innovative proactive solutions are necessary to address the water challenges we are facing now and in the future and to keep the long-term cost of the solutions viable and cost-effective.

The WSTA 13th Gulf Water Conference will focus on identifying innovative sustainable solutions for the major water challenges facing the GCC countries. The conference invited top keynote speakers and experts in the conference theme and sub-themes to address the sustainability-innovation nexus, share their knowledge, and transfer their experience. The conference will present and share innovative solutions from different countries in improving water sustainability and overcoming the water challenges in the arid GCC and Arab countries.

The WSTA 13th Gulf Water Conference is organized in the State of Kuwait in collaboration with the Kuwait Institute for Scientific Research (KISR) represented by the Water Research Center. The conference is organized in close coordination with the GCC Secretariat General and with sponsorship by the Arab Fund for Economic and Social Development (AFESD), Islamic Development Bank (IDB), and Kuwait Foundation for the Advancement of Science (KFAS). The conference is strongly supported and endorsed by the active UN organizations in the region of UNESCO Cairo Office, UN ESCWA, CEHA/WHO, UN Environment, and FAO; and the international/regional organizations of ICBA, ICARDA, ACWUA, IDA and EDS.

On behalf of the Conference Scientific Committee, I would like to thank all authors and panelists from various parts of the world for joining us in our Thirteenth Gulf Water Conference and sharing their experiences and innovative solutions in improving water sustainability and overcoming the water challenges in the arid GCC and Arab countries.

Prof. Waleed K Al-Zubari
Chairman
Conference Scientific Committee

Conference Objectives

- Evaluation and prioritizing of major water challenges facing the GCC countries.
- Presenting innovative technological and non-technological solutions implemented in the region and internationally to address water sector challenges.
- Facilitating an open discussion platform and network to share knowledge, experiences, and best practices between researchers, executives, decision and policy makers, private sector, and other stakeholders, on innovative water solutions in the GCC and other Arab countries and beyond.
- Recommendation of potential innovative solutions to eminent water challenges facing the GCC countries.

Conference Recommendations

The WSTA 13th Gulf Conference was held in the State of Kuwait during the period 12–14 March 2019, under the patronage of HH Sheikh Jaber Mubarak Al-Hamad Al-Sabah, The Prime Minister, represented by HE Dr. Hamed Mohammed Al-Aazmi, Minister of Higher Education, and the presence of HE Dr. Abdullateef Al-Zayani, GCC Secretary General, and was attended by more than 250 GCC, Arab and international water professionals from the executive, legislative, academic, NGO and private sectors. The Conference was organized by the WSTA in cooperation with and kind hosting by the Kuwait Institute for Scientific Research (KISR) and the GCC Secretariat General, and was supported by the international, regional, and local organizations of UNESCWA, UNESCO Cairo Office, CEHA/WHO, UN Environment, ICARDA, ICBA, IDA, ACWUA, EDS, Arabian Gulf University, Kuwaiti Ministry of Electricity and Water, OWS.

The WSTA 13th Gulf Water Conference focused on identifying innovative sustainable solutions for the major water challenges the GCC countries are facing. The conference invited top keynote speakers and experts in the conference theme and sub-themes to address the sustainability-innovation nexus, share their knowledge, and transfer their experience. The conference presented and shared innovative solutions from different countries in improving water sustainability and overcoming the water challenges in the arid GCC and Arab countries.

The conference calls on the GCC countries:

On desalination

1. To strengthen joint GCC efforts to localize and indigenize desalination industry and increase its added value to the economies of the GCC countries, including joint investments, research coordination, education and training programs, to contribute to the achievement of the sustainability and security of the municipal water supply sector.

On groundwater and surface water resources

2. To enhance groundwater storage by Managed Aquifer Recharge (MAR) through its various schemes (e.g., ASR, ASTR, SAT), while addressing related health and environmental risks when using impaired water, to help in aquifer restoration efforts and to establish an underground strategic reserves for emergencies, or for other beneficial conjunctive uses such as meeting agricultural demands.
3. To regulate groundwater utilization by enacting and implementing comprehensive groundwater legislation reaffirming state groundwater ownership, establishing appropriate institutional mechanism for stakeholders participation, and implementing economic incentive tools through an appropriate tariff for groundwater use based on groundwater economic valuation in order to provide a price-signaling mechanism and to raise awareness of groundwater value to help in groundwater restoration efforts.
4. To maximize the use of surface water by developing and implementing water harvesting programs to mitigate and benefits from the extreme flooding events of climate change.

On wastewater

5. To maximize wastewater collection, increase treatment level, and maximize treated wastewater reuse in appropriate sectors, through clear wastewater reuse strategies and plans, and addressing health and environmental risks including those emanating from pharmaceuticals and disinfection byproducts, and regulate and incentivize the private sector in the utilization of this renewable resource.
6. To support research and development efforts related to maximizing the beneficial utilization of wastewater, other than in irrigation, such as waste-to-energy schemes and sludge beneficial utilization in the fertilizers industry.

On municipal water management

7. To adopt a "Smart City" approach in urban planning and integrating the water sector with other city components of energy, mobility, infrastructure, and the built environment by fully utilizing the IT opportunities to achieve smart, intelligent, and efficient water management system in the GCC countries.
8. To prioritize enhancing energy efficiency in the water sector by auditing its energy use, benchmarking it with best practice, and developing energy efficiency programs, and the adoption of a life cycle and integrated assessment in technology choices in desalination and wastewater sector, and to diversify energy sources to increase the utilization of renewable energies in the water sector.
9. To meet international best practices and benchmarks for water supply and sanitation utilities, which include customer satisfaction and quality of service, leadership and capacity development programs operational optimization and resiliency, financial viability and sustainability, infrastructure stability, and environmental compliance.
10. To manage Non Revenue Water (NRW) levels at international best practices in order to enhance the municipal water supply efficiency, to reduce supply cost, and to enhance the utilities financial sustainability.

On agricultural water management

11. To support research and development efforts to enhance water productivity and water efficiency in the agricultural sector and to integrate approaches for desert farming in dry lands, with the aim to reduce the overall consumption of water in the agricultural sector.

On industrial water management

12. To increase water efficiency and manage demands in the oil and industrial sector, rapidly emerging as a major water user in the GCC countries, and enforce industrial wastewater treatment and reuse programs by appropriate legislation.

On public health and environmental protection

13. To adopt and enact legislations to develop and implement drinking water and sanitation safety plans based on risk assessment and management by all water utilities responsible for these two sectors in the GCC countries.
14. To plan and implement effective monitoring processes of the sanitation systems and other risk management interventions under a regulatory framework to ensure safe wastewater reuse for agricultural irrigation that is consistent with the national or international guidelines.
15. To enact and enforce legislation related to the protection of the marine environment from municipal and industrial wastewater and the brine reject from desalination plants.

On water sustainability and security

16. To further build on the GCC Unified water Strategy, adopted by the GCC as a guiding document for the development of national strategies, and activates its joint initiatives at the regional level by the General Secretariat.
17. To exert all efforts to achieve the water related SDGs targets which provide a practical framework for achieving water security and sustainability, to contribute to the improvement of current SDG indicator methodologies especially those related to groundwater-related challenges and based on the regional needs and existing knowledge, to research the water-related SDGs interlinkages in the region and identify their synergies and trade-offs, and to regularly monitor these targets in order to identify progress and weaknesses to formulate appropriate and optimum policies.
18. To invite and encourage governments, research institutions and researchers to make use of the technical output of the project Regional Initiative for the Assessment of Climate change Impacts on Water Resources and Socio-economic Vulnerability in the Arab Region (RICCAR) through the regional knowledge platform to assess the vulnerability of the water sector to climate change and to help in the formulation of adaptation plans.

The conference authorizes the WSTA Board of Directors to submit these recommendations to the GCC Secretariat General for presentation at the Water Ministerial Committee Meetings and to follow up the progress of its implementation. Moreover, the Board is requested to circulate these recommendations to relevant regional and local organizations and water-related forums.

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Investigation of polar and nonpolar material in the groundwater of Raudhatain and Umm Al-Aish fresh groundwater fields of Kuwait

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ABSTRACT

Parts of the fresh groundwater of Raudhatain and Umm Al-Aish freshwater fields have been contaminated with petroleum hydrocarbons leached from petroleum lakes and petroleum-contaminated soil resulting from the 1991 Gulf War. Pump and treat methodology has been suggested for treatment of contaminated groundwater. Selection and design of methodologies for the treatment of contaminants require knowledge related to types and physiochemical properties of contaminants. Therefore, as a preliminary step toward treatment of contaminated water, a study was conducted in order to identify and quantify contaminants in terms of polar and nonpolar material of contaminated water. Groundwater samples were collected from 10 monitoring wells (nine contaminated and one uncontaminated) of water fields. Collected samples were analyzed for total petroleum hydrocarbon (TPH), total organic carbon (TOC), phenol, tannin and lignin, volatile acids and Ultraviolet (UV)-induced fluorescence before and after activated silica gel. The silica gel splits aggregated polar and nonpolar material by retaining polar material on its activated surfaces. The results of the study indicated that both polar and nonpolar materials are present in the contaminated groundwater. TPH, UV-induced fluorescence, phenol, and volatile acid contents were dominantly composed of polar material at 86%, 84%, 73%, and 90%, respectively; whereas TOC, tannin and lignin contents were dominantly composed of nonpolar material at 58% and 60%, respectively. The results suggest that treatment techniques specific for polar and nonpolar contents will be required for the treatment of petroleum hydrocarbon-contaminated groundwater.

Keywords: Fresh groundwater; Contamination; Petroleum hydrocarbons; Treatment

1. Introduction

The Raudhatain–Umm Al-Aish area is situated in the northeastern part of Kuwait. Two oil fields, namely, Raudhatain and Sabriya, are located in the Raudhatain–Umm Al-Aish area (Fig. 1). Sole fresh groundwater resource of country is also located under topographic depressions of Raudhatain and Umm Al-Aish areas within and in the vicinity of Raudhatain and Sabriya oil fields. During the 1991 Gulf War, a total of 613 oil wells were set on fire by the retreating Iraqi troops. Out of these 613 wells, 101 wells were in Raudhatain and Sabriya oil fields. The resulting spillage of huge volumes of crude oil from oil wells gave rise to oil lakes and crude oil-impregnated soil (generally known as sludge). Moreover, products of crude oil combustion spread over a large area in the vicinity of the oil fields, causing widespread contamination of the soil. Oil lakes, sludge, and products of combustion are sources of contamination for the fresh groundwater source of the country. During rainy seasons, these sources of contamination generate petroleum hydrocarbon-contaminated runoff that infiltrated into groundwater and percolated into the fresh groundwater through unsaturated zone of pebbly, gravely, silty, and slightly clayey sand intercalated lenses of clay.

Studies conducted so far in this area, to assess the impact of sources of contamination on fresh groundwater, have

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focused only on the detection and quantification of nonpolar hydrocarbons, such as total petroleum hydrocarbon (TPH), polycyclic aromatic hydrocarbons (PAH) and benzene, toluene, ethylbenzene, and xylene (BTEX) in groundwater, as they are toxins and carcinogenic. However, the detection and the quantification of polar material are equally important not only to assess pollution levels but also for modeling the transport processes in the aquifer to forecast the pollution prospects in the long-term (Al-Awadi et al., 2006), as well as for the selection and designing of methodologies for the treatment of contaminants. Knowing the types and physicochemical properties of contaminants that are present would allow most treatment methods to be selectively eliminated without spending significant amounts of time and money on feasibility studies (Nyer, 1993).

The present study attempts to identify and quantify contaminants in terms of polar and nonpolar materials in the petroleum hydrocarbon-contaminated groundwater of the Raudhatain–Umm Al-Aish fresh groundwater fields.

2. Materials and methods

A total of 10 groundwater monitoring wells in the Raudhatain and Umm Al-Aish fresh groundwater fields were sampled for an investigation of the polar and nonpolar materials in the groundwater. The locations of the wells are depicted in Fig. 1. The wells P1, P12, P34R and P36R are located in Raudhatain fresh groundwater field, whereas, the wells P17, P18, P19, P33UA, P25UA and P27UA-1 are located in Umm Al-Aish fresh groundwater field. Details on the wells are presented in Table 1.

Before the collection of groundwater samples, the wells were purged. Grundfos MP1 submersible pump was used to purge the monitoring wells. During the well purging, temperature, pH, electrical conductivity (EC), dissolved oxygen (DO), and oxidation–reduction potential (ORP) of the produced water were measured at appropriate intervals using standard probes attached to a flow-through cell. After purging three volumes of the water in the well and stabilization of pH and EC values of groundwater, the groundwater samples were collected in laboratory-cleaned, sterilized amber-colored glass bottles. Groundwater recharge to the wells P12, P34R, and P36R was too low to purge using Grundfos MP1 submersible pump, even at its minimum pumping capacity. Therefore, the groundwater samples from these wells were collected using Teflon bailers.

Quality control-quality assurance (QA/QC) samples, field replicates and field blanks (FBs) were also collected. Field replicates, P33UA, and P33UA-D were collected from Well P33UA from the Umm Al-Aish fresh groundwater field. Samples to be used for TPH analysis were preserved with diluted (1:1) hydrochloric acid (HCl) to bring the pH of the sample to below 2 in order to cease possible degradation of biodegradable material. The samples were then packed into ice boxes to reduce and maintain their temperature at 4°C.

The collected groundwater samples were analyzed for total organic carbon (TOC), TPH, ultraviolet (UV)-induced fluorescence emission, phenol, tannin, and lignin and volatile acids. The analysis for TOC, TPH, UV-induced fluorescence emission, phenol, tannin and lignin, and volatile acids was carried out in the laboratories of the Water Research Center (WRC); whereas analysis for VOCs was carried out at the Central Analytical Laboratory of Kuwait Institute for Scientific Research (KISR). Table 2 presents the analytical methods and instruments used for analyses of groundwater samples.

The samples and/or the extract of the samples were treated (mixed) with silica gel to split the polar and nonpolar materials in the samples. Silica gel (silicon hydroxide

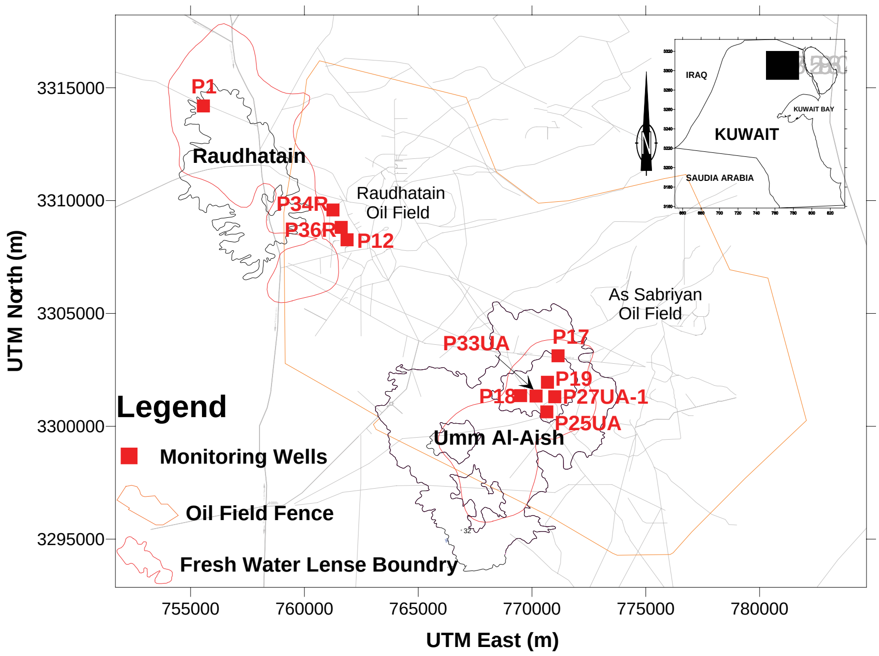

Fig. 1. Locations of the monitoring wells in the Raudhatain–Umm Al-Aish area.

Table 1
Details on the monitoring wells

Well No.	Location	North (m)	East (m)	G. Elevation a msl	Screen Interval m bgl
P1	Raudhatain	3,314,176.18	755,579.84	37.88	29.00–34.00
P12	Umm Al-Aish	3,308,251.85	761,864.59	36.92	32.00–37.00
P17	Umm Al-Aish	3,303,177.53	771,147.22	27.21	15.00–20.00
P18	Umm Al-Aish	3,301,243.66	770,052.68	27.35	15.00–43.00
P19	Umm Al-Aish	3,301,953.06	770,678.21	26.76	16.00–21.00
P25UA	Umm Al-Aish	3,300,638.69	770,650.27	26.50	16.00–19.00
P27UA-1	Umm Al-Aish	3,301,306.88	770,417.23	26.99	16.50–19.50
P33UA	Umm Al-Aish	3,301,341.79	770,175.17	26.47	17.50–20.50
P34R	Raudhatain	3,309,584.02	761,254.53	40.25	33.00–36.00
P36R	Raudhatain	3,308,813.19	761,617.55	42.44	32.00–35.00

Note: R: Raudhatain; UA: Umm Al-Aish.

Table 2
Analytical methods used for analysis of groundwater samples

Parameter	Method	Instrument
TOC	USEAP Method 5310B	TOC analyzer
TPH	USEPA Method 418.1	FT/IR Spectrometer
Fluorescence	Saenz et al. 1991	Spectrofluorophotometer
Phenol	4-Aminoantipyrine method	DR/2000 Spectrophotometer
Tannin and lignin	Tyrosine method	DR/2000 Spectrophotometer
Volatile acids	Esterification method	DR/2000 Spectrophotometer

[SiOH]) is a chemically inert, nontoxic, polar, amorphous form of silicon dioxide (SiO_2). In analytical chemistry, silica gel has been used to separate polar material from solutions. For example, USEPA Methods 418.1 (1993) (Total Petroleum Hydrocarbon) and 1664 (Oil and Grease) (2009) prescribe the use of silica gel to remove polar material from samples to be analyzed for TPH. Similarly, Method 5520 F (hydrocarbons) (APHA, 1998) also prescribes the use of silica gel to remove polar materials. It states that if a solution of hydrocarbons and fatty materials in a nonpolar solvent is mixed with silica gel, the fatty acids are removed selectively from the solution. The materials not eliminated by silica gel adsorption are designated as hydrocarbons. The highly active polar surfaces of the silica gel adsorb polar material by the means of hydrogen or dipole–dipole interaction that binds material onto the surface of the silica gel.

To isolate nonpolar material and measure it as TOC, the water samples were passed through silica gel (4 g) taken into a glass column. The effluent collected, 10 mL, was then analyzed for TOC using a TOC analyzer. To split nonpolar material and to measure it as TPH, the carbon tetra chloride (CCl_4) extracts of the water samples were mixed with 1.5 g of silica gel for 5 min using Teflon-coated magnetic stirrer. The silica-gel-treated extracts were then analyzed for TPH using Fourier transform infrared (FTIR) spectrometer. Same silica-gel-treated extracts of the samples were exposed to 265 nm of UV light in order to estimate the quantity of nonpolar material using a spectrofluorophotometer. To isolate the nonpolar material and measure it as phenol, tannin and lignin, and volatile acids, 100 mL of the sample was mixed with 3 g of silica gel in capped bottles for 15 min using a shaker. The silica-gel-treated water sample was then filtered through Whatman No. 42 filter paper and analyzed for phenol, tannin, and lignin, and volatile acids.

3. Results

Mixing of water from different strata in a well, and in some instances, exposure of the water to the atmosphere may induce chemical instability, even though the original water in place is in equilibrium with its surroundings. This chemical instability may cause changes in certain constituents and requires sample preservation or on-site determination of certain properties of the water (Hem, 1985). Temperature, pH, DO, ORP, CO_2, and alkalinity are so closely related to the environment of the water that they are likely to be altered during sampling and storage. Therefore, meaningful values of these quality parameters can be obtained only when they are measured immediately on-site. Therefore, after completion of well purging, pH, EC, DO, and ORP were measured during purging at appropriate intervals and at the end of well purging. The final values of these parameters are presented in Table 3.

The concentrations of combined polar and nonpolar material in the groundwater samples are presented in Table 4. The concentration of nonpolar material represented the

Table 3
Groundwater quality parameters measured on site

Well No.	Temperature (°C)	pH	EC (µS/cm)	DO (mg/L)	ORP (mg/L)	Odor
P1	28.4	7.82	698	5.33	15.4	–
P12	28.0	6.80	5,240	0.00	–192.4	H_2S
P17	28.0	6.90	900	0.00	–30.4	Hydrocarbon
P18	27.6	6.50	8,190	0.00	–78.8	Hydrocarbon
P19	29.0	6.72	2,753	0.00	–51.1	–
P25UA	28.4	6.98	3,230	5.29	40.0	–
P27UA-1	29.0	6.67	6,750	0.00	–34.0	Hydrocarbon
P33UA	27.7	6.91	10,130	0.00	–56.7	Hydrocarbon
P34R	28.0	7.87	4,650	6.36	41.8	–
P36R	28.0	7.54	12,880	3.24	91.0	–
FB	28.0	7.83	10.50	3.07	2.15	–

EC = electrical conductivity, DO = dissolved oxygen, ORP = oxidation reduction potential.

material that remains in the water sample and/or in the extract of the sample after treatment with silica gel. The concentrations of polar material represent the material removed (adsorbed) by silica gel from the water sample and/or from the CCl_4 extract of the sample. The concentration of polar material was obtained by subtracting the concentration of nonpolar material from the combined concentration of polar and nonpolar material in the sample and/or extract of the sample before silica-gel treatment. Table 5 presents minimum, maximum, and average (%) concentrations of TOC, TPH, UV-induced fluorescence, phenol, tannin and lignin, and volatile acids in terms of polar and nonpolar material as percentage.

3.1. Polar and nonpolar materials as total organic carbon

The concentrations of polar and nonpolar materials as TOC in the groundwater samples from the Raudhatain–Umm Al-Aish fresh groundwater field are presented in Table 4 and plotted in Fig. 2. The TOC (polar and nonpolar) of the groundwater samples ranged between 0.53 and 38.12 mg/L, with a mean value of 12.29 mg/L.

The results with regard to polar and nonpolar materials as TOC indicated material in the groundwater dominance of nonpolar material (58%) compared with polar material (42%; Table 5). Polar material as TOC was not detected in the groundwater samples from the monitoring wells P1, P12, P25UA, P34R, and P36R.The slight higher amount of nonpolar material as TOC in the samples from monitoring wells P1, P12, P34R, and P36R may be attributed to leaching of trace amounts of organics either from the silica gel or from the glass wares during testing.

3.2. Polar and nonpolar materials as total petroleum hydrocarbon

TPH is the total concentration of the hydrocarbons extracted and measured in groundwater samples. The concentrations of polar and nonpolar materials as TPH in the groundwater samples are presented in Table 4 and plotted in Fig. 3.

The combined concentration of polar and nonpolar material in the groundwater ranged between 0.06 and 2.21 mg/L, with a mean value of 0.75 mg/L. The overall comparison of polar and nonpolar materials indicated that the groundwater was dominantly composed of polar material (86%) as compared with nonpolar material (14%) (Table 5). However, it was dominantly composed of nonpolar material (67%) when compared with polar material (33%) in the groundwater samples from the wells P1.

3.3. Ultraviolet-induced fluorescence

UV-induced fluorescence intensity is a qualitative measure used for identification of the presence of organic contaminants (Al-Awadi et al., 2001). Fluorescence is extremely sensitive and many factors (type of solution, pH, ionic strength, temperature, ORP, and interactions with metal ions and organic substances) affect its emission (Senesi, 1990). Of the dissolved organic matter, only 40% to 60% was fluorescent; this fluorescent material principally comprised of protein and organic acids (Senesi, 1993).

The UV-induced fluorescence intensities due to polar and nonpolar materials in the CCl_4 extracts of the samples are presented in Table 4. Fluorescence was not detected in the CCl_4 extracts of water samples from wells P1, P12, and P34R. A high fluorescence intensity indicated a high concentration of the material. The comparison indicated that the material in the groundwater samples was dominantly composed of polar material (84%) as compared with nonpolar material (16%; Table 5). While it was dominantly composed of polar material in the groundwater samples of the monitoring wells P17, P18, P19, P27UA-1, and P33UA, it was entirely of polar material in groundwater samples from wells P25U and P36R. A comparison of fluorescence intensities of groundwater samples is presented in Fig. 4.

3.4. Polar and nonpolar materials as phenol

Phenols are organic compounds which contain a hydroxyl (–OH) group attached to a carbon atom in a benzene ring or in a more complex aromatic ring system. The simplest member of this group is phenol. It is also known as carbolic acid, benzenol, phenylic acid, hydroxybenzene, and phenic acid. Due to hydrogen bonding, most low-molecular-weight

Table 4
Polar and nonpolar materials in groundwater samples

Well	TOC (mg/L)			TPH (mg/L)			Fluorescence			Phenol (mg/L)			Tannin and lignin (mg/L)			Volatile acids (mg/L)		
No.	P&NP	P	NP	P&NP	P	NP	P&NP	P	NP	P&NP	P	NP	P&NP	P	NP	P&NP	P	NP
P1R	0.74	–	0.80	0.06	0.02	0.04	–	–	–	–	–	–	–	–	–	–	–	–
P12R	1.31	–	1.40	0.20	0.17	0.03	–	–	–	0.016	0.016	0.000	2.40	1.60	0.80	27.00	2.00	25.00
P17U	10.61	6.50	4.11	0.42	0.37	0.05	3.23	2.39	0.84	–	–	–	0.10	0.10	0.00	10.00	10.00	0.00
P18R	38.12	31.69	6.43	2.21	2.19	0.02	13.05	9.51	3.54	0.019	0.019	0.000	2.80	0.20	2.60	24.00	24.00	0.00
P19R	11.80	8.42	3.38	0.38	0.34	0.04	4.53	3.24	1.29	0.001	0.001	0.000	0.60	0.10	0.50	18.00	18.00	0.00
P25UA	0.69	–	0.75	0.11	0.08	0.03	2.24	2.24	–	–	–	–	–	–	–	–	–	–
P27UA-1	21.89	17.57	4.32	1.45	1.38	0.07	15.51	13.53	1.98	0.034	0.020	0.014	1.90	0.50	1.40	24.00	23.00	1.00
P33UA	24.79	20.01	4.78	1.63	1.54	0.09	16.48	13.69	2.79	0.005	0.001	0.004	3.20	1.00	2.20	1.00	1.00	0.00
P33UA-D	24.15	19.48	4.67	1.54	1.47	0.07	16.63	14.08	2.55	0.016	0.005	0.011	3.20	1.00	2.20	1.00	1.00	0.00
P34R	0.53	–	0.60	0.10	0.09	0.01	–	–	–	–	–	–	0.50	0.10	0.40	2.00	2.00	0.00
P36R	0.59	–	0.61	0.13	0.13	–	1.29	1.29	–	0.001	0.001	0.000	0.80	0.50	0.30	1.00	1.00	0.00
FB	0.37	–	0.50	0.23	0.16	0.07	–	–	–	–	–	–	–	–	–	–	–	–

Note: P&NP: Polar and nonpolar; P: polar; NP: nonpolar. –: not detected.

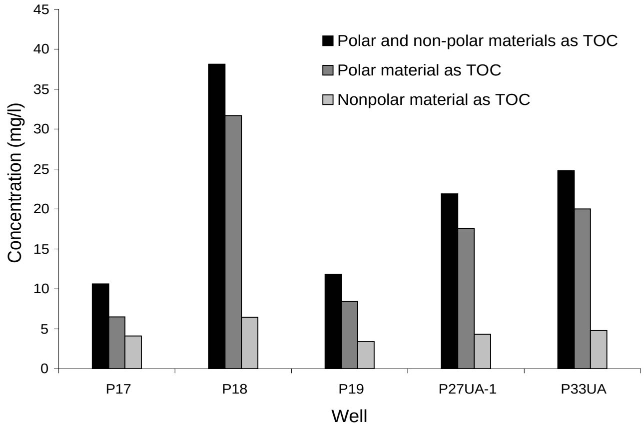

Fig. 2. Polar and nonpolar materials as total organic carbon.

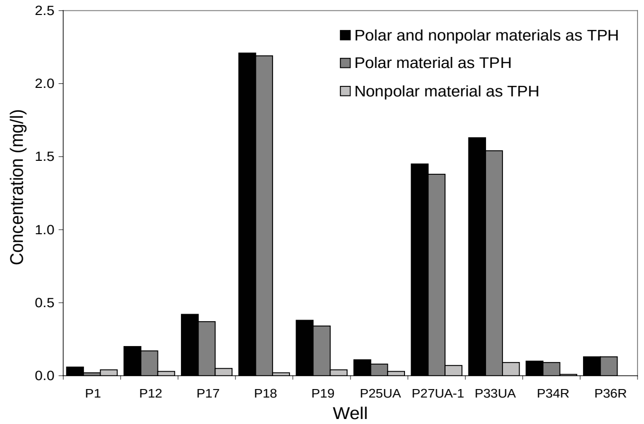

Fig. 3. Polar and nonpolar materials as total petroleum hydrocarbon.

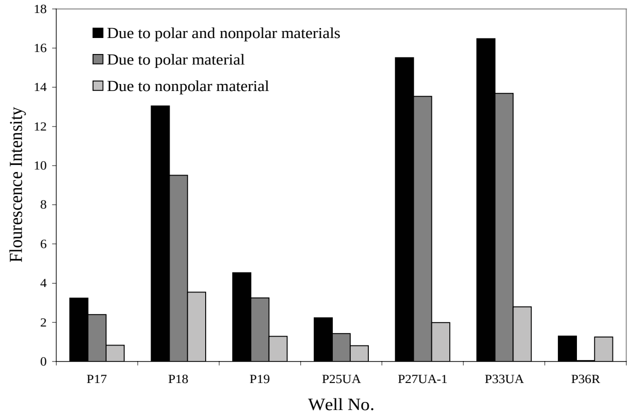

Fig. 4. Comparison of fluorescence intensities.

phenols are water-soluble (i.e., polar) while high-molecular weight phenols are less water-soluble (i.e., nonpolar).

Phenol and its structurally related compounds are toxic at relatively low concentration and have been listed as priority pollutants by USEPA. Natural waters normally contain less than 1 μg/L (0.001 mg/L), but concentrations up to 20 μg/L (0.02 mg/L) may occur in some areas (Rittmann and McCarty, 2001).

The observed concentrations of phenol (polar and nonpolar) and phenol (as polar) and phenol (as nonpolar) materials in the groundwater are presented in Table 4 and plotted in Fig. 5. The concentration of phenol in the groundwater samples ranged between 0.001 and 0.034 mg/L, with a mean value 0.013 mg/L. Phenol was not detected in groundwater samples from the wells P1, P17, P25UA, and P34R. The monitoring well P1 is located at uncontaminated site of the Raudhatain fresh groundwater field. The monitoring wells P17, P25UA, and P34R are located at contaminated sites, and TOC and TPH analysis of water samples from these wells indicated presence of hydrocarbon contaminants. However, the lack of phenol in the groundwater samples from monitoring wells P17, P25UA, and P34R may be attributed to lack of phenol in the source of contamination and/or its biodegradation at these monitoring well locations.

Overall comparison indicated that phenol was dominantly composed of polar material (73%) as compared with nonpolar material (27%) (Table 5), and it was entirely composed of polar material in the groundwater samples from monitoring wells P12R, P18UA, P19UA, and P36R.

3.5. Polar and nonpolar materials as tannin and lignin

Tannin and lignin are naturally occurring chemical compounds, most frequently found where large quantities of vegetation have decayed. Water that has tannin and lignin appears to be faint yellow to brown in color and may have a slightly bitter taste. The USEPA has no guidelines for expected levels in drinking water, because there is no risk associated with these compounds other than possibly that of a slight stimulant; however, some migraine sufferers believe that tannin can trigger a migraine (Belkraft.com, 2005).

The concentrations of tannin and lignin (polar and nonpolar materials) and polar and nonpolar materials as tannin and lignin concentrations in the groundwater samples are presented in Table 4 and plotted in Fig. 6. Tannin and lignin were not detected in the groundwater samples from the wells P1 and P25UA.

The concentrations of tannin and lignin (polar and nonpolar) in the groundwater ranged between 0.10 and 3.20 mg/L, with a mean value 1.72 mg/L. The comparison of polar and nonpolar materials as tannin and lignin indicates that it is dominantly composed of nonpolar material (60%) as compared with nonpolar material (40%; Table 5).

3.6. Polar and nonpolar materials as volatile acids

The method employed to measure the concentrations of volatile acids in the groundwater samples is based on the esterification of carboxylic acids present and the determination of the esters by ferric hydroxamate reaction. Carboxylic acids are organic acids characterized by the presence of a carboxyl group, –C(=O)OH, usually written as –COOH (Mc Naught and Wilkinson, 1997). The simplest series of carboxylic acids is the alkanoic acids, R–COOH, where R is hydrogen or an alkyl group (C_nH_{2n+1}). They are produced by oxidation of primary alcohols or aldehydes; they may also be produced by the oxidative cleavage of olefins (unsaturated open-chain hydrocarbons) by means of ozonolysis. In particular, any alkyl group on a benzene ring is fully oxidized to a carboxylic acid, regardless of its chain length. Hydrolysis of nitriles, esters, or amins can also produce carboxylic acids. Lower carboxylic acids (1 to 4 carbon) are miscible (i.e., polar) with water; whereas, higher carboxylic acids are less soluble (nonpolar) due to the increasing hydrophobic nature of the alkyl chain (Morrison and Boyd, 1992).

The concentrations of volatile acids (polar and nonpolar combined), polar and nonpolar components of volatile

Table 5
Comparison of polar and nonpolar materials in the groundwater of the study areas

Parameter	Polar material (%) Min, Max, (Avg)	Nonpolar material (%) Min, Max, (Avg)
TOC	0, 83.13, (41.58)	16.87, 100, (58.42)
TPH	33.33, 100, (85.71)	0, 66.67, (14.29)
UV-induced	71.52, 100, (84.17)	0, 28.48, (15.83)
Phenol	20, 100, (72.87)	0, 68.75, (27.13)
Tannin and lignin	7.14, 66.67, (40.20)	0, 92.86, (59.80)
Volatile acids	7.41, 100, (89.96)	0, 92.59, (10.72)

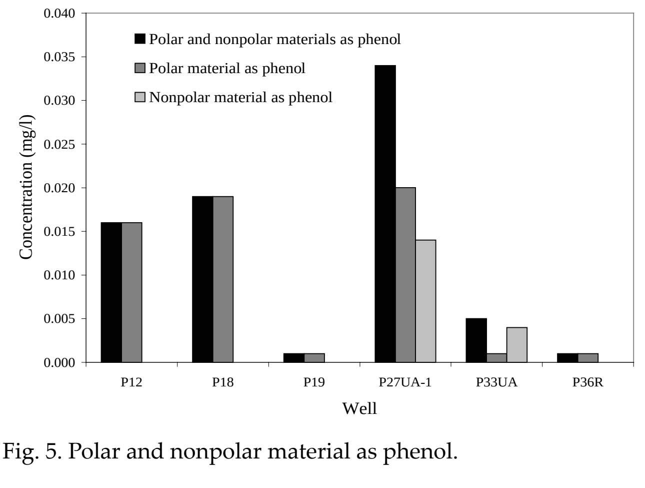

Fig. 5. Polar and nonpolar material as phenol.

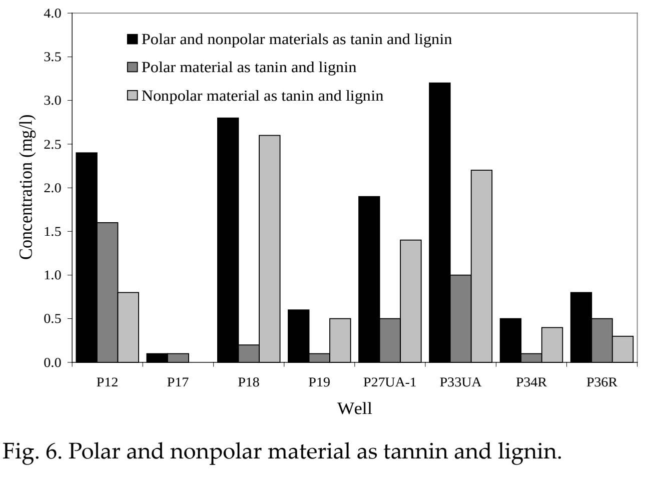

Fig. 6. Polar and nonpolar material as tannin and lignin.

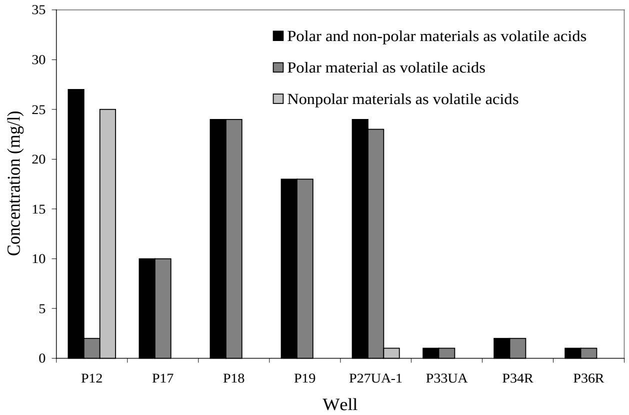

Fig. 7. Polar and nonpolar material as volatile acids.

acids observed in the groundwater samples are presented in Table 4 and plotted in Fig. 7. The concentrations of volatile acids (polar and nonpolar combined) ranged between 1.00 and 27.00 mg/L, with a mean value of 12.00 mg/L. Volatile acids were not detected in the groundwater samples from the wells P1 and P25UA.

A comparison of polar and nonpolar materials as volatile acids indicated that the material in the groundwater samples was dominantly composed of polar material (89%) as compared with nonpolar material (11%; Table 5), and was entirely composed of polar material in groundwater samples from monitoring wells P17, P18, P19, P33UA, P34R, and P36R.

4. Conclusion and recommendations

The results of groundwater quality measurements, taken on site, indicated the presence of slightly acidic, fresh to brackish groundwater in reduced environments at organic- and hydrocarbon-contaminated groundwater sites in the Raudhatain and Umm Al-Aish fresh groundwater fields. The acidic character of the groundwater was ascribed to the presence of organic acids and H_2S.

The TPH, UV-induced fluorescence, phenol, and volatile acids results indicated that the contaminants in the groundwater of the Raudhatain and Umm Al-Aish fresh groundwater fields were dominantly composed of polar material (86%, 84%, 73%, and 90%, respectively), whereas, the TOC, and tannin and lignin results indicated that they were dominantly composed of nonpolar material (58% and 60%, respectively). The higher concentration of polar material in the groundwater may be attributed to weathering of crude oil and its combustion products. When crude oil is exposed to atmospheric conditions, a number of natural processes such as evaporation, emulsification, dispersion, sedimentation, dissolution, photo-oxidation, and biodegradation take place simultaneously. The most significant weathering process for oil spill is evaporation, due to which, more volatile fraction of oil was lost within the few hours. Oxidation of crude oil by the action of ultraviolet radiation in sunlight (photo-oxidation) and by microbes which utilize them as food source (bio-oxidation or bio-degradation) produces oxidation products which are generally more soluble (polar). The results suggest that treatment techniques specific for polar and nonpolar contents will be required for the treatment of petroleum hydrocarbon-contaminated groundwater.

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Study on the local sea water temperature variation for the industrial water use of Al-Zour coastal area in Kuwait

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ABSTRACT

Ras Al-Zour coastal area, located in southern part of Kuwait, is the region of concentrated industrial water use and sea intake-outfall of existing power plants. There are some of undergoing construction projects such as Al-Zour Refinery, Al-Zour LNG import facility projects, and the expansion planning of existing power plant. The site of Al-Zour LNG import facility project is located close to the power plant in north direction approximately 0.6 km away from the shore between the Sulphur pier and the small boat harbor north of the breakwater. Being located only 3 km away from the massive thermal and brine discharge from power plants, the future water use of LNG regasification facility will be under the direct influence of thermal discharge from power plants and the further development of seawater resources within this area such as Al-Zour North power plant project. There are two issues regarding the seawater temperature in this area to be considered: (1) variations in background water temperature mostly under combined effect of local meteorology and global climate change; (2) increase of temperature due to the expansion of the thermal discharge of expanded power plant. Annual water temperatures of two candidate locations of the seawater intake for Al-Zour LNG regasification facility were measured during 2017, which shows a typical seasonal variation of a local seawater temperature with an added effect of the neighboring thermal outfall. The numerical model study was performed by using MIKE3-DHI to reproduce 2017-measurement of the sea water temperature during June–July based on the meteorological hindcast data from ECMWF (European Centre for Medium-Range Weather Forecasts) and the thermal discharge input from the southern power plants. It was found that the daily sea water temperature at the measurement location is mainly affected by thermal plume dispersion oscillating with the phase of tidal current. Thermal discharge expansion plan in ~10 km area around the new facility should be considered to obtain the exactly estimated intake water temperature limit during the design life of the facility.

Keywords: Al-Zour area; Industrial water use; Thermal discharge; Seawater temperature; Heat exchange

1. Introduction

Along the coastline of Arabian Gulf, increase of demand of industrial water use and sea water intake-outfall is one of the key factors of environmental changes. Nowadays, many construction projects are ongoing along the coastline of Arabian Gulf including the coastal area of Kuwait as well.

Nowadays, industrial plants are developed to be clustered in a specific complex supporting common infrastructures and utilities, thus the additive sea water intakes and outfalls tend to be installed adjacent to those of existing plants. This makes the prediction of local sea water temperature much more complicated. Therefore, it becomes gradually important to assess the sea water temperature of existing condition exactly and predict the future sea water temperature with possible expansion scenarios.

Impact of overall global warming should be considered as well because local coastal water is closely affected by the seasonal and annual variation of regional sea water temperature. Nandkeolyar et al., (2013) reported that a sharp increase (warming) in sea water temperature was found in the Arabian Gulf from 1992 to 2009. Since 1995, it is reported that repeated extended periods of elevated temperature

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in the Gulf have resulted in mass coral bleaching (Coles & Riegl, 2012).

Al-Zour area become one of the major industrial complex in Kuwait, in which many of power and oil refinery plants are developed and still under development. Among them, Al-Zour LNG import facility projects, and the expansion planning of existing power plant are also in progress. The site of Al-Zour LNG import facility project is located near to the power plant in north direction approximately 0.6 km away from the shore between the Sulphur pier and the small boat harbor's north of the breakwater. Being located only 3 km away from the massive thermal and brine discharge from power plants, the future water use of LNG regasification facility will be under the direct influence of thermal discharge from the southern power plants and the further development of seawater resources within this area.

Uddin et al. (2011) provide recorded sea water temperature during 1993 and 2003 by KEPA (Kuwait Environment Public Authority) at Ras Al-Zour station – the seasonal variation of sea water temperature at Al-Zour is reaching 35°C in summer and 14° in winter. Pokavanich et al. (2015) also provide sea water temperature measured data for their model validation at off-Khiran (28°56.805′N, 48°34.397′E). The data are varied from 15°C to 35°C for a year.

Being reviewed ECMWF(European Centre for Medium-Range Weather Forecasts)'s ERA-interim reanalysis climatology data, the hindcast data at 28.66°N, 48.43°E indicated that the annual mean sea water temperature is 25.03°C during year 1979–2015, meanwhile the maximum and minimum sea water temperature was 33.9°C in August and 15.1°C in February. Table 1 shows monthly mean of daily mean climatology of sea water temperature close to Al-Zour area from ERA-interim reanalysis data.

In this study, the sea water temperature variation in 2017 around the Al-Zour LNG Import Facility under construction was reproduced by the numerical modeling. Real water temperature was measured during 2017 in 5 min interval at two candidate points (T1 and T2 in Fig. 1 and Table 2) for the intake head. Together with the marine meteorological condition during the measurement period, thermal discharge from southern power plant was also considered in the reproduction of local water temperature. With those conditions, it was assessed its effect on the temperature variation.

2. Hydrodynamic model setup

The hydrodynamic and thermal study in Al-Zour site was carried out with MIKE 3-FM (Flexible Mesh) of DHI.

Table 1
Climatology of sea water temperature near Al-Zour location (28.66°N, 48.43°E) during 1979–2015 (extracted from ECMWF ERA-interim atmospheric reanalysis model)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Mean	17.9	17.0	18.2	21.6	25.9	29.1	31.0	32.2	31.4	29.1	25.4	21.1
Max	20.4	18.6	19.9	23.3	27.3	30.5	32.1	33.9	33.1	30.9	26.6	22.9
Min	15.6	15.1	16.0	20.0	24.0	26.4	29.2	29.7	29.4	27.2	23.4	18.3

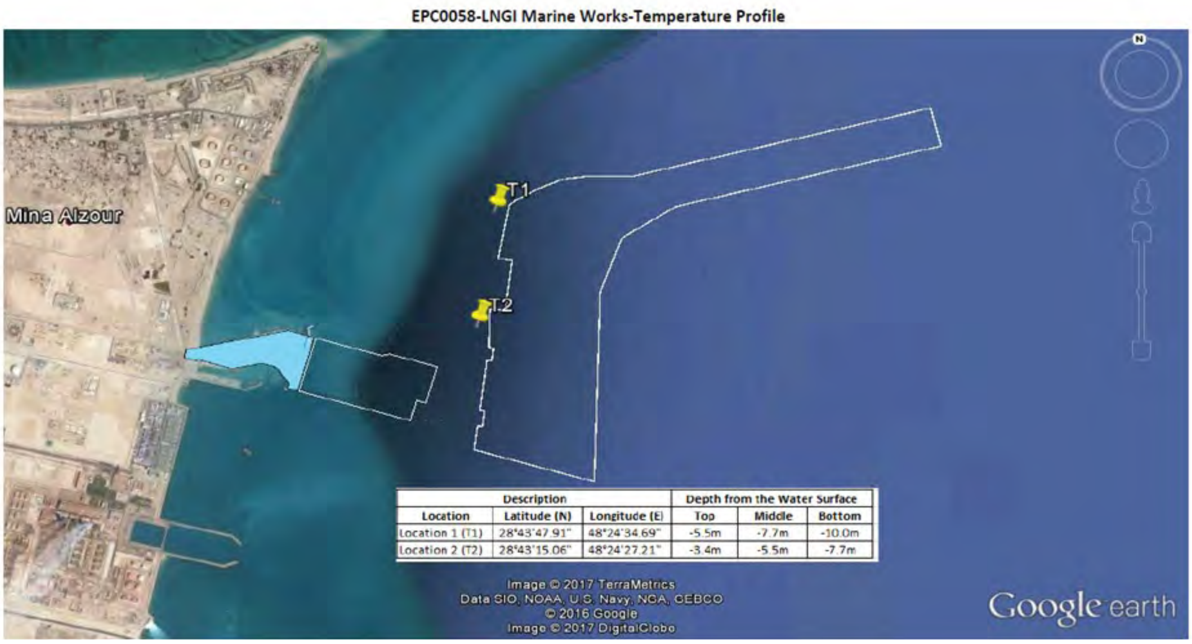

Fig. 1. Schematic layout of Al-Zour LNG site and sea water temperature monitoring points.

Table 2
Coordinate and vertical depth of measurement at each location

No	Description	Coordinate			
		on UTM (39 R)		on Degrees, Minutes, Seconds	
1	T1	3,180,820.222 N	246,999.002 E	28°43′47.91″ N	48°24′34.69″ E
		Surface	Top	Middle	Bottom
		N/A	–5.5 m	–7.7 m	–10.0 m
2	T2	3,179,813.336 N	246,774.098 E	28°43′15.06″ N	48°24′27.21″ E
		Surface	Top	Middle	Bottom
		–3.4 m	–5.5 m	–7.7 m	N/A

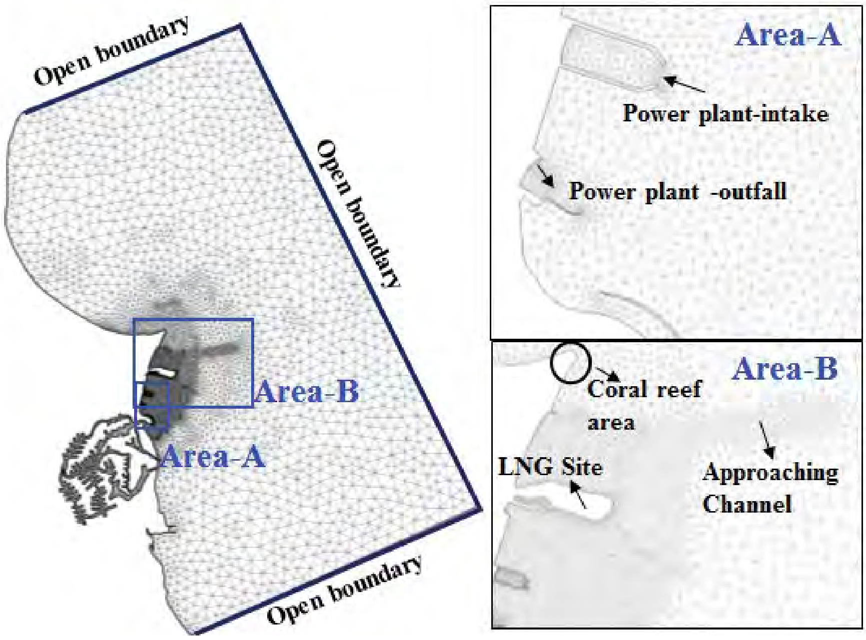

Fig. 2. Al-Zour hydrodynamic model mesh including vicinity facilities.

MIKE 3 is a general numerical modeling system for the simulation of flows in estuaries, bays and coastal areas as well as in oceans. It simulates unsteady three-dimensional flows taking into account density variations, bathymetry and natural forcing such as tide, wind and atmospheric temperature based on the Boussinesq approximation in buoyancy. The model was nested from Arabian Gulf – regional model to provide open-boundary conditions on the nested boundaries. Nested Al-Zour model was developed in 5 sigma vertical layered model with 14,173 elements of horizontal triangular grid. Minimum size of mesh is 20 meters along outfalls and maximum size of mesh is 1 km near open boundaries. The bathymetry information was extracted from MIKE C-MAP. The model covers 20 km towards shoreline and 35 km along-shore line. Fig. 2 shows project area and vicinity facilities.

The simulation period determined 2 months from June to July of 2017 in order to see the model's reproduction of the increasing seawater temperature in this period and to find out the contribution of local thermal discharge from southern power plant. Open boundary condition was extracted from Arabian Gulf – regional model. This regional model has been calibrated in current velocity, current direction and water surface elevation in several coastal locations in Arabian Gulf. Smagorinsky formulation was applied for the horizontal eddy viscosity and k-epsilon formulation was used for the vertical eddy viscosity. Bed resistance was set by the roughness height with constant value 0.05 m. Wind forcing was incorporated with ERA-5 hourly data set provided by ECMWF in timely and spatially varied wind speed and surface pressure.

Latent and sensible heat exchange was based on the given formula in MIKE3. The time series of short wave radiation was included from the extracted data of ERA-interim dataset of ECMWF. The maximum surface short wave was reaching 978 W/m^2 during June–July 2017 in this area. The long wave radiation was calculated with MIKE3 provided formula with using air temperature data input. Air temperature was obtained both from ECMWF hindcast reanalysis data and the hourly records of meteorological observation inside Kuwait City. Applied atmospheric temperature in Kuwait City and sea water temperature measured at T1 surface was compared in Fig. 3. Relative humidity and clearance was set 17% and 70% for whole simulation period. Model parameters related to heat exchange between sea water surface and atmosphere is summarized in Table 3. The open-boundaries sea water temperature was obtained from the surface water temperature in 6 hourly data of ERA-interim dataset (Fig. 4).

3. Simulation without thermal discharge

Model calibration was implemented without introduction of thermal discharge in the domain. Natural sea water temperature was driven by the modeling only with meteorological conditions such as radiation stress, wind and others. In this sense, natural heat transfer in the water body can be described without any interruption of other sources.

Heat exchange parameters are tuned to fit the sea water surface temperature data of ERA-interim. Iteratively, each parameter was tested to check sensitivity of sea water temperature changes. With different parameters, the sensitivity of difference was compared in RMSE base. Calibration sequences are numbered below and its results are shown in Fig. 5.

- *Sequence 1*. Open boundary input of sea surface water temperature from ERA-interim data set + air temperature from ERA-interim data set
- *Sequence 2*. Sequence 1 setup + ERA-interim short wave radiation data
- *Sequence 3*. Sequence 2 setup + heating coefficient calibration
- *Sequence 4*. Sequence 3 + measured air temperature at Kuwait City instead of air temperature from ERA-interim data set in Sequence 1

It is shown that short wave radiation, heating coefficient and air temperature can be major parameter for calibration of water body's temperature (Table 4).

4. Simulation with thermal discharge

Local hydrodynamics during simulation period was reproduced by the tidal elevation change on the open

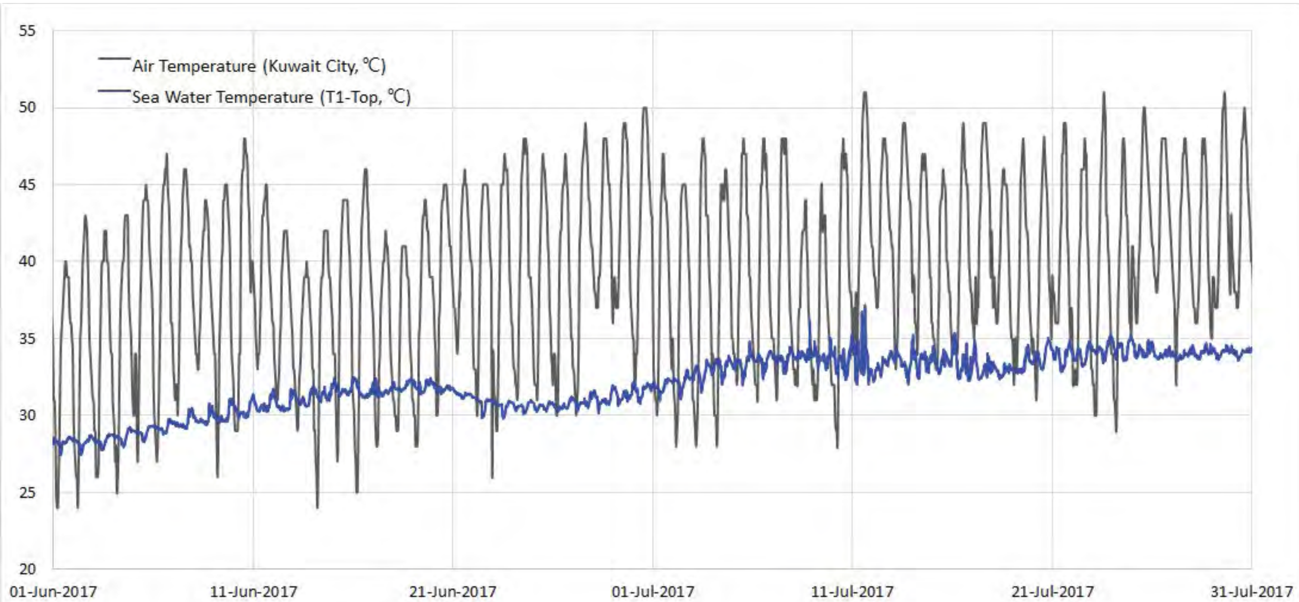

Fig. 3. Sea surface temperature for boundary condition, extracted from ECMWF interim data set.

Table 3
Heat-exchange parameters

Parameter	References or sources	Remarks
Heating coefficient	Calibration factor	Mostly major impact
Short wave radiation	Empirical method, ECMWF dataset	ECMWF dataset was selected
Air temperature	ECMWF dataset, local measurement	Local measurement was selected
Relative humidity	17%	Fixed
Clearance	Calibration factor (Minor impact)	70% was selected
Evaporation rate	Minor impact (almost no changes)	Not included

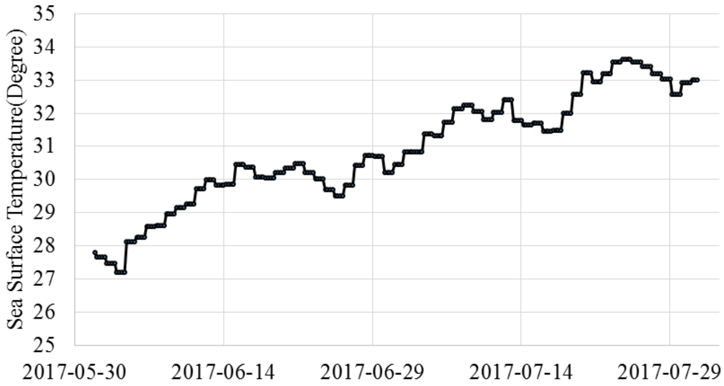

Fig. 4. Sea surface temperature for boundary condition, extracted from ERA-interim data set.

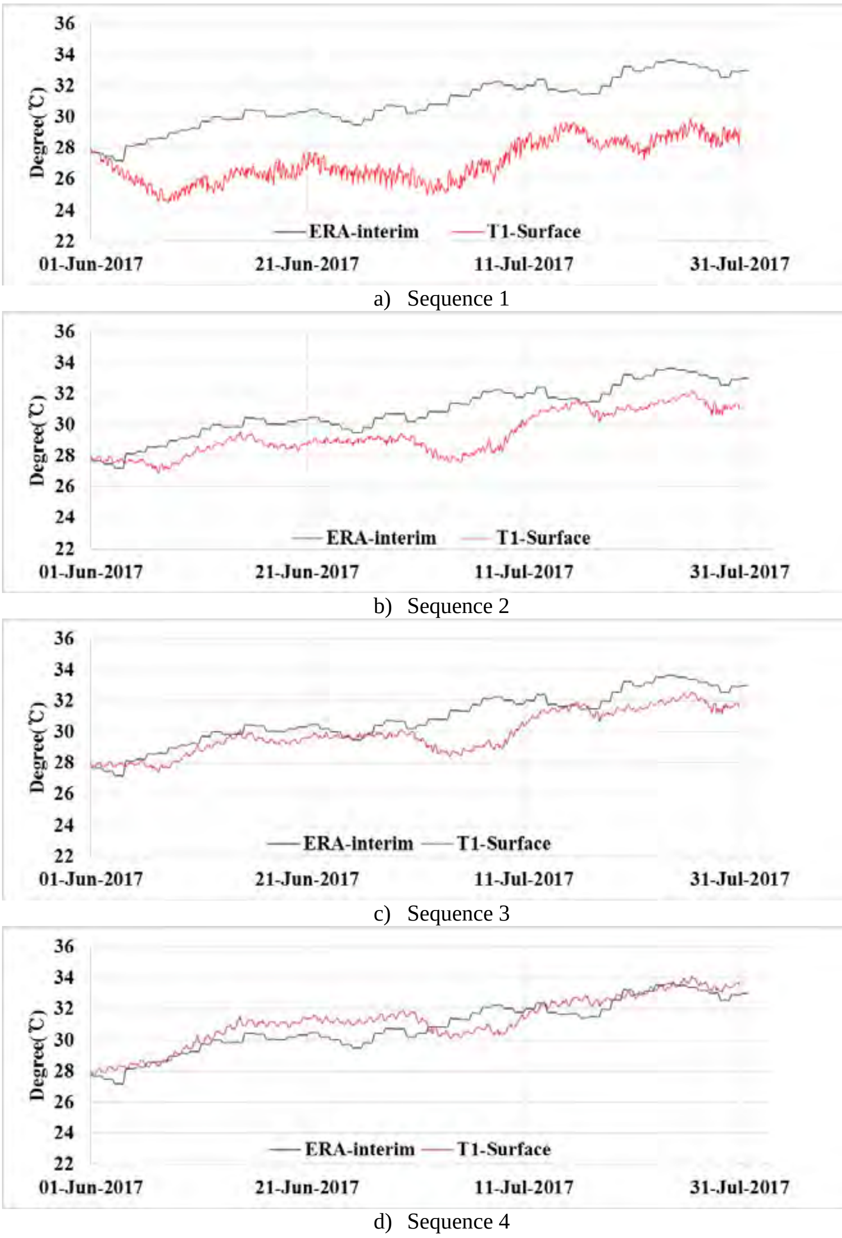

Fig. 5. Comparison result of heat-exchange in different parameter setting. (a) Sequence 1, (b) sequence 2, (c) sequence 3, (d) sequence 4.

Table 4
Comparison of calibration result, subtracted in series

Sequence	RMSE (°C)	NRMSE (%)
1	3.95	78.5
2	1.76	34.0
3	1.27	25.2
4	0.80	13.6

boundaries and the wind forcing on the surface. Thermal discharge from the surface outfall of southern power plant was defined in the model with 131 m³/s of flowrate and 6°C of excess water temperature in the one-through cooling system but this is roughly averaged discharge scenario due to the absence of detailed operation record of the power plant. The resultant mean current speed around the LNG site is varied in 0.1 to 0.15 m/s whereas Ras-Al Zour reef area (Northern part of Kuwait LNG Import site) reaches by

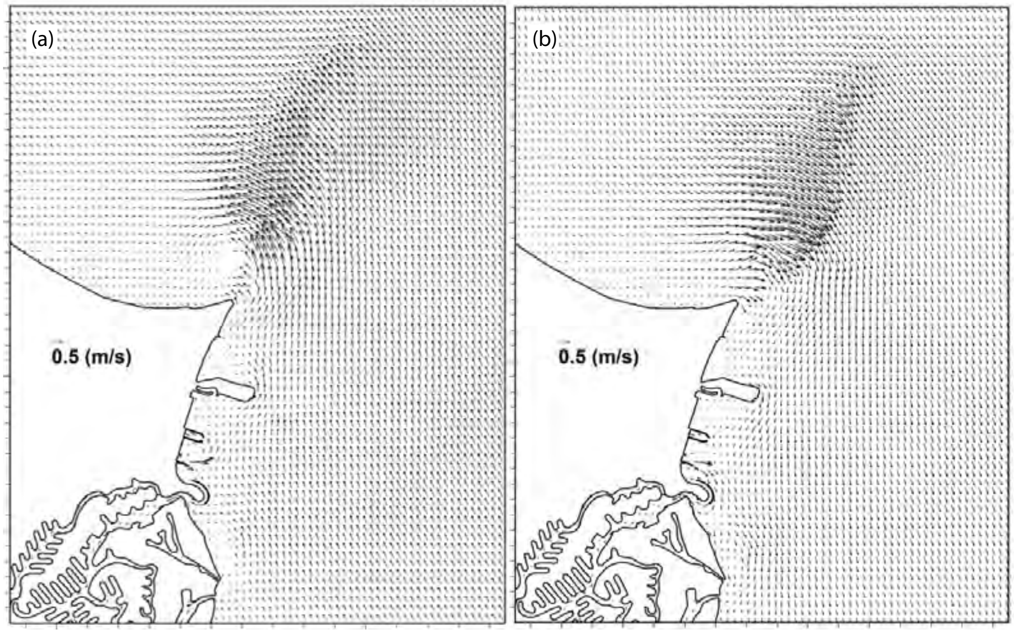

Fig. 6. Local hydrodynamic in flood (a) and ebb (b) tide.

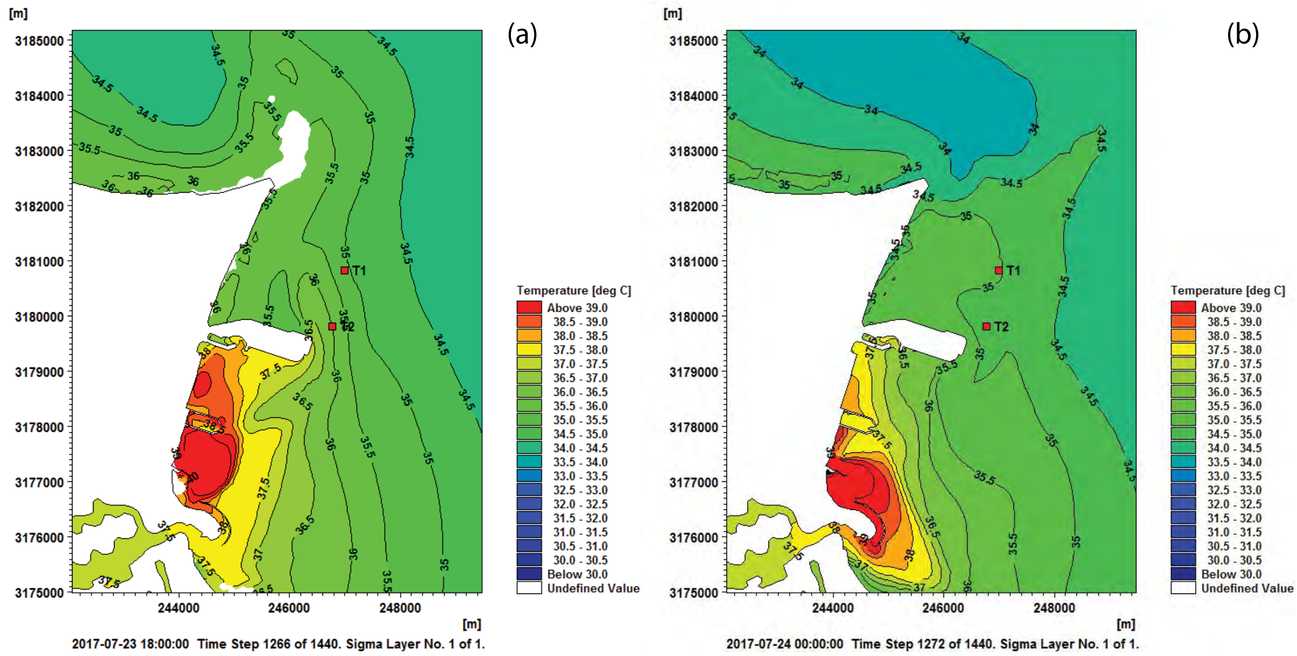

Fig. 7. Sea water temperature distribution with thermal discharge in flood (a) and ebb (b) tide.

0.4 m/s. Maximum current speed around LNG site is 0.2 to 0.3 m/s, whereas Ras Al-Zour coral reef area is over 0.7 m/s. The overall circulation pattern is tidally driven oscillatory current in alongshore direction.

Discharged plume from the southern power plant's outfall is moving back and forth in north and south direction forming a large thermal cloud reaches from the entrance of Al Khiran to the corner of coral reef area (Fig. 7).

The overall rise of measured water temperatures during simulation period were compared with simulation results at corresponding points in Figs. 8 and 9. Simulation results correspond well with the daily mean temperature increase in measurement especially on the top measurement point. Crests in temperature fluctuation occur when the sea current direction is toward north. The amplification of fluctuations is higher in measurement than in simulation results, especially in the bottom layer.

The water temperature at T2 is more dependent on the thermal dispersion from power plant than the temperature at T1 because of its closer distance from outfall point. Temperature fluctuation is also more severe in T2 than T1, which is under direct tidal fluctuation depending on the thermal plume movement. Fluctuation in simulation results reaches to 2°C at T2 whereas it was reduced to 1°C level

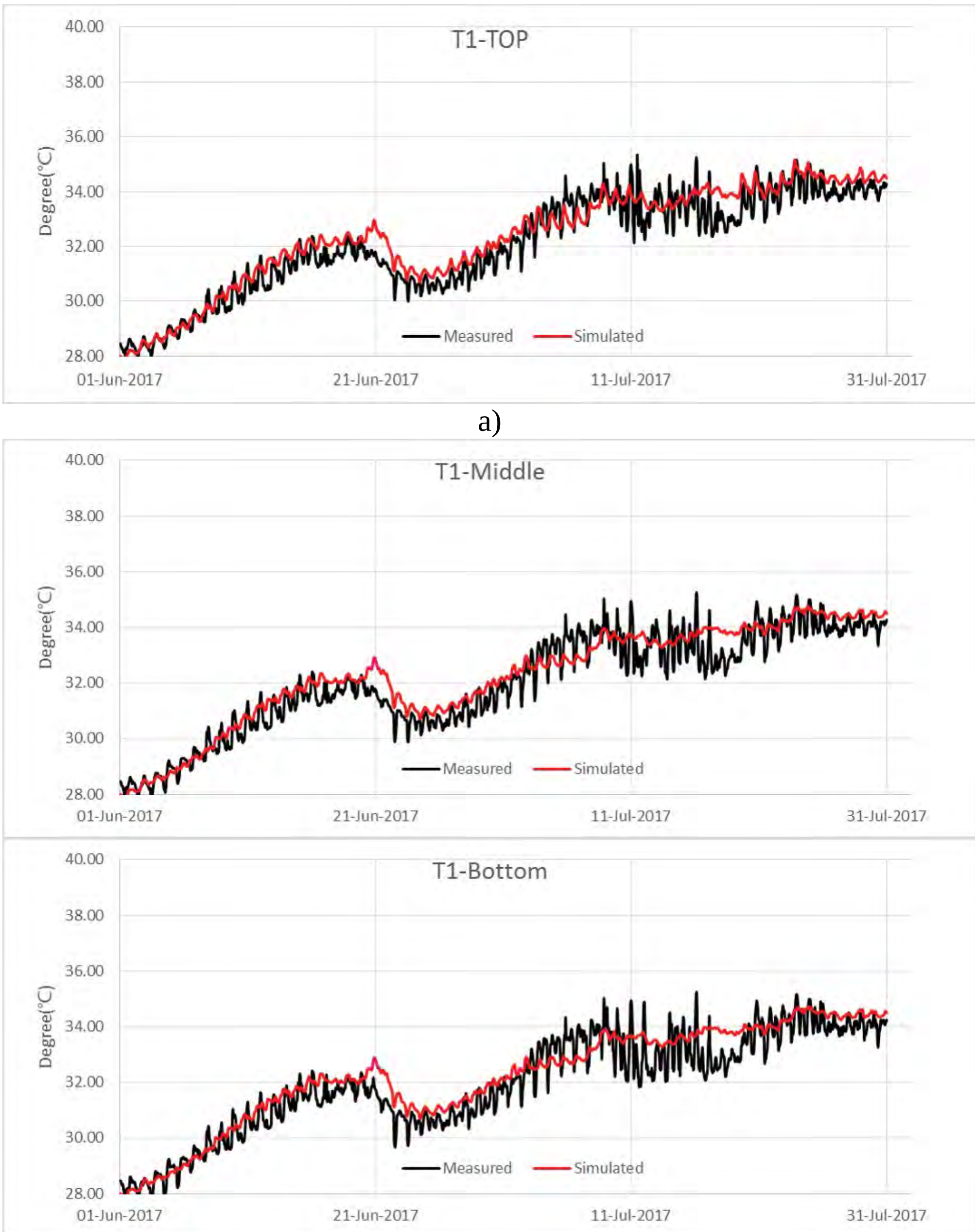

Fig. 8. Comparison of simulation result and measured data at T1 during simulation period Jun–July 2016 (Top:–5.5 m, middle: –7.7 m and bottom –10 m from the sea surface).

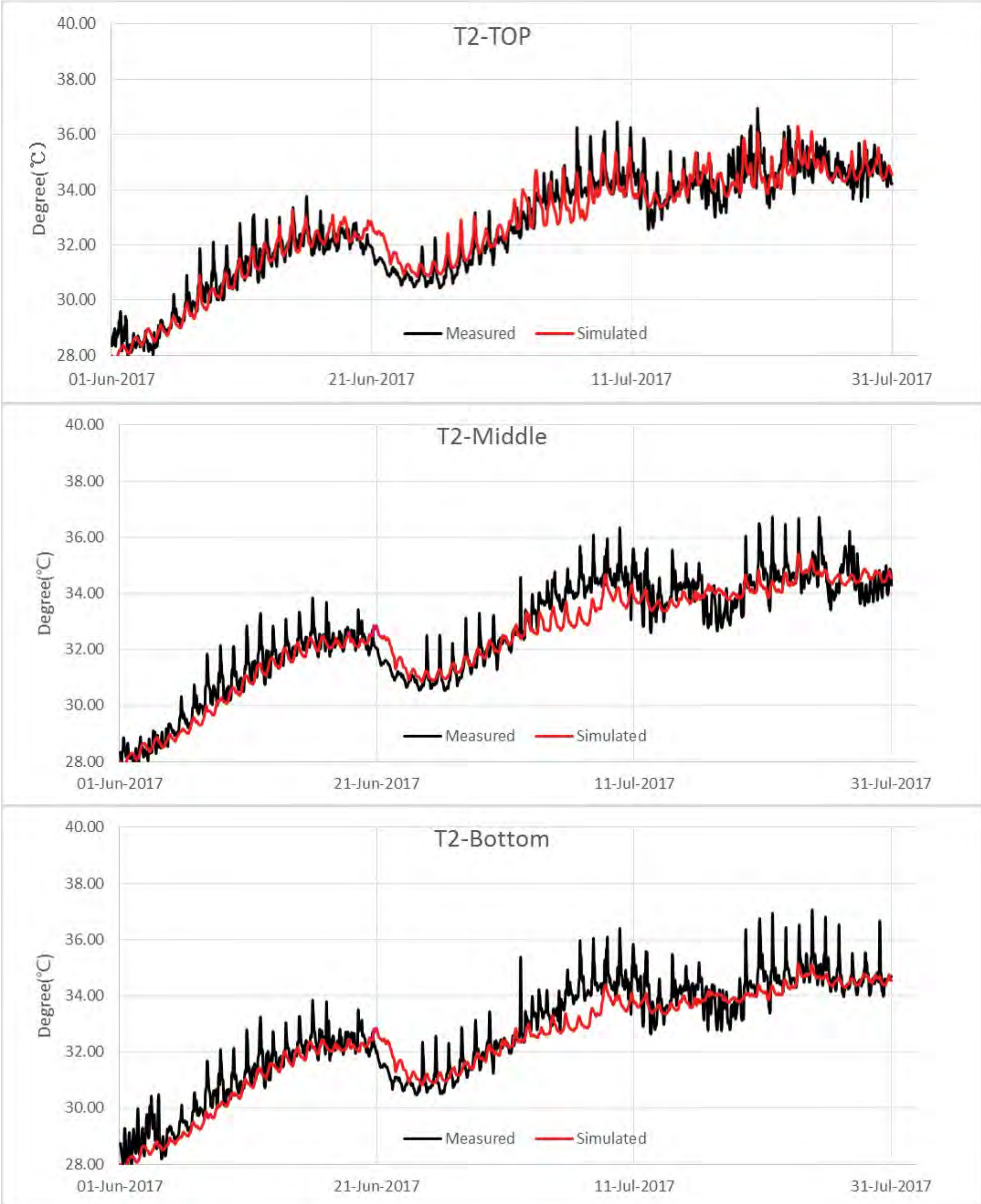

Fig. 9. Comparison of simulation result and measured data at T1 during simulation period Jun–July 2016 (Top:–3.5 m, middle: –5.5 m and bottom –7.7 m from the sea surface).

at T1. This amplification is 2–4 times larger than the 0.5°C fluctuation of thermal plume temperature of simulation without local discharge (Fig. 5).

The maximum temperature of measurement and simulation results during June–July was listed in Table 5. Compared with the regional maximum surface water temperature from ERA-interim hindcast data was 33.63°C (Fig. 4), the effect of thermal discharge on the local water temperature can be estimated at least 1.7°C at T1 and 3.3°C at T2. The simulation results underestimated the maximum

Table 5
Comparison of maximum temperatures

	Measurement (°C)		Simulation (°C)	
	T1	T2	T1	T2
Top	35.34	36.91	35.15	36.29
Middle	35.25	36.72	34.76	35.40
Bottom	35.23	37.03	34.72	35.14

temperature in a range of 0.2°C–0.6°C in top layer, whereas 0.5°C–1.9°C in bottom layer. Model simulation result could approximate measurement more closely through input of the detailed thermal outfall operation record and the more elaborate calibration of physical parameter related to heat exchange and hydrodynamic dispersion.

The measured temperature at T2 bottom has maximum value of temperature distribution. Considering normal thermal stratification of discharged water on the surface, this weak vertical stratification in measurement show that there exists strong vertical mixing in the initial mixing zone due to the strong discharge momentum.

4. Conclusion and discussion

Through the simulation with thermal discharge input, it was found that the daily sea water temperature distribution in this specific area can be greatly affected by the local thermal plume dispersion oscillating with the phase of tidal current. The regional meteorological condition also provided major contribution as a baseline condition of sea water temperature. Thus the long-term variation of water temperature around Al-Zour Site due to the global warming also needs to be considered. In the planning of the future water use in the Al-Zour industrial site, it will be necessary to consider major outfall discharges to be planned in adjacent facility in ~10 km area.

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Meeting refinery wastewater challenges through membrane-based biological treatment complemented by an integrated asset sustainability program

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ABSTRACT

The Middle East and North Africa region is blessed with many natural resources, but it is no secret that when it comes to freshwater, scarcity is abundant. Potable water supply to industries needs to be curtailed and industry needs to meet its regular needs through alternate reuse methodologies. Adequate quantities. Scaling, corrosion and microbial fouling can all be the concerns of intrepid operators, but the use of wastewater that is treated to an advanced level using proven technologies can offer all the benefits of pristine freshwater without the issues of supply constraints and cost overburden. In designing a water reuse system in industrial applications, a holistic approach requires looking at water balance calculations covering availability, makeup and blow down, water quality considerations, ease of system operation, power consumption, and capital and operating costs. With these considerations in mind, well-designed systems may incorporate any or a combination of reverse osmosis, ultrafiltration and membrane bioreactor solutions supported by the right chemistry, delivered in the right quantity at the right spot under a smart digital Internet of Things (IoT) approach. With the right engineered and chemical systems in fixed or packaged mobile configuration, there is no reason why the bar cannot be set higher today in attaining improved onsite water and wastewater operations. The Bahrain Petroleum Company Sitra Refinery in Bahrain is a good example of a holistic approach to addressing water and wastewater needs in industry. The refinery upgraded its existing wastewater treatment plant to improve the quality of its effluent and comply with stricter requirements using the best available technology in biological membrane-based treatment for its challenging operations. It further engaged packaged mobile water desalination to streamline its water supply challenges.

Keywords: Refinery; MBR; Mobile Water; IoT; Water balance

1. Introduction

The Middle East and North Africa region is blessed with many natural resources, but it is no secret that when it comes to freshwater, scarcity is abundant; whereas, potable use receives priority, it is only prudent that we create the infrastructure to maximize water reuse in industrial settings, without exception. Potable water remains limited and it is only sensible to retain as much of it for sustainable use today and for generations to come. The potable water supplies for industries need to be curtailed and the industries need to meet its regular needs through alternate reuse methodologies.

At any industrial plant, its water requirements are continuous and any shortcomings in water quantity and quality can affect plant asset integrity, overall production and ultimately the profitability. Along with the attention to chemistry and system monitoring and control, water reuse can go a long way in supporting water sustainability in today's industrial establishments. Adequate quantities. Scaling, corrosion and microbial fouling can all be the concerns of intrepid operators, but the use of wastewater treated to an advanced level using proven technologies can offer all the benefits of pristine freshwater without the issues of supply constraints and cost overburden.

In designing a water reuse system in industrial applications, a holistic approach requires looking at water balance

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calculations covering availability, makeup and blow down, water quality considerations, ease of system operation, power consumption and capital and operating costs. With these considerations in mind, well-designed systems may incorporate any of or a combination of reverse osmosis, ultrafiltration and membrane bioreactor solutions supported by the right chemistry, delivered in the right quantity at the right spot under a smart digital IoT approach. With the right engineered and chemical systems in fixed or packaged mobile configuration, there is no reason why the bar cannot be set higher today in attaining improved onsite water and wastewater operations.

The Bahrain Petroleum Company (BAPCO) Sitra Refinery, located near Bahrain's capital Manama, is a perfect example of a holistic approach to addressing water and wastewater needs in industry. Following its commitment to environmental protection, BAPCO decided to upgrade its existing wastewater treatment plant to improve the quality of its effluent and comply with stricter requirements using the best available technology in biological membrane-based treatment for its operations. It further engaged packaged mobile water desalination to streamline its erratic and dated water supply arrangement.

2. Refinery water balance and wastewater

Wastewater systems are used to prepare process water streams for either re-use or discharge. In refineries, aqueous generated waste is the result of utility blowdown, wash waters, regenerant waste, stripper blowdown, knockout drums and run-off. Contaminants are high in TSS and COD and are typically treated with a primary separation followed by a secondary biological oxidation. A concentrated sludge is generated and then disposed. Discharge permits are dictated by the effluent receiving body. Regulatory compliance and environmental stewardship are the drivers of successful wastewater treatment operations.

Refineries and petrochemical plants have unique needs for water treatment and they use a large quantity of water, making it critical that the refiner has the quantity and quality of the water they need (Fig. 1). If the process water used is not properly treated, the soluble minerals, suspended solids and inorganic contaminants could affect the processing

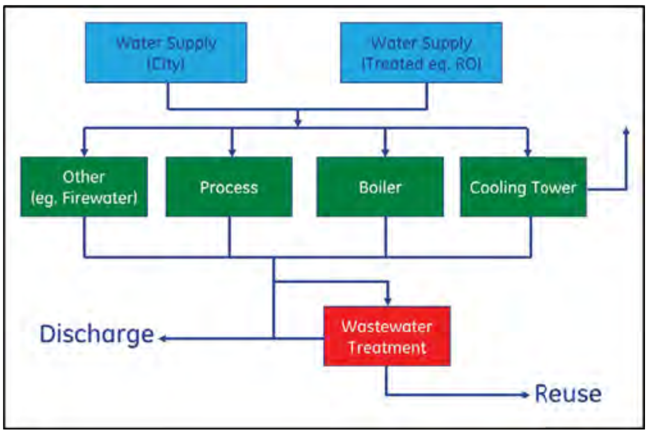

Fig. 1. Typical refinery water balance.

equipment by means of corrosion and deposition, leading to problems in heat transfer, water flow reduction, increased energy consumption and higher waste treatment cost. Further, regulations and water scarcity are making it more and more difficult for refineries and petrochemical plants to have access to conventional water.

3. MBR and wastewater treatment

The membrane bio reactor (MBR) system consists of a biological treatment system followed by membrane ultrafiltration (UF) trains. Biological treatment has been a regularly adopted practice in oil refineries because of the high flow rates and the nature and concentration of the contaminants it can handle. Hollow fiber submerged membranes are employed with the membranes being the key to effective wastewater treatment (Alsalhy et al. 2016). The reinforced hollow-fiber membrane acts as a physical barrier, preventing suspended solids, and colloidal material from being released in the final effluent. Typically, raw water from the plant is pumped to a grit removal system for the removal of heavy solids, and then through an oil–water separator before entering the bioreactor. Mixed liquor overflows to the membrane tank. Filtration is achieved by drawing water to the inside of the membrane fiber using suction created by permeate pumps. Recirculation pumps take the remainder of the flow back to the bioreactor to ensure these tanks remain at the same relative MLSS concentration. Sludge is wasted from the recirculation line to a filter press, where it is thickened and then hauled off site.

4. Supplemental supplies and mobile water

Some plants in water-challenged areas need, in addition to water reuse, turn to desalination to mitigate their water challenges and sustain their production levels. Modular, pre-engineered mobile water and wastewater treatment systems deliver performance, reliability and economics. These make long distance networking infrastructures or trucking redundant, often saving significant capital and operating expenditure costs. Mobile water is an area in which industries can manage their water needs while minimizing their investment. Offered on rental or even build-own-operate basis utilizing fleets deployable from service centers at a short notice, industries such as power, chemical, refinery, metal, municipal and others can achieve quality, quantity and cost-effective water at their site (Fig. 2).

Taking up only a minimal footprint and on-site requirements, modular, containerized mobile water units help meet emergency outages or equipment failure, planned outages for equipment repair, seasonal demands, product expansion, start-ups and change in raw water quality or effluent specifications. Often industry is faced with immediate challenges to meet shortfalls in existing production capacities. While many have plans to increase installed capacity, this is often not easily achievable. Planning, funding, procuring, constructing and commissioning new plants can take several years. Even with plans in place, emergency situations can arise requiring a quick solution to overcome unplanned conditions. Mobile water offers a water availability solution literally on demand, for periods ranging from several days to months and longer.

Fig. 2. Mobile water.

5. Digital internet-of-things asset performance management

For all industries, the key to enhancing productivity, improving asset life, and operating more proactively lies in the internet-of-things (IoT), which brings together people, machines and data to work in a faster, more predictive way. IoT-based asset performance management (APM) tools are designed specifically to improve the reliability and longevity of equipment. The Industrial Internet is one of the critical services driving the future of water and energy management for all users.

InSight*, an APM solution, uses data and analytics to ensure assets – such as boilers, cooling towers, reverse osmosis and ultrafiltration membranes and other key components – operate at optimal levels of reliability, efficiency and output. InSight has been able to prevent unplanned downtime, increase asset reliability, and extend asset life, and deliver greater operational efficiency and transparency across a variety of industries. The remote monitoring and diagnostic solutions aggregate, capture and display data in meaningful ways, giving operators the insight they need to make informed decisions (Fig. 3). These solutions – and the physical assets they control – are infused with digital capabilities to drive better system outcomes through next-level predictive operations.

InSight provides analytics to help see at any point in time the historical and current performance against success criteria, and the trajectory of future performance; where it is on track; and the weaknesses that need improvement. Early detection is a key goal, detecting emerging problems, so that action can be taken now, before a failure is experienced in the future. Asset optimization helps identify opportunities to optimize the applications that lower the total cost of operations, without sacrificing production performance. Another measure is in the context of safety where acid leaks, chemical storage tank leaks or chemical overfeed are common occurrences that can be detected before a problem becomes serious. InSight also leads to improved productivity, helping people get more done with tools that enhance their personal productivity, enabling them to see and do more. It enables operators to choose the way they manage information with a wide range of functionality.

The output of the remote monitoring can be followed up at centralized service reliability centers (SRC; Fig. 4), which are an integral part of the InSight APM platform, providing the means to troubleshoot and resolve account issues. Utilizing highly trained experts, the SRC integrates data acquisition, software, analytics and domain expertise

Fig. 3. InSight asset performance management.

*Mark of SUEZ.

Fig. 4. Service reliability center.

to help site teams improve the reliability and efficiency of their production assets; as well as reduce the cost of their operations.

6. BAPCO refinery integrated water and wastewater case study

The BAPCO Sitra refinery, located near Bahrain's capital Manama, remains among the largest refineries in the Middle East processing more than 250,000 barrels a day. Over the last several years, it has undertaken several steps to achieve best-in-class facilities and practices in water and wastewater management that have included biological wastewater treatment, utility chemicals and mobile water.

Following its commitment to environmental protection, BAPCO decided to upgrade its existing wastewater treatment plant to improve the quality of its effluent and comply with stricter requirements using the best available technology; MBR was the technology chosen for this project (Daigger et al. 2009). The MBR system consists of a biological treatment system followed by membrane ultrafiltration (UF) trains. Biological treatment has been a regularly adopted practice in oil refineries because of the high flow rates and the nature and concentration of the contaminants it can handle. During the initial performance test carried out to ensure suitability of the biological treatment approach prior to full-scale implementation, each of the four UF trains with a maximum treatment capacity of 4,400 USgpm were operated at design instantaneous flow rates ranging from 1,470 to 1,820 USgpm to simulate the different design flow conditions expected during long-term operation (Ginzburg 2015). The rest of the operational parameters of the membrane trains such as membrane aeration flow rates and chemical cleaning frequency were kept according to operational guidelines and the performance of the UF system key performance indicators (e.g., transmembrane pressure, etc.) monitored. The obtained results showed that the UF system was not only able to consistently meet the required treatment capacities but also the required effluent parameters at all times (Fig. 5).

The measured transmembrane pressure during the performance test did not exceed 2.2 psig which is significantly lower than the maximum allowable value of 8 psig. Also, the membrane system did not require additional chemical cleanings outside those needed for the original design conditions. The effluent quality was also significantly lower than the guaranteed values. The measured average turbidity was

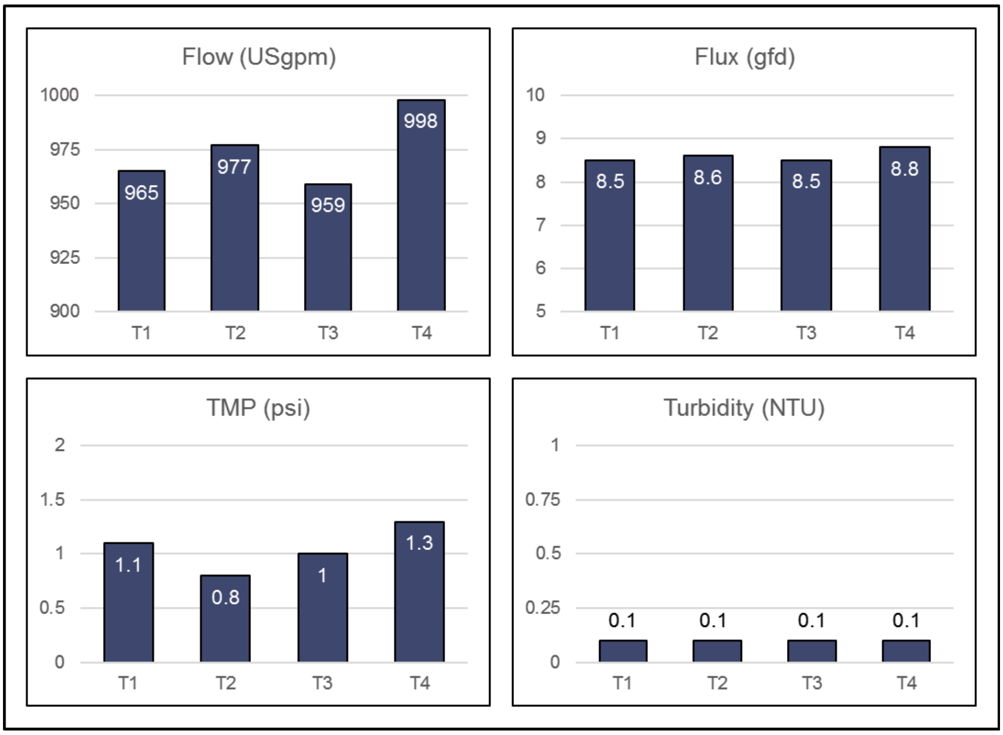

Fig. 5. Pilot test results.

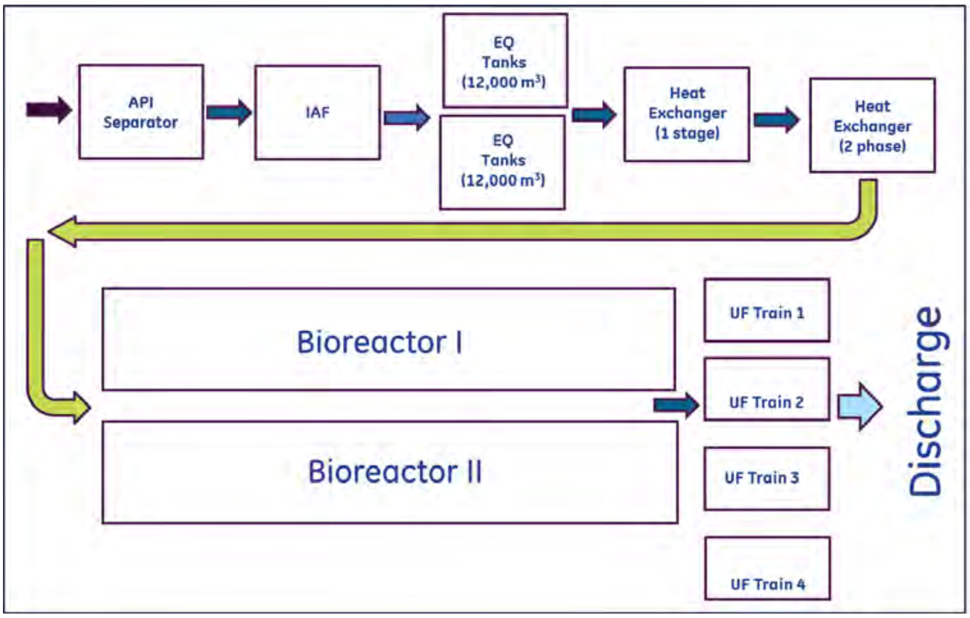

Fig. 6. BAPCO refinery wastewater treatment setup.

0.8 NTU which is lower than the maximum allowable value of 5 NTU. Similarly, the measured average total suspended solids were 1 mg/L, much lower than the maximum allowable value of 7 mg/L. Following the successful completion of the performance test, the UF system was put in operation. The performance of the first 3 months of operation confirmed the results obtained earlier during the performance test. The UF system consistently met the treatment capacity on a daily basis as well as all effluent quality parameters including total suspended solids and turbidity.

Following the extensive bench and pilot-scale testing to increase the level of confidence and to provide further insight into the selected solution, a 24,000 CM/D MBR was designed and installed as being the ideal technology for the refinery high salinity wastewater that exhibited poor biomass flocculation and low filterability. Today, the installed MBR consists of a four-stage biological treatment system followed by four membrane ultrafiltration (UF) trains (Fig. 6). Treatment challenges included stringent nutrient wastewater discharge limits and organic carbon and biological treatment complications from elevated temperatures. The latter was addressed through a double-stage cooling system to bring the wastewater temperature down from 48°C to 35°C. Spent caustic was used as a source of nutrients for the biomass. There was a concern on membrane fouling by oil but the pilot plant demonstrated the manageability of this risk and no problems with oil on the membrane or other issues concerning the membrane material have since been encountered.

Since its full operation commenced, the UF system has consistently met all effluent quality parameters, including total suspended solids and turbidity. With the success of the wastewater management program, BAPCO refinery has gone on to adopt mobile water to support its source water needs through seawater desalination, reducing its water bill and streamlining its water security operations.

In recognition of the treatment put in place by the BAPCO refinery and its commitment to water sustainability in industry, the project was awarded a Distinction Award at the GWI Global Water Awards event in Paris, France. Furthermore, the project won the 'Meed Quality Project of the Year 2014' and 'Meed Sustainable Project of the Year 2014 for the GCC'.

7. Conclusion and recommendations

Meeting refinery wastewater challenges through membrane-based biological treatment complemented by an integrated asset sustainability program offers excellent benefits in terms of environmental, operational and commercial gains. The prudent reuse of water can be accomplished through a creative combination of mechanical and chemical approaches, confidently addressing any corrosion, deposition and biological fouling issues that may be foreseen in reuse applications. Taking a holistic approach, the BAPCO Refinery in Bahrain, following intensive tests, has implemented a wastewater treatment system on best available technology basis to address its wastewater discharge concerns. Further, it has improved its water and wastewater footprint by engaging suitable chemical treatment and mobile water to meet its source water needs. A water reuse target in refineries can help with the economics of their water bill and with suitable polishing technologies, applications towards cooling and boiler water needs can be met. A review of the water balance at each industrial site is recommended to fully understand the economic and operational setting to achieve full results.

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Successful implementation of closed water cycle approach for industrial wastewater treatment and reuse in Saudi Arabia: a case study

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1. Introduction

During the past three decades, and with increasing water shortages in GCC and most Arab countries, the use of non-conventional water resources such as treated industrial and domestic wastewater has been an integral component of every water strategy in the region. This has been to reduce the gap between increasing demands and limited fresh water supplies, to achieve sustainable water and wastewater services, and to meet sustainable development goals by 2030. In spite of the above facts, the planned targets for the reuse of wastewater effluents remain limited and far below the expectations of the water planners and decision makers in many Arab countries including some GCC countries. This has been mainly due to several factors such as deficiencies in policies, strategies, and technical capabilities, weak governance frameworks including organizational structures, institutional and legal issues, and lack for enough financial and technical supports.

Saudi Arabia has been among few Arab countries that succeeded in adoption and implementation of full-scale industrial wastewater treatment and reuse (closed water cycle) in all industrial cities on national level. This paper describes the adopted policies and executed plans utilizing integrated water resources management tools that enabled Saudi Arabia to achieve such success. It also defines the positive impacts and benefits of such large-scale implementations of wastewater reuse on conservation and sustainability of water and energy.

2. Adopted policies and executed plans utilizing integrated water resources management tools for industrial wastewater treatment and reuse in Saudi Arabia

The remarkable successes of Saudi Arabia in large-scale implementation of treatment and reuse of industrial wastewater in industrial cities have been due to comprehensive adoption and implementation of sound governance frameworks utilizing integrated water resources management tools since the beginning of the new century. These comprised of three main components: creation of enabling environment, development and implementation of sound institutional and legal frameworks, and development and implementation of sound management instruments for successful utilization of public–private partnership (PPP) in implementation of closed water cycle (CWC) approach contracts.

3. Creation of enabling environment

Creation of enabling environment included the following: (i) development of National Water Strategy and action plans in accordance with KSA 2030 Vision which emphasized the reuse of wastewater utilizing PPP schemes, (ii) a royal decree was issued in 2002 approving the recommendation of the Higher Economic Council to adopt PPP schemes in six sectors including the water sector, (iii) strong political support by higher authorities for the adopted strategy, (iv) development of legal frameworks including national water law and enforcement measures that facilitated the execution of the action plans, (iv) identification of investment and financial structures to support action plans.

4. Wastewater reuse market

Development and implementation of wastewater reuse market include (i) development of sound institutional and legal frameworks for sound treatment and reuse of industrial wastewater, that included the establishment of the Saudi Industrial Property Authority (MODON) in 2001 to be responsible for the development of industrial cities including integrated infrastructure and services working in partnership with the private sector, (ii) development of Water Regulator as regulatory body and enforcement agency for protection of interests of all stakeholders, (iii) creation of industrial cities hosting thousands of industrial plants, (iv) development of required infrastructure including water supplies and wastewater collection and treatment facilities, (v) implementation of capacity building and training programs for different levels of technicians, managers and water professionals.

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5. Sound management instruments

Development and implementation of sound management instruments include (i) attraction of private sector to participate in PPP contracts by development of bankable BOT projects and mobilization of additional financing for PPP projects, (ii) selection of proper entity from experienced and qualified private sector that fit for PPP through BOT schemes, (iii) development and execution of transparent and sound PPP contracts, (iv) selection of sound, economic and effective technology to maximize wastewater treatment and reuse such as CWC that leads to zero liquid discharge in industrial plants and cities, (v) development of proper legal frameworks for effective control on qualities of wastewater influents and effluents, (vi) setting of sound KPIs for effective implementation of PPP schemes, (vii) development of fair and regulated water reuse tariff, (viii) development of sound customer services for serving various industrial clients within the industrial cities.

The CWC approach has been introduced and implemented successfully to industrial cities in Saudi Arabia to maximize wastewater reuse, to reduce consumption of conventional water resources, desalinated seawater and electricity, in addition to protection of the environment in accordance with Saudi Arabia's 2030 Vision. In 2008, the first BOT contract for duration of 25 years was agreed and signed with local specialized company for industrial wastewater treatment and reuse in Jeddah Industrial City. This was followed by a second BOT contract for 25 years in 2012 for Dammam and Al-Hassa industrial cities between MODON and specialized private sector company. Similar BOT schemes for other extensions and other industrial cities have been implemented during the past 3 years. In 2012, MODON was overseeing 29 cities, hosting more than 4,700 factories with investments exceeding SR250 billion, and more than 300,000 employees. The number of the industrial cities shall reach 40 by 2019. The produced industrial wastewaters from each factory are monitored to meet special set of quality guidelines prior to be discharged into the wastewater collection networks. The collected industrial wastewater is subjected to conventional preliminary and primary treatment facilities including fine screening, grit removal and rectangular primary clarifier. This is followed by secondary treatment including anti-bulking reactor, aeration tanks and clarifiers. After passing through balance tanks, influents enter the tertiary treatment stage, which is comprised of sand filter, followed by chlorination system. This stage is followed by the quaternary treatment by reverse osmosis desalination process to reduce the salinity to acceptable levels.

6. Results of implementation of CWC in industrial cities

The implementation of CWC within the First and Second Industrial Cities of Dammam and Al-Hassa during the past 3 years has resulted in saving of about 28.72 million m^3/year of desalinated and transported seawater. This is in addition to saving of electricity consumption of about 855,742 MWh/year, which is equivalent of saving 1,608,555 barrels per year, worth about US$ 96.5 million at oil price of US$ 60/barrel.

7. Conclusion and recommendations

The successful experience of Saudi Arabia in full-scale treatment and reuse of industrial wastewater in industrial cities utilizing CWC has been attributed to successful adoption and execution of comprehensive and sound governance frameworks utilizing integrated water resources management tools since the beginning of the new century. The gained substantial benefits represented by savings of significant values of conventional fresh water resources, desalinated sea water, electricity and oil consumption has been a major step forward toward achieving sustainable water and energy security in the kingdom. The Saudi experience is a good model for other GCC and Arab countries to adopt for achieving sustainable water and energy security.

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Role of oil and gas industry in groundwater conservation

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The oil and gas industry is the main industry in the GCC. It is also a main consumer and a major producer of water in these countries, as well as at the global level. In GCC, oil and gas operations consume about 50 to 80 billion gallons (about 200 to 300 million cubic meters) of ground water annually and it generate about 300 billion gallons (1.1 billion cubic meters) of water every year and increasing. With the increasing global energy demand, the GCC oil and gas industry is on the verge of rapidly increasing its water production. Over the next 10 years, it is forecasted that the generated water from the oil and gas industry may double in volume.

Produced water is mostly reinjected into the crude producing reservoirs for enhanced oil recovery. However, this task consumes a substantial amount of energy, which requires additional amount of fresh water. The reinjection process consumes 400 to 700 MW annually, which is equivalent to several decent size power plant productions.

Produced water has a very wide range of chemistry. It includes oil, heavy metals and naturally radioactive elements. This makes it unfeasible for many applications. However, technological development is closing this gap very fast.

1. Is produced water a burden or a resource?

Fresh water resources in the GCC are highly stressed. In addition, increasingly stringent laws are forcing GCC producers to actively look for alternatives for consuming precious ground water. Oman has been leading the exploration of produced water reuse. At NIMR Field, PDO successfully tested the use of reed beds to treat 240,000 barrels per day of produced water to recover oil and produced water with a quality that can be reused in other oil operations. This project used 90% less power should conventional methods were adopted. Similarly, other efforts are ongoing to explore desalination high hypersaline produced water to generate wash water for oil processing. Several universities are researching the use of advanced ceramic membranes to desalinate produced water.

2. Concluding thoughts

Oil and gas industry is the main user of scarce ground water and a major producer of a water that is not yet very attractive as a source of usable water. A lot of research is still required in order to change this reality. Lowering cost of desalination of hypersaline produced water can result in significant reduction in ground water consumption by the oil and gas industry. Oil and gas companies are continuously working with regulatory bodies in the region to conserve precious ground water.

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Initiatives of the petroleum sector for efficient water management to enhance water sector climate resilience in Bahrain

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Keywords: Oil-associated-water; Mangroves; Wetland; Aquifer recharge

The water sector of the Kingdom of Bahrain, a Small Island Developing State, is severely threatened by multiple climate change impacts and a growing population. The main climate change threats are (i) sea level rise causing saline intrusion into aquifers; (ii) rising temperatures and greater intensity of rainfall causing reduced rates of aquifer recharge and (iii) rising temperatures causing increase in water demand across all sectors. In combination, these threats are likely to reduce Bahrain's freshwater supplies by at least 50 to 100 million m^3 of water per year in the short term.

Securing water and energy needs represents a critical issue, which has not yet received the attention that it merits. Energy production consumes significant amounts of water; providing water, in turn, consumes energy. In Bahrain like other countries in the region, confronting the issues of water scarcity and the increasing demand on energy to realize sustainable development plans represents a challenge that needs to be tackled through an integrated set of wise energy and water policy decisions.

Focusing on using efficient technologies in relevance to water usage in the production process of energy is an important issue. In the oil and gas sector for example, water is used in upstream oil and gas exploration and production for purposes such as injection water for wells and to assist in the recovery of crude oil and gas. In the process of electricity generation, water is essential for the production of all conventional fuels, where it is needed as part of almost every step in the production processes. It is noted that raw water usage for cooling in various fossil fuel-powered power plants constitutes around 79%–99% of total water usage; the remaining water is used for applications such as ash and ling, in the humidifier and condenser and in flue-gas desulfurization (FGD) at combustion-steam plants. Consequently, due considerations have to be given for improving cooling process to make the electricity production more water efficient.

Thus, Bahrain petroleum sector assessed all available options to use water and treated wastewater efficiently and has started executing some water projects such as construct a 110-ha wetland to replace the mechanical and chemical treatment processes that are currently being used to treat ~80,000 m^3 of produced water per day. The system will reduce the oil in water (OiW) concentration of the produced water from ~500 ppm to under 5 ppm. The improved quality of the treated water and absence of potentially harmful added chemicals will make the water treated in the wetland suitable for managed aquifer recharge. While there will be some loss as a result of evapotranspiration, a substantial proportion of the water entering the wetland will be available for injection into the Rus-UER aquifer after it leaves the wetland. The quantity of water treated through the wetland will vary by season, ranging from 62,000 m^3 per day in summer (April to October) to 72,000 m^3 per day in winter (November to March), and totaling 24.5 million m^3 annually. 80%–100% of the treated water will be injected into the Rus-UER aquifer to mitigate the extraction impacts of the Abu-Jarjur Reverse Osmosis Desalination Plant. This project will enhance directly the climate resilience of water resources in Bahrain.

This paper will shed light on assessment outcomes and sector project including wetland, planting mangrove using STP water, and other related projects.

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Effect of brine discharge from Al-Dur RO desalination plant on the infauna species composition in the East Coast of Bahrain

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ABSTRACT

The GCC countries have been experiencing an accelerated socio-economic development process since 1970s, resulting in rapid demographic and urbanization growth and associated with rapidly increasing municipal water demands. To meet these demands' quantity and quality, the GCC countries resorted to desalination. Currently, the GCC countries collectively possess the largest desalination capacity in the world (~45%), and based on the current urbanization trends, it is expected that current rates in desalination capacity growth will continue in the future. However, desalination has a number of environmental externalities on the marine, and their severity will depend on various factors (i.e., site-specific). As a pre-requisite for designing and implementing programs to minimize these environmental externalities, the impact of desalination has to be investigated and characterized. The study objective is to investigate the impacts of Al-Dur RO desalination plant on the coastal infauna benthic species composition on the east coast of Bahrain. The in situ measurements over high and low tide cycles in winter and summer were conducted at 42 selected locations for surface and bottom waters. Sediment samples were collected from 10 locations selected at different distances from the discharge outlet. The species composition of infauna was investigated using the univariate analysis (number of species and individuals, species richness, evenness index and diversity index). The results showed an extreme elevation in temperature (>38°C) and hypersaline waters (>55‰) at locations nearby the discharge outlet, and also at bottom waters of depths more than 3 m during the high and low tide cycles in both seasons with exceptional levels in summer. Four main groups of benthic infauna identified are represented by polychaetes (12 taxa), bivalves (4 taxa), Gastropoda (2 taxa) and Amphipoda (3 taxa) including 256 specimens. The univariate analysis indicated spatial variations in infauna species composition where the lower diversity indices were found at locations close to the discharge outlet and at station 5 at which noticeable vertical differences were observed indicating exceptional elevation of temperature and hypersaline waters at bottom layer. However, the highest species diversity indices characterized the most offshore stations. Polychaetes are considered as the most useful bio-indicators to reveal any contamination from desalination brine discharge, due to their sensitivity and their capability to adopt to any environmental alteration.

Keywords: RO desalination; Univariate analysis; Infauna; Species diversity; Bahrain

1. Introduction

The GCC countries are located in an arid or semi-arid region characterized by low rainfall, high temperature (high evaporation), and limited conventional water resources. This region experienced rapid demographic and urbanization along with social and economic development. Population growth, increase in standard of living, reliance on desalination to meet urban rate demand, which is made possible due to the availability of financial and energy resources in the country. In any desalination technology, the process generates two main types of effluents; the first is a stream used as fresh water and the second is a stream represents high concentration of salt called brine water.

The Arabian Gulf area is distinguished as having the highest number of desalination plants and largest desalination

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capacity worldwide, where it accounted for more than 64% of the world's total production capacity from 2000 to 2010. In all the GCC countries, the desalination capacity has been increased substantially during the last three decades. This trend is expected to be continued in the coming decades (Al-Jamal and Schiffler, 2009). Desalination water production is expected to increase from about 8,000 Mm^2 per year to about 41,000 Mm^3 per year 2050 (AGEDI, 2016).

Due to a rapid population growth synchronized with industrial development in Bahrain, a rapid increase in water consumption reliance on desalination is being of great importance to meet urban rate demand facilitated by the availability of financial and energy resources in the country. Bahrain has introduced desalination in 1975 by establishing Sitra MSF desalination plant and moved steadily toward constructing further five desalination plants located on the eastern coastline of Bahrain including 1 MSF (Al-Hidd), 2 MED (Al-Hidd and Alba) and 3 RO (Ras Abu Jarjur and Al-Dur) (Al-Zubari, 2014). Al-Dur desalination plant is designed to produce 220,000 m^3/d. The plant was developed as a build-own-operate (BOO) project basis, which consist of a combined power plant and an RO desalination plant (Suez, 2012).

Despite the socioeconomic benefits, which desalination plants offer and the key role it plays in sustainable development (Dawoud, 2005), the potential negative impacts associated with desalination plant operation as a land-based source of pollution have been of concerted international attention (UNEP, 2006).

Generally, the impacts on coastal and marine environment derived from desalination plants are mostly due to routine discharge of brine water. The discharged brine water probably includes additional chemical pollutants, which potentially affect the chemical properties of both water and sediment quality as well.

The brine discharged into the sea induce the formation of a stratified system, with the brine forming a bottom layer that can affect the benthic communities habituated to stable salinity environments. The magnitude of this impact depends not only on the characteristics of the desalination plant and its reject brine but also on the nature of the physical and biological conditions of the receiving marine environment (Fernandez Torquemada et al., 2005). Khordagui (2002) reported the impingement biological effects and entrainment effects caused by desalination plants taking into consideration the role of inflow rate, intake design, and seasonal changes impacts on seawater temperature and species behaviour. Osmotic regulation is well known as the most response to salinity variation. This relationship has been investigated by Einav et al. (2002). Macpherson et al. (2006) assessed the impacts of desalination on macro benthic assemblages during pre and post of desalination plant commissioned. The study revealed that the variations in benthic species richness largely attributed to the brine discharged particularly within the surrounding environment.

The territorial waters of Bahrain cover sensitive marine habitats such as seagrass beds, coral reefs and mangroves, in addition to intertidal mudflat, which substantially support the marine biodiversity by providing nursery, spawning, and feeding grounds for broad scale of fishery species (Loughland & Zainal, 2009). However, these ecosystems are being heavily exposed to chronic anthropogenic impacts along the last few decades.

The seagrass bed nearby Al-Dur coast extends eastward to Hawar Islands. This vital sensitive habitat plays an important biological role as feeding, nursery, and spawning ground for broad-scale finfish and shellfish species and endangered megafauna species such as dugong, dolphins, and green turtles. Moreover, the Al-Dur coast representing a fishing ground for many fishermen using traditional fishing gears (wire metal and barrier traps), which more or less located within the vicinity of the desalination plant discharge. The brine water effect may extend to the bottom layer, which potentially reflect on species diversity of benthic community those comprise the base of marine trophic pyramid.

The aim of the study is to assess the impacts caused by the effluent discharged from Al-Dur desalination plant on the coastal species composition of benthic infauna.

2. Materials and methods

2.1. Study area

The present study is conducted on Al-Dur coast, east of Bahrain within the vicinity of the Al-Dur power and desalination plant (Fig. 1). Al-Dur reverse osmosis desalination plant is located in the south-east coast of the Kingdom of Bahrain commissioned in February 2012 and was designed with a daily capacity of 220,000 m^3/d to meet the growing demand of drinking water and electricity in Bahrain as well. The plant was developed as a BOO project engaged as a private sector.

The tidal regime circulation along the Bahrain coasts is diurnal twice a day with a depth range between 0 and 7 m. The water intake is located at a distance of 1.5 km and the pipe is supplemented by two subsurface intake filters each consisted of 4 units. A total of 20 barrier fishing traps (locally known as hadrah) are distributed along the Al-Dur coast. Further fishing activities are practiced by drift nets and wire metal traps (locally known as gargoor).

2.2. Sampling

Sediment samples were collected in May 2017 using Van Veen grab sampler. Ten stations were selected at different distances from the discharge outlet as illustrated in Fig. 2 associated with different depths to provide the opportunity for spatial variation in relation to distance, depth and sediment texture. The in situ water quality measurements including depth, temperature, and salinity were conducted during both high and low tide cycles at each location by using Pro DSS multi-meter probe. The parameters have been measured at surface and bottom layers.

2.3. Laboratory analysis

2.3.1. Grain size analysis

The sediment grain size analysis is conducted following the granulometry based on the median size of sediment particles. The procedure involved two steps, the first deals with determination of the distribution of the coarser, larger-size particles of sediments using sieve analysis. The second step

Fig. 1. Location map showing the site of the Al-Dur power and desalination plant.

Fig. 2. Locations of sediment sampling at Al-Dur Coast east of Bahrain.

is to determine the fine particles, which were obtained by applying the hydrometer.

The sediment samples collected for infauna identification were washed at boat using a sieve of mesh size 0.5 mm. Samples for infaunal benthic identification were divided into two jars for duplicate microscopic diagnosis. The samples have been preserved as soon as collected in a solution of dilute formalin (5%).

2.3.2. Identification of infauna

The samples were preserved with Rose Bengal prior to the normal sorting process by which specimens separated from the sediment. Sorting was carried out by placing a small quantity of sample in a petri dish and viewed under a dissecting stereomicroscope. Sorting was repeated three times for each petri dish to confirm that every single individual organism has been well diagnosed. The remainder residue was saved until the termination of the identification process.

2.3.3. Data analysis

The univariate analysis has been applied using PRIMER package Plymouth Routines in Multivariate Ecological Research V6 (Clark & Gorley, 2006). The raw data represented by a sum of duplicates of each species were imported from Microsoft Excel into the PRIMER work sheet and the following univariate ecological indices have been calculated:

- ***No. species (S)***: simply the number of species present in an ecosystem
- ***No. individuals (N)***: number of specimens belongs to *i*th species
- ***Richness (D)***: Margalef's index: $D = (S - 1)/\ln N$
- ***Diversity (H`)***: Shannon–Weiner index: $H` = -[\sum (\rho i \ln \rho i)]$

  where ρi is the proportion of individuals found in the *i*th species.

- Evenness (*J*): Pielou index $J = H`/H\text{max}$

where Hmax is the maximum possible diversity = ln *S*.

3. Results and discussion

3.1. Water temperature

A clear seasonal variation could be found between winter and summer temperatures. The measurements in winter were ranged between 17.0°C and 21.8°C, however in summer the readings varied between 35.4°C and 38.8°C (Table 1).

Relatively, the temperature was differed on spatial basis following to distance from the desalination plant outlet. The maximum values were found at station 10; the most close to the outlet at which the range of degrees varied from 21.2°C to 21.8°C in winter and from 37.4°C to 38.8°C in summer. The rest of the locations had an average of 18.5°C in winter and 36.5°C in summer.

Little variations could be noticed between temperatures during high tide and low tide cycle in summer, however no real variations were observed in winter. Thermocline (temperature stratification considered with temperature difference of >3°C) of difference slightly below 3°C was observed in winter where the bottom layers were characterized by higher temperature particularly at station 5 with a difference of 2.1°C–2.7°C between surface and bottom layer. The other sampling locations exhibited marginal fluctuations on vertical basis between surface and bottom layers mostly with less than 2°C. In summer, the water column seems to be thermally well mixed.

3.2. Salinity

The salinity levels throughout the study area were varied between 42‰ to 60‰ in winter and 44‰ to 59‰ in summer indicating slightly higher levels in summer (Table 2).

Spatially, the salinity showed obvious variations based on a distance from the desalination outlet. Extreme salinity levels (58‰–60‰) were found at station 10; the nearest

Table 1
Water temperature at sampling locations of Al-Dur coast east of Bahrain

Sampling locations	Winter				Summer			
	High tide		Low tide		High tide		Low tide	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
Station 1	18.0	18.7	18.4	20.4	36.2	36.2	37.6	37.8
Station 2	18.0	18.7	18.2	20.4	36.2	36.2	37.6	37.8
Station 3	18.0	18.2	18.4	20.3	36.0	36.2	37.2	37.6
Station 4	18.0	18.4	18.6	20.4	36.2	36.2	37.6	37.8
Station 5	18.0	20.1	18.4	21.1	36.0	36.8	37.0	38.6
Station 6	18.0	19.0	19.0	20.4	36.2	36.2	37.6	38.0
Station 7	18.0	18.2	19.0	20.4	36.4	36.4	37.8	38.0
Station 8	17.5	17.5	19.8	19.8	36.4	35.4	37.8	37.8
Station 9	17.0	17.0	20.0	20.0	36.8	36.8	38.0	38.0
Station 10	21.2	21.2	21.8	21.8	37.4	37.4	38.8	38.8

Table 2
Salinity at sampling stations of Al-Dur coast east of Bahrain

Sampling locations	Winter				Summer			
	High tide		Low tide		High tide		Low tide	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
Station 1	42.0	46.0	44.0	48.0	44.0	47.0	44.0	47.0
Station 2	42.0	47.1	44.0	48.0	45.0	48.0	44.0	47.0
Station 3	43.3	45.8	44.0	48.0	44.0	47.5	44.0	46.0
Station 4	42.0	46.0	44.0	45.7	44.5	48.0	44.0	47.0
Station 5	43.4	52.8	43.5	54.4	44.0	48.0	43.2	49.0
Station 6	42.0	46.0	43.7	45.7	45.0	45.0	46.0	46.0
Station 7	43.5	46.0	43.5	48.0	47.0	48.0	46.0	47.0
Station 8	44.7	43.3	47.3	48.0	46.0	46.0	47.0	47.0
Station 9	48.0	48.0	49.0	49.0	48.0	48.0	48.0	48.0
Station 10	58.8	59.3	60.0	59.5	58.2	58.2	59.0	59.0

sampling location to the outlet. The salinity levels at other locations were ranged between 42‰ and 49‰.

The salinity levels during high tide cycle were slightly higher than relevant ones during low tide cycle. Halocline (salinity stratification with difference >1‰) was observed at all sampling locations except stations 8, 9 and 10 which were located nearby the outlet associated with shallow depths (<1 m). Again, station 5 was found to be the most salinity stratified where the difference was 9.4‰ during the high tide and 11.9‰ during the low tide. More or less the vertical differences of salinity in summer were slightly lower than those occurred in winter.

3.3. Sediment texture

Generally, the sediments grain size analysis based on the 10 locations revealed that the sand fraction predominated the sediment types in the study area. As presented in Fig. 3, four sediment textures were obtained, which were categorized into sand (4 stations), sandy loam (3 stations), loamy sand (2 stations), and loam (1 station).

The fine sediment presented by silt fraction was noticeably occurred at stations 1, 2, 3, and 5 associated with 14%–16% clay. On the other hand, sand fraction represented the whole texture of four stations (6, 7, 9, and 10) by 100%. Moreover, the sediment texture at stations 4 and 8 is mostly composed of sand (>80%).

Generally, the stations close to the outlet site are characterized by sand fraction; however the other stations more or less are composed of mixture sediments with tendency to sand fraction.

3.4. Infauna species composition

The species composition of infauna was investigated, and the univariate analysis was applied for sediment samples collected from the 10 stations. The infaunal organisms were diagnosed to possible identification of minor taxon for which four main groups were identified including Polychaeta (12 taxa), Bivalves (4 taxa), Gastropod (2 taxa) and Amphipod (3 taxa) with a total of 21 taxa mostly at a level of family represented by 256 specimens (Table 3).

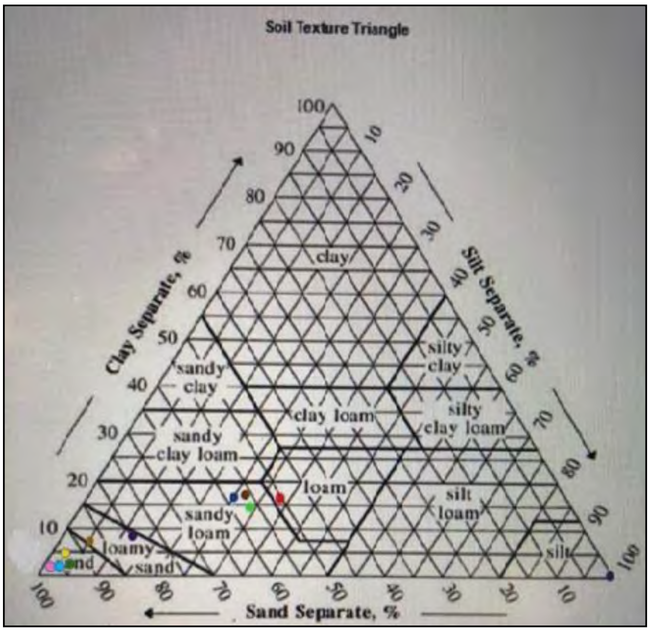

Fig. 3. Sediment texture of the sampling stations at Al-Dur coast.

The percentages of the main infaunal groups are presented in Fig. 4. The results as an overall for the 10 locations showed that Polychaeta comprised the majority (91%) of the infaunal species composition; however the other three groups (amphipod, bivalves and gastropod) constituted minor portions by 7%, 1.5% and 0.5%, respectively.

Similar trends found individually at most of the monitoring stations (Fig. 5). Station 4 seems to be characterized by considerable percentages of amphipod and gastropod; however bivalves at station 7 represent the second main group.

Capitellidae was the most abundant taxa (45.7%) at most of the monitoring stations particularly at stations 9 and 10 those located close to the discharge outlet followed

Table 3
Species composition of infauna at Al-Dur coast east of Bahrain

Taxa	Stations										Total
	1	2	3	4	5	6	7	8	9	10	
Polychaetes											
Terebellidae	0	3	0	0	0	1	0	0	0	0	4
Capitellidae	9	14	15	2	1	0	1	11	38	26	117
Lumbrineridae	1	3	0	1	0	1	3	2	5	2	18
Maldanidae	1	6	0	0	0	0	0	0	0	0	7
Spionidae	1	3	0	1	0	1	1	0	0	0	7
Orbiniidae	3	1	4	0	0	2	0	0	0	0	10
Nereididae	16	1	7	5	9	4	10	1	9	0	62
Syllidae	0	2	0	0	0	0	0	0	0	0	2
Eunicidae	1	0	0	0	0	0	0	0	0	0	1
Opheliidae	0	0	1	1	0	0	0	0	0	0	2
Saccocirridae	0	0	1	0	0	0	0	0	0	1	2
Ampharetidae	0	0	1	0	0	0	0	0	0	0	1
Subtotal											233
Bivalve											
Diplodonta globosa	1	0	0	0	0	0	0	0	0	0	1
Antigona lamellaris	0	0	1	0	0	0	0	0	0	0	1
Atactodea glabrata (*bahreinenisis*)	0	0	0	0	0	0	1	0	0	0	1
Circe callipyga	0	0	0	0	0	0	1	0	0	0	1
Subtotal											4
Gastropoda											
Cerithium scabridum	0	0	0	1	0	0	0	0	0	0	1
Pirenella conica	0	0	0	1	0	0	0	0	0	0	1
Subtotal											2
Amphipoda											
Caprellidae	0	0	0	0	0	0	0	0	7	5	12
Maeridae	1	0	0	2	0	0	0	0	0	0	3
Aoridae	0	0	0	0	0	1	0	1	0	0	2
Subtotal											17
Total no. of individuals	34	33	30	14	10	10	17	15	59	34	2 256

by Nereididae (24.2%). However each of the rest of the taxa formed <7%.

The diversity indices obtained by the univariate analysis are illustrated in Fig. 6. The lowest number of species was recorded at S5 (Fig. 6a), that is located at depth 4 m in which the highest bottom salinity and temperature with lowest DO are noticed. The highest number of species (9) was collected at S1 representing the most offshore station at the intake site. The number of species exhibited a decrease trend toward the outlet site where the samples are collected from stations 8 to 10. The number of individuals showed different trend to that of number of species (Fig. 6b). The decrease trend toward the outlet was shifted to noticeable peak at station 9 where the highest number of individuals (59) was found represented by the dominance Capitellidae constituting 64.4%. The lowest number of individuals was recorded at stations 5 and 6 represented by 10 specimens.

The species richness index (*D*) seem to be of similar pattern of distribution to that found for number of species as presented in Fig. 6c. The highest value was 2.65 at station 4 and the lowest (0.43) at station 5. Stations 9 and 10 associated with the outlet were also distinguished by low species richness (<1).

The evenness index (*J*) showed no regular pattern, however the lowest value (0.47), as other previous indices, found at station 5 (Fig. 6d). Stations 4 and 6 characterized by the most proportional infauna species compositions indicating the highest evenness values (0.90). Most of the rest of stations found to be of moderate proportional of species composition in which the evenness index was over 0.70. The highest

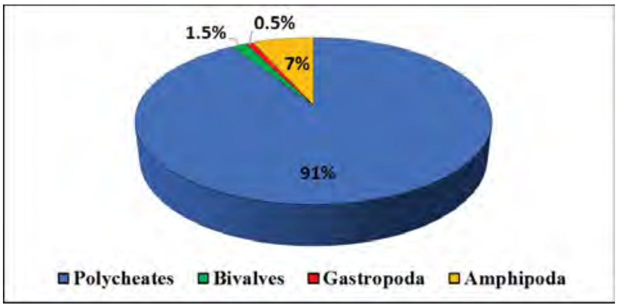

Fig. 4. Major groups of infauna collected from monitoring stations at Al-Dur coast.

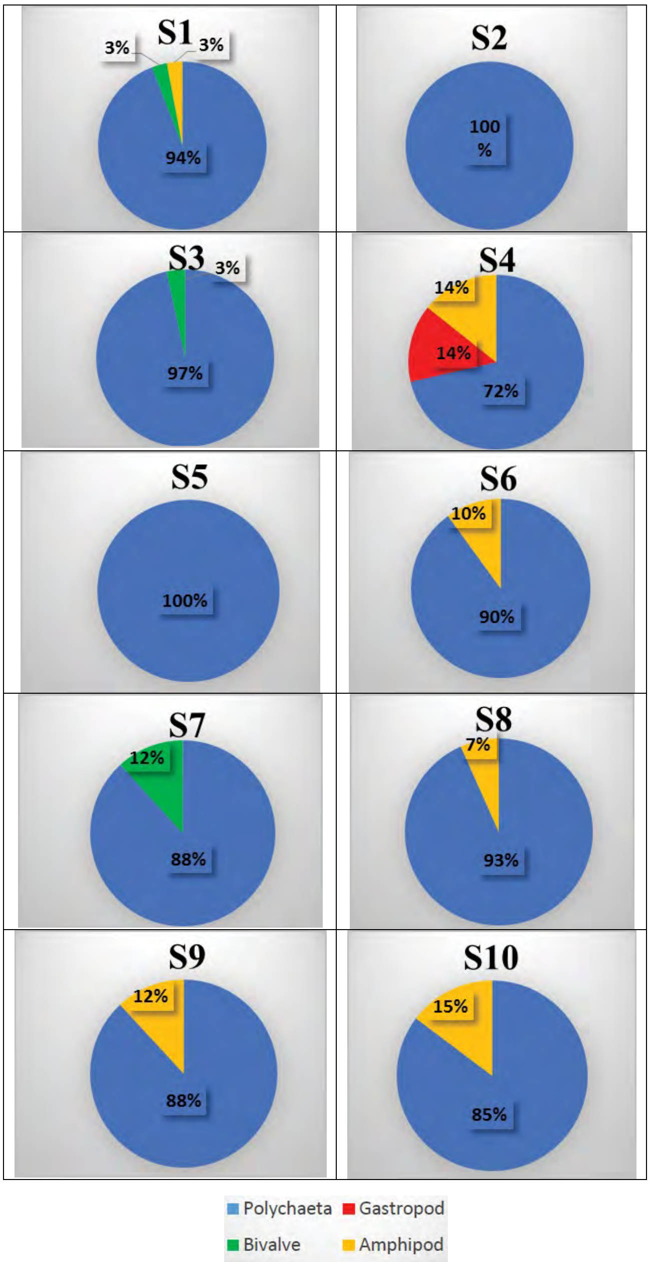

Fig. 5. Infauna species composition in the monitoring stations at Al-Dur coast.

diversity index (*H*) was found at station 4 (1.87) followed by station 2 (1.71) and station 6 (1.61). The diversity index showed a decrease pattern toward the outlet site with a noticeable low diversity at station 5 (0.33) as shown in Fig. 6e.

4. Conclusion and recommendations

The grain size analysis of sediments was investigated to sort out the factors that control the distribution of infauna species composition whether related to water quality or sediment texture. Benthic community structure and composition have a strong relationship with sediment structure. The macrobenthic communities reveal distinct relationship with sediment granulometry (Hyland et al., 2005).

To investigate the interaction of physical and biotic factors in an ecosystem, the species diversity is the most representative indicator. Diversity of the species is usually proportional to the stability of the ecosystem in question as the high number of species refers to the most stable community. In contrast an ecosystem beneath stress has few species, which is characterized by a dominance of few species.

Several studies have been carried out in order to determine how the distribution and abundance of marine flora and fauna species react to a change in temperature. The temperature of the brine discharge is one of the major concerns for any desalination plant project. Marine biologists indicated that a significant impact can occur to the natural balance and distribution of the marine life if a temperature alteration is applied to the ambient environment (Buros, 1994). A direct correlation can be determined between the temperature alteration and the behaviour of marine species. Sea temperature is one of the key variables to monitor and can play a great role in the marine flora and fauna's life.

The impact of desalination plant may extend to benthic community where these organisms are characterized either as sessile or of limited locomotion such as molluscs and echinoderms. The latter is well known as stenohaline organism, representing a bio-indicator for salinity effect (Fernandez-Torquemada et al., 2005). Naser (2013) investigated the impacts of MSF and RO desalination plants in Bahrain. The study revealed a reduction in biodiversity and abundance of microbenthic assemblages mostly at locations adjacent to the outlet of MSF desalination plant. As reported by Khordagui (2002) and Fernandez-Torquemada et al. (2005), several cases of fish kills and disappearance of marine benthic species such as echinoderms have been noticed at the vicinity of desalination plant due to slow growth rate, failure of the osmoregulatory mechanism, shrinkage of body cells, and malfunction of the endocrine system.

The univariate analysis indicated the variation of the species composition and species richness of benthic assemblages at the study area. The most diverse species was recorded in a family Capitellidae, where 12 species have been identified. Several reasons may justify the dominance of Polychaeta in the study area. Marine communities are impacted by the increasing human activities as reported by Del-Pilar-Ruso et al. (2008), indicating a reduction in abundance, diversity, and richness of the polychaete assemblages. Moreover, polychaetes are considered as the most useful bio-indicator to reveal any contamination from desalination brine discharge, due to their sensitivity and their capability to adopt to any environmental alteration.

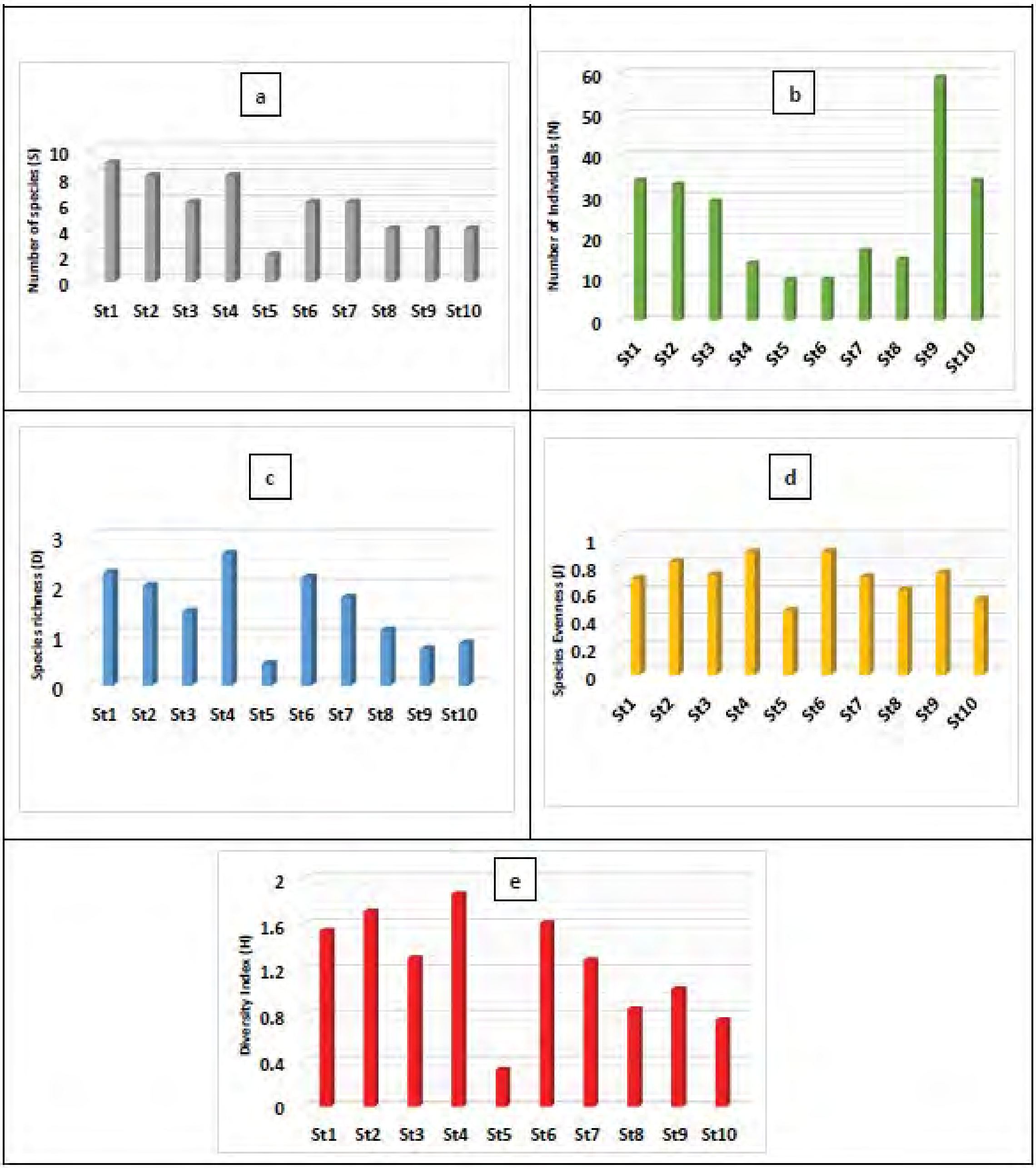

Fig. 6. Diversity indices of infauna species composition at Al-Dur coast.

Bivalves were present in 3% stations of all collected areas mostly represented by earlier stages where the sizes were too small. Amphipods as bivalves were present in 3% of the benthic assemblage in the study area notably in S9. This group contributes an important part of the base trophic level as other higher species preyed on. Gastropods were absent at all stations except S4 in which represented by small size (2 mm).

The benthic assemblage comprised the majority of fish food habit. The availability of benthic organisms by abundance and wide species diversity substantially contribute the fisheries status. This kind of sensitive marine species needs to be measured and monitored to mitigate any environmental effluence by making biotic indices (de-la-Ossa-Carretero et al., 2016).

No attempt has been made in the Bahrain marine environment to find out the discharge impacts of desalination plants neither on fish assemblage nor on benthic community. The exceedances noticed were restricted for salinity gradient at monitoring locations associated with the site nearby the outlet and bottom waters at locations associated with depths more than 3 m indicating the sinking of the hypersaline water mass at these depths. Consequently, the species composition of the benthic fauna was found to be largely related to the water quality rather than sediment texture. The lowest diverse composition found at locations was characterized by exceptional elevation of temperature and salinity in bottom waters such as those close to the outlet and station 5 as well. A pretreatment process needs to be implemented for brine waters of Al-Dur desalination plant before direct discharge to mitigate the impacts on physical, chemical and biological properties around the vicinity extent and buffer zone. Suggest passing the discharged waters through a long channel before releasing to natural coastal environment or extending the discharge pipe to deep water by diffuser lines", which promote better mixing of the brine and sea water where high current will improve the mixing process of the outlet.

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Analysis of some pharmaceuticals in surface water in Jordan

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ABSTRACT

A quantitative assessment of pharmaceuticals in surface water in Jordan was conducted using liquid chromatography-tandem mass spectrometry (LC-MS/MS) to evaluate the occurrence, source and distribution of 18 pharmaceutical compounds. Grab samples were collected in the summer from the effluent of two dams in Jordan. Among all of the pharmaceuticals analyzed, the results showed that 10 pharmaceutical compounds were detected in the effluent of King Talal Dam including 1,7-dimethylxanthine, acetaminophen, amphetamine, caffeine, carbamazepine, cotinine, phenazone, sulfamethoxazole, sulfamethazine, trimethoprim. However, four pharmaceutical compounds detected in the effluent of Mujib Dam include 1,7-dimethylxanthine, caffeine, cotinine, phenazone. Moreover, eight pharmaceutical compounds were not detected in both dams (<0.005 μg/L) including cimetidine, diphenhydramine, MDA, MDMA, methamphetamine, morphine, sulfachloropyridazine and thiabendazole. The results also indicated that the compound detected at the highest concentration levels in King Talal Dam was carbamazepine at concentration of 0.358 μg/L. It is very clear that the occurrence of pharmaceuticals at King Talal Dam is higher than in Mujib Dam. This is mainly due to the fact that King Talal Dam is receiving runoff water and treated wastewater from the wastewater treatment plant (WWTP), while the Mujib Dam is only receiving surface runoff water. This is consistent with many studies reported in the literature that municipal WWTPs are considered a primary source for the discharge of pharmaceuticals and personal care products into surface waters.

Keywords: Pharmaceuticals and personal care products; Surface water; Jordan

1. Introduction

Jordan's water resources are very vulnerable as the current water consumption had already exceeded its renewable supply. In fact, the deficit between supply and demand is currently covered by over pumping of some of the country's aquifers causing a massive drop in water table and deteriorating the water quality (Al-Hadidi and Al-Kharabsheh 2015). To resolve the water shortages at Jordan, potential water solutions currently implemented include desalination, reduction water demands, reuse wastewater in the agriculture sector and building dams to harvest surface water.

There are 14 dams in Jordan with total reservoir capacity of about 336 million cubic meter (MCM), including the desert dams. Stored water from these dams is used for drinking water, agriculture activities and groundwater recharge (Ministry of Water and Irrigation, Jordan Valley Authority, 2018). Some of these dams are collecting surface runoff and treated wastewater while other dams are collecting only runoff. As mentioned before, Jordan is reusing treated wastewater. The treated wastewater is discharged from wastewater treatment plants (WWTPs) directly to wades and streams and then stored at dam to be used for irrigation. According to the Jordanian Water Authority data, there are 32 WWTPs operating in different Jordanian cities in 2018. The estimated annual amount of treated wastewater discharged by these plants is more than 166 MCM.

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It is well known in the literature that conventional WWTPs are not designed to remove emerging pollutants such as pharmaceuticals (Díaz-Gardu~no et al., 2017). Most of these low-level contaminants can pass the WWTPs and eventually reach surface water and groundwater (Lapworth et al., 2012; Lopez-Doval et al., 2017). Recent studies conducted in Europe, the USA and Canada have shown that reuse of wastewater effluents (treated and untreated) can result in contamination of ground water and surface water resources by pharmaceuticals (Kolpin et al., 2002; Veach and Bernot, 2011; Li et al., 2010; Barnes et al., 2008). The literature indicates that effluent from municipal WWTPs is the main source for the discharge of pharmaceuticals into surface waters. A recent study showed that treated wastewater in Jordan is contaminated by some pharmaceutical compounds such as caffeine (182.5 μg/L), acetaminophen (28.7 μg/L), 1,7-dimethylxanthine (7.47 μg/L), cotinine (4.67 μg/L) and carbamazepine (1.54 μg/L; Al-Mashaqbeh et al., 2018).

With an increase in the contamination of waterways and water supply systems from these pollutants and the greater reliance on alternative water sources such as reuse of treated wastewater, it has become apparent that there is a need for further monitoring and research on the impacts of pharmaceutical compounds carried by treated wastewater on the surface water. However, the research efforts made to address this issue has not received enough attention in Jordan. Therefore, very little data are currently available on the occurrence and fate of pharmaceutical compounds in water dams in Jordan.

The objective of this study was to determine some pharmaceutical compounds in King Talal dam and Mujib dam in Jordan during summer season.

2. Materials and methods

2.1. Chemicals

Reference materials, metabolites and labeled standards were obtained from Sigma-Aldrich (St. Louis, MO). Solvents used in sample preparation were of high-purity grade (OPTIMA, Fisher Scientific, St. Louis, MO).

2.2. Sample collection

Grab samples were collected from the effluent of King Talal dam on 17/6/2017 and Mujib dam on 19/6/2017. Grab samples for the analysis of pharmaceutical compounds were collected in 1 L, rinsed glass bottles and acidified using 1.5 mL hydrochloric acid (HCl, 33%). All samples were stored in a refrigerator under dark conditions at 4°C to 8°C.

2.3. Sample extraction

The extraction process was implemented according to provided procedure from Water Sciences Laboratory at the University of Nebraska–Lincoln (WSL/UNL) in the United States and included pharmaceuticals from a previous study (Bartelt-Hunt et al.. 2009). Samples were pre-concentrated using solid-phase extraction (SPE) within 24 h after collection. The collected samples were first decanted to remove suspended particles and then filtered through 0.45 micron glass fiber filters using a vacuum filtration unit. A 500 mg polymeric HLB Oasis 6CC cartridge from Waters (Milford, MA, USA) was connected to a SPE manifold and vacuum pump and preconditioned by passing 6 mL acetone and 6 mL methanol sequentially through the cartridge, followed by 6 mL distilled deionized water (DDI H_2O). The filtered sample was then pumped via tube to the cartridge using a vacuum manifold system. The sample flow through the SPE cartridge was kept at ~10 mL/min or less. After the whole sample was extracted, the cartridge was rinsed with 5 mL of DDI H_2O. Room air was allowed to flow through the cartridge by continued suction for a minimum of 5 min to help dry the cartridge. All cartridges were labeled with necessary information and separately stored in a clean bag at –20°C.

2.4. Analytical methods

All extracted samples were then shipped to WSL/UNL for elution and analysis. The pharmaceuticals were analyzed by liquid chromatography and tandem mass spectrometry (LC–MS/MS). The pharmaceuticals analysis method used by UNL contains a significant number of compounds (Bartelt-Hunt et al., 2009). The selected pharmaceutical compounds (18 compounds) and their physical and chemical properties are shown in Table 1.

2.5. Surface water dams

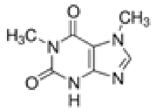
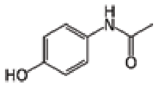
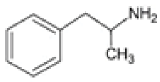
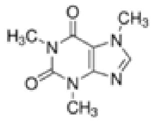
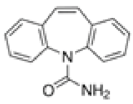
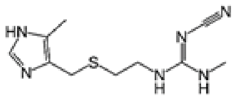
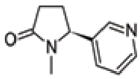
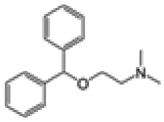
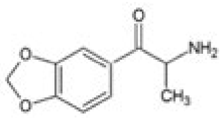
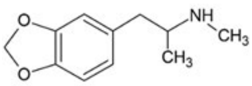
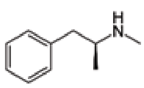
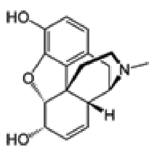
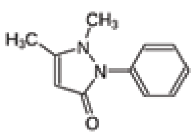
King Talal Dam (KTD) is located in Amman-Zarqa basin (AZB) which comprises several cities (Amman, Zarqa, Mafraq, Jerash and Balqa). The reservoir receives drainage from most of the watershed in AZB (Fig. 1). The total area of the basin is 3,860 km^2 where around 95% of the area is within Jordan and 5% is in Syria reaching to the Syrian city of Salkhad in Jebal al-Arab the Syrian boarders. The Zarqa river is the main watercourse passing through AZB and discharge into KTD (Fig. 1). KTD is currently receiving surface flow including surface runoff from AZB and treated wastewater discharged by the four WWTPs (As Samra, Al-Baqa, Abu Nusair and Jarash). Therefore, KTD water is being only used for agriculture activities in Jordan valley.

Mujib dam is located in southern Jordan at Mujib basin (90 km south of Amman). The Mujib watershed covers an area of 6,571.4 km^2. It comprises two major tributaries: the northern tributary, termed Wadi Wala (2,063.6 km^2), and the southern tributary, known as Wadi Mujib (4,507.8 km^2). Both tributaries merge 3 km before the Wadi discharges into the Dead Sea. Five dams have been constructed across the catchment. The most important is Mujib dam with a capacity of 16.8 MCM per year. The Mujib dam is currently receiving only surface runoff from Mujib catchment. Therefore, its water quality is being used for drinking supplies water for the southern Ghor and Amman. The water samples for this study were collected from the discharge of dam.

3. Results and discussion

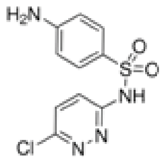
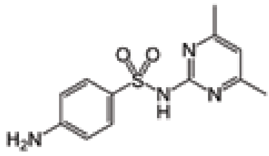
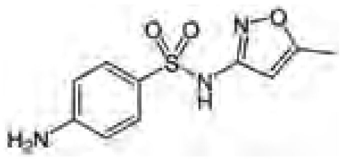
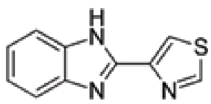
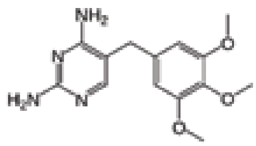
The results show that 10 pharmaceutical compounds were detected in the effluent of KTD including 1,7-dimethylxanthine (a metabolite of caffeine), acetaminophen,

Table 1
Classification and physical and chemical properties of target pharmaceuticals

Compound	Chemical structure	Family and use	CAS number
1,7-Dimethylxanthine		Stimulant	611-59-6
Acetaminophen		Analgesic	103-90-2
Amphetamine		Stimulant	300-62-9
Caffeine		(CNS) stimulant	58-08-2
Carbamazepine		Anticonvulsant	298-46-4
Cimetidine		Antacid	51481-61-9
Cotinine		Stimulant	486-56-6
Diphenhydramine		Antihistamine	58-73-1
MDA		Abuse drug	101-77-9
MDMA		Abuse drug	42542-10-9
Methamphetamine		Stimulant	51-57-0
Morphine		Narcotic analgesics	57-27-2
Phenazone		Analgesic	60-80-0

Ccontinued)

Table 1–*(Continued)*

Compound	Chemical structure	Family and use	CAS number
Sulfachloropyridazine		Antibacterial	201-269-9
Sulfamethazine		Antibacterial	57-68-1
Sulfamethoxazole		Antibiotic	723-46-6
Tiabendazole		Fungicide and parasiticide	148-79-8
Trimethoprim		Antibiotic	738-70-5

amphetamine, caffeine, carbamazepine, cotinine, phenazone, sulfamethoxazole, sulfamethazine, trimethoprim. However, eight pharmaceutical compounds were not detected and below the detection limits (<0.005 µg/L) include cimetidine, diphenhydramine, MDA, MDMA, methamphetamine, morphine, sulfachloropyridazine and thiabendazole. In Mujib dam, the results showed that four pharmaceutical compounds were detected in the effluent of Al-Mujeb Dam including 1,7-dimethylxanthine, caffeine, cotinine, phenazone, Moreover, 14 pharmaceutical compounds were below the detection limits (<0.005 µg/L) including acetaminophen, amphetamine, carbamazepine, cimetidine, diphenhydramine, MDA, MDMA, methamphetamine, morphine, sulfachloropyradazine, sulfamethoxazole, sulfamethazine, thiabendazole, and trimethoprim.

For KTD, the results showed that carbamazepine was the pharmaceutical present at the highest concentration levels 0.358 µg/L, followed by caffeine 0.076 µg/L, phenazone 0.059 µg/L, 1,7-dimethylxanthine 0.053 µg/L, sulfamethazine 0.041 µg/L, sulfamethoxazole 0.039 µg/L, acetaminophen 0.036 µg/L, amphetamine 0.018 µg/L, cotinine 0.015 µg/L, trimethoprim 0.015 µg/L. However, for Mujib dam, caffeine was present with the highest concentration levels 0.089 µg/L, followed by phenazone 0.050 µg/L, cotinine 0.015 µg/L and 1,7-dimethylxanthine 0.010 µg/L.

The concentrations of pharmaceuticals and personal care products (PPCPs) measured in the effluent of KTD were generally higher than those in Mujib dam (Table 2). It is well known that KTD is one of the most polluted reservoir in Jordan. This is mainly due to existence of several pollution sources at AZB such as wastewater treatment effluents, effluents from industries, overflows from broken septic tanks pipelines, inefficient drainage system, domestic waste. In addition, there are several public and private hospitals, clinics, and medical analysis laboratories located AZB. Moreover, it is well known that As-Samra WWTP is the largest wastewater treatment facility in Jordan which is located at AZB. It is annually discharging about 100 MCM of treated wastewater to Zarqa river and finally stored at KTD. A recent study has showed that the levels detected in collected samples from the effluent of As-Samra WWTP were caffeine, acetaminophen, 1,7-dimethylxanthine, cotinine and carbamazepine at concentration of 182.5, 28.7, 7.47, 4.67 and 1.54 µg/L, respectively (Al-Mashaqbeh et al., 2018). The analysis of surface water samples at KTD reveals the persistent presence of pharmaceutical compounds in KTD water with the same distribution as in effluent samples from As-Samra WWTP. It is likely that WWTPs operating at AZB watersheds do not properly remove pharmaceutical compounds, ultimately form the main source of pharmaceutical compounds to this important aquatic ecosystem. On the other hand, the low concentration levels of pharmaceutical compounds found in Mujib Dam can be explained because of the fact that its location is relatively far from other industrial activities and also because of the relatively scarce number of WWTPs in its surrounding catchment.

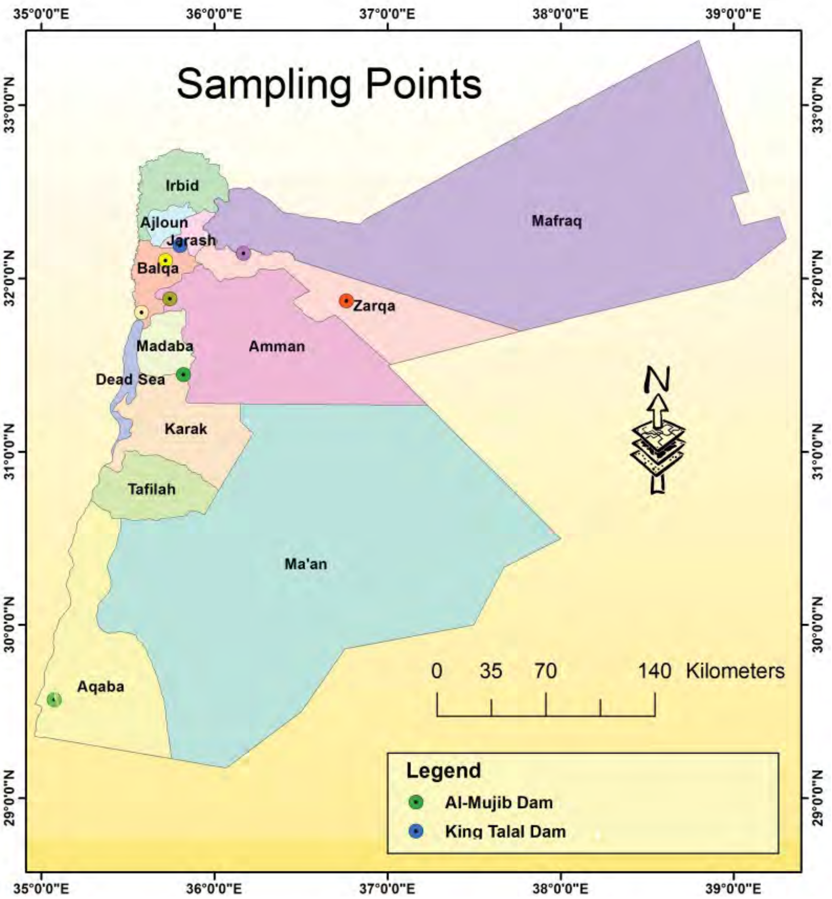


Fig. 1. Location of sampling sites.

Table 2
Concentrations of pharmaceutical compounds detected in collected grab samples (μg/L) from King Talal Dam and Mujib Dam

Pharmaceutical compound	King Talal Dam (KTD) effluent concentration (μg/L)	Mujib Dam effluent concentration (μg/L)
1,7-Dimethylxanthine	0.053	0.010
Acetaminophen	0.036	<0.005
Amphetamine	0.018	<0.005
Caffeine	0.076	0.089
Carbamazepine	0.358	<0.005
Cimetidine	<0.005	<0.005
Cotinine	0.015	0.015
Diphenhydramine	<0.005	<0.005
MDA	<0.005	<0.005
MDMA	<0.005	<0.005
Methamphetamine	<0.005	<0.005
Morphine	<0.005	<0.005
Phenazone	0.059	0.050
Sulfachloropyridazine	<0.005	<0.005
Sulfamethazine	0.041	0.008
Sulfamethoxazole	0.039	<0.005
Thiabendazole	<0.005	<0.005
Trimethoprim	0.015	<0.005

Table 3
Comparison of concentrations of pharmaceutical compounds (ng/L) between surface water at Jordan and worldwide

Compound	Location	Worldwide concentration (ng/L)	This study concentration (ng/L)	Reference
1,7-Dimethylxanthine	Lake Michigan-USA	25–75	10–53	Ferguson et al. (2013)
Acetaminophen	Lake Michigan-USA	2.5–17	<5–36	Ferguson et al. (2013)
Amphetamine	Pearl river-China	17.4–58.2	<5–18	Li et al. (2016)
Caffeine	Lake Michigan-USA	18–100	76–89	Ferguson et al. (2013)
Carbamazepine	Lake Michigan-USA	0.5–10	<5–358	Ferguson et al. (2013)
Cotinine	Lake Michigan-USA	1.5–11	15	Ferguson et al. (2013)
Phenazone	Czech Republic, Germany	35–2,500	50–59	Roig (2010)
Sulfamethazine	Lake Michigan-USA	0.5–1.5	8–41	Ferguson et al. (2013)
Sulfamethoxazole	Lake Michigan-USA	1.5–220	<5–39	Ferguson et al. (2013)
	Selangor River-Malaysia	84.31–114.24		Praveena et al. (2018)
Trimethoprim	Lake Michigan-USA	2.5–18	<5–15	Ferguson et al. (2013)

Overall, all of selected pharmaceuticals compounds were detected along the KTD and Mujib Dam indicating that the continuous output of treated wastewater, urban run-off is among the sources that lead to the presence of pharmaceutical residues along the surface water. The KTD is a valuable water source used for irrigation, hence the presence of PPCPs may have an effect on the quality and grade of vegetables grown in the region.

The concentrations of detected pharmaceuticals in this study were compared with those reported in previous studies globally as presented in Table 3. In general, the targeted pharmaceuticals in the current study are comparable with reported data and within the range reported by the literature on pharmaceutical present in surface water worldwide except for carbamazepine.

4. Conclusion

Within this study, 18 pharmaceutical compounds were screened in the water samples collected from KTD and Mujib Dam to evaluate the influence of discharging treated wastewater to surface water. The results revealed that KTD detected more pharmaceutical compounds compared with Mujib Dam. The results showed that 10 pharmaceutical compounds (1,7-dimethylxanthine, acetaminophen, amphetamine, caffeine, carbamazepine, cotinine, phenazone, sulfamethoxazole, sulfamethazine, trimethoprim) were detected in the effluent of King Talal Dam; while four pharmaceutical compounds 1,7-dimethylxanthine, caffeine, cotinine, phenazone were detected at Al-Mujb Dam. Among the detected compounds at KTD, carbamazepine was the pharmaceutical present at the highest concentration levels 0.358 µg/L; while in Mujib Dam, caffeine was present at the highest concentration levels 0.089. The number of detected pharmaceuticals in KTD was distinctly higher than in Mujib Dam, suggesting that treated wastewater discharged by WWTPs might be the major source of the increase of these pharmaceuticals in the KTD. The results showed that the contamination of KTD water by carbamazepine is certainly related to treated wastewater discharged by WWTPs in Zarqa river. The study points out the need for continuous monitoring of contamination levels not only in the KTD but also in other major Jordanian dams which are receiving treated wastewater.

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Impact assessment of desalination plants on Kuwait Bay using GIS/water quality index analysis

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ABSTRACT

Desalination plants are located along the Kuwait Bay which receives the hypersaline brine effluent discharged from such plants. Kuwait Bay is a semi-enclosed water body that suffers from various pollution loads. The bay covers an area of 735 km^2 and has 130 km coastline. It is a unique ecosystem in Kuwait's territorial waters. This study presents a new approach, which integrates the water quality index with the GIS technology, to assess the impact of desalination plants on Kuwait Bay. The water quality of the bay was determined by a number of parameters. The water quality index was used to translate a set of a large number of variables to a single value describing the water quality to be used in the management of the bay's water, as communicated to policy makers, service personnel, and the public. In this study, the World Health Organization maximum permissible limit values and Kuwait Environment Public Authority water quality standards were used to compare with the results of GIS analysis. The water quality index was consistently higher than 75 in the winter season and higher than 100 in the summer season, showing that the Kuwait Bay is suffering from a very poor to unsuitable water quality all over the year due to the discharge of desalination plants brines and other polluted effluents. GIS mapping was used to indicate the most affected areas in the bay. For a rehabilitation plan, new locations for the outfalls are proposed based on GIS mapping.

Keywords: Brine discharge; Desalination plants; GIS; Water quality index

1. Introduction

Kuwait suffers from fresh water scarcity, therefore, desalination of seawater withdrawn from the Arabian Gulf became an essential part of the water resource management system for supply of fresh water to satisfy a growing demand for potable water. Intakes of such plants as well as outfalls of their brine effluents are distributed along the Kuwait Bay. The bay is located at the upper northwest section of the Arabian Gulf. It is a semi-enclosed water body that suffers from increasing pollution loads. The bay covers an area of 735 km^2 and has 130 km coastline. It is a unique ecosystem in Kuwait's territorial waters.

In addition to brine water, the bay receives discharges from power plants, treated and partially treated wastewater effluents, and storm waters through 32 discharge outfalls. Water quality degradation is caused by the discharge of such wastes which threaten the marine environment and is becoming a serious problem today causing fish kills, in spite of endless efforts to control it. In the Arab countries, in general, and in the Arabian Gulf countries, in particular, marine pollution has recently received much attention since it adversely affects not only the fisheries but also the water supply since these countries depend primarily on seawater desalination as a source for fresh water (Hamoda, 2004).

Perhaps, the Arabian Gulf is the most affected marine environment in the Middle East, where almost all countries along the gulf shore discharge polluted effluents into the gulf waters. In this regard, the State of Kuwait discharges various polluted effluents into the Kuwait Bay. Six large desalination plants located along the bay extract large volumes of seawater and discharge hyper-saline brine back into

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the marine environment. It is stated that desalination plants have strong potential to detrimentally impact the environmental, physicochemical, and ecological attributes of receiving marine environments (Al-Ghadban et al., 2002; Miri and Chouikhi, 2005; Mauguin and Corsin, 2005; Naser, 2015). A comprehensive review of the impact of brine discharge in sea water was conducted by Roberts et al. (2010) who concluded that there is a widespread belief and recognition that discharge of desalination plants brine adversely affects water quality of the sea and poses a potentially serious threat to marine ecosystems. According to Tomlin (1990), the GIS technology could be used in mapping the water quality but such an approach was not applied to the Kuwait Bay.

This study presents a new approach, which integrates the water quality with the GIS technology, to assess the impact of desalination plants and the discharge of wastewaters on pollution of Kuwait Bay.

2. Methodology

Kuwait Environmental Public Authority (KEPA) provided the data of 12 monitoring stations and 15 buoys stations which are located in Kuwait Bay (Fig. 1). Such data were collected during the period from the year 2014 to the year 2017. The data were analyzed to determine the water quality index (WQI) and the weighted arithmetic water quality index method was used to classify the water quality according to the degree of purity by using commonly measured water quality parameters such as salinity, nitrates, phosphates, DO, TSS, and total coliforms.

2.1. Water quality index calculation

The collected data (Table 1) of total dissolved oxygen, ammonia, nitrate, nitrite, total coliform bacteria, phosphate, pH, total suspended solids, and salinity from the 11 monitoring stations were used to calculate the water quality index. In this study, the weighted arithmetic method was used to calculate the water quality index following the approach of Garcia et al. (2014).

2.2. Weighted arithmetic water quality index method

Weighted arithmetic water quality index method classified the water quality according to the degree of purity by using the most commonly measured water quality variables.

The calculation of WQI was performed using the following equation:

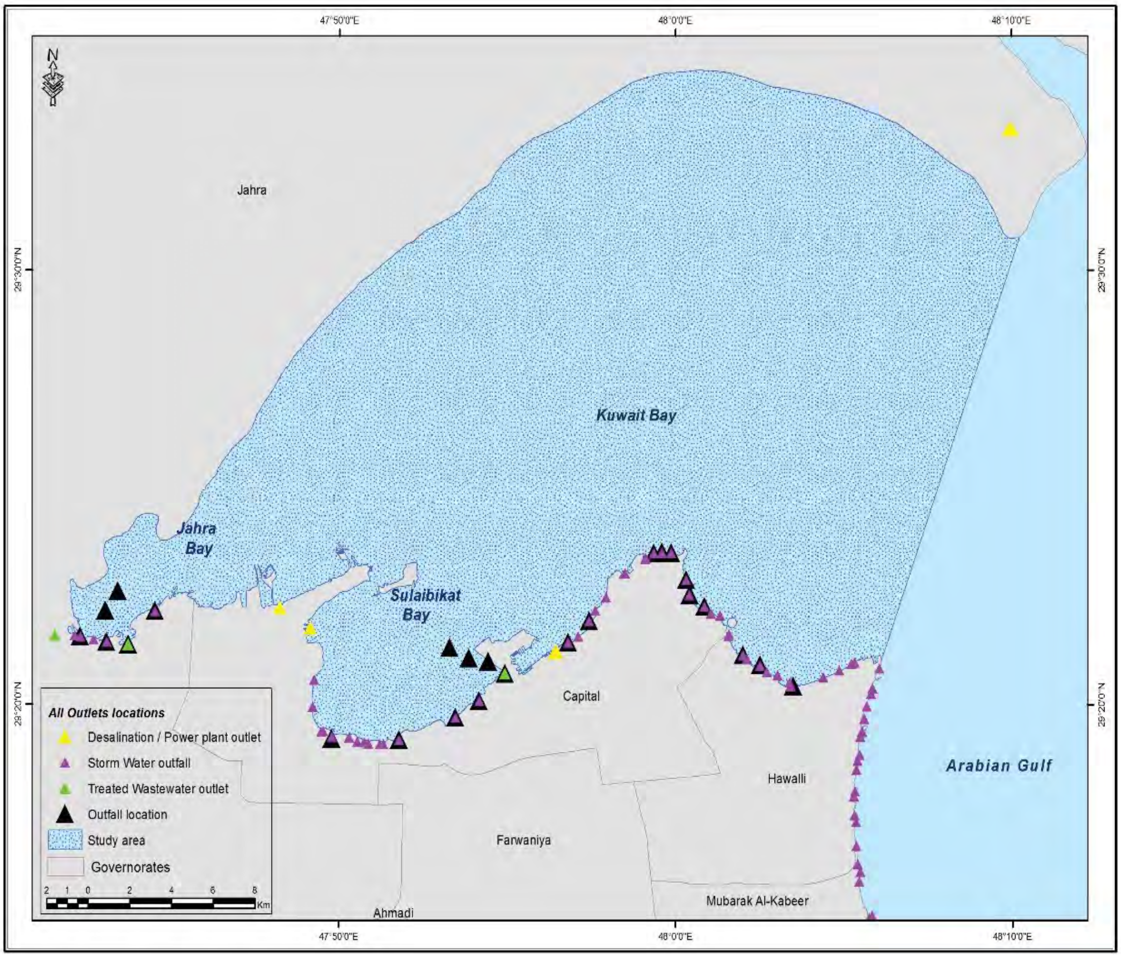

Fig. 1. Outfalls along Kuwait Bay.

Table 1
Water quality parameters from monitoring stations

Location ID	Station	Ammonia	DO	pH	Nitrate	Nitrite	Phosphate	Total coliform	TSS	Salinity
Z00	Al-Beda'a	141.22	6.05	7.91		2.735	16.85	0	18,500	36.31
Z02	Al-Doha	143.15	3.52	8.68	4.85	3.62	28.125	40	14,400	42.15
Z08	Al-Fintas	119.98	6.24	7.95		3.45	23.58	0	9,600	36.54
Z09	Al-Mangaf	130.61	6.75	7.97		2.75	26.98	0	10,700	36.63
Z07	Al-Messila	120.68	7.95	7.93		3.935	19.44	0	11,200	36.21
Z04	Al-Shuwaikh	127.52	3.37	8.61	3.84	4.42	17.165	100	23,600	41.71
Z01	Medayrah (Jal Az-Zour)	131.17	3.19	8.57	3.13	3.23	18.96	10	20,120	41.81
Z10	Mina Abdulla	127.82	6.07	7.94		3.905	23.73	0	11,600	36.55
Z05	Ras Ajuzah	131.94	5.79	7.9		3.68	25.75	0	15,400	38.15
Z06	Ras Al-Ard	149.065	5.11	7.87		7.155	22.98	0	15,100	37.57
Z03	Ras Ushayrij	201.295	3.12	8.57	3.51	4.54	30.905	20	16,000	42

$$\text{WQI} = \frac{\sum Q_i W_i}{\sum W_i} \quad (1)$$

The quality rating scale (Q_i) for each parameter is calculated by using this expression:

$$Q_i = 100\left[\frac{(V_i - V_0)}{S_i - V_0}\right] \quad (2)$$

where,

V_i = measured concentration of *i*th parameter in the analyzed water
V_0 = the ideal value of this parameter in pure water
V_0 = 0 (except pH = 7.0 and DO = 14.6 mg/L)
S_i = recommended standard value of *i*th parameter

The unit weight (W_i) for each water quality parameter is calculated by using the following formula:

$$W_i = \frac{K}{S_i} \quad (3)$$

where,
K = proportionality constant and can also be calculated by using the following equation:

$$K = \frac{1}{\sum \frac{1}{S_i}} \quad (4)$$

3. Results and discussion

Tables 2 and 3 show the WQI for stationary and buoyant stations, respectively, based on data obtained from KEPA. The values of WQI were all high (above 75) indicating that the water quality is poor. Meanwhile, Fig. 2 presents variations in WQI between different stations in the years 2014 and 2015. Such variations were consistent and indicate that

Table 2
Water quality index for the 12 monitoring stations year 2014 and 2015

Buoys station number	WQI_Jan_2017	WQI_June_2017
St-01	83.81	117.24
St-02	82.40	117.87
St-03	81.82	109.17
St-04	84.03	118.17
St-05	82.76	120.89
St-06	81.80	121.11
St-07	79.57	118.17
St-08	90.98	120.14
St-09	88.76	121.97
St-10	87.52	122.06
St-11	97.26	122.70
St-12	88.11	119.04
St-13	95.98	127.70
St-14	90.69	121.99
St-15	83.81	117.24

Table 3
Water quality index for the 15 Buoys monitoring station for year January and June 2017

Name	WQI_Sep_2014	WQI_May_2015
Al-Beda'a	78.0771	86.76192
Medayrah (Jal Az-Zour)	105.8206	85.61359
Al-Doha	107.6095	77.29153
Ras Ushayrij	111.8248	81.68797
Al-Shuwaikh	105.4712	79.75187
Ras Ajuzah	79.78159	94.37651
Ras Al-Ard	84.43719	88.17478
Al-Messila	67.26932	83.72505
Al-Fintas	77.07395	85.87413
Al-Mangaf	75.46737	83.87686
Mina Abdulla	78.41669	82.68312

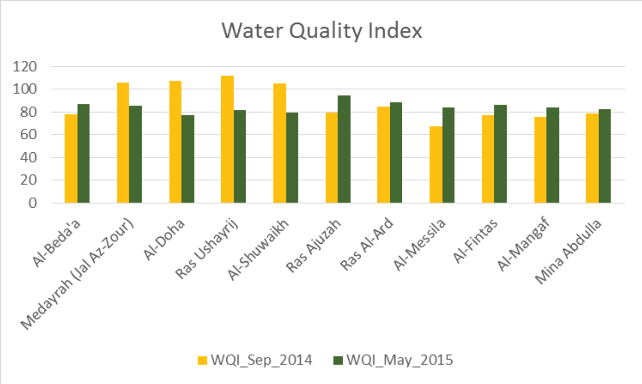

Fig. 2. Comparison between water quality index year 2014 and year 2015.

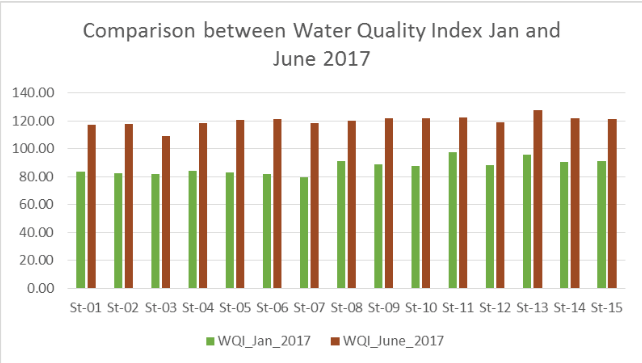

Fig. 3. Comparison between water quality index January and June 2017 based on 15 buoys stations.

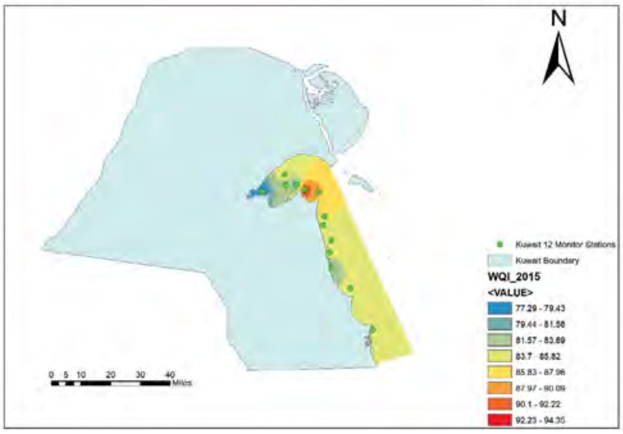

Fig. 4. Spatial distribution for water quality index year 2014 based on 13 monitoring stations.

the water quality was poor in all locations across the bay. Fig. 3 displays seasonal variations in WQI based on WQI obtained in January and June 2017. This figure clearly shows that WQI in summer (June 2017) is higher than in winter (January 2017) showing that the water quality is even worse in the summer season.

Based on values calculated in Table 2, the inverse distance weighting interpolation generated the spatial distribution

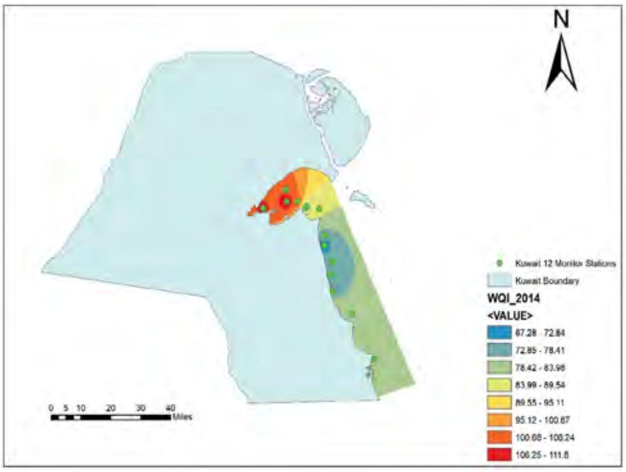

Fig. 5. Spatial distribution for Water quality index year 2015 based on 13 monitor stations.

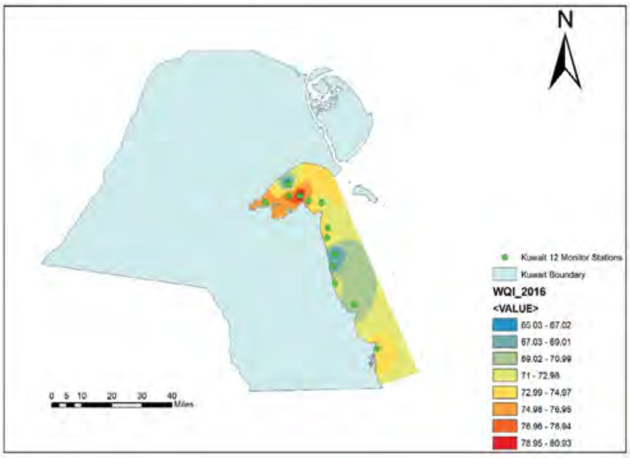

Fig. 6. Spatial distribution for Water quality index year 2016 based on 12 monitor stations.

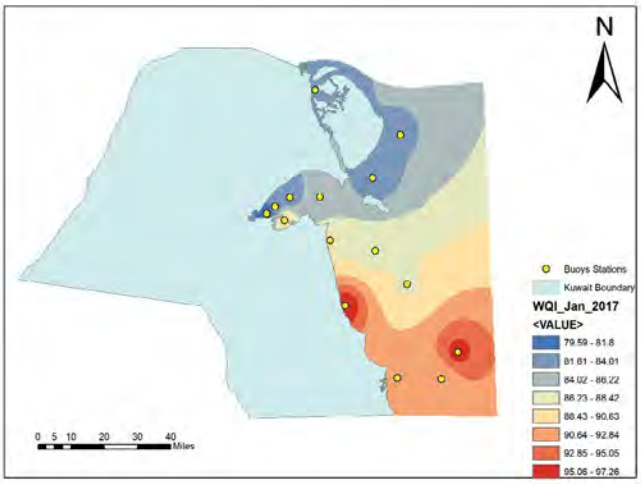

Fig. 7. Spatial distribution for Water quality index year January 2017 based on 15 Buoys monitor stations.

Table 4
Water quality rating as per weight arithmetic water quality index nethod

WQI value	Status	Grading	Possible usage
0–25	Excellent water quality	A	Drinking, irrigation and industrial
26–50	Good water quality	B	Domestic, irrigation and industrial
51–75	Fair water quality	C	Irrigation and industrial
76–100	Poor water quality	D	Irrigation
101–150	Unsuitable for drinking purpose	E	Restricted use for irrigation
Above 150	Unfit for drinking	F	Proper treatment required before use

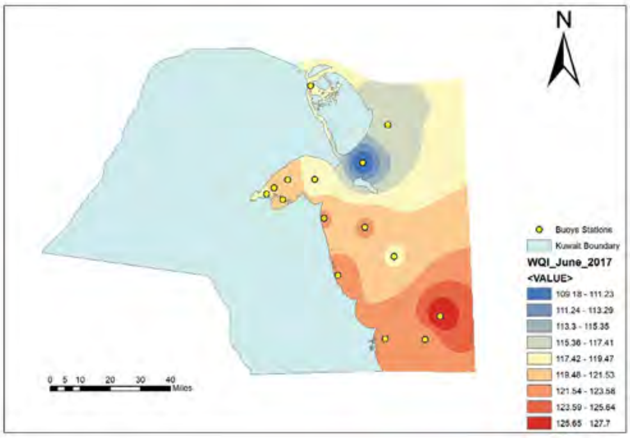

Fig. 8. Spatial distribution for Water quality index year June 2017 based on 15 Buoys monitor stations.

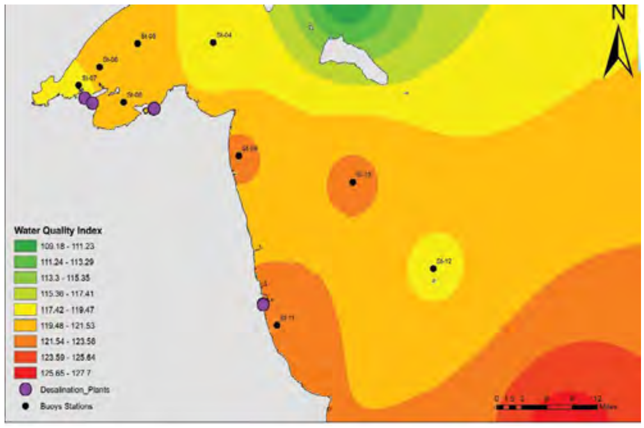

Fig. 9. Water quality index near desalination plants showing a score higher than 100 (June 2017).

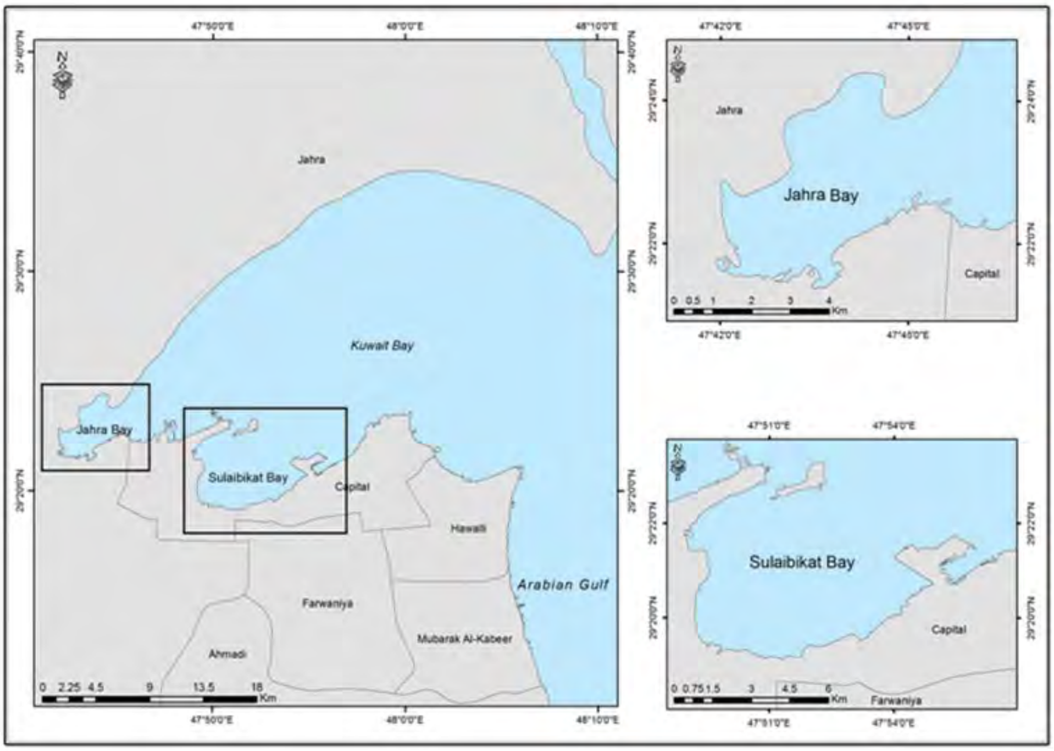

Fig. 10. Highly risk zones in Kuwait Bay.

map of water quality index as shown in Fig. 4 for year 2014; Fig. 5 for year 2015; Fig. 6 for year 2016; Fig. 7 for January 2017; and Fig. 8 for June 2017.

For the years 2014, 2015, and 2016, the readings of 12 monitoring stations were used while for year 2017 15 buoys stations were used for WQI calculation. The rating of water quality according to this WQI was determined according to the weighted arithmetic water quality index method and the results are presented in Table 4.

Fig. 9 shows the buoys station 7, station 8, and station 11 near the desalination plants with WQI higher than 100. Fig. 10 illustrates the risk zones in Kuwait bay according to WQI scores.

4. Conclusions

- The WQI scores show very poor to unsuitable quality of water samples in almost all the outfalls sampling sites and desalination plants along the bay, suggesting that a rehabilitation plan should consider relocation of many of the existing outfalls.
- Use of GIS mapping proved to be a useful technique in identifying the most affected areas in the Bay.
- The Sulaibikhat Bay and Jahra Bay locations of effluent discharge outfalls are badly sited and their adverse impact on the WQI was clearly identified. For a rehabilitation plan, new locations for the outfalls are proposed based on GIS mapping.
- Desalination plants need to stop discharging the brines or treat the brine before discharging it into the sea since the score of WQI is above 100 in the summer season and status of the water is unsuitable according to the WHO criteria.

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Water Sciences and Technology Association

قياس تركيز البرومات في مياه الشرب المعبأة في أسواق السلطنة التحديات والحلول في المصانع

سعيد بن علي الشبلي، فاطمة بنت يوسف العريمية، متعب بن راشد المعمري

دائرة الرقابة الغذائية بوزارة البلديات الإقليمية وموارد المياه- قسم الصناعات الغذائية والتراخيص، البريد الالكتروني: alaraimi-aa@hotmail.com

الملخص

يلجأ أغلب الناس في البلدان المتقدمة الى استخدام مياه الشرب المعبأة في حياتهم باعتبار أن الماء شريان الحياه وكذلك يتم استخدامه في الطبخ باعتقادهم بأنه أكثر أماناً وعالي الجودة وأنه أفضل من مياه الشبكة الذي توفره الحكومة أو الشركات، لذلك انتشرت مصانع ومعامل تعبئة مياه الشرب في قوارير بلاستيكية أو زجاجية وبأحجام وأشكال مختلفة وتشرف على هذه المصانع الجهات الرقابية في السلطنة للتأكد من التزامها بكافة الاشتراطات الصحية للمصانع ومراقبة سلامة و جودة هذه المنتجات لعدم الإضرار بصحة المستهلك، حيث في حالة عدم الالتزام لا تتردد الجهات المختصة باتخاذ الإجراءات اللازمة لردع المخالف بأشد العقوبات وقد تتطرق الإجراءات الى غلق المنشأة. وقد ظهرت مع التقدم والتطور في مجال تعقيم المياه أن لجات الكثير من المصانع الى استخدام محاليل الهيبوكلورايت والبعض استخدام الاوزون لتعقيم مياه الشرب ومنها قد ظهرت إملاح البرومات في مياه الشرب ولكثرة ما أُثير حول الاشتباه بقدرة مادة البرومات في التسبب بالسرطان، فقد عمدت الكثير من الجهات الرقابية في البلدان في العالم على تحديد تركيز وجود هذه المادة في مواصفات مياه الشرب المعبأة لديها على أن لا تزيد عن ١٠ جزء بالمليون، ومن منطلق التأكد من صحة وسلامة المنتجات المتداولة في الأسواق للاستهلاك الآدمي حسب المواصفات والمقاييس المعتمدة ، فقد تطرقت هذه الدراسة الى قياس نسبة تركيز البرومات في مياه الشرب المعبأة في أسواق السلطنة من المنتجات المستوردة والمحلية خلال ثلاثة أشهر، وتم التركيز خاصة على المياه المعبأة محلياً ليتم التأكد من مدى مطابقة العناصر الموجودة في المياه للحدود المسموح بها حسب المواصفة القياسية لمياه الشرب المعبأة (GSO 1025-2014) وبالتحديد عنصر البرومات، حيث تم سحب عينات عشوائية لمنتجات مختلفة من المياه وبتواريخ صلاحية مختلفة وبأحجام مختلفة خلال فترة الدراسة وتحليلها في مركز المختبرات للأغذية والمياه التابع للوزارة خلال عام ٨١٠٢م وأظهرت النتائج مطابقة جميع العينات للمواصفة القياسية لمياه الشرب المعبأة لجميع أنواع المنتجات المستوردة والمحلية التي وقعت تحت نطاق الحدود المسموح بها من تراكيز البرومات، حيث كانت جميعها أقل من (١٠ميكروجرام/ لتر)، وبالتالي التأكد من خلو أسواق السلطنة من منتجات المياه المخالفة والغير مطابقة لحدود البرومات حسب المواصفة القياسية، ومنها تم التطرق الى التحديات التي تواجه المختصين على الرقابة على مصانع مياه الشرب والحلول المقترحة لتلك التحديات، حيث كانت أهم التوصيات عدم توزيع المنتجات في الأسواق قبل التأكد من مطابقتها للمواصفات المعتمدة وتوفير الكادر المختص بالمختبرات التابعة للمصانع وتفعيلها، وتطبيق أنظمة تحليل المخاطر ونقاط التحكم الحرجة (HACCP) ونظام ايزو ٢٢٠٠٠.

الكلمات الدالة: برومات؛ المواصفة القياسية (GSO 1025-2014)؛ الرقابة الغذائية ٨١٠٢؛ تحديات وحلول

١. المقدمة

ةعجزم ءاملامن الله عدوأ ،قلاخلعجزات امبها ريثكلامن اهيف امب ةيضرالأ ةركللى اع ةيحلت االنأكلل ةيويح ةيمهأ هنم تعلج يتلا ةديرفلا صئاصخلاورراسالأ ىلاعت املا ،ناسنالإله من تانيتوبرلاو اتردیهوبركلت اائيزج ريسكت في ايساساً أرود بلعي هنأ اكم ،مجسلاب ةددعتم فئاظووله ديعدلامن ىذلا ناسنلإل ةيصحلوائد افلا جاتحيمن ٢-٣ ايموي ءام رتلً حيث أكثر شيعيلا هنكل ماعط نودب رأهش شيعي نأ ناسنلإل نكميمن ،ءام نودب عبوسأقال اتواسملا نا أورفك نيذلر اي ملو))أ .)ء: ٣٠ ايبنالا( ))ننومؤي ي أفلاح يءشل ء كاملا نم اعلنجو امهانقتفف اقتر اتناك ضرالاو

ص واخلا نوكتي ءاملء ايزجومن ذرة لك بذاجتت هنمو ،نيجورديه يترذب ةيمهاست طةبراب بطةترم نيأكسجذرة ءاملء ايزج في نيجورديهمع ذرة في نيأكسج عنوب روامجلء ايجزلامن ،ةينيجورديهلطة ابرالة ايلء قطليئ يابرهكلا بذاجتلاحيث ةينيجورديهلاو ةيمهاستلا طباورلعد اتبين ةلوسؤم ءاملت اائيزجعن

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الفريدة للماء. مصادر المياه على الارض إما سطحية أو جوفية [١]، ومع التطور الكبير في مجال العلوم والتقنيات واكتشاف العلاقة بين مياه الشرب وبعض الأمراض السائدة، فقد حدث تطور سريع في مجال تقنيات المعالجة حيث أضيفت العديد من العمليات التي تهدف بشكل عام إلى الوصول الى أعلى الدرجات من النقاوة، بحيث تكون خالية من العكارة وعديمة اللون والطعم والرائحة ومأمونة الاستخدام من النواحي الكيميائية والبيولوجية.

تتعدد مراحل معالجة المياه وتنقيتها الى التنقية الذاتية والترسيب والترشيح والتعقيم، وبما أن الترشيح لا يقوم بالتخلص من جميع البكتيريا لذلك يستلزم تعقيمها بعد الترشيح ضماناً لسلامتها من الناحية الصحية، ولقد استخدم في تعقيم المياه وسائل مختلفة منها الفيزيائية والكيميائية [٢]، حيث يعتبر (التسخين والغليان) أو استخدام الأشعة فوق البنفسجية من الطرق الفيزيائية. أما بالنسبة لطرق التعقيم الكيميائية التي تعتمد على إضافة بعض المواد مثل الكلور أو الهيبوكلوريت البروم أو ثاني أكسيد الكلور أو الكلورامين أو اليود أو الاوزون [٢].

الأوزون هو غاز يتكون من ثلاث ذرات أوكسجين تحمل الصيغة الكيميائية O_3، وهو غاز نشط وشفاف يميل الى اللون الازرق حيث يوجد في الطبقات العليا في طبقة الستراتوسفير، بفعل سلسلة من التفاعلات بين الأكسجين الجزيئي والذري ليتكون جزيء الاوزون O_3 بالشكل الطبيعي ثم يتفكك بواسطة الاشعة فوق البنفسجية التي تكسر الرابطة التساهمية الثنائية الموجودة في جزيء الأكسجين وتستمر سلسلة التفاعلات بشكل متوازن للحفاظ على نسبة الاوزون في الطبقات العليا [٣]. أما تجميع الاوزون صناعياً للاستفادة منة يتم باستخدام جهاز يقوم بتمرير الهواء على تيار كهربائي بعد التخلص من الغبار والرطوبة منه فيتحول الهواء الى غاز الأكسجين وبتفاعل ذرة الأكسجين مع جزيء الأكسجين يتكون جزيء الأوزون. ويعتبر غاز الأوزون غالي التكلفة لأنه سريع التفكك ولا يمكن تخزينه وهو مادة مؤكسدة قوية، وأيضاً يعتبر التعقيم بالأوزون من أكثر طرق التعقيم فعالية حيث يقضي على الفيروسات والجراثيم والطفيليات وغيرها من مسببات الامراض [٤]. ومن المشاكل المرتبطة بالتعقيم بواسطة الاوزون وجود البرومات في المياه وذلك عند وجود عنصر البروميد في التربة وخلال مرور الماء عبره فإنه يصبح كأحد مكونات الماء الطبيعية من الأملاح وخلال عملية التعقيم بالأوزون يتحد البروميد وجزيء الأوزون ويتكون البرومات بالصيغة الكيميائية Bro_3 ويزداد تكونها بزيادة قلوية الماء [٥] وزيادة درجة الحرارة [٦، ٧] وزمن المعاملة به والتركيز [٨]. وبما أن المعالجة بالأوزون تحتاج الى أجهزة متطورة لحقن الاوزون بالماء بكمية معينة وحيث أن بعض الشركات تحقنه بشكل عشوائي وذلك يسبب التفاعل بينه وبين البروميد وتكون البرومات وبالتالي تزيد نسبته عن الحد المسموح به حسب المواصفات المعتمدة. وأيضاً يمكن تكون البرومات في الماء خلال عملية التطهير بمحاليل الهيبوكلوريت [٩] وذلك عند وجود البروميد في المواد الاولية عند مراحل تطهيره، وكذلك عند وجود ثاني أكسيد الكلور والضوء في الماء يتكون البرومات [٠١، ١١]، حيث أثبتت الدراسات أن استخدام الاوزون في عملية تعقيم مياه الشرب واحتمالية تكون البرومات به، فإن جرعة البرومات المحتملة للإنسان تتراوح بين ٠٢١ الى ٠٨١ مايكروجرام /يوم [٢١]، وكذلك هناك العديد من الدراسات في هذا المجال حيث تم إعطاء فئران التجارب نوع F344 مياه شرب تحتوي على برومات البوتاسيوم بجرعات معينة يومياً لمدة ٠١١ أسبوع، حيث ثبتت الدراسة حدوث الاورام الكلوية وأورام الغدة الدرقية بنسب مختلفة بين الفئران الإناث والذكور حسب الجرعات المسجلة [٣١]. ولكن لا توجد أدلة كافية تثبت العلاقة بين البرومات في مياه الشرب وتسببها بحدوث هذه الاورام على الإنسان، ومع ذلك فان خطورة هذه المادة على صحة الانسان أتت من الدراسات التي أجريت على حيوانات التجارب (الفئران والجرذان) ولم يتم تجاهل النتائج من قبل المنظمات الدولية وتم وضع مواصفات ومقاييس دولية ومحلية لتحدد المواصفات والحدود المسموح بها في مياه الشرب المعبأة بحيث لا تزيد عن ٠١ مايكروجرام لكل لتر.

تم تصنيف البرومات على أنه مسرطن بشري محتمل ومن النوع (group 2B) من قبل الوكالة الدولية لأبحاث السرطان [٤١] على أساس وجود الادلة الكافية على حيوانات المختبر، مع عدم وجود الأدلة الكافية على البشر. وتمثلت أعراض التسمم المباشر عن طريق الفم بأملاح البرومات بحدوث التقيؤ، الغثيان، آلام في البطن، احتباس البول، إسهال، ودرجات مختلفة من التأثير على الجهاز العصبي المركزي والصمم والفشل الكلوي [٥١]. ومعظم هذه الأعراض قابلة للشفاء، وهناك بعض الأعراض الغير قابلة للشفاء منها الصمم والفشل الكلوي الذي تم تسجيله عند التعرض لجرعات بين ٢٤٠-٥٠٠ مليجرام من برومات البوتاسيوم لكل كيلوجرام من وزن الجسم، ١٨٥-٣٨٥ مليجرام من البرومات لكل كيلوجرام من وزن الجسم [٦١].

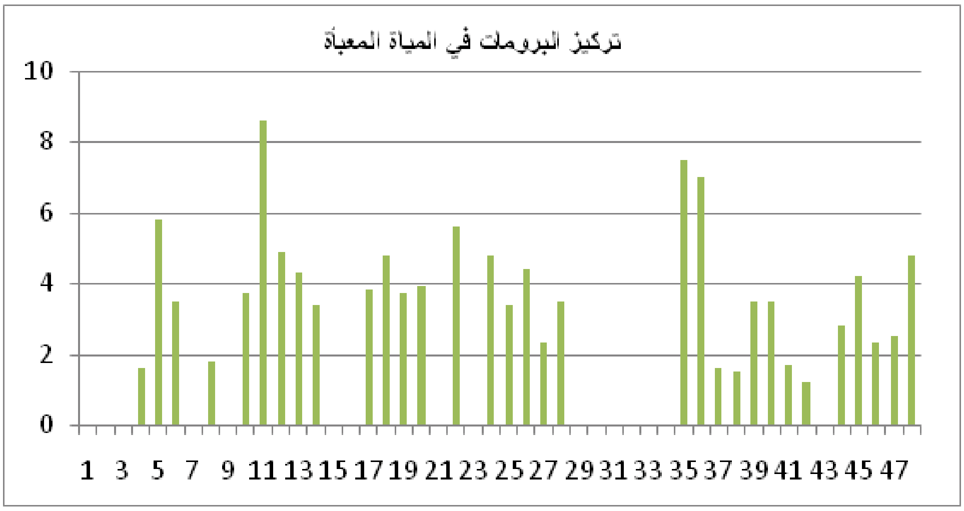
الغرض من هذه الدراسة هو دراسة تركيز البرومات الموجودة في مياه الشرب المعبأة في أسواق السلطنة لكل منتج محلي ومستورد ومعرفة مدى مطابقتها للحدود المسموح بها للمواصفات القياسية لمياه الشرب المعبأة (GSO 1025-2014)، للتأكد من مأمونيتها للاستهلاك الآدمي خلال فترة الدراسة.

٢. المنهجية

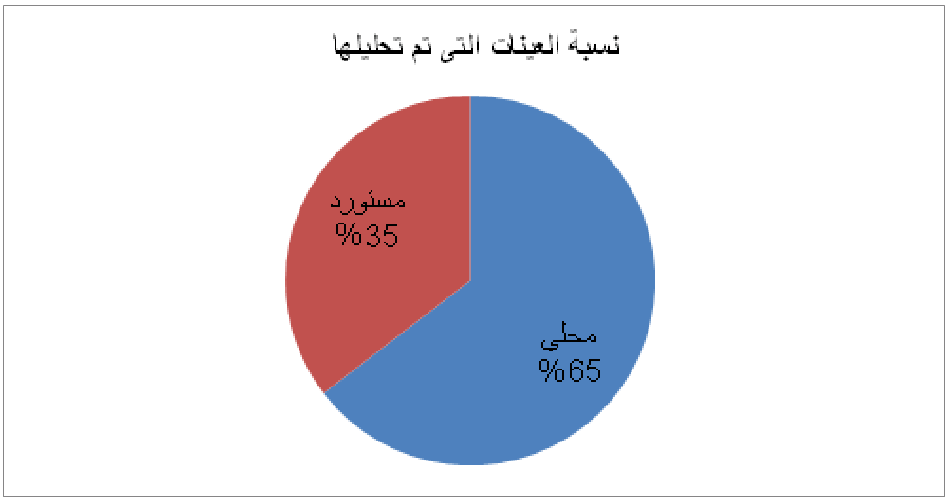
تم سحب عينات مياه الشرب المعبأة من الاسواق المحلية بأنواع وأحجام مختلفة من قبل المختصين وإرسالها الى (مركز مختبرات الأغذية والمياه) لعمل التحاليل من قبل المختصين والفنيين بالمختبر وفق المواصفة القياسية المعتمدة لمياه الشرب المعبأة (GSO 1025-2014)، وتم اعتماد النتائج بحيث تكون الحدود القصوى لتركيز البرومات في مياه الشرب المعبأة لا تتعدى ٠١ مايكرو جرام لكل لتر كناتج من نواتج التطهير وتم استخدام طريقة التبادل الايوني في التحليل باستخدام جهاز (ion chromatography).

٣. النتائج والمناقشة

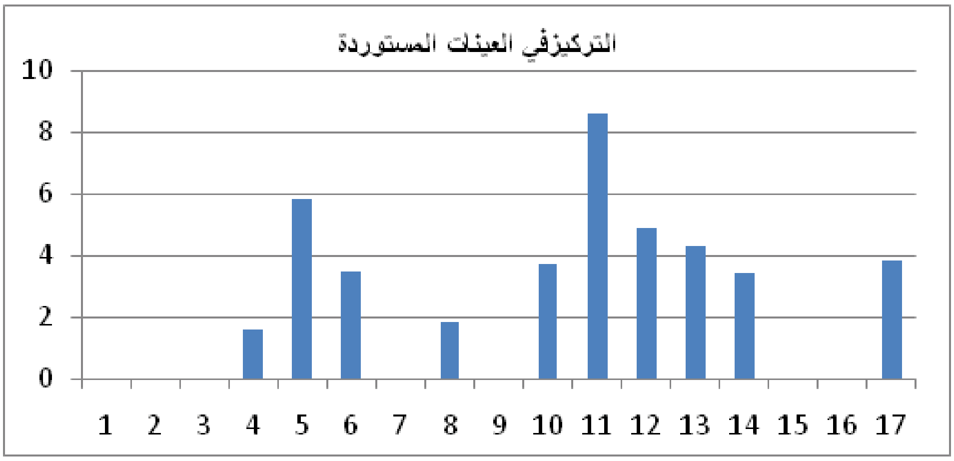
تشير النتائج إلى تفاوت في تراكيز البرومات وجميعها تقع ضمن الحدود المسموح بها ولا تزيد عن (٠١ميكروجرام/لتر) حسب المواصفة القياسية لمياه الشرب المعبأة (GSO 1025-2014) التي أوضحت في جدول المكونات الكيميائية التي تستعمل في معالجة مياه الشرب أو التي تلامسها في عمود نواتج مواد التطهير نسبة (البرومات) والحد الاعلى المسموح به في المياه المعبأة للشرب وهو (٠١ميكروجرام/لتر). حيث كانت أعلى نسبة ٩,٨ ميكروجرام/لتر وكانت معظم نتائج العينات لا تحتوي على البرومات. ويوضح شكل [١] نسب نتائج تركيز البرومات في العينات التي تم تحليلها، حيث كانت ٥٣٪ من المنتجات التي تم تحليلها مستورده و٥٦٪ منتجات محلية (شكل [٢])، ويوضح الشكل [٣] نتائج تركيز البرومات في العينات المستوردة مقارنةً بالحد الأعلى المسموح به (٠١ ميكروجرام/لتر) والشكل [٤] يوضح نتائج تركيز البرومات في العينات المحلية مقارنةً بالحد الاعلى المسموح به. وحيث أن الجهات المختصة تسعى بالتعاون مع الشركات لوجود المنتجات الاستهلاكية الغذائية بالأسواق ليس فقط أن تكون صالحة للاستهلاك الادمي، بل يتعدى ذلك لتكون ذات جودة عالية، فقد تم التنسيق مع الشركات المحلية ليتم المناقشة



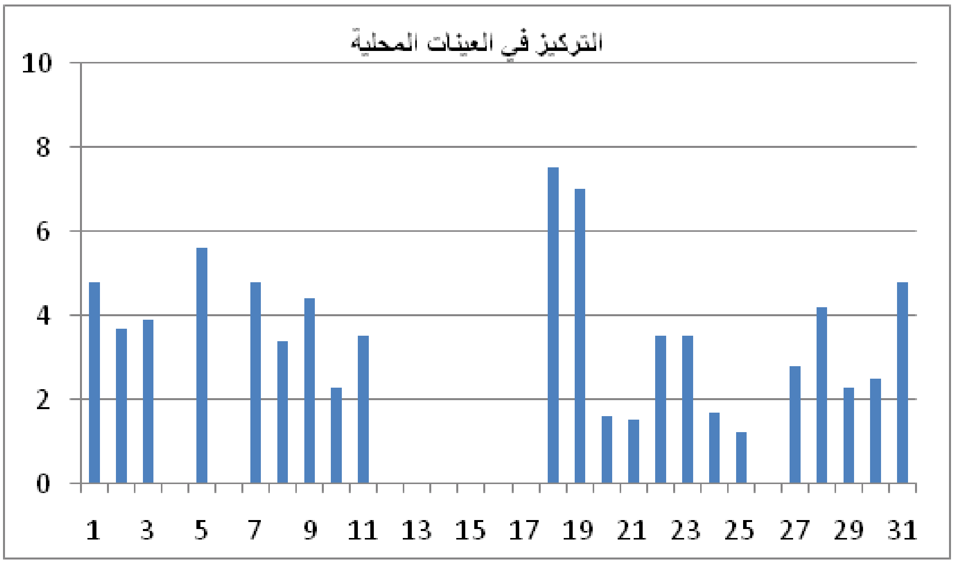
الشكل [١]: نتائج تركيز البرومات في العينات مقارنةً بالحد الأعلى المسموح به (١٠ ميكروجرام/لتر).



الشكل [٢]: نتائج نسبة العينات التي تم تحليلها من المنتجات المستوردة والمحلية.



الشكل [٣]: نتائج تركيز البرومات في العينات المستوردة مقارنةً بالحد الاعلى المسموح به ١٠ ميكروجرام/لتر.



الشكل [٤]: نتائج تركيز البرومات في العينات المحلية مقارنةً بالحد الاعلى المسموح به ١٠ ميكروجرام/لتر.

معها حول الحلول المقترحة لكي تكون جميع منتجات المياه المعبأة تخلو من تركيز البرومات نهائياً. وتم مناقشة بعض الابحاث والدراسات العالمية التي توضح كيفية منع تكون البرومات خلال المعاملة بالأوزون أو عن طريق المعالجة بمحاليل الهيبوكلوريت [٦١]، حيث توجد دراسات علمية تحدثت عن العوامل التي تساعد على تكون البرومات خلال المعاملة بالأوزون ومنها تركيز البروميد، جرعة الأوزون، درجة الحرارة، الرقم الهيدروجيني، القلوية، المواد العضوية، الأمونيا والهيدروجين بيروكسيد [٦١]. وقد أشارت بعض الدراسات العالمية أن بعد تكّون البرومات في مياه الشرب يصعب التخلص منه [٦١]، وتناولت الدراسات أيضاً إمكانية إزالة البرومات بعد تكونها في المياه المعالجة بعدة طرق منها: إضافة الكربون النشط وعامل مختزل Fe^{2+} والتعرض للأشعة فوق البنفسجية والتبادل الأيوني ولكنها طرق غير مرغوبة لارتفاع تكلفتها. وأيضاً يمكن منع تكّون البرومات عن طريق التخلص من البروميد في المياه الاولية قبل معالجتها عن طريق التناضح العكسي والتبادل الايوني، والدليزة الكهربائية (Electrodialyis) [٦١]. ومنه تم التطرق في النقاش الى تعامل هذه الشركات مع تفاوت وتذبذب تركيز البرومات والحلول العلمية لحلها والاستفادة من الدراسات والابحاث العلمية المعتمدة واستخدام التقنيات الحديثة من الاجهزة لضبط نسب المواد الكيميائية في المياه بعد الموازنة وتوظيف الكوادر المتخصصة في هذا المجال وضبط جودة المنتجات للحفاظ على صحة وسلامة المستهلك عن طريق سلامة وجودة المنتجات الموجودة بالأسواق.

٤. الإجراءات المتخذة الى الآن

1) التنسيق مع الشركات والمصانع ومناقشة أفضل الحلول لتوفير منتجات مطابقة للمواصفات وذات جودة عالية.
2) الاستمرار في تحليل منتجات المصانع في مركز مختبرات الاغذية والمياه أو أي مختبر معتمد من قبل الجهات المختصة قبل توزيعها لكل تشغيله.
3) تكثيف الجهود للرقابة على مصانع مياه الشرب ومدى التزامها للاشتراطات الصحية وتطبيقها الآمن حول استخدام الأجهزة الخاصة في التعقيم.
4) وضع مقترح لجائزة الإجادة للمصانع الغذائية.
5) وضع خطة تفصيلية لسحب عينات من منتجات المياه المعبأة للعام القادم.
6) عمل مسودة لتعديل في لائحة الاشتراطات الصحية للأنشطة ذات الصلة بالصحة العامة.
7) عقد حلقة نقاشية للمختصين بالدائرة لعرض التحديات التي تواجهه المختصين في الرقابة الميدانية حيث كان أبرزها.

- زيادة عدد مصانع المياه.
- ضعف الرقابة الذاتية لدى المنشآت.
- الكوادر المتخصصة.
- التقنيات الحديثة.
- تطبيق أنظمة ضبط الجودة.

٥. التوصيات

اتضح من خلال النتائج والمناقشة حول الدراسة على أهمية المتابعة لعبوات المياه المتداولة بالأسواق والتأكد من سلامتها لعدم الاضرار بصحة الانسان والفرد، وخرجت الدراسة الى عدة توصيات وهي كالتالي:

1) متابعة سحب عينات تأكيدية من منتجات الشركات المستوردة والمحلية والتركيز على المنتجات نتائجها تحتوي على نسب ولو بسيطة من البرومات ومخاطبة المصانع التي تقع تحت اشراف الوزارة.

2) العمل على تعديل بعض البنود في لائحة الاشتراطات الصحية الخاصة بالأنشطة ذات الصلة بالصحة العامة.
3) التنسيق مع الجهات المختصة لضمان عدم تسويق أي منتج قبل التأكد من مطابقته للمواصفات القياسية المعتمدة وذلك بعد تحليل المنتجات في المختبرات المعتمدة.
4) تكثيف وتوحيد الجهود للرقابة على مصانع المياه المحلية.
5) إحكام الرقابة على دخول المنتجات المستوردة عن طريق التحليل اللازمة لكل شحنة مستوردة من الخارج قبل توزيعها في الاسواق.
6) عمل زيارات لمصانع مياه عالمية للاطلاع على التجارب والخبرات.
7) تدريب المختصين في الرقابة للحصول على شهادة مدققين دوليين.
8) يجب على مصانع المياه توفير اجهزة متطورة لقياس نسبة البرومات في مياه الشرب.
9) على أصحاب المصانع توظيف الكوادر المتخصصة وتفعيل عمل المختبرات بها بجميع أقسامه.
01) تفعيل جائزة الإجادة للمصانع الغذائية لرفع المستوى الصحي وجودة المنتجات المصنعة.

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The 13th Gulf Water Conference

التأثيرات البيئية لمحطة تحلية تاجوراء العاملة بتقنية التناضح العكسي

بشير بريكة

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الملخص

تعاني ليبيا التي تقع ضمن نطاق مناخ شبه صحراوي من مشكلة حقيقية في المياه، وتتمثل هذه المشكلة في نقص شديد في المياه الصالحة للشرب. حيث يعتمد السكان على المياه الجوفية التي تعتبر هي المصدر الرئيسي للمياه في ليبيا، غير أن هذا المصدر غير كافي لتغطية احتياجات السكان، ويعود هذا النقص في المياه الصالحة للشرب لعدة أسباب، منها تداخل مياه البحر مع المياه الجوفية وخاصة على طول الساحل الليبي، وكذلك تداخل مياه الصرف الصحي والمياه المصاحبة من الإنتاج النفطي مع المياه الجوفية في مناطق أخرى من البلاد. وتعد تقنية تحلية المياه هي أحد الخيارات البديلة لتعويض الفاقد من المياه الجوفية في ليبيا وفي باقي دول الشمال الإفريقي. وعلى الرغم من أن تقنية تحلية المياه تعد خياراً مهماً لتوفير مياه الشرب والمياه الصناعية، إلا أن هذه التقنية لها بعض التأثيرات السلبية على البيئة المحيطة إذا لم تُشغل محطات التحلية بأسس علمية وسليمة. وتعد محطة تاجوراء لتحلية المياه إحدى أقدم محطات تحلية المياه العاملة بطريقة التناضح العكسي في ليبيا، وتتجاوز فترة تشغيلها حتى الآن الثلاثة عقود، ولذلك فهي تعد أرضاً خصبة لإجراء العديد من الدراسات والأبحاث عليها. وتعتبر هذه الدراسة المتمثلة في دراسة التأثيرات البيئية لمحطة تاجوراء لتحلية المياه هي إحدى هذه الدراسات التي قام بها الباحث في هذا الصدد. خلال هذه الدراسة قام الباحث بعدة زيارات ميدانية وتفقدية إلى محطة تحلية المياه في تاجوراء، وأجرى العديد من النقاشات مع بعض العاملين بالمحطة. وبناءً على الزيارات الميدانية والنقاشات الحوارية ومن خلال الوصف والتدقيق والرجوع للدراسات السابقة على محطة تحلية المياه في تاجوراء وبعض محطات التحلية في الدول الأخرى يستعرض الباحث خلال هذه الورقة البحثية مجموعة من العوامل والمؤثرات التي ساهمت وتساهم في بعض التأثيرات السلبية على البيئة المحيطة للإنسان والحيوان والنبات والناتجة عن تشغيل هذه المحطات. وأهم نتائج هذه الدراسة تتركز في أن نقطة ترجيع المحلول الملحي (brine disposal point) هي أحد المواقع التي تساهم في بعض التأثيرات السلبية على الإنسان والكائنات البحرية على الشاطئ القريب، كما أن مخازن المواد الكيميائية داخل محطة تحلية تاجوراء والظروف التخزينية بداخلها لا تعد بيئة صحية سواء للعاملين داخل المحطة أو حتى للمقيمين في المناطق القريبة من محطة التحلية. هذا بالإضافة لتأثيرها على بنية المناطق المحيطة نفسها، حيث تعد المنطقة المجاورة لمحطة تحلية تاجوراء من المناطق الأثرية ذات القيمة التراثية المهمة وقد بدأت هذه المنطقة تتأثر بالنشاطات التي تجرى بالقرب منها مما يستلزم إجراء بعض الأعمال المسحية عليها من قبل المهتمين، وذلك للمحافظة على قيمتها الأثرية.

الكلمات الدالة: تحلية المياه؛ التناضح العكسي؛ تصريف الرجيع الملحي؛ الضجيج والضوضاء

1. ةمدقملا

على الرغم من امتلاك ليبيا لأطول ساحل جنوب البحر الأبيض المتوسط (٠٥٩١ كيلو متر)، إلا أن تقنية تحلية مياه البحر لا تعد الطريقة الشائعة الاستخدام فيها كمصدر رئيسي لتوفير المياه الصالحة للشرب. وقد تبنى نظام الحكم السابق فكرة مشروع النهر الصناعي كبديل وخيار استراتيجي لحل مشكلة شح المياه في البلاد وخاصة في الجزء الشمالي منها.

وقد اعتمدت استراتيجية هذا المشروع على جلب المياه من الأحواض المائية (الجوفية) في الوسط والجنوب الليبي إلى المدن الساحلية والقرى والبلدات الريفية المنتشرة في كامل التراب الليبي عبر شبكة من الأنابيب الضخمة المدفونة في الأرض التي يبلغ قطر كل منها أربعة أمتار، وبطول سبعة أمتار، لتشكل في مجموعها نهراً صناعياً بطول تجاوز في مراحله الأولى أربعة آلاف كيلومتر.

وصاحبت أعمال إنشاء وتشغيل المراحل الأولى من مشروع النهر الصناعي العديد من الصعوبات والتحديات نتج عنها عدم القدرة على تزويد بعض المدن الساحلية -كمدينة تاجوراء- بالمياه الصالحة للشرب، وبالتالي فإن مشروع النهر الصناعي لم يحقق كامل الأهداف المنتظرة والموعودة فيما يتعلق بتوفير الاحتياجات المائية لكل المواطنين. وفي المقابل فإنه وبالرغم من أن بعض المدن الساحلية كانت أوفر حظاً في الحصول على المياه من خلال منظومة النهر الصناعي إلا أن

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سكان هذه المدن لا يشعرون بالارتياح التام حول جودة المياه الواصلة إليهم. وبناءً على ذلك، فإن نسبة كبيرة من سكان المدن الكبرى كطرابلس وبنغازي ومصراتة يقتصر استخدامهم للمياه الواصلة إليهم عبر شبكة منظومة النهر الصناعي فقط على أعمال الغسيل والتنظيف والزراعة، حيث أنهم لا يعتبرونها مياهً صالحة للشرب. هذا الشك أو عدم اليقين فيما يتعلق بجودة هذه المياه تولد عند الأهالي لاعتقادهم أن المياه المجمعة في خزانات عملاقة قبل أن تأخذ مسارها عبر شبكة الأنابيب العامة لا تخضع لعمليات التحليل والمعالجة الدورية، مما قد يجعلها غير مطابقة للمواصفات والمعايير القياسية لمياه الشرب المحلية والعالمية.

وبالإضافة إلى هذا فإن الوضع الحالي لمشروع النهر الصناعي والظروف غير المستقرة المصاحبة له تجعل من مشكلة شح المياه لا تزال مشكلة قائمة وبحاجة إلى حلول طارئة.

وقد أوصت اللجنة الوطنية المختصة بالنظر في البحث عن الحلول الاستراتيجية المتعلقة بالأمن المائي بأن يتم وبشكل عاجل توطين تقنية تحلية مياه البحر على طول الساحل الليبي، على أن يؤخذ بعين الاعتبار أن تكون التقنية المقترحة صديقة للبيئة.

وينوي المؤلف من خلال هذه الدراسة تسليط الضوء على التأثيرات البيئية لمحطة تحلية مياه محلية كانت قد دخلت العمل منذ أكثر من ثلاثة عقود، وذلك من أجل الحصول على قدر من المعلومات من شأنها أن تكون نافعة وذات قيمة كبيرة عند إنشاء محطة تحلية جديدة ذات سعة أكبر تكون بالقرب من المحطة القديمة (محور الدراسة).

2. الحالة الدراسية: محطة تحلية تاجوراء العاملة بتقنية التناضح العكسي

٢. ١ الوصف العام للمحطة

تعد محطة تحلية المياه في تاجوراء العاملة بتقنية التناضح العكسي إحدى المحطات الرئيسية من هذا النوع في ليبيا بسعة تصميمية تبلغ ١٠,٠٠٠ متر مكعب/اليوم. وتقع المحطة على ساحل البحر الأبيض المتوسط، شرق العاصمة طرابلس. وعلى الرغم من أن هذه المحطة قد دخلت فترة التشغيل منذ أكثر من ثلاثة عقود، إلا أنه لم يتم إجراء أي دراسات شاملة تتعلق بالآثار البيئية الناتجة عن هذه المحطة. وفي هذه الدراسة سيتم استعراض بعض الاعتبارات البيئية لمحطة تحلية مياه تاجوراء، كما سنحاول من خلال هذه الدراسة تسليط الضوء على المخاوف البيئية الرئيسية التي تتضمن اعتبارات لها علاقة بالموقع، خطر المواد الكيميائية، الضجيج والضوضاء، وأيضا طريقة التخلص من الرجيع الملحي المركز.

٢. ٢ وصف عام لعمليات تشغيل المحطة

يوضح الشكل رقم ١ رسم تخطيطي لمكونات محطة تحلية المياه في تاجوراء ومراحل عملها. ويبدأ عمل المحطة بضخ مياه البحر بواسطة الجاذبية عبر أنبوبين بلاستيكيين بقطر ٧٦٠ مم إلى ما يعرف بخزان مياه البحر (سعة ١٩٢٠ متر مكعب). ويتم بعد ذلك ضخ مياه البحر إلى وحدة المعالجة الأولية (معدل التدفق = ١٥٧٦ متر مكعب/الساعة). وتتكون وحدة المعالجة الأولية من عدد ثماني مرشحات مزدوجة ومرشح كاتريدج (الفلتر الخرطوشي) ذو مسام ٥ ميكرون، ووحدة حقن المواد الكيميائية. وتتكون منظومة المرشحات المزدوجة من ثلاث طبقات: طبقة الرمل ومكانها أسفل المرشح، وطبقة الحصى وهي الطبقة الوسطي، وطبقة الأنثراسيت وهي الطبقة العليا في المرشح.

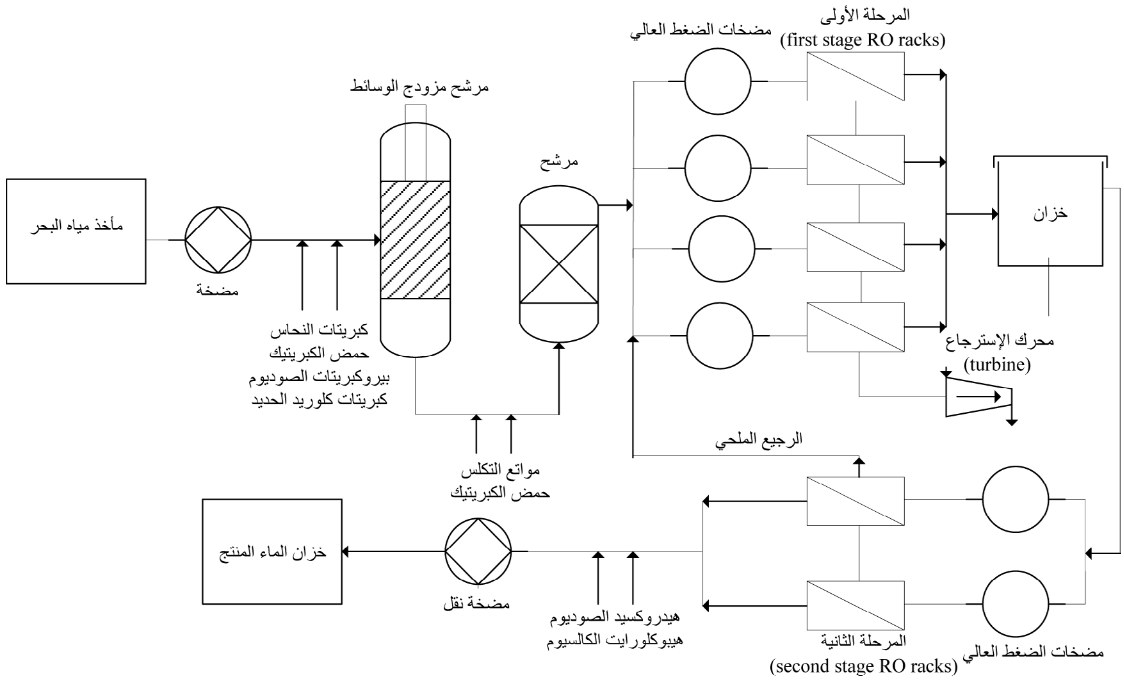
ويتم حقن المواد الكيميائية بشكل مباشر في وحدة المعالجة الأولية وذلك قبل دخول مياه البحر لمنظومة المرشحات المزدوجة. وفيما يلي بيان للمواد الكيميائية المستخدمة في وحدة المعالجة الأولية في محطة تحلية تاجوراء:

١. كبريتات النحاس ($CuSO_4$) وتستخدم لغرض التعقيم.
٢. حمض الكبريتيك (H_2SO_4) ويستخدم لغرض تعديل درجة الحموضة.
٣. بيروكبريتات الصوديوم (Na_2S_2O) وتستخدم لغرض إزالة الأكسجين.
٤. كبريتات كلوريد الحديد ($ClfeSO_4$) وتستخدم لغرض التخثير (flocculation) وإزالة المواد العالقة.
٥. الفوسفات AF 200وتستخدم لغرض إزالة التكلس (antiscalant)، حيث تمنع ترسيب كبريتات الكالسيوم على سطح الأغشية الأسموزية. يتم إضافة موانع التكلس قبل مرشح الكاتريدج.
٦. هيدروكسيد الصوديوم (NaOH) ويستخدم لغرض تعديل درجة الحموضة.
٧. محلول هيبوكلورايت الكالسيوم [$Ca(ClO_2)_2$] ويستخدم لغرض منع النمو البكتيري.

وبعد مرحلة المعالجة الأولية، تأتي عملية ضخ ماء البحر المُعالج إلى وحدة التحلية الرئيسية. وتتكون محطة تحلية تاجوراء من مرحلتين وهو ما يعرف بنظام متعدد المسارات "permeate staged system" وهو نظام تستخدم فيه المياه المحلاة من المسار الأول في تغذية المسار الثاني وذلك لزيادة جودة المياه المنتجة.

وتتكون المرحلة الأولى من أربعة صفوف مشتملة على عدد ٩٩ وعاء ضغط (pressure vessel) في كل صف. ويحتوي كل وعاء ضغط على عدد ستة أغشية من النوع اللولبي (Spiral wound).

ويساوي معدل الإرجاع التصميمي للمحطة (النسبة بين المياه المنتجة المحلاة الي المياه المغذية) ٣٠٪. ويتم تجميع الماء المنتج من المرحلة الأولى في خزان تبلغ سعته ٥٠ متر مكعب. ويتم ضخ الماء المُجمع في هذا الخزان بواسطة مضخات الضغط العالي للمرحلة الثانية (second stage racks). ويتم استعادة حوالي ٨٥٪ من المياه المنتجة من المرحلة الأولى بواسطة المرحلة الثانية ويتم تجميعها في خزان لأجل إجراء عمليات المعالجة النهائية، بينما يتم إعادة الرجيع الملحي الناتج من المرحلة الثانية وذلك بخلطه مع الماء الداخل للمرحلة الأولى.



شكل ١. رسم تخطيطي لمكونات محطة تحلية المياه في تاجوراء

3. الاعتبارات البيئية لمحطة تحلية المياه بتاجوراء

يُسلط القسم التالي من الدراسة الضوء على أهم الاعتبارات البيئية لمحطة تحلية المياه بتاجوراء.

٣. ١ الأرض المشغولة بواسطة محطة التحلية (الموقع)

تقع محطة التحلية في منطقة تدعى «بيار السبابيل»، وهي تبعد ٠١ كيلو متر عن مركز المدينة. وكان اختيار هذا الموقع إبان فترة إنشاء المحطة خياراً مناسباً لعدة اعتبارات من بينها:

١. وقوع المحطة بالقرب من البحر يحافظ على جودة الماء المراد تحليته. كما إن خاصية قرب المحطة من البحر يقلل من خطر تلوث الأرض الذي قد ينجم من عملية نقل الرجيع الملحي إلى البحر.
٢. وقوع المحطة بالقرب من مركز البحوث النووية الذي يعتبر المزوَد الرئيسي للمياه المحلاة.
٣. تعد مياه البحر (المراد تحليتها) ذات جودة مناسبة، حيث أن مأخذ مياه البحر بعيد عن أي موانئ أو نقاط تصريف من أي نوع.
٤. وقوع المحطة بعيداً عن الأحياء السكنية، إلا أنه حديثاً قد طرأت بعض التغيرات العمرانية بالقرب من المحطة حيث تم إنشاء قرية صغيرة يقطنها حوالي ٢٠٠-٠٠٥ ساكن، وذلك على بعد ٠٠٠١ متر من المحطة.

هذا وتبلغ مساحة الأراضي المشغولة بواسطة محطة تحلية المياه في تاجوراء والوحدات والمرافق التابعة لها حوالي سبعة هكتارات مقسمة كالتالي: (١) هكتار واحد مستغل بواسطة الأبنية الرئيسية. وهذه الأبنية لا تشمل المأخذ، ومخازن المواد الكيميائية، وخزان المياه المنتجة، (٢) نصف هكتار مستغل بواسطة مخازن المواد الكيميائية، (٣) هكتار واحد مخصص لخزان المياه المنتجة، (٤) هكتار واحد مخصص للأرض التي تضم مأخذ مياه البحر، (٥) حوالي هكتار واحد مخصص للشبكة الكهربائية وأيضاً لمحطات التحلية الحرارية التي لا تزال قيد الإنشاء. أما فيما يتعلق بالمساحة المتبقية (المقدرة بهكتارين ونصف) فهي مخصصة كمساحة خضراء تحيط بالمحطة ومرافقها.

٣. ٢ التأثيرات البصرية

لا تحمل البنية التحتية الهندسية لمحطة التحلية أي مؤثرات بصرية ضارة. كما إن محطة التحلية محاطة بمنطقة خضراء من ثلاث جهات (الجنوب، الشرق، والغرب) مما يجعلها غير مرئية بشكل واضح للمنطقة المحيطة ولا سيما الطريق العام الرابط بين الشرق والغرب.

ويتم تشغيل منظومة الإضاءة داخل المحطة بشكل يتلاءم فقط واحتياجات التشغيل والسلامة مما يقلل و/أو يمنع أي تأثير سلبي غير مرغوب قد ينتج من الأضواء. كما أن أسطح الأبنية الرئيسية للمحطة تخلو في تركيبها من أي مواد عاكسة قد تسبب تأثيرات بيئية أخرى.

٣. ٣ نظام شبكة الأنابيب

إن شبكة الأنابيب الناقلة لمياه البحر إلى محطة التحلية، والناقلة للرجيع الملحي من المحطة إلى البحر مطمورة بالكامل تحت الأرض، الأمر الذي يمنع حدوث أي تأثيرات بصرية ولكن قد يكون له بعض الأثر على الحوض الجوفي في حال كان هناك أي نوع من التسرب من هذه الأنابيب نتيجة التآكل.

واستناداً على المعلومات المتاحة الخاصة بالمحطة، لم تتعرض شبكة الأنابيب المطمورة لأي أعمال تسرب وبالتالي لم يكن هناك أي حاجة لأعمال الصيانة. وفي المقابل فإن المعلومات المتحصل عليها من العمال والفنيين والمهندسين العاملين داخل المحطة تشير إلى أنه لا تتوفر بالمحطة أي أجهزة أو أدوات تحسسية مرفقة بشبكة الأنابيب منذ عمليات الإنشاء.

٣. ٤ تأثيرات الضوضاء والضجيج (التلوث السمعي)

تُعرَف الضوضاء على أنها الصوت المزعج غير المرغوب فيه. وتقاس مستويات الصوت (الضوضاء) غالباً بوحدة الديسبل (dB) التي تتراوح قيمها ما بين ٠ و١٤٠. هذا وإن من الممارسة العامة قياس مستوى الصوت باستخدام جهاز قياس مزود بفلتر وهو قياس موحد دولياً يستخدم لمقاربة هذه الخاصية. كما أن النظام المحدد لقياس التردد المستخدم في هذا المقياس هو المقياس-أ، حيث يتم التعبير عن مستوى الصوت المحدد بمقياس-أ بوحدات ديسبل-أ "dB(A)".

وإذا كان الصوت في مستوى ١٠ ديسبل، فإن الأذن البشرية الطبيعية لا تلتقطه إلا بصعوبة. وربما يكون مستوى ضغط الصوت في غرفة هادئة حوالي ٤٠ ديسبل، ولكن إذا بلغ مستواه ٧٠ ديسبل، فإنه يُعتبر صوتاً مزعجاً، إذ أن الصوت في مستوى ٧٠ ديسبل يبث من الطاقة أكثر مما يبثه الصوت في مستوى ٤٠ ديسبل بألف مرة [1، ٢].

ولا تعد أصوات الضجيج المرتفعة مصدراً غير مرغوب فيه فحسب، بل يمكن أن تسبب أضرارا فسيولوجية ونفسية أيضا. ويعتمد مقدار الأذى المُسبَب عن طريق الضجيج أساساً على عدة عوامل منها: ١- شدة الصوت ودرجته، ويتناسب التأثير وشدة الخطورة طردياً مع فترة التعرض، ٢- حدة الصوت، فالأصوات الحادة أكثر تأثيراً من الغليظة، ٣- المسافة من مصدر الصوت، كلما قلت المسافة زاد التأثير، ٤- فجائية الصوت، فالصوت المفاجئ أكثر تأثيراً من الضجة المستمرة، ٥- نوع العمل الذي يزاوله الإنسان أثناء تعرضه للضوضاء، مثل الأعمال التي تحتاج لتركيز شديد غير الأعمال العادية.

وكأي مشروع صناعي أخر، فإن محطة تحلية المياه في تاجوراء العاملة بتقنية التناضح العكسي قد تكون مصدرا للضجيج والضوضاء ومبعثاً للإزعاج. هذا وتنتج انبعاثات الضجيج والضوضاء في محطة تحلية عاملة بتقنية التناضح العكسي أساساً من وجود مضخات الضغط العالي والتوربينات المستخدمة في عمليات استرجاع الطاقة [3-5].

وتضم محطة تحلية المياه بتاجوراء عدد ست مضخات ضغط عالي (أربع مضخات لضخ ماء البحر للمرحلة الأولى، ومضختين للضخ في المرحلة الثانية). وتولد هذه المضخات الضغط اللازم لعملية التحلية (جدول ١).

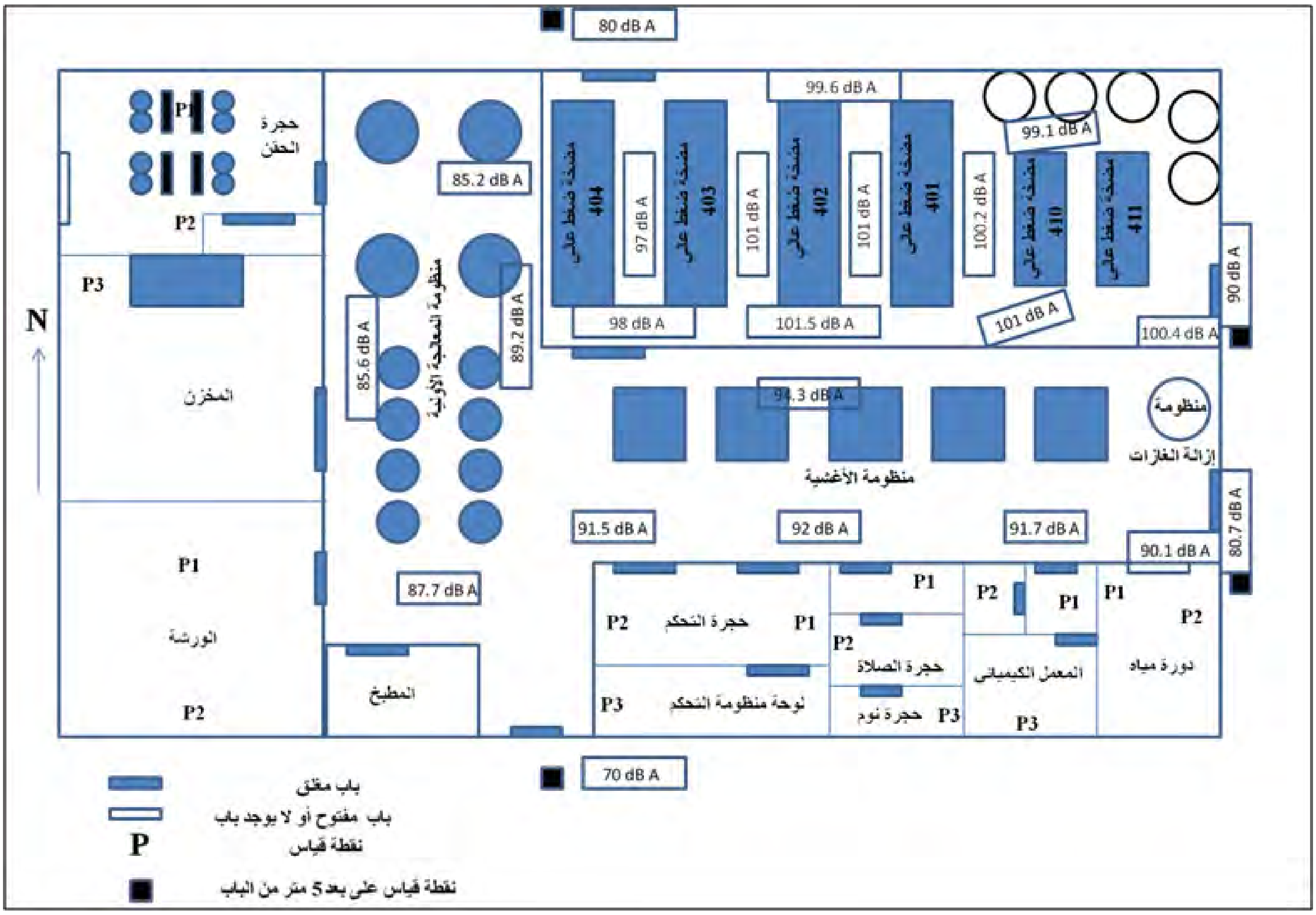
أما حالياً، فيتم تشغيل محطة التحلية بواسطة ثلاث مضخات فقط حيث أن المضخات الثلاث الأخرى عاطلة عن العمل. المضختان الموسومتان بــ ١٠٤ و٢٠٤ تستخدمان في عملية الضخ للمرحلة الأولى، بينما المضخة الموسومة بـ ١١٤ فتستخدم للضخ للمرحلة الثانية.

وتجدر الإشارة هنا إلى أن الدراسة الوحيدة التي اهتمت بموضوع الضجيج المنبعث من مضخات الضغط العالي في محطة التحلية بتاجوراء قام بها فريق متكون من مجموعة من المهندسين والتقنيين العاملين في مركز البحوث النووية المجاور للمحطة بإشراف المهندس عزام حلمي [6]. وقد ظهرت نتائج هذه الدراسة في صورة تقرير داخلي خاص بمركز البحوث النووية ولم يتم نشره في أي مجلة علمية متخصصة. حالياً، ونظراً لضعف الإمكانات المعملية والأجهزة المختبرية رأي المؤلف -بعد أخذ الموافقة من مشرف الدراسة السابقة- أن يعتمد نتائج الدراسة السابقة لتكون المصدر الرئيسي للمعلومات الخاصة بموضوع انبعاثات الضجيج والضوضاء في الدراسة الحالية.

تم قياس مستويات الضجيج في مواقع (نقاط) مختلفة داخل المبنى الرئيسي للمحطة. وتضمنت مواقع القياس كلاً من: حجرة مضخات الضغط العالي، الصالة الرئيسية، المعمل الكيميائي، حجرة الحقن، حجرة التحكم، الورشة، حجرات النوم، المطبخ، ومواقع أخرى كما هو مبين في الشكل رقم ٢. ويوضح

جدول ١. البارامترات التصميمية الرئيسية لمضخات الضغط العالي المستخدمة في المرحلة الأولى والمرحلة الثانية في محطة التحلية بتاجوراء

البارامتر	مضخات الضغط العالي	
	المرحلة الأولى	المرحلة الثانية_
المُصنع	KSB، ألمانيا	KSB، ألمانيا
النوع	١٥٠HDAO	HDAO 150
السائل المُراد ضخه	ماء بحر	الناتج من المرحلة الأولى
معدل التدفق	٤٩٣ متر مكعب/ساعة	٢٧٥ متر مكعب/ساعة
كفاءة المضخة	٪٧٦	٪٧٢
الضغط	١٧ بار	٥٤ بار
القوة اللازمة	1,040 كيلو واط	٥٠٠ كيلو واط



شكل ٢. مستويات الضجيج في مواقع مختلفة في محطة التحلية بتاجوراء

جدول رقم ٢. نتائج مستويات الضجيج في المواقع المبينة في الشكل رقم ٢

الموقع	القياس العالمي [7، ٨]	مستوى الضجيج (dBA)					
		نقطة القياس					
		P1		P2		P3	
		بابلا					
		مفتوح	قلغم	حوتفم	مغلق	مفتوح	مغلق
حجرة التحكم	٠٦	80.6	70.3	82.6	70	67.5	66.5
المعمل الكيميائي	-	85	73.2	78.5	68.5	75.3	62
حجرة الحقن	-	73	71.3	74.5	70.1	70.8	69.5
حجرة النوم	٥٥	81	68	71	57.4	68	55.5
الورشة	٠٧	75.6	70.3	74	69.8		
المطبخ	٠٦	82	79.8				
دورة المياه	٠٦			82			

أ- أحماض مُراقة على أرضية المخزن

ب- أغبرة تنتشر في عموم المكان

شكل ٣. مخازن المواد الكيميائية داخل محطة التحلية بتاجوراء

جدول ٣. كمية الجرعات الكيميائية المستخدمة في محطة التحلية بتاجوراء

المادة الكيميائية	Kg/m^3	ppm
كبريتات النحاس ($CuSO_4$)	0.026	4
هيدروكسيد الصوديوم (NaOH)	0.026	16
حمض الكبريتيك (H_2SO_4)	0.16	40
المخثر (flocculant)	0.015-0.031	4-2
مانع التكلس (antiscalant)	0.125	5
مزيل الأكسدة (Deoxidant)	0.019	2.5

تتكيف أغلب الأصناف البحرية المحلية عادة ضمن مساحات بمستويات

جدول ٤. التركيبة الكيميائية لمكونات مياه البحر والرجيع الملحي الناتج من محطة التحلية بتاجوراء

المادة/ المكون	التركيز في ماء البحر (مصدر مياه التحلية) ملي غرام/لتر	التركيز في الرجيع الملحي (brine) ملي غرام/لتر
مجموع الأملاح الذائبة (TDS)	37,050	49,335
الملوحة	37,900	52,600
الصوديوم	13,230	17,788
الكالسيوم	420	1,160
البوتاسيوم	452	608
الكلوريد	22,500	30,841
الكبريتات	2,800	4,333
النترات	0.53	1.07
السيليكون	0.25	0.7
النحاس	0.30	0.45
الحديد (Fe^{2+})	0.009 ≥	0.009 ≥
الكروم (Cr^{6+})	0.11	0.21
المنغنيز	0.20	0.45

إن الطريقة المتبعة في تخزين المواد الكيميائية داخل محطة التحلية بتاجوراء من شأنها أن تشكل خطراً متربصاً لكل من العاملين و/أو البيئة المحيطة وذلك أثناء حوادث التسرب أو الانبعاثات الغازية للمواد الكيميائية. والصور الظاهرة في الشكل ٣ (أ، ب) تتحدث عن نفسها.

٣. ٦ نقطة تصريف الرجيع الملحي

الرجيع الملحي هو عبارة عن المخلفات السائلة الناتجة من محطة التحلية والمحتوية على كمية كبيرة من الأملاح، وبواقي المواد الكيميائية المستخدمة في عمليتي المعالجة الأولية والمعالجة النهائية. ويتم تصريف الرجيع الملحي إلى البحر وفيه ينتشر وفق اعتبارات وظروف معينة. وإنه لمن الضروري النظر في مسألة المواد الكيميائية المستخدمة لأن مخلفاتها تبقى مع الرجيع الملحي [4]. أما كمية المواد الكيميائية المستخدمة في عملية المعالجة الأولية فهي موضحة في الجدول رقم ٣.

وقد أظهرت نتائج دراسة سابقة قام بها بشير بريكة وآخرون، ٦١٠٢ [9] أن الرجيع الملحي الخارج من محطة التحلية بتاجوراء يحتوي على تراكيز منخفضة من النحاس، والكروم، والمنجنيز، والسيليكون. ووجدت كل العناصر الكيميائية بتراكيز أقل من ٥,٠ ملي غرام/لتر وبالتالي، فلا توجد مخاوف حول حدوث أضرار من هذه العناصر. وبشكل عام، فإن أكثر الأيونات الكيميائية التي تصاحب الرجيع الملحي التي قد يكون لها أثاراً سُمية على البيئة البحرية هي أيونات الكلوريد التي قد تتفاعل أيضاً مع المركبات العضوية في مياه البحر لتشكل مركبات أخرى كالنواتج الثانوية للهالوجينات العضوية الضارة بالحياة البحرية [10، 11].

تتراوح كمية الملوحة في الرجيع الملحي -وفقاً لبعض المصادر- من ٢٥ إلى ٠٧ جزءً من الألف [12]، ومن خلال الجدول (٤) الذي يلخص التركيبة الكيميائية لمكونات الرجيع الملحي الناتج من محطة التحلية بتاجوراء كما أظهرته نتائج الدراسة السابقة [9] فإن الرجيع الملحي يحتوي على نسبة ملوحة زائدة يبلغ قدرها ٩٣٪ عن ملوحة مياه المصدر.

ملوحة عالية، ولكن هناك أنواعاً أخرى من المحتمل ألا تتكيف مع الملوحة المتزايدة الناتجة عن عمليات ضخ الرجيع الملحي المركز المتواصلة إلى شاطئ البحر. وباعتبار أن محطة التحلية بتاجوراء يتم حالياً تشغيلها بشكل متقطع ولفترات محدودة جداً، فإننا نستطيع القول بأنه لا توجد تغييرات مفاجئة مخيفة لمستويات الملوحة في المناطق القريبة من نقطة التصريف التي قد تؤدي إلى أثار ضارة بالكائنات البحرية.

وبشكل عام، فإنه لا توجد حالياً مواصفات قياسية أو حدوداً مثالية عالمية لتركيز الملوحة الذي ينبغي ألا يُصرف إلى مياه البحر. وإن غياب أو عدم توفر لوائح (مواصفات قياسية) خاصة بالرجيع الملحي الناتج من محطات التحلية أدى إلى عمليات تصريف مطلقة و/أو غير مستدامة. وبالتالي فإن وجود لوائح وقوانين وتشريعات تحدد المستويات المسموح بها لمكونات الرجيع الملحي أمر ضروري جداً.

وتجدر الإشارة إلى أن الدراسة السابقة التي تناولت التركيبة الكيميائية للرجيع الملحي الخارج من محطة التحلية بتاجوراء لم تتناول الجزء المتعلق بألية توزيع وانتشار مكونات الرجيع الملحي (خاصة الملوحة) في مياه البحر بالقرب من نقطة التصريف وكان الاهتمام مقتصراً فقط على تركيبة مياه الرجيع الملحي ومقارنتها بمياه البحر.

بيئياً، فإن نقطة تصريف الرجيع الملحي (شكل ٤) لا تعد اختياراً موفقاً لتصريف كمية كبيرة من سائل شديد الملوحة. حيث سيكون الوضع أفضل حالاً وأقل ضرراً لو كانت نقطة التصريف بعيدة عن الشاطئ وعن المناطق الصخرية الغنية بالتنوع الحيوي، وكذلك بعيدة عن النشاطات العائلية التي تشهدها المصائف القريبة من الشاطئ حيث توجد نقطة التصريف.

من الملاحظ في الشكل ٤ وجود خيمة اصطياف على مسافة قريبة جداً من نقطة تصريف الرجيع الملحي. وفي ذات السياق، فإنه وخلال فترة أشهر الصيف تم مشاهدة بعض المصطافين يقومون بالسباحة أمام أو/بالقرب من نقطة التصريف دون أية دراية أو معرفة بالتأثيرات الضارة التي قد تنجم من ممارسة هكذا نشاط في هذا المكان (شكل ٥).

٣. ٧ شواهد أثرية

كل دولة من دول العالم لها قوانينها المتعلقة بحفظ موروثها الثقافي والحضاري، وفي ليبيا فإن القانون رقم ٧ لسنة ٢٨٩١ بشأن حماية البيئة يعطي أهمية كبيرة لحماية المناطق التاريخية والأثرية والثقافية، وينص القانون على مراعاة المواصفات والمعايير القياسية البيئية المعتمدة عند تصميم وتنفيذ وصيانة المشروعات والمنشآت وما في حكمها، وينص أيضاً على اتخاذ كافة التدابير العلاجية المناسبة التي تضمن إزالة التلوث.

وبعد عدة زيارات ميدانية لمحطة التحلية بتاجوراء والمساحات المحيطة بها والتي تقع ضمن حدودها -ضمن نطاق الموقع الخاص بالمحطة ومرافقها- تم رصد بعض الشواهد والإشارات الأثرية. بالتالي، فإن عمليات تشغيل المحطة طيلة العقود الثلاثة الماضية أثرت بشكل أو بأخر على هذه الموجودات الأثرية. إن غياب تطبيق مواد القانون رقم ٧ الخاص بحماية البيئة والذي يعتبر حماية المواقع التاريخية والأثرية هو من حماية البيئة، وعدم توفر أي أدوات أو أجهزة تساعد في حماية المواقع المرصودة أدى إلى زيادة الأضرار على هذه المواقع من أعمال تشغيل المحطة.

ومن بين الشواهد الأثرية المكتشفة حديثاً داخل نطاق المساحة المخصصة لمحطة التحلية أحد السراديب التي يُعتقد بأنها تعود إلى الفترة الرومانية في مدينة تاجوراء، أي قبل أكثر من ٠٠٧١ سنة. وتجدر الإشارة إلى أنه لا تتوفر أي معلومات مكتوبة أو موثقة حول هذا السرداب سواء من قبل مصلحة الآثار أو من قبل

شكل ٤. نقطة تصريف الرجيع الملحي

شكل ٥. السباحة واللعب بالقرب من نقطة تصريف الرجيع الملحي

شكل ٦. سرداب أثري يقع في محيط محطة التحلية بتاجوراء

شكل ٧. أحد الأبنية المتهدمة يرجح أنها رومانية بالقرب من المحطة

مؤرخين أو مهتمين بهذا الشأن. إضافة إلى ذلك، فإنه حتى لحظة إعداد هذه الورقة العلمية فإن مصلحة الآثار لم تضع يدها على هذا الموقع الأثري أو ربما لا تكون حتى على علم بوجوده.

ويؤمن الباحث بأن السرداب المكتشف حديثاً (شكل ٦) يمكن أن يحوي داخله مفاتيح مهمة لألغاز تاريخية للحقبة الرومانية التي عاشتها مدينة تاجوراء. وللأسف لم نشهد أي اهتمام ملحوظ بهذا الأثر المكتشف من أي جهة رسمية، بالتالي، فإن هذا الموقع قد يتعرض للانهيار بسبب أعمال التنظيف التي تقام بين الفترة والأخرى بواسطة الآلات الكبيرة، لذلك يتوجب التدخل العاجل من أجل إنقاذ هذا الاكتشاف وإلزام الجهات الرسمية بتطبيق القوانين المتعلقة بذلك.

وفي ذات السياق، لُوحظ انهيار بعض الأبنية الأثرية بالقرب من محطة التحلية (شكل ٧)، والتي يرجح على أنها انهارت حديثا نتيجةً لأسباب قد تُعزى إلى أعمال التنظيف والتوسع في المنطقة الواقعة ضمن محيط محطة التحلية مما أدى إلى فقدان المدينة لأحد أبنيتها التاريخية.

4. الاستنتاجات

لم تُول تقنية تحلية المياه في ليبيا في السابق اهتماماً كبيراً وبالتالي، لم تكن هناك حاجة شديدة لدراسة التأثيرات البيئية التي قد تنتج عنها. ومن خلال الدراسة الحالية تم التوصل إلى الاستنتاجات التالية:

- إن استخدام مضخات الضغط العالي والتوربينات المستخدمة في عملية استرجاع الطاقة في محطة تحلية المياه في تاجوراء ينتج عنها أثاراً سلبية مرتبطة بالضوضاء والضجيج، كما أنها غير مزودة بأي أدوات أو أجهزة للتقليل من ضررها. وبالتالي، فإنه يتوجب توفير هذه الأدوات للحد من مستويات الضجيج الصادرة منها. كما يتوجب على الإدارة العليا لمحطة تحلية المياه في تاجوراء اتخاذ التدابير الوقائية اللازمة فيما يتعلق بسلامة موظفيها والرعاية الصحية التي يحتاجون لها قبل وبعد تعرضهم للأضرار الناتجة عن هذا التلوث السمعي.
- يجب إعادة النظر في موقع مخازن المواد الكيميائية باعتباره هاجساً يؤرق العاملين بالمحطة بشكل يومي. وفي هذا الصدد يجب البحث عن آلية آمنة للتخلص من كل المواد الكيميائية منتهية الصلاحية والمواد الأخرى غير القابلة لإعادة الاستخدام.
- بعد الوقوف على الظروف الحالية لنقطة تصريف الرجيع الملحي فإن موقعها لا يعد مثالياً وذلك لقربه من الشواطئ التي تشهد نشاطات عائلية في فصل الصيف وبالتالي، يجب إعادة النظر في البحث عن موقع جديد لنقطة التصريف على أن يكون على الأقل على بعد ١٠٠٠ متر في داخل البحر.
- هناك غياب شبه تام لوعي السكان القاطنين في القرية القريبة من محطة التحلية فيما يتعلق بالأضرار البيئية التي نتجت/قد تنتج من محطة التحلية. ويعزى جهل السكان بهذه الأضرار إلى عدة أسباب منها: عدم وجود أناس مؤهلين من بين العاملين في محطة التحلية أو أي منظمة اجتماعية أخرى تعمل على نشر الوعي وتثقيف السكان بيئياً.

5. التوصيات

- نوصي بأن تأخذ النشاطات الاستجمامية كالمصائف العائلية، وأعمال الصيد مكانا بعيداً عن محطة التحلية، ويتوجب على الإدارة العليا في كل من محطة التحلية ومركز البحوث النووية أن تأخذ قرارات حاسمة فيما يتعلق بوضع قيود/حدود اصطناعية لمنطقة مأخذ مياه البحر ونقطة تصريف الرجيع الملحي.

- نوصي بإجراء دراسات مكثفة فيما يتعلق بدراسة تأثير الرجيع الملحي الناتج من محطة تحلية تاجوراء على الكائنات والبيئة البحرية.
- نوصي بأن يكون هناك تعاون جاد بين إدارة مركز البحوث النووية ومصلحة الآثار لتقييم الوضع الحالي للمواقع الأثرية المكتشفة حديثاً، واتخاذ التدابير العاجلة لحمياتها من أي أضرار مستقبلية.

الإهداء

يود الباحث أن يشكر كل العاملين في محطة تحلية المياه في تاجوراء على تقديم يد العون طيلة فترة إجراء الدراسة، فلقد أظهروا اهتماماً جاداً بالاعتبارات البيئية، وأظهروا رغبتهم في الاستمرار بالعمل الجاد من أجل ضمان استمرار تشغيل المحطة دون أن تنتج عنها أي أضرار بيئية.

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نبذة عن الباحث

بشير بريكة مهندس كيميائي حامل لدرجة الماجستير في مجال الهندسة الكيميائية من جامعة ستالنبوش في دولة جنوب إفريقيا، وهو يعمل حالياً باحثا علميا في المعمل المتقدم للتحاليل الكيميائية بطرابلس، وله عدد من الأوراق العلمية المنشورة في مجال مصادر المياه وتحلية المياه، ومشارك في عدد من المؤتمرات العلمية المتخصصة.

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جمعية علوم وتقنية المياه
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THINK BIG, START SMALL and SCALE UP: A road map to support country-level implementation of water safety plans and sanitation safety plans

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In 2004, the 3rd edition of WHO Guidelines for Drinking Water Quality recommended the use of Water Safety Plans (WSPs). In 2015, WHO introduced the Sanitation Safety Planning (SSP) manual. The use of comprehensive risk-based management framework is considered a very effective means of managing water supply and sanitation systems. There are many risk-based systems available to water and sanitation utilities such as ISO9001 and Hazard Analysis and Critical Control Point.

In 2004, WHO guidelines on Drinking Water Quality recommended the WSPs. In 2015, WHO introduced the SSP manual. Both approaches are promoted by WHO and the International Water Association as the most reliable and effective approaches for managing water and sanitation systems and for ensuring reliable drinking water safety and sanitation safety. WSP and SSP are risk assessment and risk management tools comprising:

- A systematic process of hazard identification along the entire chain of a specific drinking water supply system and the entire chain of a specific sanitation system;
- Implementation and monitoring of risk management control measures (improvement plan) by the service providers;
- Independent verification by a surveillance agency.

WSP and SSP are adaptable to all types and sizes of water supply, and can be effectively applied in all socioeconomic settings. The WSP and the SSP approaches are increasingly being adopted globally as best practices for managing water and sanitation systems.

Yet promoters of WSP and SSP must overcome barriers based on misconception such as: developing a WSP makes it seem as though water is not safe; utility will incur high cost of WSP or SSP development; SSP or WSP is additional workload; SSP or WSP is a plan to be developed by a hired consultant.

Driving forces to introducing WSP and SSP within a country may include: (a) commitment to public health and safety of water and sanitation (for this purpose national regulators and health authorities may promote supportive legislation and policies) and (b) enhanced performance, compliance to regulations and reduced costs of the water and sanitation systems (for this purpose, an active surveillance system is necessary). A benchmarking system helps utilities to measure progress over time and compare the performance of utilities.

A strategic roadmap to introducing and scaling up the use of WSP and SSP in a country involves several steps that can be implemented in a manner adapted to the country context: (1) understand and appreciate the benefits; (2) establish a national preliminary vision with milestones and timelines; (3) attain practical experience through demonstration intervention; (4) review the preliminary visions and establish a national plan for scaling up; (5) establish supportive mechanisms (e.g., training programmes, codes of practice, tools, utility–utility partnerships); (6) establish policy and regulatory instruments (empower institutions, legislative instruments, financial instruments); (7) implement WSP and SSP and verify their effectiveness; (8) review experience periodically, share lessons and improve.

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Aquifer storage and recovery, and managed aquifer recharge of reclaimed water for management of coastal aquifers

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ABSTRACT

The hydrological and economic feasibility of aquifer storage and recovery (ASR) of excess desalinated water and managed aquifer recharge (MAR) using tertiary treated wastewater (TTWW) to manage stressed coastal aquifers in Oman has been studied numerically using the code, MODFLOW 2005 and the different transport packages MT3DMS, and MODPATH. The current ASR study aims to assess the feasibility of saving and recovering water for the purpose of supply to the city of MUSCAT during high demand periods by banking excess-desalted water during winter and recover it during the rest of the year. The second objective of the study is to explore the feasibility of MAR using TTWW to mitigate salinity in two costal aquifers in North of Oman exploited for different purposes: domestic water supply (Al-Khod aquifer), and for irrigation purposes (Jamma aquifer). ASR in the Al-Khod Aquifer was explored using Simulation Optimization multi-objective modeling using evolutionary algorithm NSGA-II (namely, the Non-dominated Sorting Genetic Algorithm-II), to generate the set of Pareto optimal solutions according to recharging scenarios. The results show that the potential net benefit of storage and recovery might reach as high as $17.80 million/year. The maximum profitable volume that can be recharged into the aquifer, given the limited number of wells and their locations, is estimated at 8.4 Mm^3/year, which is lower than the current excess estimated of 10 Mm^3/year. For MAR using TTWW, different managerial scenarios were simulated and analysis of the results reveals that the Jamma aquifer will further deteriorate in the next 20 years if it remains poorly managed. The groundwater level will decline further to exceed 3 m on average, and the iso-concentric salinity line of 1,500 mg/L will advance 2.7 km inland that will severely affect farming activities in the area. However, MAR using TTWW when integrated with the management of groundwater abstraction (e.g., smart water meter, higher irrigation efficiency to reduce the abstraction rate) becomes hydrologically feasible to augment the aquifer storage and controlling seawater intrusion, and hence sustains farming activities. The economic analyses of such situation recommend: (1) injecting TTWW in the vicinity of irrigation wells; (2) investing in smart water meters and online control of pumping from the wells to reduce the abstraction rate by 25%; and (3) a combination of both are feasible scenarios with positive net present values. Recharge in upstream areas is found not economically feasible because of high investment cost of the installation of pipes to transport the TTWW over a distance of 12.5 km. Because the financial resources for investments are limited, scenario (2) shows a Net Benefit Investment Ratio of 4.41 (i.e., investment of a $1 yields $4.41). Although option (3) shows the lowest Net Benefit Investment, it is very attractive from a social perspective because it entails an integrated demand and supply management of groundwater. Farmers are requested to reduce pumping, and the government will invest in injecting TTWW to improve groundwater quality in the vicinity of irrigation wells and to form a hydrological barrier to control seawater intrusion in the long run. The primary objective of MAR for the Al-Khod aquifer is to increase the urban water supply and to sustain the aquifer service with the lowest possible damages from seawater intrusion. A number of managerial scenarios were simulated and progressively developed to reduce seawater intrusion and outflow of the groundwater to the sea. An economic analysis was conducted to characterize

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the trade-off between the benefits of MAR and seawater inflow to the aquifer under increased abstraction for domestic supply. The results show that the abstracted volume for domestic supply can be doubled under MAR practices if irrigation wells are properly managed and public wells are better located. Even though injection of TTWW is more expensive (due to the injection cost), will result in higher benefits. The results indicate that managing the aquifer would produce a net benefit ranging from $8.22 million to $15.21 million compared with $1.57 million with the current practice. MAR using TTWW is feasible to develop water resources in arid regions, and the best scenario depends on the decision maker's preference when weighing the benefits of MAR and the level of damage to the aquifer. MAR, as a smart water governance technology, mitigates stresses on aquifer systems in arid zones, maximizes the benefit of using groundwater for both agricultural and domestic purposes while minimizing the adverse socio-hydrological and agricultural consequences of mismanagement of commingled groundwater-TTWW resources at all scales (national, catchment, metropolitan area, village, farm).

Keywords: Managed aquifer recharge; Aquifer storage and recovery; Salinity; Coastal aquifer; Oman

1. Introduction

In arid regions, such as Oman, water resources are inadequate, and therefore, the development of different sectors (e.g., agriculture, industry, tourism, and municipal) is threatened. Groundwater is overexploited in densely populated/developed coastal areas, which depletes aquifer storage and causes seawater intrusion that degrades agricultural land and hence adversely affects the socioeconomic aspects of the farming community (MRMWR, 2005). Along with the proper management of water resources, additional water sources are needed to augment stressed coastal aquifers. In drought seasons, groundwater abstraction exceeds the safe yield, intensifying the deterioration of aquifer water. Abdalla and Al-Rawahi (2013) reported that since the 1970s, aggravated development of coastal groundwater has resulted in the progressive advancement of seawater and deterioration of water quality (Bajjali 2003; Al Barwani and Helmi 2006). The construction of recharge dams, control/rationing of the development of groundwater abstraction and desalination of seawater are standard measures to manage and augment water resources in arid areas. However, rainfall is irregular, unpredictable and low (annual average rainfall is approximately 100 mm in Oman). Thus, the role of recharge dams is tightly linked to weather conditions, which are characterized by long dry spells and low frequency rainfall (Sen 2008). Desalinated water is expensive (approximately 1$/m^3 – as estimated by Zekri et al., 2013) and has negative environmental impacts. Recently, managed aquifer recharge (MAR) using TWW as a non-conventional water resource has been viewed as a feasible option (Asano and Cotruvo 2004; Khan et al. 2008; Al-Assa'd and Abdulla 2010, Missimer et al. 2012; Ebrahim et al. 2015). MAR is defined as the intentional recharge of water into an aquifer either by injection or infiltration and recovery by planned extraction (Hayder Consulting, 2006). MAR has been identified as a potential major water management practice to support groundwater storage in arid and semiarid areas (Ebrahim et al. 2015). MAR has been widely practiced. Li et al. (2006) numerically investigated the impact of MAR on Perth Basin, Western Australia. The developed model helped to create flexibility to manage groundwater levels and improve its quality, particularly along the coast and river margins. MAR storage and recovery were found to be feasible water management tools for reducing the impact of droughts in Australia (Khan et al. 2008). Shammas (2008) and Baawain (2010) have assessed the effectiveness of areal injection of tertiary treated wastewater (TTWW) in combating seawater intrusion in the Salalah coastal aquifer (Oman) numerically. Ebrahim et al. (2015) and Al-Maktoumi et al. (2016), by using both simulation and optimization codes, found that MAR using TTWW is a feasible solution to manage coastal aquifers in Oman. The response of the Mujib aquifer in Jordan to different MAR scenarios has been studied by Al-Assa'd and Abdulla (2010). MAR further improved the groundwater quality and augmented the storage of an alluvial Wadi aquifer in Saudi Arabia (Missimer et al., 2012). Moreover, injected TTWW acted as a hydraulic barrier to decelerate seawater intrusion in the Damour and Jieh regions in Lebanon (Masciopinto 2013). Economically, MAR often provides the cheapest form of new water supply (Dillon 2005; Zekri et al. 2013). Khan et al. (2008) suggested that underground storage is much cheaper than surface storage facilities, with less environmental consequences or evaporation losses. Zekri et al. (2013) proposed the reuse of TTWW to farmers through injection/recovery systems via aquifers. The injection of TTWW in aquifers for later use in irrigation will further result in natural treatment and quality improvement. Zekri et al. (2013) estimated the current TTWW cost in Oman for reuse to be $0.55 per m^3, while the cost of injection and recovery of TTWW in an aquifer is approximately $0.026 per m^3. Along with the MAR advantages mentioned above, MAR has some disadvantages. In most cases, only a part of the recharged water is recovered. The quality of water used for aquifer recharge could alter the physical and chemical characteristics of the porous medium. To reduce the associated risks, the injected TTWW must undergo treatment processes that can satisfy drinking water standards (Hayder Consulting 2006; Dillon et al. 2009). In Oman, Haya Water Company (http://www.haya.com.om), the main entity responsible for the collection and treatment of sewage water, produces TTWW. The hydrochemistry of MAR practices is beyond the scope of this paper and will be considered in future studies. According to Zekri et al. (2013), the TTWW volume in Muscat is 100,000 m^3/d. The volume of

TTWW is expected to reach 274,000 m^3/d by 2030 in Muscat, the capital city of Oman (Zekri et al. 2016).

2. Aims of the study

- Assess numerically (using MODFLOW 2005 and MT3-DMS) the feasibility of saving and recovering water for the purpose of supply to the city of MUSCAT during high demand periods by banking excess-desalted water during winter and recover it during the rest of the year.
- Explore the numerical feasibility of MAR using TTWW to mitigate salinity in two costal aquifers in North of Oman exploited for different purposes: domestic water supply (Al-Khod aquifer), and irrigation purposes (Jamma aquifer).

2.1. Description of the study areas

Two aquifer systems were used in the study. Al-Khod aquifer which is used for both aims of the work presented in this paper and Jamma aquifer which is located in the Al-Batinah area of northern Oman (Fig. 1). For detailed description of both aquifers geological settings and in depth hydrological and hydrogeological descriptions readers are referred to Ebrahim et al., 2015, Al-Maktoumi et al. (2016), El-Rawy et al. (2018). However, highlights of both aquifers are presented below:

2.1.1. Al-Khod aquifer

Several papers presented detailed discussions concerning the geological and hydrogeological properties of the Al-Khod aquifer, therefore, only a brief discussion is provided below (Abdalla and Al-Abri 2011; Abdalla and Al-Rawahi 2013, Ebrahim 2013; Zekri et al. 2014a, 2015a). The study area consists of the coastal plain of the Wadi Samail catchment and covers an area of approximately 59 km^2 (Fig. 1). From the North, the study area is bounded by the Oman Sea and by Wadi Samail catchment from the South, Wadi Taww from the west and the Wadi Rusayl from the east. In addition to irrigation water, the aquifer has been an important source of potable water supply to major cities in Muscat Governorate throughout the last three decades. Currently, the aquifer is considered a strategic reserve. Al Khod recharge dam was constructed in March 1985 approximately 7 km from the coastal line (Fig. 1) (Abdalla and Al-Abri 2011; Al-Maktoumi et al., 2016). Over years and because of reduction of abstraction for domestic supply (as government shifted to desalination as the main source for domestic water supply in the area) and dam functionality, the aquifer storage recovered and the hydraulic gradient maintained seaward direction, hence mitigating seawater intrusion observed during the stressful period the aquifer experienced. Hydrologically, the aquifer is modeled as two primary units. Details of modeling conceptualization, setup, and calibration are presented in Al-Maktoumi et al. (2016).

2.1.2. Jamma aquifer

Jamma being a coastal unconfined alluvium aquifer (located in the Al-Batinah area of northern Oman) is mainly used for irrigation purposes (Figs. 1e–h). The Al-Batinah area represents approximately 50% of the total agricultural land in Oman (Oman Salinity Strategy 2012). Over-pumping during the last few decades has resulted in a significant decline in the groundwater level (up to 5 m), which has consequently caused seawater intrusion (>3 km and in adjacent aquifers the saline interface encroached up to 10 km) and hence salinization of agricultural land (MRMWR 2005; Al Barwani and Helmi 2006; Zekri 2008). As a result, suitable agricultural lands in the Al-Batinah plain were reduced by 7% in the period of 2000–2005, which has had socioeconomic consequences (Al Barwani and Helmi 2006; Zekri 2009; Oman Salinity Strategy 2012). It turns to be of paramount importance to manage the aquifer. That is why in this study, to what extent MAR using TTWW can help to mitigate the deteriorated condition of the aquifer and improve farming practices is the core research question. The injection of TTWW will form a hydraulic barrier against seawater intrusion, expected to improve water quality within the vicinity of the injection and furnish additional water for irrigation. In the current study, we will assess numerically the feasibility of MAR in controlling the seawater intrusion and augmenting the depleted storage in the coastal aquifer of Jamma under different scenarios that include the management of irrigation wells. In this study, the geochemistry interactions that may cause clogging effect during the recharge as mentioned by Voudouris 2011 is not considered.

The study area is characterized by a warm winter with low humidity and a very hot and humid summer. The rainfall is low, sporadic and erratic and ranges between 60 mm in the coastal area and 140 mm in the upstream part of the catchment, mountains (Weyhenmeyer et al. 2002).

The aquifer is exploited by about 1,037 unmonitored irrigation shallow dug wells concentrated along a narrow coastal strip (5 km width; Fig. 1e). The total abstracted volume is about 89 Mm^3/year (Mott MacDonald 2013) with an average abstraction rate for each well of 235 m^3/d. The cropped land in the study area is about 1,090 hectares, of which 80% is irrigated by flood irrigation system whereas the remaining 20% adapted modern irrigation systems. A simplified geological map of the Jamma study area is constructed based on the study by Lakey et al. (1995) and presented in Figs. 1–f. For more detailed descriptions, readers are referred to (El-Rawy et al. 2018).

2.2. Approach

MODFLOW-2005 code (Harbaugh 2005) with ModelMuse (Winston 2009) as a graphical user interface (GUI) was used to simulate groundwater flow. The solute transport for seawater intrusion was simulated using the MT3DM model (Zheng and Wang 1999) which is based on a constant density approach. Detailed modeling setup and parameters were presented in Ebrahim et al. 2015, Al-Maktoumi et al. 2016, El-Rawy et al. 2018.

2.3. Simulated scenarios for Al-Khod aquifer, discussion and results

2.3.1. ASR of excess desalinated water

Muscat city depends mainly on desalinated water (approximately 94% [Zekri et al. 2014b]) by a number of desalination

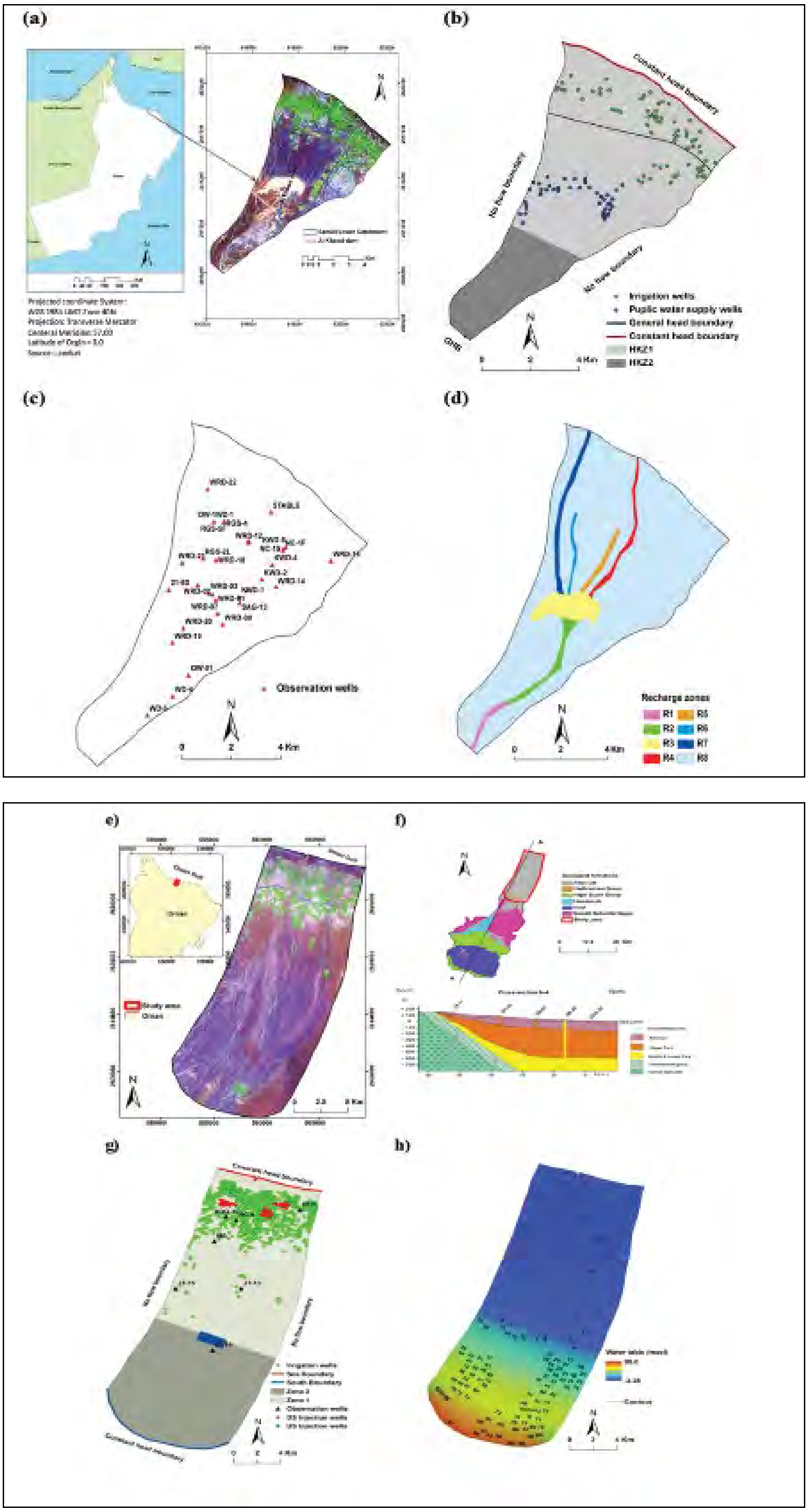

Fig. 1. (a) Location and characteristics of the Al-Khod aquifer, (b) the boundary conditions, locations of public and irrigation wells and zones of different hydraulic conductivities and (c) the location of observation wells (upper panel) and (d) recharge zones (adapted from Al-Maktoumi et al., 2016), (e–h) study area and characteristics of the Jamma aquifer site (El-Rawy et al., 2018).

plants that are connected to the urban network of the city. The desalination plants' capacity is designed for the high demand period corresponding to the summer months (Zekri et al. 2016). As that, an excess of produced desalinated water (more than the demand) is observed during the period of low demand, 4 months (November through February). ASR could be implemented to store the surplus amount and then recovered during the 8 months of high demand period. Two types of desalination plants are operational in Muscat, multi-stage flash (MSF) desalination plant and the reverse osmosis (RO) plants. The MSF plant's production capacity cannot be adjusted, and it produces a constant volume of water throughout the year. However, the RO plants are flexible, and the volume produced can be adjusted daily. The excess volume is thus produced by the MSF plant. The MSF plant, a private operation, sells to the Public Authority for Electricity and Water (PAEW) a fixed daily volume according to the contract that was established prior to start of the construction of the plant. It is the exclusive responsibility of the PAEW to distribute the water produced and manage the excess water. Currently the PAEW reduces the volume of desalinated water produced from the RO plants to balance the total supply, but there is still some excess water produced by the MSF plants which ends up being sent to the sea. The current excess desalinated water in Oman is estimated at approximately 10 Mm^3 (PAEW 2017, personnel interview). At present, groundwater is abstracted daily year round from a number of wellfields in Muscat including the Al-Khod aquifer which is tapped by 45 public utility wells (shown in Fig. 1) with lower abstraction rates in the low demand season. The abstracted groundwater is delivered to the city through the urban network mixed with desalinated water. The work considers banking the excess desalinated water in the unconfined Al-Khod aquifer via injection to make use of the scarce water resource during high demand and emergency periods instead of losing it to the sea. The constraints on the volume to be injected into the aquifer are related to the capacity of the existing pumps installed in the wells and on the hydrogeological characteristics of the aquifer (Zekri et al. 2016).

The results of the numerical simulations illustrated the possibility of recharging the periodic excess desalinated water in the Al-Khod aquifer. Out of the 10 Mm^3/year of excess desalinated water that is discharged to the sea, 8.4 Mm^3/year can be banked in the aquifer. By storing the excess water, a net benefit estimated at $17.80 million/year will be generated. The water authorities in the country must work together to better use this scarce water resource. The existing wells and their locations do not allow the injection of all the excess volume. Furthermore, the current practice of RO plants reducing their production during the low demand winter period is a very costly solution. In fact, the PAEW still must pay up to 85% of the cost, despite the reduction in the desalinated water volume. Further research is thus required to determine the optimal locations of new injection/recovery wells and the optimal volume of excess water to be produced by the desalination plants in conjunction with the storage capacity of the aquifers (Zekri et al. 2016).

2.3.2. MAR using TTWW in Al-Khod aquifer

The management scenarios were designed under the constraint that the injected TTWW in the Al-Khod aquifer does not mix with the native water used for urban supplies. Because the existing legislation does not allow a mixing of TTWW with drinking water, MAR practices are constrained. However, MAR be practiced to generate a hydraulic barrier to seawater intrusion and hence reduce the stress to the aquifer caused by abstraction for both urban and farming uses. Thus, allowing more water to be abstracted for urban water uses. Therefore, the supply of desalinated water could be reduced and considerable cost cuts could be achieved given the high cost of seawater desalination both financially and environmentally. However, the TTWW volumes disposed of in the sea should be minimized (Zekri et al. 2015b). Table 1 summaries the different scenarios considered. The assigned volume of the injected TTWW was chosen based on the current abstracted volume from the irrigation wells and the constraints mentioned above. The main focus of this part of the study was to explore MAR's effect on enhancing the urban supply with the lowest possible damage to the aquifer at low cost. Ideally, optimization techniques would have been used to come up with the optimum values of injected volume and number of injection wells coupled with minimizing loss to

Table 1
Description of the simulated scenarios

Scenario	Description
Base case (BCS)	This case represents the current condition.
S1	This scenario illustrates the case when the abstraction rate from the public wells is increased as recommended by Zekri et al. (2015a) with no MAR.
S2	This scenario is similar to S1 with MAR injecting TTWW for farmer's use.
S3	In this scenario, a volume of 3,536 m^3/d of TTWW is provided free of charge to farmers through direct pipelines in exchange for shutting down their agricultural wells.
S4	This scenario is similar to S2 except that the injection wells are located near the coast (Pattern 2-Fig. 2) using 38 injection wells with an injection rate of 121 m^3/d per well.
S5	This scenario is similar to S4 with reduced pumping from public wells.
S6	This scenario is similar to S5 with relocated public wells.
S7	This scenario is similar to S6 with a 25% reduced abstracted volume.
S8	This scenario is similar to S7 but without injection of TTWW.

the sea and preventing the injected TTWW from reaching the capture zone of public wells. This was not attempted in this study and is a subject of future work. Only a limited number of scenarios were evaluated in this study. Eight scenarios were proposed and simulated as presented in Table 1.

As obvious, the water table mounds under recharge causing a steeper hydraulic gradient in the vicinity of the injection zone. As a result, dynamics of the injected water and its residence time are affected. Fig. 2 presents the location of the injection wells and the head distribution in the aquifer after 12 years of simulation. In this study, two patterns of injection well distribution were used. In Pattern 1, 10 injection wells were modeled with an injection rate of 459.6 m^3/d per well, and in Pattern 2, 38 injection wells were modeled with an injection rate of 121 m^3/d per well and the injection wells were relocated seaward direction. In Pattern 1, injection wells were located at an average distance of 2.3 km from the coastal line and approximately 2 km from the public wells, while there was an average distance of 0.8 and 4 km, respectively, for Pattern 2. The spacing between the injection wells was kept between 100 and 300 m as recommended by Pyne (1995) to avoid overlapping of developing mounds by each injection well as fusion of adjacent mounds may result in higher mound which may cause geotechnical and environmental problems.

3. Results and discussion of the simulated scenarios for Jamma aquifer

Eight scenarios (divided into three main clusters: A, B and C) were simulated and are presented in Table 2. The simulation time is set to 20 years, with 244 stress periods and time steps of 30 d. Scenario A considers the case “Business as Usual”, which simulates the current situation assuming that no changes (in terms of management and climatic conditions) will take place for the next 20 years, and hence considered “a base case scenario”, with which the results of the other scenarios are compared. Suggestion of injection well locations, considering the land availability as the area is densely urbanized and the lands are of private ownership (Scenarios A1 and A2 in Table 2). The locations of wells are given subscripts of 1 (for upstream) and 2 (for downstream location, vicinity of farms), as shown in Fig. 1g. The injected volume is based on the availability of excess TTWW, as reported by the Haya Water Company (Zekri et al. 2013). Scenarios B and C are based on policies recommended by the Ministry of Agriculture and Fisheries (Oman Salinity Strategy 2012) and by the MRMWR in Oman (Abdel-Rahman and Abdel-Magid 1993), Table 2.

The injection of 60,000 m^3/d of TTWW in the upstream location (Scenario A1) causes a decrease in the inflow from the sea and southern boundaries by 12,012 and 601 m^3/d, respectively, compared with the base case (scenario A). The groundwater level rises by 0.85 m on average with respect to the base case (A). Implementing MAR in the farming area (scenario A2), the inflows from both the sea and the southern boundaries into the aquifer decreased by 11,608 and 44 m^3/d, respectively, with respect to the base flow (scenario A). It is nearly similar to scenario A1 because of the effect of the active irrigation wells as the injected TTWW is recovered simultaneously and hence slow gain in storage. The groundwater level rises by 0.2 m on average (Table 3) with respect to the base case.

The impact of reducing the abstraction rate of groundwater (Scenario B) is much higher than that induced by MAR in scenarios A1 and A2. However, when Scenario B is complemented with MAR (with 60,000 m^3/d) at the locations described by scenarios B1 and B2, the inflows from both the sea and southern boundaries decreased by 48,344 and 1,554 m^3/d, respectively, for scenario B1 and the groundwater level rises by 1.66 m on average (Table 3). For scenario B2, the volumetric rate of intruded seawater is reduced by 33.5%. MAR increased the average water table rise by 100% for B1 and by 23% for B2 with respect to the case of no MAR (B). This emphasizes the role of active irrigation wells on the recovery of the injected TTWW, providing less opportunity for the water table mound to develop and hence the aquifer storage to recover (Table 3).

A further drop in the volumetric abstraction rate by 50% (Scenario C), even in the absence of MAR, will decrease the seawater intrusion rate by 63% with respect to scenario A. This results in augmentation of the aquifer storage, which

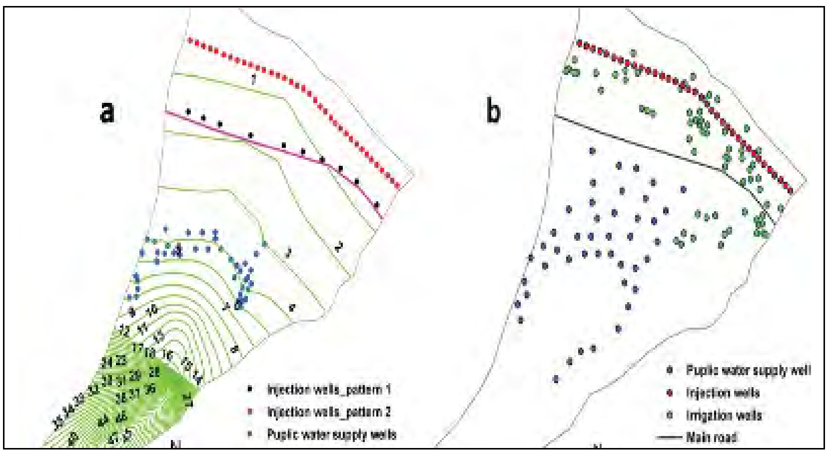

Fig. 2. (a) Simulated groundwater head at the end of stress period 144 (end of year 12) along with the locations of proposed injection wells (Patterns 1 & 2). (b) Locations of the redistributed public wells (blue) [adapted from Al-Maktoumi et al. (2018)].

Table 2
Simulated scenarios for MAR using TTWW in Jamma aquifer (adapted from El-Rawy et al. (2018))

Scenario	Location of the injection	Description	Injection rate and number of wells	Period of injection	Total abstraction rate
A base case	No injection	Represents the current situation	None	None	243,695 m^3/d
A1	Injection was performed 16.5 km upstream of the coastal line (approximately 12.5 km from the highway (water supply line). The blue dots in Fig. 1e represent the proposed injection wells.	This scenario tested the feasibility of upstream injection on augmentation of aquifer storage.	40 wells with injection rates of 1,500 m^3/d, with 240 m spacing, as recommended by Pyne (1995).	4 months followed by 8 months of recovery without injection (WMAR).	243,695 m^3/d
A2	Downstream, in the vicinity of the farming area. Approximately 2.7 km from the highway (water supply line). Red dots represent the injection wells in Fig. 1e.	Aim of this scenario is to test the feasibility of MAR to form a hydraulic barrier against seawater intrusion.	40 wells with injection rates of 1,500 m^3/d, with 240 m spacing.	4 months followed by 8 months of recovery without injection (WMAR).	243,695 m^3/d
B	No injection	This scenario suggests that improvement in irrigation water use efficiency will take place by regulating the abstraction rate. This is expected to reduce the abstraction volume by 25%.	None	None	194,956 m^3/d (dropped by 25% from that for scenario A - base case).
B1	Injection was performed 16.5 km upstream of the coastal line (approximately 12.5 km from the highway (water supply line). The blue dots represent the proposed injection wells in Fig. 1e.	Reduction of the abstraction volume by 25% (same as for Scenario B).	40 wells with injection rates of 1,500 m^3/d, with 240 m spacing.	4 months followed by 8 months of recovery without injection (WMAR).	194,956 m^3/d (dropped by 25% from that for scenario A - base case).
B2	Downstream, in the vicinity of the farming area. Approximately 2.7 km from the highway (water supply line). Red dots represent the injection wells in Fig. 1e.	Reduction of the abstraction volume by 25% (same as for Scenario B).	40 wells with injection rates of 1,500 m^3/d, with 240 m spacing.	4 months followed by 8 months of recovery without injection (WMAR).	194,956 m^3/d (dropped by 25% from that for scenario A - base case).
C	No injection	Adaptation of modern irrigation systems will reduce the abstracted irrigation water by 50% to increase irrigation efficiency (Abdel-Rahman and Abdel-Magid 1993). Approximately 80% of the agricultural area in the study area is irrigated by flood irrigation.	None	None	128,888 m^3/d (dropped by 50% from that for scenario A – base case).
C1	Injection was performed at 16.5 km upstream the coastal line (approximately 12.5 km from the highway (water supply line). The blue dots represent the proposed injection wells in Fig. 1e.	Reduction in the abstraction rate by 50% (as in Scenario C)	40 wells with injection rates of 1,500 m^3/d, with 240 m spacing	4 months followed by 8 months of recovery without injection (WMAR).	128,888 m^3/d (dropped by 50% from that for scenario A – base case).
C2	Downstream, in the vicinity of the farming area. Approximately 2.7 km from the highway (water supply line). Red dots represent the injection wells in Fig. 1e.	Reduction in the abstraction rate by 50% (as in Scenario C).	40 wells with injection rates of 1,500 m^3/d, with 240 m spacing	4 months followed by 8 months of recovery without injection (WMAR).	128,888 m^3/d (dropped by 50% from that for scenario A – base case).

Table 3
Abstraction and injection rates as well as changes in inflow from the sea boundary, discharge through evapotranspiration, and change in the average groundwater level of all scenarios with respect to the base case (El-Rawy et al. 2018)

Scenario	Abstraction from agric. Wells	Injection rate	Change in inflow from the sea boundary	Change in evapotranspiration	Average change in groundwater level
			(m^3/d)		(m)
A (base case)	243,695	0	–	–	–
A1	243,695	60,000	12,012	351	0.85
A2	243,695	60,000	11,608	318	0.2
B	194,956	0	46,235	1,560	0.82
B1	194,956	60,000	58,344	2,106	1.66
B2	194,956	60,000	57,628	2,029	1.01
C	128,888	0	107,881	4,701	1.91
C1	128,888	60,000	119,704	5,608	2.75
C2	128,888	60,000	118,901	5,438	2.1

is reflected in the increase of the average groundwater level by 1.91 m (Table 3).

Similar to the finding of the B1 and B2 scenarios, the injection of TTWW will further enhance the hydrological condition of the aquifer. The inflow of saline water decreases by 70% and the average groundwater level rises by 2.72 m (Table 3) for C1 and C2 scenarios.

The results suggest that MAR will be more effective in restoring the stressed coastal aquifer when integrated with the management of abstraction from irrigation wells. It is obvious that injecting more TTWW will augment more than the aquifer storage, but the availability of TTWW is a limitation. Moreover, the cost-benefit aspect must be considered when the optimization of MAR and irrigation practices are considered, which is not discussed in this paper.

The 1,500 mg/L iso-concentration salinity line for the base case and management scenarios (A1, A2, B1, B2, C1 and C2) has been compared to assess the impact of MAR on the aquifer water quality (Fig. 3). The salinity line receded seaward direction by nearly 1 km at the end of 20 years for scenario A2 and by approximately 1.3 km for B2. The results show that MAR becomes more effective in both restoring the head distribution in the depressed zone and

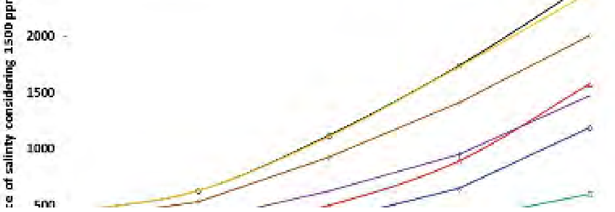

Fig. 3. Intruded distance of the 1,500 mg/L iso-concentration salinity line for selected scenarios.

augmenting the groundwater quality when MAR is practiced in the downstream area and integrated with a 50% reduction in abstracted irrigation water (scenario C2). Comparisons of the results of the different simulated scenarios are presented in Table 3 and Fig. 3 (for their effects on seawater intrusion).

Table 4 presents the salinized water volume and its changes considering the 1,500 mg/L iso-concentration salinity line for the base case and simulated scenarios at the end of the simulation time. In scenario C2, 79% of the salinized water is cleaned to a salinity level lower than 1,500 mg/L and hence becomes suitable for farming activities (for the types of crops and trees cultivated in the study area, i.e., date palm trees, lime trees and fodder crops). Values of the other simulated scenarios are presented in Table 4.

3.1. Economic analysis of the different management scenarios

The economic feasibility of MAR using TTWW in Jamma aquifer is based on a cost-benefit analysis. The net present value (NPV) is used as an indicator of profitability (if NPV is positive, the project is feasible). All simulated scenarios are compared with the base case scenario, A. The benefit of each scenario is the incremental benefit with respect to scenario A. A life span of 20 years and a discount rate of 5% are considered for the calculations of the NPV which is based on the investment costs and operation and maintenance costs on a yearly basis, as well as the indicator of feasibility, the NPV. For the calculations of the benefit cost analysis, the following assumptions are used: the pipes cover a maximum distance of 16.5 km (for the upstream injection location) with a cost of US$31.2 per linear meter. The operating cost for the injection is estimated at US$0.104/$m^3$ with variable amounts. The cost of the bubbler/drip irrigation system is estimated at US$4,875/ha replaced every 7 years. The smart meters will last for the whole duration of the project and their cost is assumed to be US$1,500 each considering 1,037 wells. The annual operating cost of the meters is estimated at US$62.5. The results show that only

Table 4
Salinized water volume for different simulated scenarios and its comparison with the base case considering the 1,500 mg/L iso-concentration salinity line at the end of simulation period (at the end of stress period 244)

Scenario	Salinized water volume
	Million m^3
A (Base case)	2,561
A1	2,488
A2	1,443
B	2,123
B1	2,030
B2	1,067
C	1,400
C1	1,300
C2	537

Scenarios A2, B and B2 are economically feasible since they present positive NPVs. Practicing MAR far from the STPs found to be not economically feasible. This is because of the very high investment cost ($20,592,000) needed to cover the associated cost for constructing pipes to transport water from the STPs to the recharge wells at a distance of 16.5 km. adding to that, the cost of operation and maintenance of the pipes is also high, $748,800/year. A2 represents the scenario in which recharge in the downstream area is considered and has the highest NPV of all the feasible scenarios. Although both A1 and A2 are recharging scenarios, A2 is much more affordable in terms of the investment cost ($1,248,000), as well as the operation and maintenance costs ($374,400/year), making it a feasible option compared with non-feasible option A1. As in scenario B, no MAR involved rather than only water demand management, legislating with proper metering and monitoring abstraction for irrigation water based on predetermined quota will control the over-irrigation. The expected result is that farmers will be more careful about water usage and hence about 25% of water savings. The investment cost in this scenario is related to the cost of installation of smart groundwater meters in each of the 1,037 wells and online monitoring of the pumping (Zekri et al. 2017). The NPV is estimated to be $7,585,026. Scenario B2 is a combination of scenarios A2 and B. It assumes that the injection of TTWW will take place in the downstream area, which will increase the recharge of the aquifer, and at the same time, pumping will be controlled as in scenario B above. Consequently, the cost of investment is the sum of the investments of the A2 and B scenarios for a total of $2,803,500. The resulting NPV of $11,442,837 is quite comparable with that of scenario A2 NPV, which is $11,973,877. In fact, this scenario has a higher chance of sustainability compared with A2, where only a supply increase is proposed. The major issue in groundwater management is the common pool resource and consequent absence of incentives for farmers to use water efficiently. The implication is that when farmers find more free water in the aquifer, they will pump it, and there will be no improvement in the aquifer's storage and quality of the water. Finally, given that financial resources for investments are scarce, the decision

Table 5
Economic feasibility of MAR using TTWW in Jamma aquifer based on a cost-benefit analysis (El-Rawy et al. 2018)

Scenario		Investment cost in $	Operation and maintenance cost in $/year	Net present value $	Net benefit investment ratio
A1	Investment in pipelines to transfer water from the wastewater treatment plant up to the recharging wells upstream at a distance of 16.5 km from source	20,592,000	748,800	–12,122,585	0.57
A2	Investment in pipelines to transfer water from the wastewater treatment plant up to the recharging wells downstream at a distance of 1 km from source	1,248,000	374,400	11,973,877	3.18
B	Investment in smart water meters & online control of pumping from the wells	1,555,500	64,709	7,585,026	4.41
B1	Investment in A1 + investment in smart water meters to control pumping	22,147,500	813,509	–19,489,484	0.36
B2	Investment in A2 + investment in smart water meters to control pumping	2,803,500	439,109	11,442,837	2.48
C	Investment in drip and sprinkler irrigation systems renewable every 7 years	12,653,125	–	–8,344,547	0.68
C1	Investment in A1 + investment in drip and sprinkler irrigation systems	33,245,125	748,800	–36,263,495	0.34
C2	Investment in A2 + investment in drip and sprinkler irrigation systems	13,901,125	374,400	–12,519,153	0.61

criteria on the best scenario should rely on the net benefit investment ratio, which is the ratio of the present value of benefits to the present value of costs presented in the last column of Table 5. The highest ratio corresponds to scenario B, with 4.41, which means that every invested dollar will produce $4.41. The second-best option is scenario A2, with a ratio of 3.38. Scenario B2 is the least best option from a profitability point of view. However, option B2 will be very attractive from a social perspective because it involves two measures at a time. As that, farmers are requested to reduce abstraction and the government will invest in recharge to improve the quality of the groundwater and to protect the aquifer against seawater intrusion in the long run. The joint effort of the water authority and farmers will increase the chance of success compared to when action and responsibility is a responsibility of a single side only.

4. Concluding remarks

The paper presents feasibility of ASR and MAR in managing coastal aquifers in Oman. The following concluding remarks were concluded:

- Banking the excess desalinated water in Al-Khod urban aquifer is a feasible practice. About 85% of the excess desalinated water in Muscat city (that was discharged to the sea) can be stored in the aquifer. This will provide a net benefit estimated at $17.80 million/year. However, the location of injection and recovery wells, and injected volume need to be optimized.
- MAR using TTWW can help to double the abstracted volume for drinking purpose when in parallel manage the pumping from agricultural wells along with better relocating existing domestic supply wells.
- MAR using TWW when integrated with the management of groundwater abstraction (e.g., using modern irrigation systems to reduce the abstraction rate) becomes hydrologically feasible to augment the aquifer storage and controlling seawater intrusion, and hence improve farming activities.
- In conclusion, MAR using TWW is a feasible solution to develop water resources in arid regions, and the best scenario depends on the decision maker's preference when weighing the benefits of MAR and the level of damage to the aquifer. MAR could help manage stressed aquifer systems in arid zones to maximize the benefit of using the water for domestic purposes while minimizing the damage to the aquifer.

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Managed aquifer recharge (MAR): from global perspective to local planning

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ABSTRACT

Global and regional changes have significant financial, socio-economic and environmental impact on water resources. This is manifested in severe depletion of groundwater levels, salinisation of soils and aquifers, and increased water pollution levels. In many cases though, this can be compensated through carefully designed adaptation measures. One such example is represented by managed (artificial) aquifer recharge (MAR), method which implies the purposeful recharge of groundwater with surface water for subsequent recovery or environmental benefits. Over decades, MAR schemes were successfully installed worldwide for a variety of reasons: to maximize the natural storage capacity of aquifers (i.e., seasonal water storage), physical aquifer management (restoration of groundwater levels in overexploited aquifers, reduction of land subsidence and prevention of saltwater intrusion), water quality management (improvement of water quality through soil percolation), ecological benefits (such as maintaining the groundwater levels and flow requirements) and other benefits (such as saving on evaporation, storage of reclaimed water, etc.). The economic feasibility of MAR schemes increases for projects with high-value uses such as potable supply while the projects with low-value uses such as irrigation are usually characterized by low capital and operating costs. To emphasize the important role of MAR in the mitigation of global change impacts, the first part of this presentation brings evidence collected from over 1,200 MAR case studies from 60 countries, including data on historical development, site characterisation, operational scheme, objectives and recharge methods used, as well as quantitative and qualitative characterisation of both influent and effluent. In the second part, the talk will include also an overview on different planning and optimisation approaches with special emphasis on the newly developed web-based groundwater modeling platform for MAR applications (the INOWAS platform). The core of the system is represented by a compilation of public domain models of different levels of complexity ported on a web server for best data accessibility. The INOWAS framework presented includes several advantages over conventional simulation approaches: (a) allows the use of various model complexities; (b) provides best accessibility of project data and multi-institutional collaboration through web-based implementation; (c) makes use of a combination of widely available open-source tools; and (d) promotes the case-based reasoning approach as additional support for parameter estimation and solution finding. Overall, the paper emphasizes the relevance of MAR for groundwater replenishment around the world with specific focus on the Arabian Gulf Region and introduces new tools aimed at boosting the uptake of MAR in the near future.

Keywords: Managed aquifer recharge; Groundwater; INOWAS; MAR

1. Introduction

The past decades have been characterized by irregular availability of water resources. This was caused by several factors, including socio-economic conditions (groundwater overexploitation caused by rapid human concentration in urban areas), socio-political influences (sharp increase in human displacements caused by political instabilities), or climatic variations (high seasonal fluctuations of precipitations, extended drought periods, flooding events, and

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changes in temperature patterns). The direct impact of these constrains can be observed in reduced water availability and restricted accessibility to water resources worldwide.

2. Managed aquifer recharge (MAR) for sustainable water management

To address these challenges, adapted management strategies are required to provide for sustainable exploitation of water resources and increase resilience of water infrastructures to extreme hydro-climatic events. One very promising approach is expressed by the redesign of the hydrological water cycle, both in spatial and temporal terms. Specifically, this implies the high water demand in the dry season to be compensated during times of higher availability or lower consumption by replenishing the subsurface reservoirs, while also managing the quality of infiltration water. This intentional replenishment of aquifers is known as "managed aquifer recharge" (MAR), which represents the purposeful recharge of water to aquifers for subsequent recovery or environmental benefits (Dillon, 2005) from both quantitative and qualitative perspective.

2.1. Benefits of MAR

The benefits of storing water underground vs. conventional above-ground solutions (dams) are manifold, including:

- very small land area required for storing large water quantities;
- water can be stored within the perimeter of the urban area;
- the capital costs can be significantly lower for a scalable technological solution;
- evaporation loses are extremely low;
- substantial removal or pathogens during soil percolation;
- additional benefits for a variety of ecosystem services.

From a general perspective, the conjunctive application of MAR can be beneficial for:

- *maximisation of natural storage capacity of the aquifers*: for seasonal, emergency and diurnal storage – for example, storing water from desalination plants – as well as long-term storage, or "water banking";
- *physical management of the aquifers*: restoration of overexploited groundwater levels and therewith the avoidance of land subsidence, prevention of saltwater intrusion in coastal aquifers, enhancement of production capacities of exploitations well fields;
- *water quality management*: water quality improvement during soil percolation – for example, in surface infiltration basins or during river bank filtration, additional treatment of sewage effluent;
- *ecological benefits*: such as maintenance of groundwater levels and baseflow requirements, minor environmental footprint and minimal land use, etc.

2.2. MAR worldwide

To facilitate access to different MAR experiences worldwide, to promote international sharing of information and knowledge about MAR and to demonstrate its feasibility, a comprehensive review of reported MAR studies was conducted by the research group INOWAS at TU Dresden within the MAR Commission of the International Association of Hydrogeologists (IAH-MAR). The survey identified about 1,200 MAR projects in over 60 countries worldwide, a very solid proof of MAR suitability under different climatic, geographic, social and economic conditions (Fig. 1). The collected

Fig. 1. MAR schemes worldwide (colored circles represent different MAR techniques) as measure implemented to reduce groundwater vulnerability to droughts and floods (source: Global MAR Portal, http://marportal.un-igrac.org).

case studies are included in the Global MAR Portal, a web-based repository freely accessible online under http://marportal.un-igrac.org (Stefan and Ansems, 2017).

According to data collected and reported in international literature, the first documented MAR schemes date from 1800s (Sprenger et al. 2017), although different forms of aquifers replenishment for water management have been used for more than 2,000 years. The review demonstrated a slow but steady increase in MAR implementation until 1940s, followed by a steep increase (in average, five times more case MAR projects per year) between 1950s and 1980s, when a third development phase can be observed with a worldwide average of more than 20 MAR projects being started every year (Fig. 2) – to note that this database is not comprehensive and it includes only projects reported in scientific sources. Unfortunately, the installed capacity of these schemes is not well documented but recent estimates place the numbers from 1 km^3 in 1965 to 10 km^3 in 2015 (Dillon et al., 2018). High recent growth rates of more than 8% per year (including in countries such as Oman and Qatar) indicate that MAR is becoming more and more relevant to a wide range of water-management issues (Dillon et al., 2018). In Europe, MAR plays an important role in the development of water supply systems and contributes substantially to the drinking-water production. Only in Germany, 59 active MAR schemes produce about 750 Mm^3 of freshwater per year, mainly through river bank filtration and direct surface infiltration (Sprenger et al., 2017). In Abu Dhabi Emirate (UAE), a recent project whose construction was completed in December 2017 involved about 300 wells that aim to recharge about 26 Mm^3 of desalinated seawater into the adjacent aquifer and subsequent recovery for potable use, enough to supply Abu Dhabi Emirate with emergency water for 90 d (GRIPP, 2018).

For urban areas, MAR can be used in combination with other water management approaches such as wastewater recycling, stormwater harvesting, saline groundwater intrusion and flood mitigation and management. A recent study by Page et al. (2018) describes in detail the use of MAR in urban water management, including urban water sources, suitable urban aquifers, water quality considerations and international examples, including from Australia. By comparison, Bonilla et al. (2018) compiled an inventory of MAR schemes in Latin America and the Caribbean and emphasized the benefits of MAR utilisation in irrigated agriculture.

2.3. Recharge techniques

Over decades, the technical capacities increased and different recharge techniques were developed and adapted to local hydrogeological conditions. Table 1 describes the common MAR classification based on two main categories: techniques that refer to getting water infiltrated into the ground (either through spreading the water above surface or by subsurface injection), and techniques referring primarily to water interception through engineered modifications of regular surface and groundwater flow.

Among these techniques, the infiltration basins and the infiltration wells (Fig. 3) are utilised in more than half of the MAR applications worldwide (Stefan and Ansems, 2017). The infiltration basins (or ponds) are based on the retention and spreading of water over a mostly flat area in order to enhance infiltration to the unconfined aquifers. This type of recharge technique is used when the site surface and subsurface characteristics allow the aquifer to be recharged from ground level. In case of aquifer storage and recovery, water is injected into the targeted aquifer by a constructed well. This technique known as ASR (or ASTR if the recovery is not from the same well) is mostly used when thick and low permeability strata are present above the aquifer. Moreover, well infiltration requires a higher water quality but a smaller surface area for the well construction.

The selection of the suitable technique should be made according to the local climatic and hydrogeological conditions, available water quantity and quality, as well as

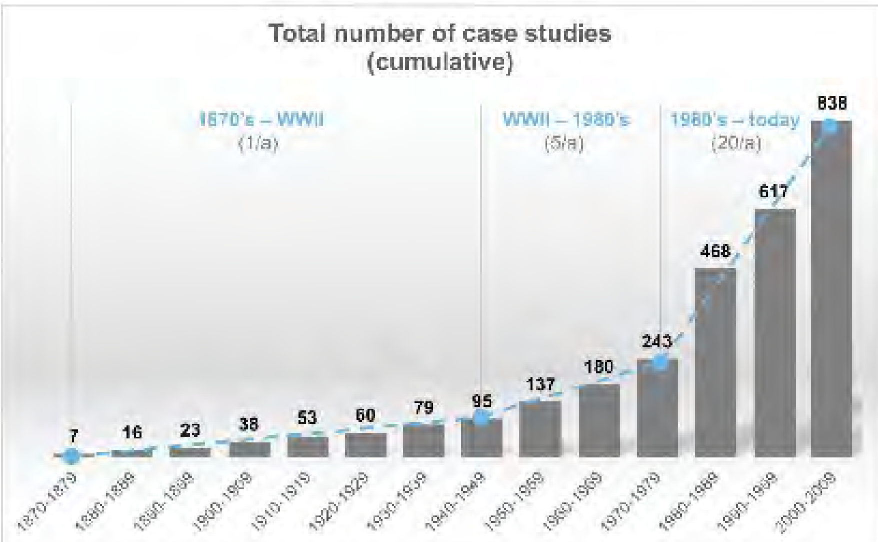

Fig. 2. Historical development on MAR applications as reported in scientific literature (after Stefan and Ansems, 2017). In reality, the number of recharge structures is estimated to be way much higher (in the order of millions!), however only a small percentage of these are well documented and monitored.

Table 1
Different MAR techniques (adapted from IGRAC, 2007). Detailed description of each recharge technique can be found at https://inowas.hydro.tu-dresden.de/managed-aquifer-recharge/ (including recommended system scale, suitable geology, topography, soils type, water sources, relative costs objectives, advantages and limitations)

	Main MAR methods	Specific MAR methods
Techniques referring primarily to getting water infiltrated	Spreading methods	Infiltration ponds & basins
		Flooding
		Ditch, furrow, drains
		Irrigation
	Induced bank infiltration	River/lake bank filtration
		Dune filtration
	Well, shaft and borehole recharge	ASR/ASTR
		Shallow well/shaft/pit infiltration
Techniques referring primarily to intercepting the water	In-channel modifications	Recharge dams
		Subsurface dams
		Sand dams
		Channel spreading
	Runoff harvesting	Rooftop rainwater harvesting
		Barriers and bunds
		Trenches

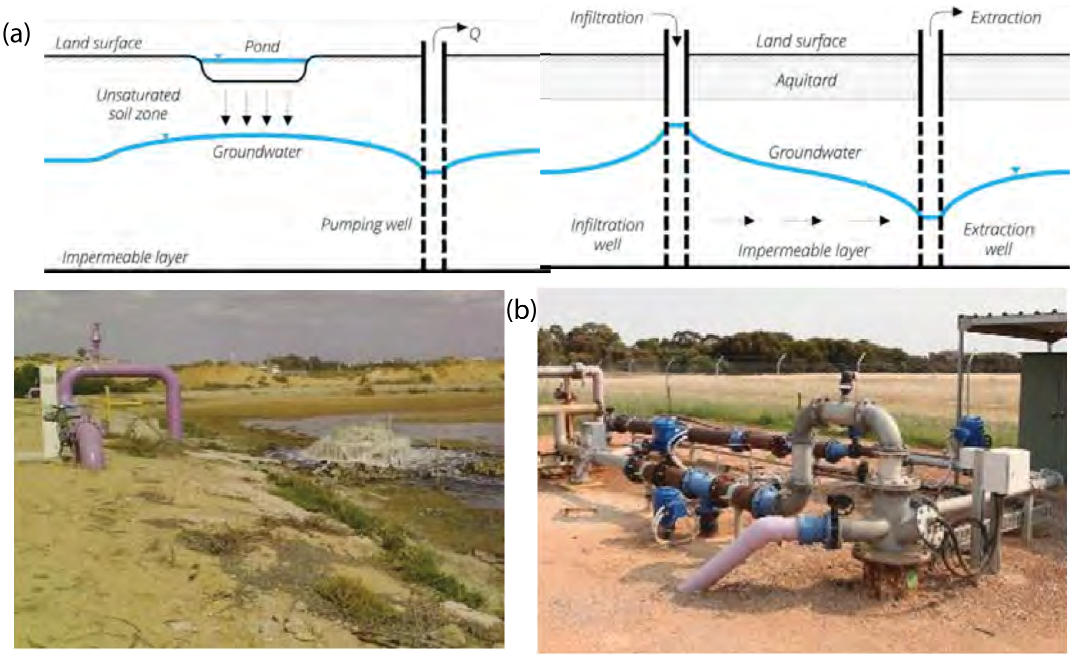

Fig. 3. Most common MAR techniques: infiltration ponds used for soil-aquifer-treatment (SAT) applications (a) and infiltration wells, used in aquifer storage and recovery (ASR) or aquifer storage, transport and recovery (ASTR) applications (b). Photos: Catalin Stefan.

following the specific demand for the recovered water. In Arabian Gulf countries, ASR has been tested and applied with success to recharge underlying aquifers. In Kuwait, for example, the technical feasibility of ASR was tested since 1970s, with further tests conducted in the 1990s in the carbonate and clastic aquifers indicating that ASR is technically possible (Mukhopadhyay et al., 1994). Nevertheless, the insufficient treatment of water to be infiltrated leads to severe clogging of the infiltration wells, which is the major reason of failure of ASR systems. Alternatively, pilot studies have been used to investigate the feasibility of infiltrating secondary to tertiary treated wastewater through surface recharge basins in Kuwait (Al-Senafy and Sherif, 2005). Besides the replenishment of underlying aquifer, the system also provides further purification of infiltration water through soil aquifer treatment (SAT). The advantage of SAT vs. ASR is that water of lower quality can be infiltrated for seasonal storage (specifically treated wastewater, which is widely available throughout the year). The drawbacks of this approach are given by the often unsuitable lithology and high evaporation rates. Nevertheless, these constrains can be partially addressed through carefully selected operational conditions. These include the construction of several shallow basins and their operation in alternative, short wet-dry cycles to maximize efficiency and enable full restoration of the infiltration rates.

2.4. Planning and assessment of MAR schemes

Despite their demonstrated benefits, solutions such as managed aquifer recharge (MAR) are still not widespread, partly due to poor access to information and lack of knowledge about the associated risks to human health and environment. So far, only few countries developed strategic guidelines for MAR (including Australia, India, Mexico, USA), among them Australia being the leader in having the first risk-based guidelines for managed aquifer recharge (NRMMC et al., 2009). In most cases, preliminary studies are required to design the process parameters and assess operational scenarios. This can be done by using pilot cases or laboratory tests, approach usually prone to boundary limitations and scale-related issues. Alternatively, computer simulations provide an excellent opportunity for analysis of scenarios and future predictions of MAR efficiency (Ringleb et al., 2016; Sallwey et al., 2018). They are used for modeling water balance at watershed scale, solute and reactive transport, transport processes in unsaturated zone, and saturated flow processes (Fig. 4).

With very few exceptions, all available software codes and decision support systems for MAR planning and assessment are desktop-based, which represents a significant constrain in the development and dissemination of smart IT solutions to a large audience, especially from an international perspective. Moreover, a large percentage has a steep learning curve and training is often linked to significant human and financial resources.

2.5. Free, web-based INOWAS modeling platform

The main idea around our approach is thus the portability of desktop-based groundwater modeling to web- and cloud-based systems. For this purpose, we developed the INOWAS platform, a web-based groundwater modeling platform that

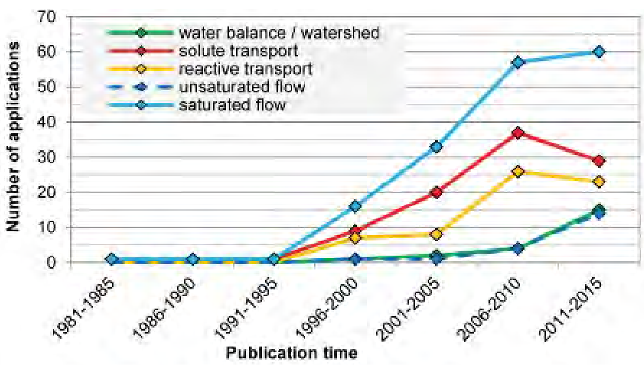

Fig. 4. Historical development of different model types for simulation of MAR-related processes (Ringleb et al., 2016).

aims to facilitate online collaboration for the development of smart MAR solutions worldwide (available online at http://inowas.hydro.tu-dresden.de). The platform combines modern web-based technologies and design elements with powerful computational capabilities to deliver reliable browser-based simulations. The platform is addressed to scientists and engineers from planning offices, environmental agencies, local and regional planners and decisions makers, as well as academia and public sector. The system is developed to provide decision-support in solving different groundwater related issues with focus on planning, assessment and optimisation of MAR schemes. To increase its attractiveness and applicability among a wider range of users, the platform contains tools grouped on three levels of complexity for empirical, analytical and numerical groundwater modeling.

The main advantage of using the INOWAS platform compared with other solutions lies in the easy set-up, calculation and dissemination of groundwater models to a wider audience using only the web browser and regular internet connection. In contrast to desktop-based computing, which requires the installation of additional computer programs and plugins (often not a straightforward process due to system incompatibilities), web-tools hold the advantage of increased software availability, device and location independence, easy maintenance and updating, independence of platform, hardware and operating system, as well as resource pooling. In addition to technical advantages, the system offers further benefits such as multi-user collaboration via internet and a short learning curve resulting from the combination of intuitive design with modern, standardized graphical user interface. Even more, the platform contains web-based implementation of well-known equations and open-source software code for groundwater management, which makes it compatible with other conventional platforms and interfaces.

The platform contains collection of simple, practical and reliable web-based tools of various degrees of complexity (Fig. 5):

- *empirical tools* – simple tools derived from data mining and empirical correlations;
- *analytical tools* – practical implementation of analytical equations of groundwater flow;
- *numerical tools* – reliable simulations using complex numerical flow models.

For numerical modeling, the INOWAS platform offers a brand-new MODFLOW interface which is accessible only from the browser, without the need for the installation of any additional software of plugins. As being the first web-based implementation of an integrated groundwater modeling platform, INOWAS brings a global perspective to water resources management.

3. Conclusions

The free, web-based INOWAS platform supports planners and decision makers in different steps of planning and assessment of MAR applications. The web-based implementation offers a whole new range of opportunities for collaboration while the multi-layered toolbox complexity

Fig. 5. Screenshots of simulation tools included in the INOWAS platform. Left: analytical tool for the calculation of saltwater upconing under a pumping well (Glass et al., 2018a). Right: scenarios analysis of a MODFLOW-based groundwater model (Glass et al., 2018b).

makes the platform easily accessible. With its technical innovation, the INOWAS platform is expected to actively contribute to the promotion and expansion of MAR applications, therewith supporting the shift to sustainable water resources management.

Acknowledgments

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Groundwater economics in arid regions: Abu Dhabi Emirate case study

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ABSTRACT

In arid and semiarid regions, groundwater is scarce, limited and non-renewable but it is a vital resource that supports a variety of societal uses and benefits. With growing demand due to extension in agriculture and domestic sectors, groundwater resources are coming under greater pressure following reductions in surface water yields, due to reduced rainfall and over abstraction. Over abstraction due to increasing demand or climate, change-driven changes in spatial distribution of precipitation can result in a reduction in groundwater quantity and deterioration in quality. Increased population and economic development inevitably result in an increase in the generation of waste products and, if disposed of inappropriately, these have the potential to contaminate groundwater resources and lead to degradation and economic costs. This creates the need for a higher profile regulatory and management regime for this limited groundwater resources. Given climate variability and the environmental challenges, the importance of groundwater as a resource is ever increasing in arid regions. Abu Dhabi emirate is an arid region facing the challenges of renewable fresh water scarcity. In the year 2014, groundwater use accounts for about 63% of total water demand in the Emirate, with the remaining portion of demand being met through desalinated (28%) and recycled water (9%). Groundwater is used mainly for agriculture, forestry sectors, which together have accounted for over 95% of total annual withdrawals. Agriculture alone has accounted for 80% of total recent withdrawals. The total present annual abstraction from the groundwater aquifers is about 2,300 million cubic meters. However, the annual natural recharge to the aquifer systems ranges between 90 and 140 million cubic meters only. Numerous wellfields abstract groundwater of various qualities and in some areas massive over-abstraction has resulted in alarming groundwater declines and a severe deterioration in groundwater quality. This policy has led to a reduction in the groundwater table which caused numerous shallow wells to go dry and impact the farms. It is estimated that there is still 641 km^3 groundwater resources available (saline, brackish and fresh), but only less than 3% of this reserve is fresh and, based on current abstraction rates, both fresh and brackish reserves will be depleted within the next 50 years. The purpose of this study is to assess the economic value of groundwater resources in the Abu Dhabi Emirate. A dynamic hydro-economic optimization model was developed and applied. This model evaluates the net benefits and economic tradeoffs across alternative water by simulating groundwater reserves and withdrawals for different regions, time periods, and development sectors. Using this model, we estimate the value of Abu Dhabi's groundwater resources (in total and per cubic meter).

Keywords: Groundwater; Recharge; Groundwater economics; Groundwater management; Desalination; Treated wastewater

1. Introduction

As an arid region with very limited renewable water resources, groundwater gains increasing recognition in Abu Dhabi Emirate, UAE. So, many governmental initiatives and projects were planned to protect and use efficiently this precious resource. Abu Dhabi Emirate is located in an arid region with scarce renewable freshwater resources. 50 years ago, the emirate freshwater requirements were met solely from groundwater resources through over pumping from non-renewable aquifer systems. Due to the deterioration of the groundwater quality and the severe drop in groundwater

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tables, the government started to invest in desalination industry. The construction of the first desalination plant in 1960 marked a milestone in the development of the Emirate allowing Abu Dhabi to grow well above the limitations imposed by its water scarcity. As per the 2015 water resources statistics, 63% of Abu Dhabi's water supply came from groundwater, 29% from desalinated water and 8% from treated wastewater as shown in Fig. 1. Only 3% of the emirate groundwater reserves are fresh, 18% brackish and 79% saline. That means that only 18% of the total groundwater reserve is usable, the remaining 79% cannot be used before treatment (desalination) as shown in Fig. 2. Water demand in Abu Dhabi Emirate has increased significantly over the last decade. The largest demand sectors are agriculture, forests and parks followed by the residential and government sectors. Recent previous studies indicated that the main driving forces are population growth, economic development and changes in lifestyle that have increased the water demand for irrigation, human consumption and industrial processes. Several public policies intensified this water demand. Some of these are the expansion of agriculture with a view to protecting the rural heritage and making Abu Dhabi less dependent on imported food; desert greening policies with a view to providing a habitat for wild animals and stabilizing the sand around roads; development of public parks to enhance the aesthetic value of outdoor spaces; residential and commercial megaprojects with a view to catering for the local population and a growing tourism industry; and industrialization driven by the government's diversification effort into non-oil industries. In 2015, the water demand was driven by six sectors: those that used mainly groundwater for irrigation: agriculture (50%), forestry (12%) and public realm amenities (10%); and those that mainly used desalinated water for a combination of indoor and outdoor purposes: residential (16%); commercial (6.5%) and government (4.5%). Some marginal demand also came from industry (0.5%) and others (0.5%) as shown in Fig. 3.

The shallow unconsolidated aquifers are the most common and productive aquifers and comprise both recent

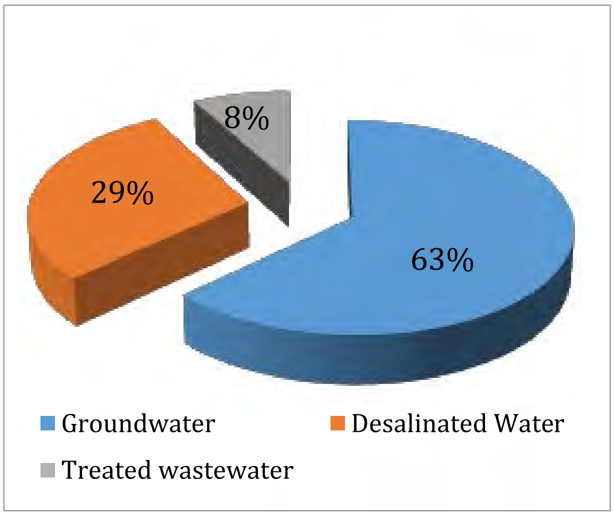

Fig. 1. water Resources in Abu Dhabi Emirate.

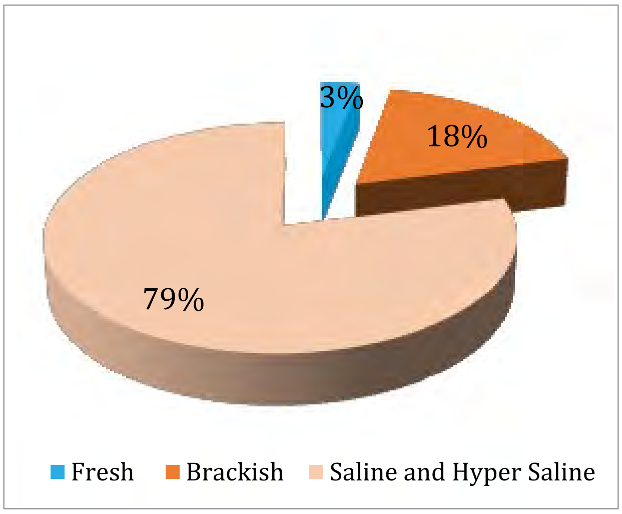

Fig. 2. Groundwater Resources in Abu Dhabi Emirate.

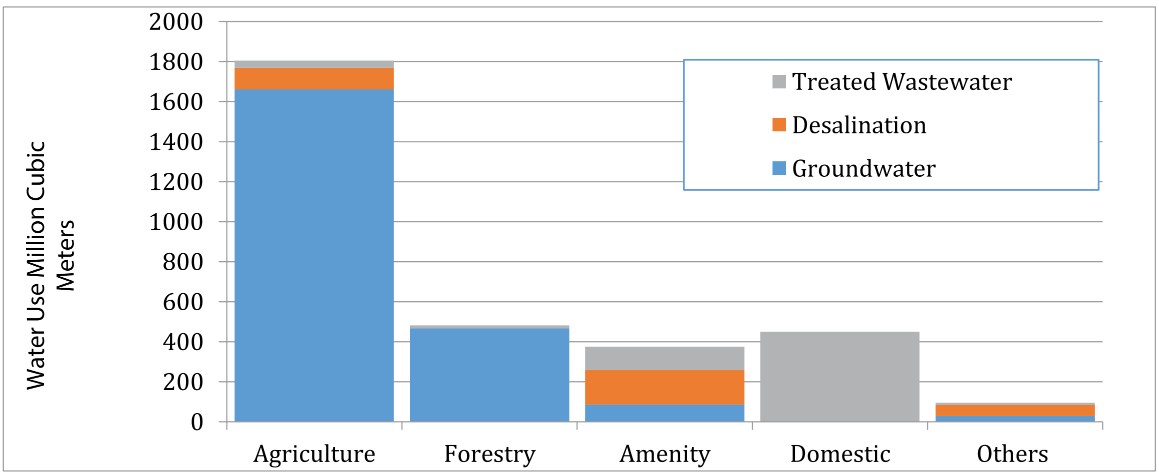

Fig. 3. Water resources demand in Abu Dhabi Emirate (2015).

sand dunes and alluvial deposits of varying age. Bedrock aquifers occur throughout the Emirate and are largely carbonate deposits laid down in shallow marine seas. Their potential as aquifers has not yet been fully proven; the aquifers occur generally at significant depth and have not been explored or exploited anywhere near to the same extent as the unconsolidated aquifers described above. Fig. 4 shows the hydrogeological map of Abu Dhabi Emirate. At the current rates of extraction, both fresh and brackish groundwater resources (about 2.07 billion cubic meters) will be exhausted in the next 50 years if the abstraction continues as it is today. Thus, it will be critical to ensure that groundwater resources are managed sustainably and in particular, the use of groundwater for irrigated agriculture, which is the largest consumer, has to be moderated by employing innovative strategies. Groundwater salinity is the concentration of dissolved solids in a defined unit of groundwater expressed as milligrams per litre. Most of the groundwater in the surficial aquifers is brackish, saline or brine. EAD considers most of groundwater in Abu Dhabi as 'useable' groundwater less than or equal to total dissolved solids not exceeding 15,000 mg/L (Dawoud, 2014). Beside the evident impact of evaporation on groundwater salinity, unsustainable groundwater abstraction contributed to the higher salinity causing movement of saline water upward as shown in Fig. 5 (EAD, 2016).

2. Groundwater economics

Groundwater aquifer systems are very important contributors to Abu Dhabi economy. It contributes to the economy through producing fresh and brackish groundwater for use in various forms of production and consumption, and through supporting a range of ecosystem functions, which in turn deliver valuable ecosystem services into the economy. Many factors affect the economic value of groundwater

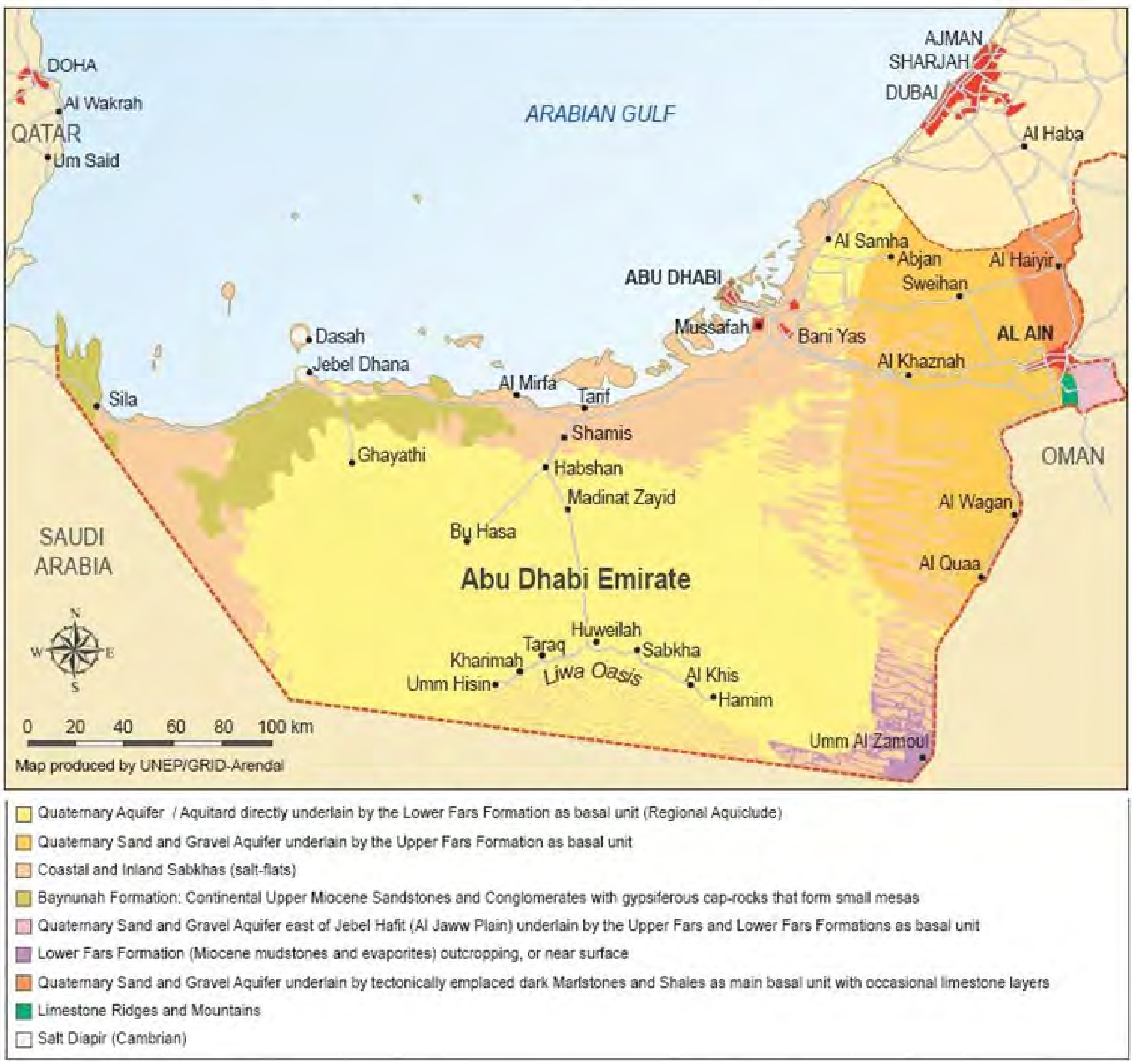

Fig. 4. Hydrogeological map of Abu Dhabi Emirate.

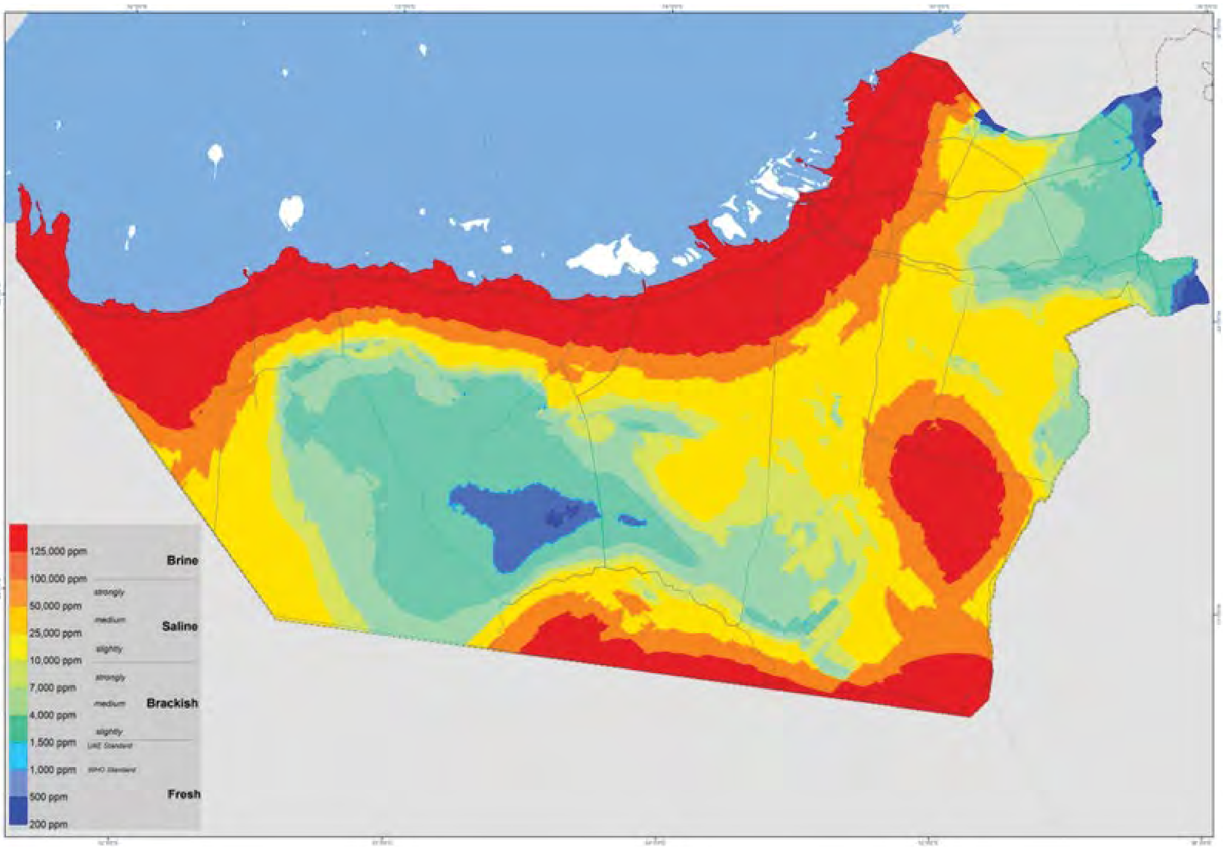

Fig. 5. Groundwater salinity in Abu Dhabi Emirate (2016).

aquifer systems in Abu Dhabi. So, it is important to distinguish between the concepts of natural asset value and ecosystem service value. Ecosystem services are the benefits that humans receive from ecosystems, and are officially defined by the Millennium Ecosystems Assessment. Ecosystems produce these ecosystem services on an annual basis, and the value of these services accrue on a country's national income statement, and should ideally be measured through indicators that relate to gross domestic product (GDP). Thus the total value of aquifer ecosystem services can be thought of to contribute to green GDP. Aquifers themselves are natural assets. They form part of the ecological infrastructure of a country and the values of these assets theoretically appear on a country's natural resources balance sheet. The asset value can be determined by calculating the net present value (NPV) of the perpetual stream of aquifer ecosystem services delivered. Natural assets of this kind are characterized by complex inter-temporal and inter-ecosystem service characteristics. For instance, although overharvesting an aquifer may yield short-term benefits (on the income statement), it will reduce the asset value of the aquifer if it reduces the future water yield of the aquifer and/or if it reduces the delivery of ecosystem services supported by the aquifer. Thus it is important to understand the links between the hydrogeology of aquifers systems and the groundwater-dependent ecosystems that are linked thereto. Only by incorporating these wide range of factors will be possible to comprehend the significance of the extractive and non-extractive uses of groundwater. Qureshi et al. (2012) present a diagram to elaborate groundwater resource linkages/interactions as shown in Fig. 6.

These in essence represent the supply side considerations relating to the assessment of groundwater resources. Simply put, they determine the cost of extraction, the amount of water available to be extracted, the quality of the water available and the linkages of groundwater to other

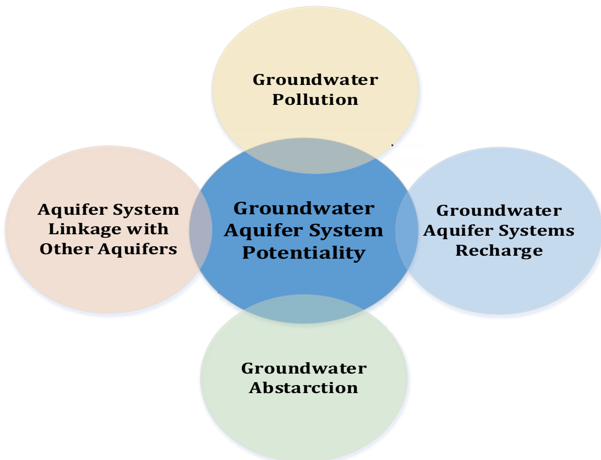

Fig. 6. Hydrogeological considerations relevant GW economic assessment.

ecosystems that be of value, and that may be affected by abstraction. These include surface water impacts of groundwater abstraction (Qureshi et al. 2012, Katic and Grafton 2012). Thus, in order to understand the value of aquifers, we need to understand the full range of ecosystem services which it supports (including ground water provisioning). Another consideration in the value of aquifers is the relative scarcity of water. Where surface water resources are abundant, sufficient and inexpensive compared with groundwater, it is likely that aquifers play a relatively small role in the economy, and thus the value of the aquifer will be low. This situation may vary geographically, and may also change over time as water demand increases. The long residence time of groundwater in and of itself provides a particular kind of economic value. It gives groundwater a greater annual assurance of supply relative to surface water sources (Colvin 2009). The quantity of water captured by a surface water storage scheme such as a dam is the function of two or three (possible) seasons of rainfall and runoff. The amount of water contained within an aquifer is the function of a much longer set of consecutive seasons of rainfall, runoff and infiltration; thus the water content of an aquifer is muted from the fluctuation of the climatic cycles, a property which makes groundwater resources particularly resilient to climatic shifts and periods of drought. This adds a strong inter-temporal consideration to the abstraction and use of groundwater resources. Qureshi et al. (2012) states that "from an economic perspective optimal (aquifer) management is defined by the rate of extraction over time and space that maximizes the NPV of benefits minus costs, subject to the physical hydrology of the aquifer and the related water sources". The marginal value of water can be represented with a downward sloping demand curve, which illustrates that inverse relationship between price and quantity demanded. An important consideration derived from the simple curve is that users allocate water to the highest value uses first and subsequently to lower value uses (Qureshi et al. 2012, Hansen 2012). This has very powerful implications for scenarios where is water resources are becoming particularly scarce. This also implies that the marginal value decreases as more value is used. Under such circumstance, the market forces will begin to reallocate water to users with a relatively higher marginal use values. The assessment of the available supply of groundwater is an important step towards sustainable groundwater use. Of course, this needs to be placed into the context of groundwater demand, and the uses that are driving that demand.

3. Materials and methods

Due to over abstraction of non-renewable groundwater resource, its quality was deteriorated and there was a severe drop in groundwater tables during the last 20 years as shown in Fig. 5. However it is still the main resource for irrigation and contributes with about 62% out of total water use in the emirate (Heal 2003). It is important to value the groundwater resources economically to understand its value against other alternatives water resources (Baker and Murray 2009). Groundwater use value is equal to the market returns from agriculture and the ecosystem services provided by forests: carbon storage, wildlife habitat, cultural heritage, and road protection; non-use value equal to the cost of establishing the strategic reserve as insurance against future threats or shocks (Brown 1997). To estimate the value of groundwater resources in Abu Dhabi we apply a hydroeconomic framework that integrates key features of the groundwater hydrology into an economic valuation analysis. This framework accounts for important interconnections between human systems (including the economy) and groundwater systems. Using this framework, we apply a dynamic (i.e., multiperiod) optimization approach to assess the value of groundwater resources in Abu Dhabi. The fundamentals of this approach are shown in Fig. 7. It assumes that users will continue to extract additional units of water as long as the value they get from the additional unit (marginal value) exceeds its price. The stopping point is where the marginal value equals price. Therefore, the optimal price (and marginal value) of groundwater is what maximizes the long-term value of the groundwater asset (stock value). If it is set too low, users will not manage groundwater efficiently and high extraction rates will lead to rapid depletion of the aquifer or quality degradation to the point that remaining groundwater is not economically usable. Using a dynamic optimization approach, we project both the optimal price (marginal value) of water withdrawals (in United Arab Emirates dirhams [AED] per cubic meter) and the corresponding total value of groundwater stocks. Dividing the total stock value by the size of the current stock, we will also estimate the average value per unit of groundwater stock (in AED per cubic meter). It is important to emphasize that, even though they are both measured in AED per cubic meter, the optimal price (flow value) and the average stock value are not the same measure of value. In a dynamic setting, it is also essential to compare values for groundwater use across periods. This is particularly true for resources that do not replenish themselves quickly, such that the availability of the resource for future users depends critically on how much is used in the present. To address these intertemporal tradeoffs in groundwater use, we apply a conventional "discounting" approach. Under this approach, benefits received (and costs incurred) farther in future periods receive less weight than those received closer to the present. For our analysis, we apply a 3% annual rate of discount, which is on the lower end but still within the range of conventional practices.

3.1. Model representation of groundwater hydrology

A key component of the hydro-economic model is the physical model representing groundwater stocks and processes in Abu Dhabi. Although there are many dimensions and complexities associated with the hydrogeology of the region, we develop a simplified representation of the groundwater system, to make best use of limited data regarding existing groundwater resources and address the needs of the analysis. The first step in developing the hydrological model was to designate general water use zones (sub-regions) that (1) represent areas with different average groundwater availability and quality conditions and (2) match the spatial resolution and dimensions of the economic model. Fig. 5 provides a map depicting the zones designated for our analysis. Each zone was then further subdivided into three layers representing different salinity conditions—fresh

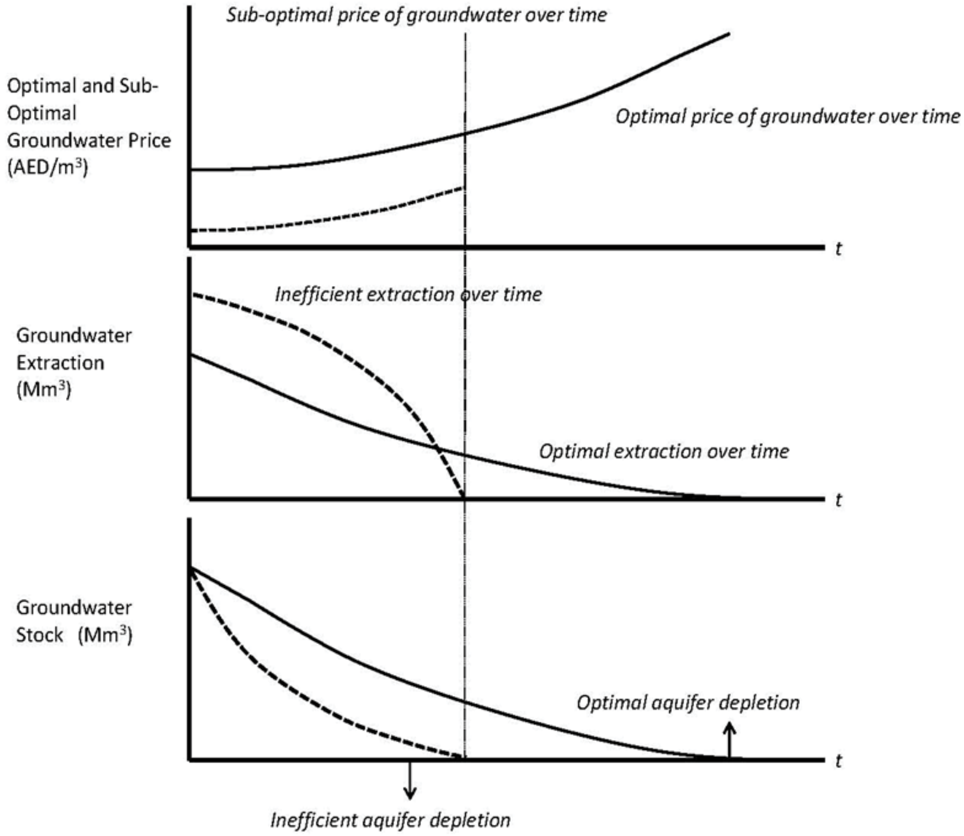

Fig. 7. Comparison of optimal and inefficient time paths of groundwater extraction.

water, brackish water, and saline water. For the Western region, information on the total saturated thickness of the aquifer (provided by EAD), combined with the conceptual model of geologic formations and hydrogeology provided a means for estimating the thickness and total volume of each layer (fresh, brackish, and saline) in each zone. Due to data limitations, a simpler framework was applied to the Eastern region.

3.2. Model representation of groundwater use sectors

3.2.1. Agricultural sector use

Agriculture is the largest source of groundwater consumption in Abu Dhabi by a wide margin, accounting for roughly 2 billion m^3 per year. Although this rate has recently declined and will most likely continue to decline as subsidies for Rhodes Grass production are phased out, agriculture is expected to be the main consumer of groundwater for the foreseeable future. To estimate the economic value of groundwater for agricultural irrigation, we developed an optimization model that maximizes producer returns to production (crops, livestock, and date palms) given various land and water resource constraints. A necessary first step is to understand the amount of water required to grow particular crops or raise livestock. Using a standard Food and Agriculture Organization (FAO) approach, we estimated crop-specific water requirements as a function of crop evaporation, crop water needs, crop-specific irrigation response factors, and maximum achievable yields. We developed similar water requirements for livestock using FAO daily water requirement guidelines for Sahelian desert conditions.

3.2.2. Forestry sector use

Next to agriculture, the forestry sector has been the largest consumer of groundwater in Abu Dhabi over the last decade. However, in contrast to agricultural lands, forests in Abu Dhabi are not cultivated and managed for harvesting and commercial production. Rather, they have mostly been planted since 1970 to support the late HH Sheikh Zayed Bin Sultan Al Nahyan's vision of "greening the desert" to provide environmental benefits for Abu Dhabi residents. The value of groundwater for the forest sector must, therefore, be assessed by examining the value of the nonmarket benefits provided by these forests. The next steps are to estimate the annual nonmarket benefits provided by these forests. For our analysis, we focus on the following four main types of ecosystem services.

- *Carbon storage*: To estimate the amount and value of carbon stored in each forest unit, we first estimated the above-ground biomass present and assumed that half of this weight is attributable to carbon. Next, we estimated the value of stored carbon as the avoided social cost of emitting that carbon to the atmosphere. Based on estimates from the United States Government's Interagency Working Group on Social Cost of Carbon (2013), we estimate the unit value of stored carbon to be roughly 560 AED per metric ton. Converting this stock value using a 3% discount rate, the resulting annual value of carbon is 16.8 AED per metric ton per year.

- *Habitat provision for wildlife and certain endangered species*: To estimate the value associated with forest wildlife habitat, we focused on the value of protecting endangered species. In the case of Abu Dhabi forests, a species of particular interest is the Arabian oryx. To our knowledge, no studies have specifically estimated the societal value of protecting the oryx or other endangered species in Abu Dhabi; however, a number of valuation studies conducted in the United States have estimated households' average willingness to pay (WTP) for protecting various species. These studies are summarized in a meta-analysis (Richardson and Loomis, 2009), which also provides a predictive model for estimating average WTP under defined conditions. Using this function, we estimated that the average WTP for protecting a charismatic terrestrial species is the equivalent of 178 AED per year for households in Abu Dhabi. Multiplying this value by an estimate of the number of households living in Abu Dhabi, we estimate an aggregate annual value of 126 million AED per year to protect forest-dwelling species. To apportion this aggregate habitat protection value to the individual forest units in the Emirate, we assume that, across the 50 forest units providing animal habitat, each planted donum contributes equally to this aggregate value (i.e., roughly 330 AED per donum per year).
- *Support of cultural heritage*: To estimate the cultural heritage value associated with these forests, we use an approach similar to the one for wildlife. As in the previous case, we are not aware of studies that specifically value cultural resources in Abu Dhabi; however, a number of cultural valuation studies have been conducted in other parts of the world. A review of this literature by Noonan (2003) provides a WTP function that can be used to predict values for different types of cultural resources. Using this function, we estimate an average annual WTP of 541 AED per household for protecting all forests with outstanding legacy value. Multiplying this value by the number of citizen households, the estimated aggregate value is 44 million AED per year to protect outstanding legacy value forests. Apportioning this value to the 36 units providing outstanding legacy value, each donum is estimated to provide an annual cultural heritage value of roughly 142 AED per year.
- *Protection of roadway infrastructure*: For these benefits, we estimated how the ground stabilization provided by forest cover reduces the costs of sand removal from nearby roadways. To estimate these values, we first used data from the Department of Transport to estimate the average annual cost of sand removal per kilometre of roadway in different regions of the Emirate. We found that average costs were higher by roughly 70% in the western areas where more roads are unprotected by forests. Assuming that half of this cost difference (35%) is attributable to forests, we estimated an annual cost savings of 860 AED per kilometre of roadway within 200 m of forest planted areas.

Finally, to estimate the value of groundwater use in each forest unit, we assume that it is equal to the total benefits that is, carbon storage, wildlife habitat, cultural heritage, plus road protection provided minus the groundwater extraction costs.

3.2.3. Amenity use

A relatively simple approach was used to value groundwater consumption for amenity purposes. Since the majority of the water used for amenity purposes comes from desalinated water and treated wastewater, the implicit social willingness to pay (or economic value) for water in this use is the costs of treating and distributing the water. Thus, we assume that the economic value of groundwater consumed for amenity purposes is equal to the costs of desalinating and distributing water. In our model, total amenity consumption of groundwater is restricted to certain zones, and the total is capped at 51 million m^3 per year, consistent with observed water resource usage rates.

3.2.4. Strategic reserve value

In addition to consumptive use values for irrigating farms, forests, and vegetation that provides amenity value, we consider the nonuse option value of maintaining fresh groundwater supplies. This option value represents the social benefit of preserving groundwater as a type of insurance for uncertain future needs. Maintaining a stock of accessible groundwater that is suitable for public consumption can provide an array of benefits, including alleviating future water and food security concerns and insulating Abu Dhabi from threats against public water infrastructure. The inclusion of this strategic reserve value in this analysis is justified given the existence of current groundwater injection projects. These projects imply a social WTP for groundwater preservation. Thus, total project costs of an existing injection project targeted at the Liwa region in Western Abu Dhabi are used as a proxy for the social WTP for the strategic reserve. Combining the four demand sectors: agriculture, forestry, amenity and strategic reserve as shown in Fig. 8, a dynamic optimization model was developed to maximize the total value of consumptive and non-consumptive groundwater use over a long time horizon of 100 years (Allen et al., 1998) as shown in Fig. 9.

4. Results and discussion

Three simulation scenarios were constructed for this analysis to project the total, average, and marginal values of groundwater over a 100-year simulation horizon, and assuming full (unsubsidized) energy costs for groundwater pumping. Three assumed discount rates were applied to the scenarios (3%, 5%, and 8%) to evaluate the implications of this important parameter on long-term groundwater management projections and estimates of the total economic value of groundwater. The total economic value of groundwater reserve in Abu Dhabi Emirate was estimated as

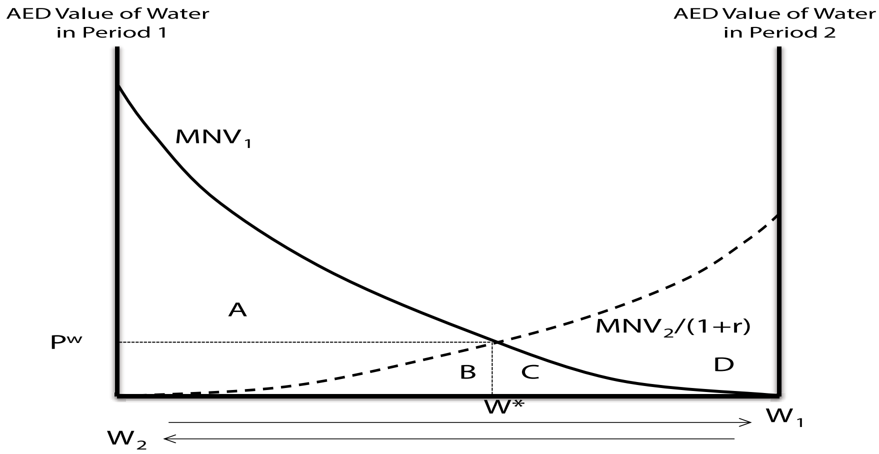

Fig. 8. Conceptual diagram of groundwater valuation model.

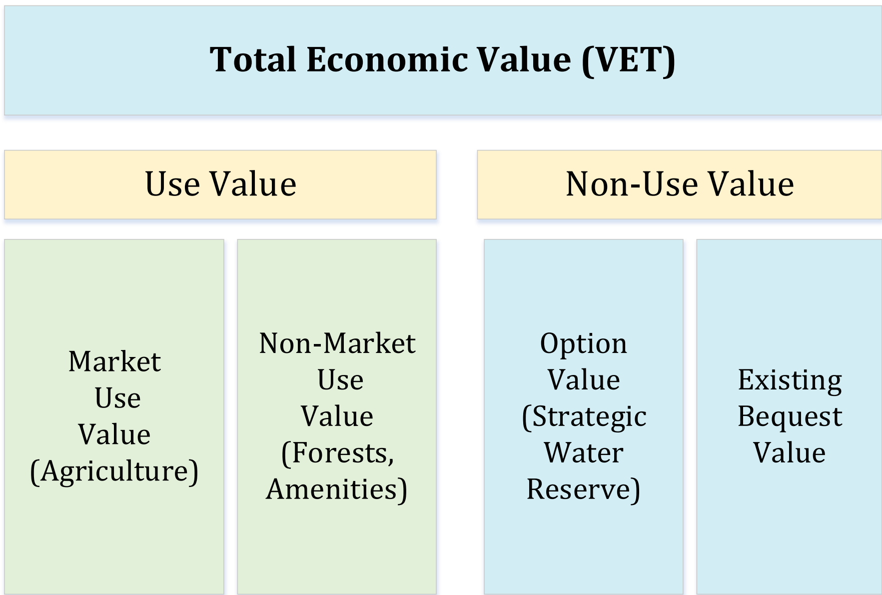

Fig. 9. Groundwater economic valuation.

Table 1
Total groundwater value over 100 year (in Billion AED)

Discount rate	Agriculture value	Forestry value	Amenity value	Strategic reserve value	Groundwater consumption costs	Total economic value
3%	164	74	233	372	63	781
5%	129	19	71	304	51	472
8%	93	4	21	365	41	443

shown in Table 1, and the marginal economic value ranges 4.5–6.0 AED/m^3 compared with 7.0 AED/m^3 for wastewater and 11.3–15 AED/m^3 for desalinated water.

5. Conclusions and recommendations

Groundwater is a vital resource in arid region such as Abu Dhabi and calculating the groundwater value can help for a better understanding and sustainable use of this resource. Many actions should be taken by the government to sustain these resources in the future such as:

- Future agricultural policy including prices and costs
- Estimating food security benefits of irrigated agriculture
- Future non-market values for forest ecosystem services
- Future population growth rates and composition

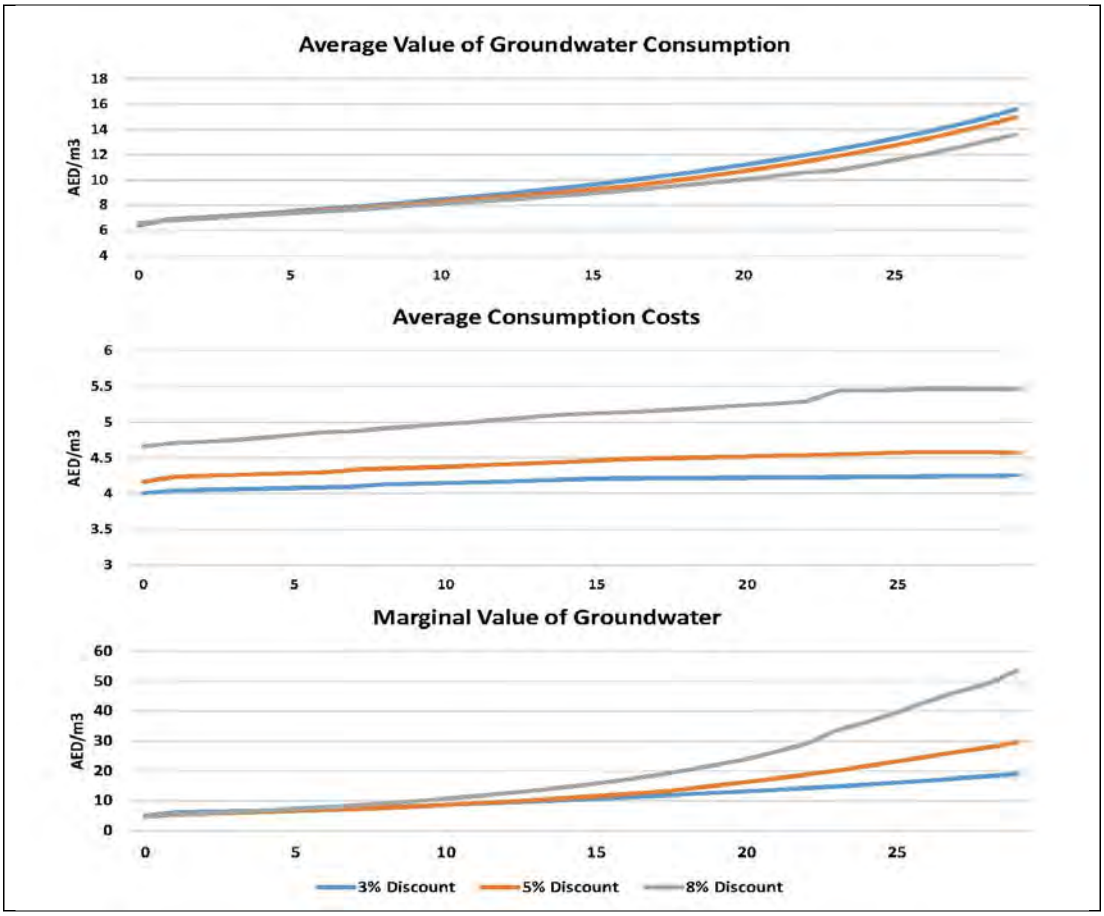

Fig. 9. Marginal groundwater value (in AED/m^3).

- Climate change impacts on the groundwater resources
- Reform the legal and intuitional water sector framework including groundwater regulation and legislations
- Infrastructure investment options
- Greenhouses, more efficient irrigation systems, and new innovative technologies in agriculture sector, etc.

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Trends in groundwater observation data and implications

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ABSTRACT

The Batinah plain in the North of the Sultanate of Oman is undergoing several severe changes. Growing population, accompanied by urbanization and industrial activities conflict with the traditional agricultural imprint. The development stresses the regional water resources. The vast aquifer, located between the Hajar mountain chain and the Oman Sea, is exploited by increased withdrawal for domestic, agricultural and industrial purposes. Especially in the highly populated coastal region, the reduced pressure due to the decreasing groundwater table leads to enlarged saltwater intrusion from the seaside. We explore time series of water table and salinity from 29 wells in Maawil catchment, South Batinah, some of them recorded for more than 30 years. Typical patterns in the measured data reflect the profound changes of the aquifer, related to saltwater intrusion, extreme rainfall events and dam construction. The analysis confirms the effectiveness of recharge dams for harvesting flash floods and implies the importance of integral management of groundwater resources. The exemplary case study shows trends that can generally be observed in stressed coastal aquifers.

Keywords: Groundwater observation; Seawater intrusion; Time series; South Batinah

1. Introduction

According to the National Centre for Statistics & Information in Oman, the total cultivated area in the Sultanate increased by 2.6% in 2016 when compared with the previous year 2015. During the last 10 years, the cultivated area has been increased by 33% from 150 thousand acres in 2007 to 202 thousand acres in 2016. The annual population growth rate in 2016 increased to 5.9% compared with 4.1% in 2015 basically due to high growth rate of expatriates (NCSI, 2017). The number of water wells used by the Public Authority for Electricity and Water for residential use is 203 wells in North and South Batinah, aside from the wells dedicated for agricultural purposes (PAEW, 2016). This development stresses the water resources especially in the Batinah plain, the most populated area in Oman (Abdallah et al., 2017).

Even though rainfall in the Sultanate of Oman is highly variable, irregular and diversified, 46 recharge dams have been constructed in Oman, eight of them are on Batinah plain, as per 2017 (Kwarteng et al., 2009; MRMWR, 2015; Almanthari, Y., personal communication, October 22, 2018; Fig. 1).

2. Geology of Batinah plain

The Alluvium deposits in Batinah plain were originated from the erosion of Hajar mountain. This mountain is composed of highly fractured siltstone, sandstone and limestone formations, as well as shallow marine carbonate and thin layers of sandstone. The alluvium deposits thickness increased gradually from the mountains foot in the south, and increased gradually towards the coastline (Young et al., 1998).

Two major clastic deposits are distinguished in Batinah plain of late Tertiary – recent age; ancient alluvium, sub-recent/recent alluvium. They are unconformably underlined by consolidated bed rock dipping north and basically composed of tertiary carbonates and marl. Clay and cemented layer might cover the carbonate bedrock as a result of erosion. This clay layer should act as an aquitard. Allochthonous

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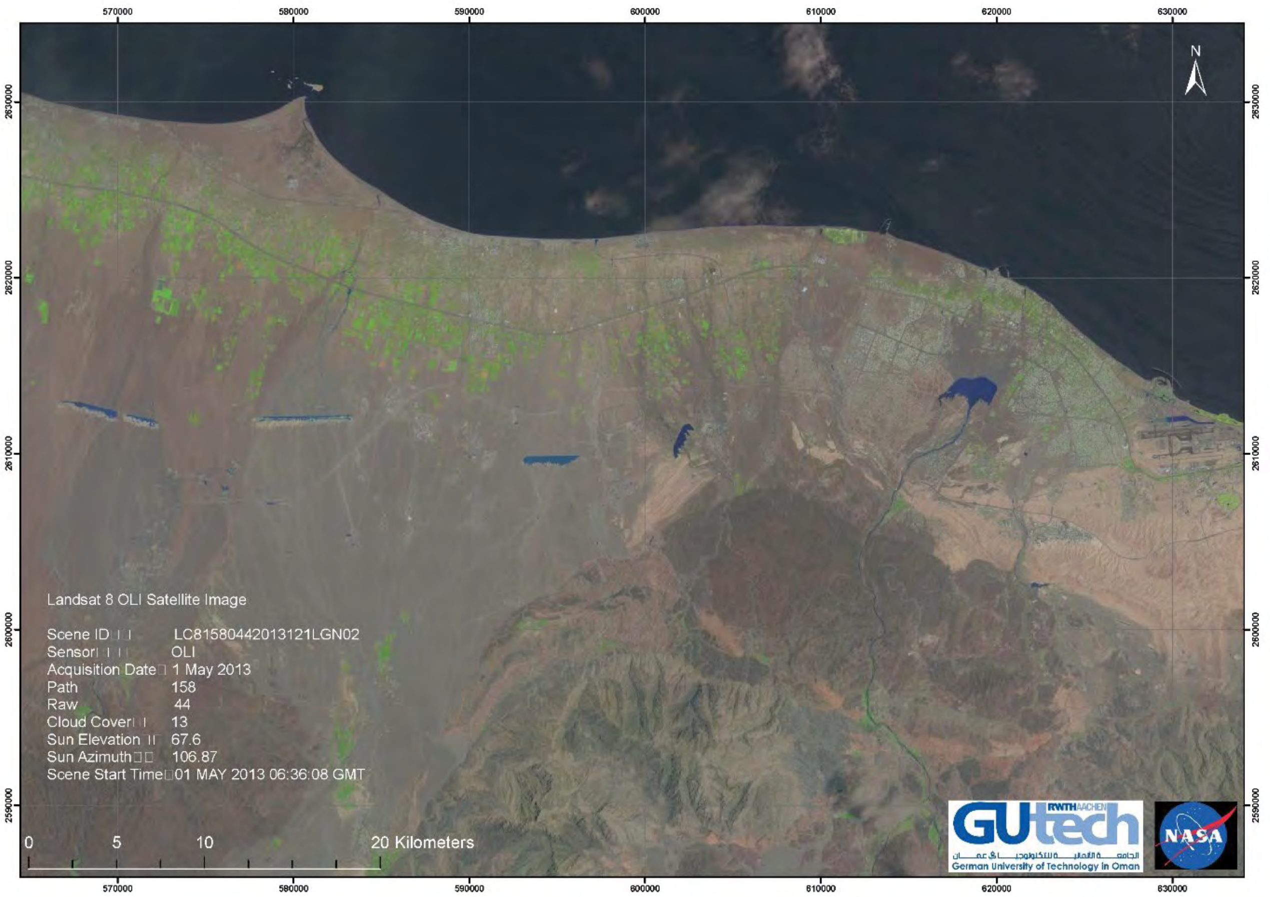

Fig. 1. Recharge dam in South Batinah, Oman. Landsat 8 OLI satellite image acquired 1 May 2013.

Samail Ophiolite is underlining the tertiary (Chitrakar and Sana, 2015).

Major lithology of quaternary deposits is heterogenic. Clastics with grain size ranging from boulders to silt includes khabra deposits. These are the finest-grained materials accumulated in a vast khabra extending parallel to the coast on the northern side of the Batinah plain. Dune and sand sheets are the best outcrops supporting rainfall infiltration (Bechennec et al., 1986). Anyway, it is not clear if such infiltrated water is recharging the aquifer or not, because of the anisotropy of the unsaturated hydraulic conductivity in vertical and horizontal directions in sand dunes (Hendricks et al., 2003).

3. Hydrogeology of Al Batinah

The estimated hydraulic conductivity of the ancient alluvium ranges between 0.2 and 5 m/d while the sub-recent and recent alluvium show values between 5 and 30 m/d (Chitrakar and Sana, 2015). As an alluvium sediment, clay and silt lenses are sparsely distributed within the Quaternary deposits. These lenses might have restricted horizontal expansion and do support the perched aquifers (Hadidi, 2016).

It is only a small percentage of the rainfall events that take place near the coast (Seeb airport 80 mm/year), while most of the events occur over Northern Oman mountains (330 mm/year) (Kwarteng et al., 2009; Ahmed and Askri, 2016). Due to rapid development associated with increased ground water consumption, sea water intrusion affected wide area next to the Batinah coast (Figs. 2 and 3; Ahmed and Askri, 2016; Al-Awadhi and Mansour, 2015).

4. Methodology

Our data-set consists of water table measurements in 29 water wells in Maawil catchment over the last few decades (Table 1; Fig. 4). The time series was analyzed using the programming language R, a well-established free software environment for statistical computing.

For each time series, the pre-analysis process began with importing the database into R and transforming the original database into a data frame consisting of time and piezometric variables. Then a Tibble object was created that was useful for analysis through the "anomalize" package of R (Dancho and Vaughan, 2018).

After this, the time series data are decomposed into observed, seasonal, trend and remainder components with the anomalize package. Once the components are decomposed, anomalize can detect and flag anomalies in the decomposed data of the reminder component which then are visualized. The method was chosen in order to identify extreme events.

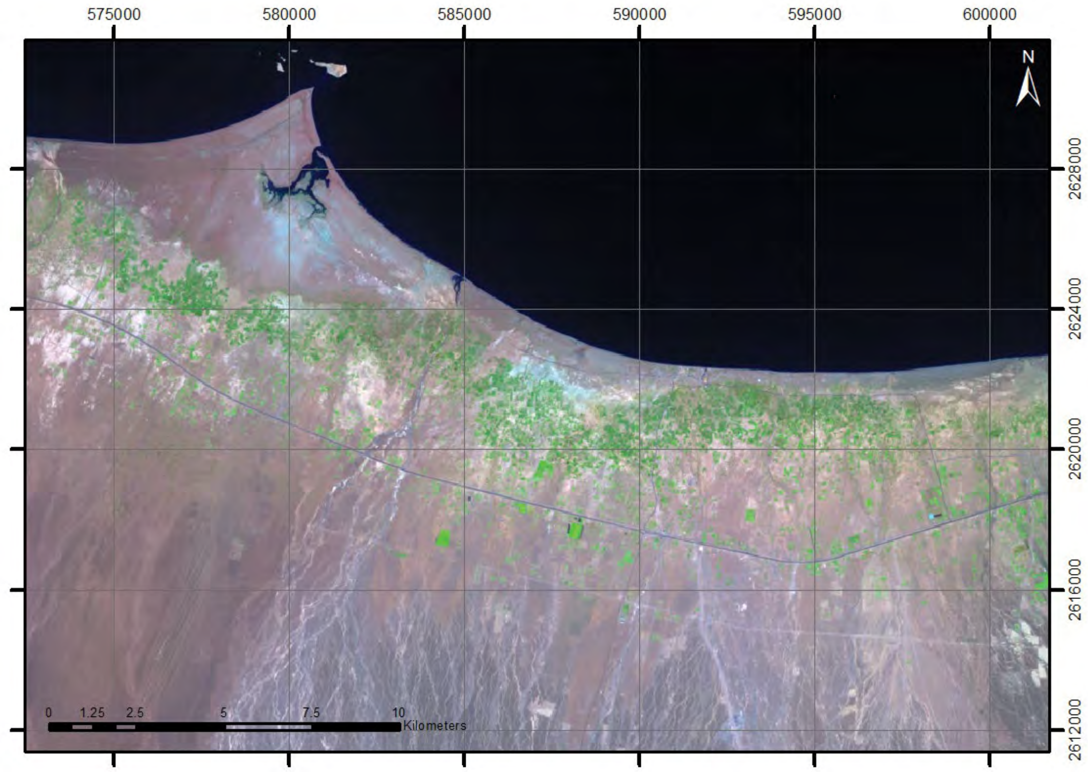

Fig. 2. Landsat satellite imagery for South Al Batinah plain, 23.05.1986.

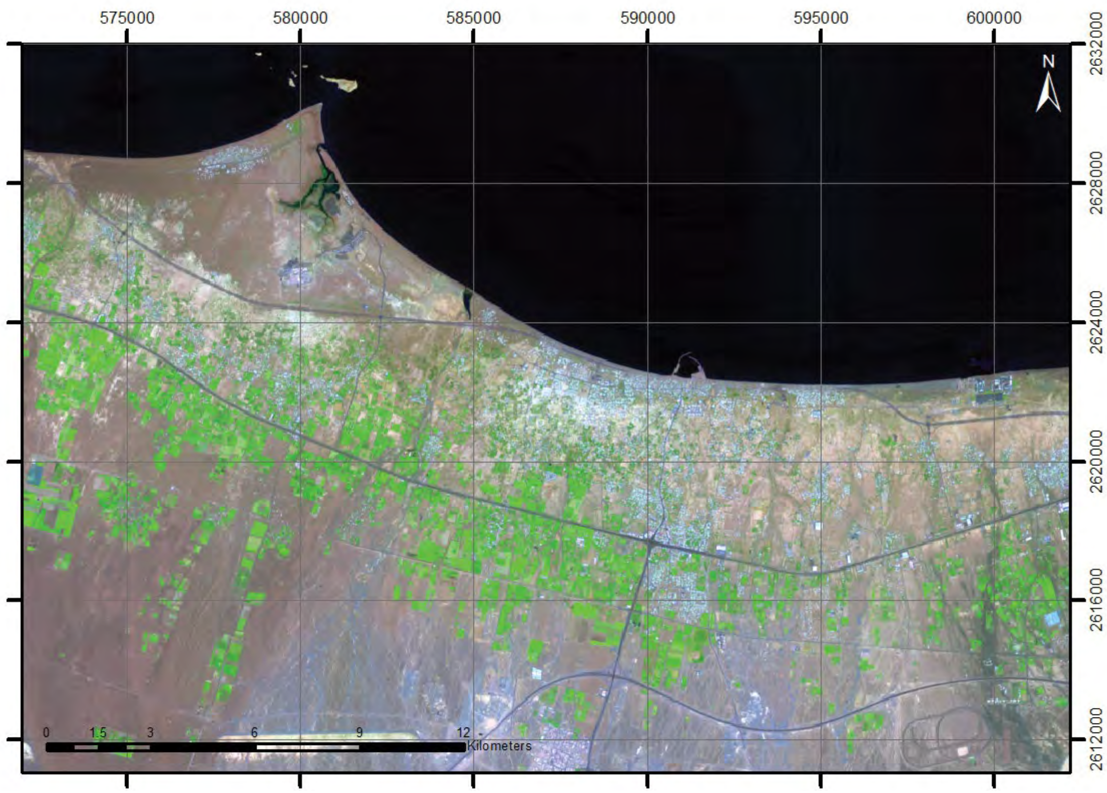

Fig. 3. Landsat satellite imagery for South Al Batinah plain, 10.04.2017.

Table 1
List of the wells and basic data

Well	Start observation		Start w.t.[a] (m)	End observation		End w.t.[a] (m)	Date to fall below NN	Number of outliers
	Month	Year		Month	Year			
21-2D	03	1993	78.71	10	2016	82.52	–	24
21-3D	04	1993	59.96	10	2016	66.76	24/09/2005	5
ADG17	07	1973	15.95	02	2018	24.54	14/04/1984	3
ADG23	05	1973	13.21	01	2015	25.98	21/01/1984	4
ADW7	01	1976	26.33	03	2018	34.14	04/10/1986	2
BM1	01	1984	4.64	02	2018	9.47	b.o.[b]	13
BM3	04	1984	22.56	03	2018	33.93	07/06/1992	5
DW4	12	1975	12.63	02	2018	25.36	29/06/1987	2
JT5	06	1973	51.05	03	2018	59.88	07/06/1992	9
JT10	04	1973	42.14	03	2018	54.71	16/09/2002	10
JT70	02	1974	2.66	08	2013	9.66	19/06/1982	33
MD1	02	1989	23.88	03	2018	33.80	b.o.[b]	0
MD2	02	1989	28.28	03	2018	39.23	24/10/1992	3
MD3D	02	1989	59.36	01	2018	68.56	25/02/2001	6
MD3S	02	1989	59.29	01	2018	68.60	25/02/2001	11
MD4	02	1989	28.27	03	2018	39.24	15/11/1992	3
MD5	02	1989	59.09	01	2018	68.39	31/03/2001	9
MD6	04	1991	53.24	01	2018	62.66	28/02/1994	3
MD7	10	1991	53.84	01	2018	64.20	29/10/2001	2
MD8	12	1991	33.44	03	2018	42.88	17/01/1993	7
MD10	01	1996	15.55	02	2018	19.36	b.o.[b]	0
MD11	12	1993	19.39	02	2018	27.41	b.o.[b]	3
MD12	04	1996	12.01	02	2018	17.18	b.o.[b]	0
MD13	04	1996	25.37	03	2018	34.32	10/1999[c]	5
NC5	06	1984	15.73	02	2018	23.11	23/04/1986	3
NC6	06	1984	15.18	02	2018	27.20	04/09/1988	5
RE3P	10	1989	87.43	01	2018	95.52	28/10/2002	2
RE4	06	1985	44.40	03	2018	53.53	12/07/1993	7
RE4P	10	1989	45.88	03	2018	53.76	13/06/1993	13

[a]Water table below the ground surface.
[b]Before the starting of observations.
[c]Estimated date.

A time series $Y(t)$ is simply the chronological record of experimental observations of a variable. From this series of data, we want to extract information for the characterization of a given phenomenon under observation. One of the fundamental purposes of the classical analysis of the time series is to break down the series into its components, isolating them in order to study them better. The components of a time series are usually the following: trend, seasonality, error or residual. They can be linked together in an additive way:

$$Y(t) = T(t) + S(t) + E(t) \tag{1}$$

or multiplicative,

$$Y(t) = T(t) \times S(t) \times E(t) \tag{2}$$

The simplest approach to classical decomposition is based on the model:

$$Y(t) = f(t) + E(t) \tag{3}$$

where $f(t)$ is a time function that describes trends and seasonality in a simple way.

In particular, in the case of an additive type model, as in our case:

$$Y(t) = T(t) + S(t) + E(t) \tag{4}$$

where $E(t)$ is independent and identically distributed variables IID (the errors are normally distributed with average zero, constant variance and independent).

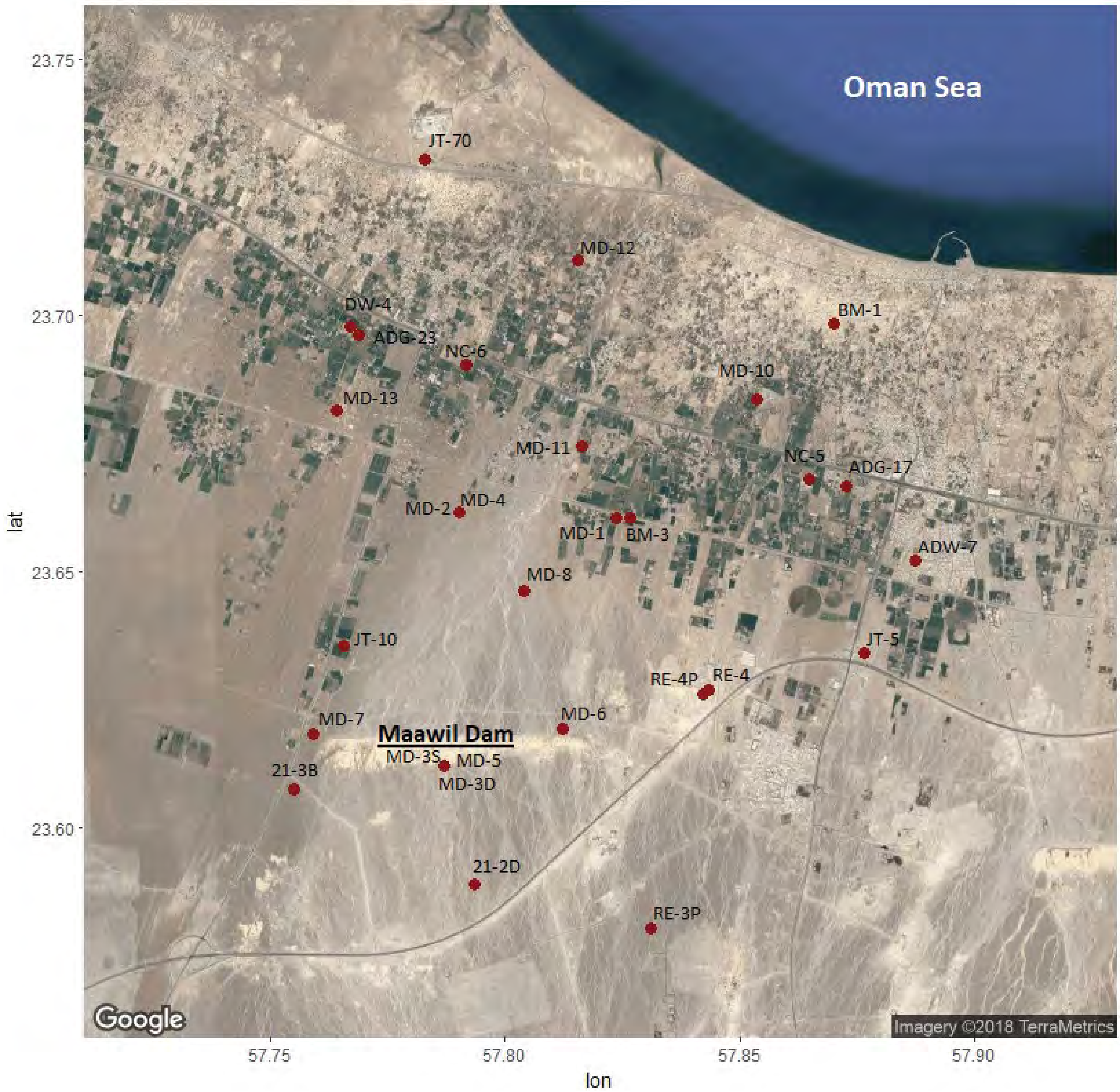

Fig. 4. Overview with observation wells location and Maawil recharge dam.

With R software, it is possible to determine and to extract the three components.

The function STL ("Seasonal decomposition of Time series by Loess") of R uses the method "loess" (local polynomial regression fitting) for the decomposition and applies locally weighted polynomial regressions at each point in the data set (Cleaveland, 1990).

The explanatory variables being the values closest to the point whose response are being estimated. Performs local regression over a sub set of data and repeats the process for the rest of the dataset.

The STL decomposition procedure was chosen because it has important advantages for extensive applications to a large number of time series.

The decomposition separates the "season" and "trend" components from the "observed" values leaving the "remainder" for anomaly detection. Using anomalize, the "IQR" method was chosen for anomaly detection. Anomalies are detected by using the inner quartile range (IQR) method. The IQR takes a distribution and uses the 25% and 75% IQR to establish the distribution of the remainder. Limits are set by default to a factor of 3X above and below the IQR, and any remainders beyond the limits are considered anomalies. The bandwidth control parameter alpha adjusts the 3X factor. Alpha was used with its default value of 0.05. The maximum number of anomalies was set to 20% of the sample.

At the end, the frequency parameter adjusts the "season" component that is removed from the "observed" values, and the trend parameter adjusts the trend window. Both are set in "auto", which predetermines the frequency and/or trend based on the scale of the time series. In the figures below, anomalies are highlighted by red colour.

5. Results

The time-series of groundwater tables of the observation wells owned of the Ministry of Regional Municipality and Water Resources in the downstream watershed of Wadi Maawil shows different characteristics over time. These trends can be classified into six different groups:

5.1. Group 1

JT-5, RE-3P and ADW-7 wells share the fact that they show gradual increase in water table between 1996 and 1998 by 2 m, while the general trend is decreasing (Fig. 5).

5.2. Group 2

This group of wells is located near Maawil dam and share the fact that they have a sudden change in water table during 2007. This group can be subdivided into two subgroups where the trends are more comparable: Group 2/A includes (MD-6 and MD-7), and Group 2/B includes (MD-3D, JT-10, MD-5 and MD3S; Fig. 6).

5.3. Group 3

It consists of ADG-17, NC-5, RE-4P and RE4 wells. They all have in common that their water tables slightly increase between 1996 and 1998, and they show a sudden change in water table (outlier) in 2007 (Fig. 7).

5.4. Group 4

The general trend of this group is the linear decrease in water table over the last three decades and there is no sudden change in trend and there are no outliers. It also can be subdivided into two groups were the trend is more compatible: Group 4/A includes (MD-12 and MD-10), and Group 4/B includes (BM-1, MD-13 and NC-6; Fig. 8).

5.5. Group 5

It shows similarity to Group 4 but there is a stronger decrease in the trend of water table. It includes ADG-23, MD-4, MD-2, DW-4, MD-1, BM-3 and MD-8 (Fig. 9).

5.6. Group 6

This group includes all the wells where no distinguish trend has been comparable to the others. However, they all show decreasing in the groundwater table. This group includes: JT-70, 21-2D, 21-3D and BM-1 (Fig. 10).

6. Discussion

6.1. Group 1

This group of wells is located in dunes and sand sheet according to the geological map. Also, there are no important Wadi routes according to the topographical map. Such type of well are affected to a bigger extent by local rainfall events, and to smaller extent by Wadi runoff which might result from upstream rainfall in the mountain. So, the rainfall event of 1998 affected the water table more than the 2007 and 2010 events (Fig. 11).

6.2. Group 2

This group of wells is located nearby Maawil dam which was constructed by 1991. This group is strongly affected by the 2007 event. 2010 event did not make important impacts

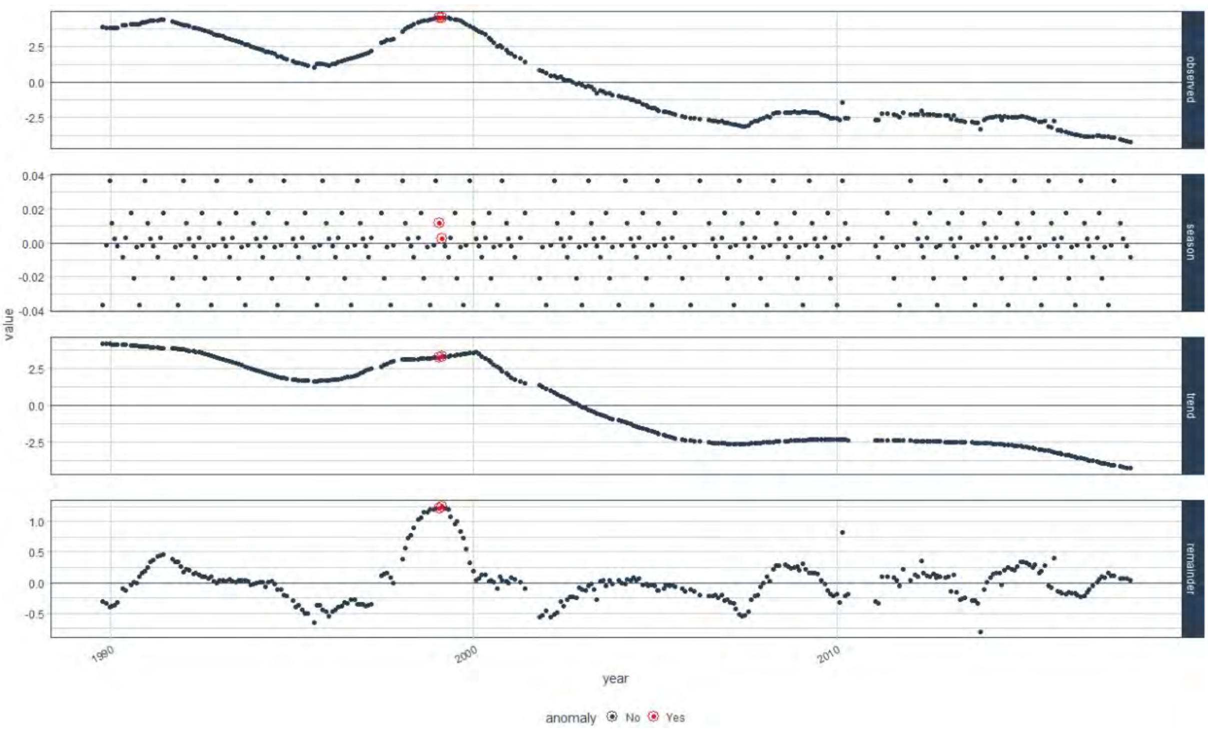

Fig. 5. RE-3P water well time series analysis. An example of group 1 trend.

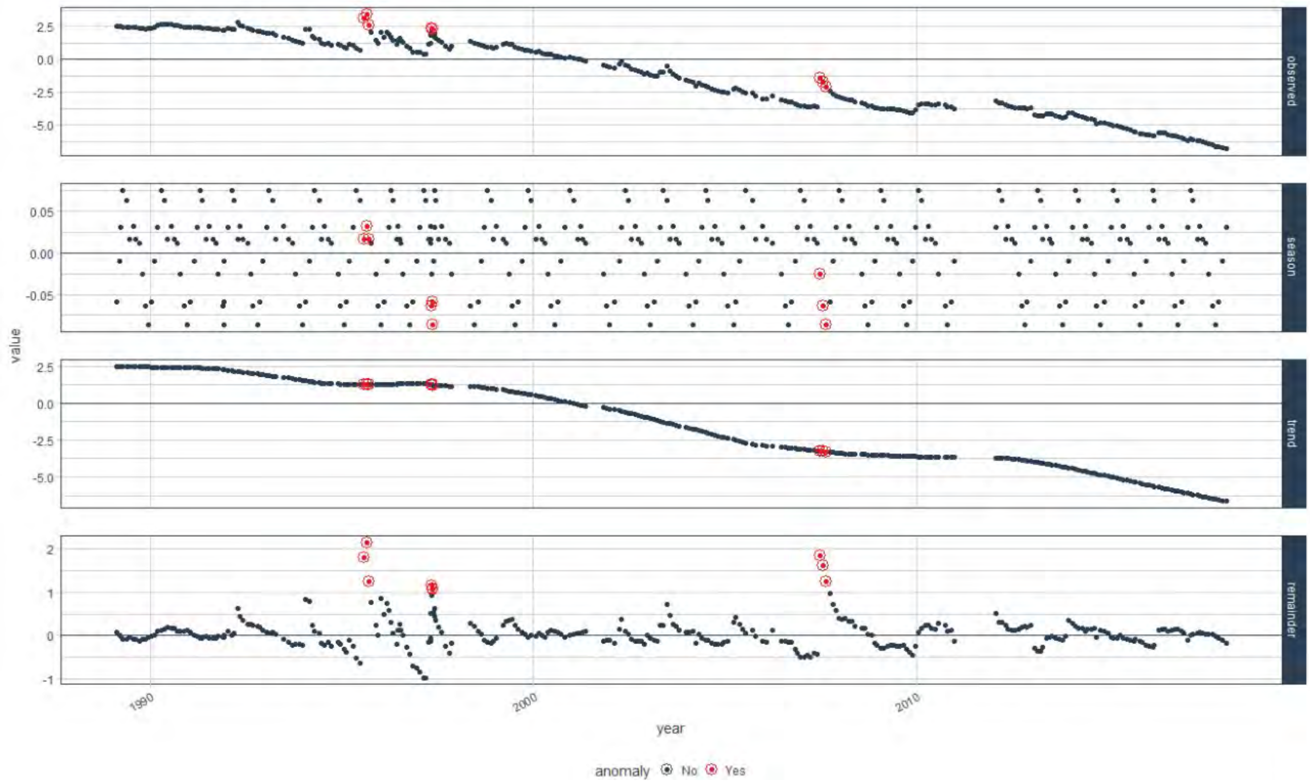

Fig. 6. MD5 water well time series analysis. An example of group 2 trend.

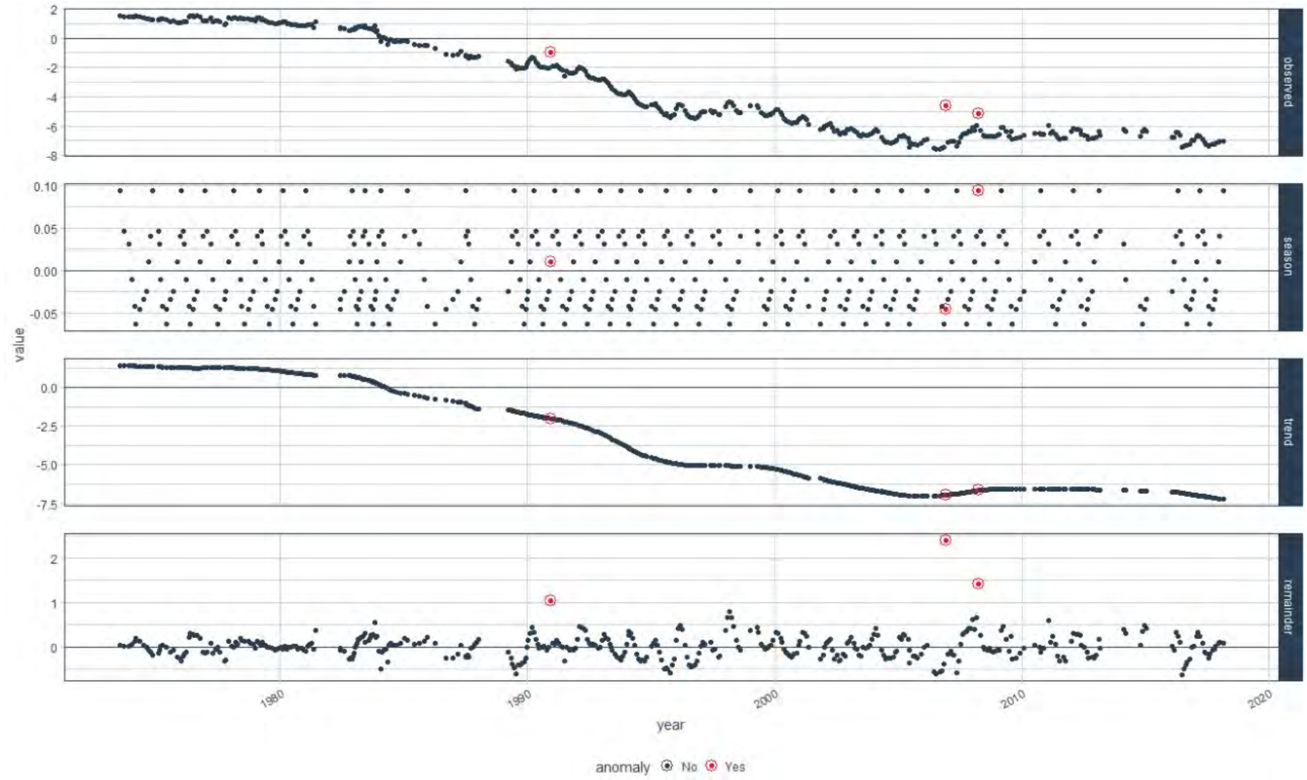

Fig. 7. ADG17 water well time series analysis. An example of group 3 trend.

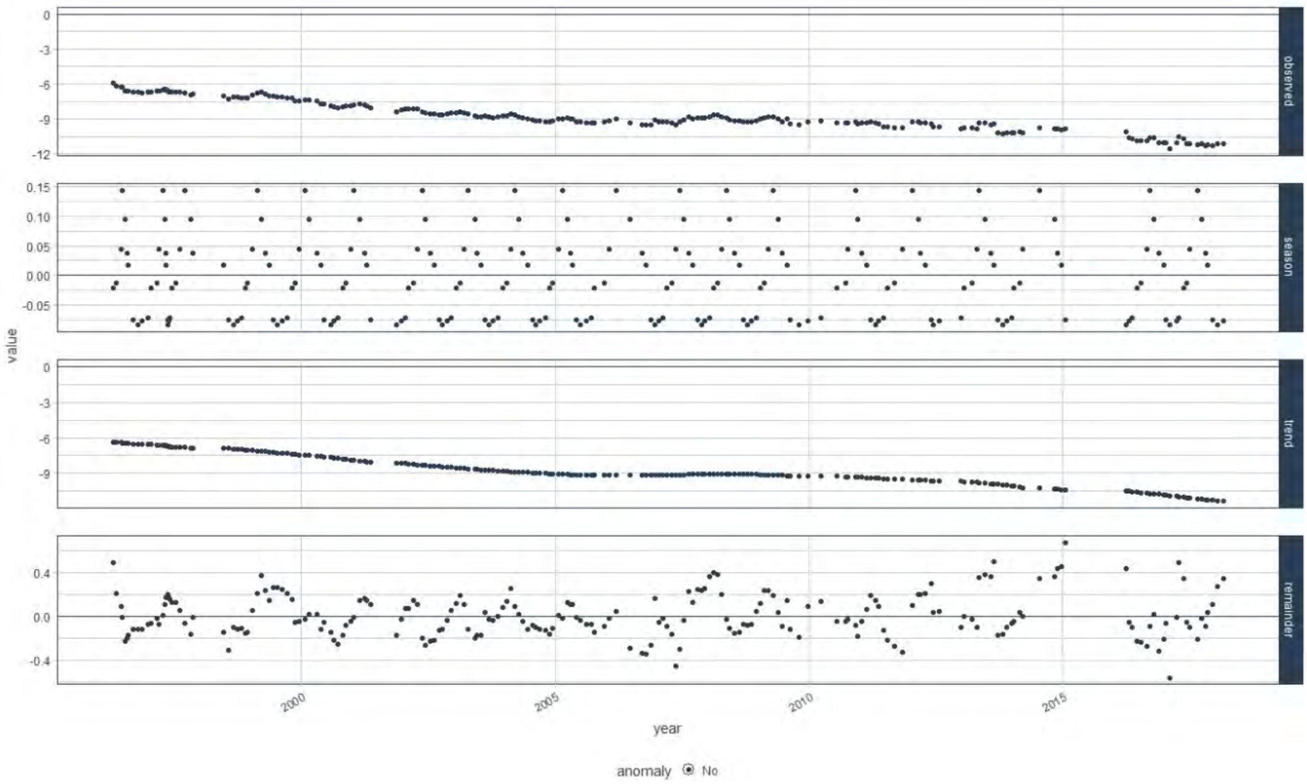

Fig. 8. MD12 water well time series analysis. An example of group 4 trend.

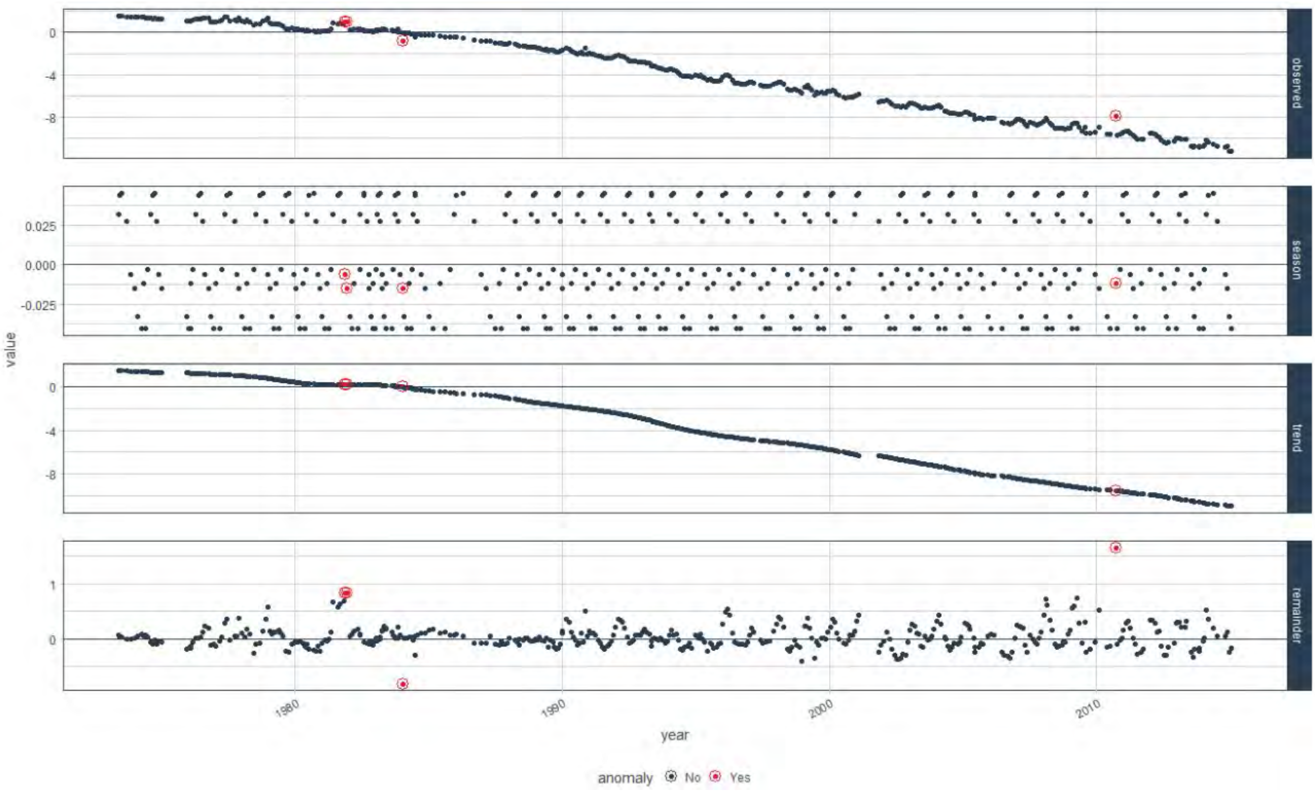

Fig. 9. ADG23 water well time series analysis. An example of group 5 trend.

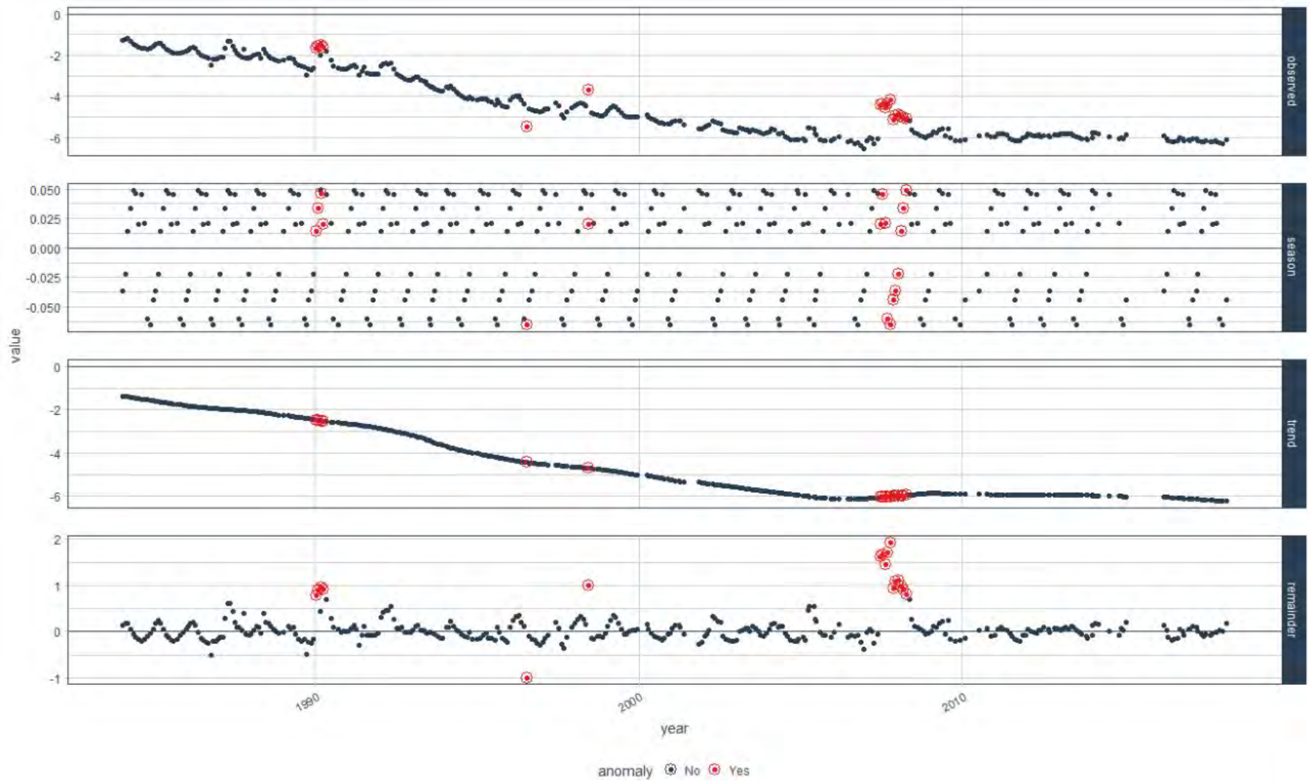

Fig. 10. BM-1 water well time series analysis. An example of group 6 trend.

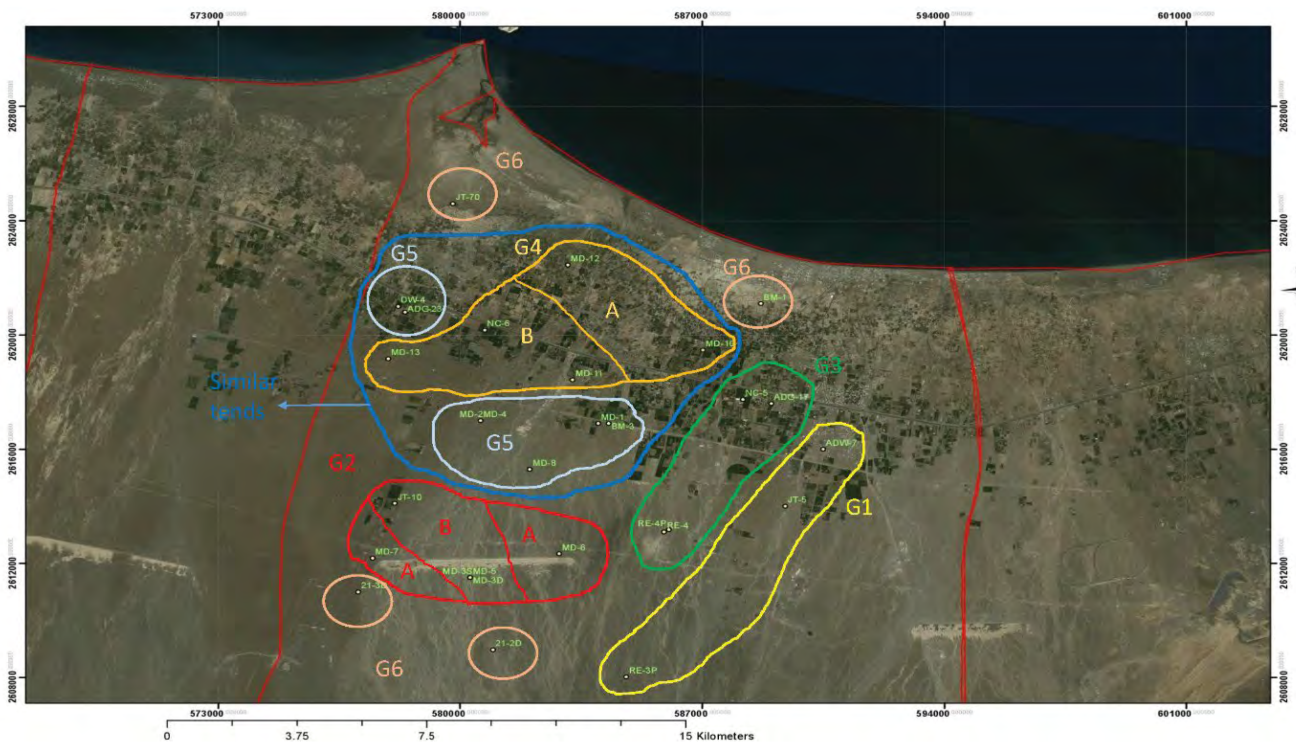

Fig. 11. Water well groups with similarity in trends. Group 1: yellow; Group 2: red; Group 3: green; Group 4: gold; Group 5: light blue; Group 6: rose.

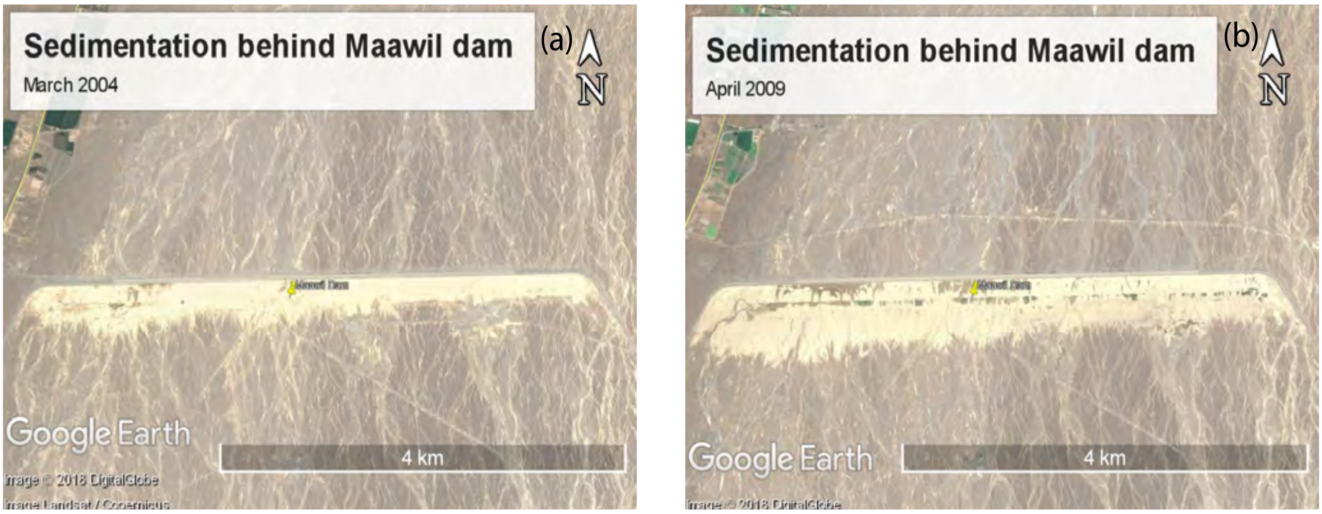

Fig. 12. Sedimentation behind Maawil dam on (a) March 2004 and (b) April 2009.

on the water table. Fig. 12 shows the difference in sedimentation accumulation before 2007 event (Guno), and before 2010 event (Phet). The wide accumulation of sediment with mismanagement of the dam valves during the flood events might cause such results.

6.3. Group 3

This group shows the impact of 2007 event but less than for Group 2, which is closer to the dam.

6.4. Group 4

This group is relatively closer to the saltwater/fresh water boundary, also it has water table close to the sea level. This situation makes the trend without abrupt changes, even that general trend shows linear decrease. The effect of infiltrated irrigation water might affect the water table as well, because it is close to the wider cultivated area. This group is located downstream of Maawil dam.

6.5. Group 5

This group shares similar trend with group 4. It is also located downstream of Maawil dam.

6.6. Group 6

These wells do not show any special trend. Two of the wells are located very close to the sea, and the other two are located upstream Maawil dam.

7. Conclusion

The approach used in this study can provide a quick and independent overview of groundwater trends by simple groundwater water table measurements. Despite the benefits of the proposed method and considering the structure of our dataset, we propose to evaluate this particular case by "time series forecasting method" in order to estimate towards where the system directs and show the usefulness of such methodology for decisions of public interest.

This work shows the possibility of making successful water-table-changes trend analysis of alluvial aquifer in arid region using statistical analysis. The interpretation of these trends for the Batinah region in Oman proves the following: (1) recharge dams with design used in Oman are effective on alluvial fans and it increase storage in the aquifer. (2) Integral management of recharge dam is necessary to improve its efficiency – this includes fine sediments removal: the sediments might be sold as soil enhancement. (3) Local rainfall affects the aquifers where the outcrop is mostly sand dunes and sand sheets.

Acknowledgments

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Evaluation of the Nubian sandstone aquifer system (NSAS) in Al Kufra Oasis, Southeast Libya

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ABSTRACT

Groundwater resources, developed in the Nubian Sandstone Aquifer System (NSAS), in Al Kufra Oasis in Libya are becoming increasingly vulnerable due to increasing pressures to meet the demand of economic development. These activities are represented mainly by agriculture activities in addition to the inefficient water use by other consuming sectors. Their misuse and violations are a result of the country's political instability, in addition to the lack of effective legislation, policies, strategies, and law enforcement instruments in current Libyan water management practices. This research investigates, examines and brings to the fore the groundwater conditions in Al Kufra oasis in terms of water quantity and quality, and evaluates the current management practices of water resources.

Evaluation of groundwater resources in terms of quantity is made by analyzing depth to water level in 26 monitoring wells for the period from 2005 to 2015, which showed average drawdown value of about 5.54 m during 10 years in the urban area and the agriculture projects areas. In terms of water quality, water samples were collected from 16 water wells, and chemical analysis was conducted for the determination of concentration of major anions and cations. The result showed increase in the value of total dissolved solids in the urban area and the agriculture project areas, which can be interpreted as the result of the increase in the amount of water extraction or the contamination by urban activities. Groundwater classification by Piper diagram and Wilcox diagram indicated that water is still suitable for agricultural purposes. Evaluation of the water resources management practices was undertaken through a survey examining the efficacy of water institutions relative to institutional framework, functions, activities, and their influence in the current management. The results indicate that current inadequacy of water management is due to many reasons, including centralized planning and financing, limited financial resources, overlap of water institutions, lack of stakeholders' participation, lack of coordination, and organizational instability. It is clear that the current water challenge is a managerial rather than a technical one. A comprehensive reform of the water sector is needed, based on the following recommended set of actions: institutional integration and engagement of stakeholders; evaluation of the current status of the NSAS beneath the main oases in terms of groundwater quality and quantity assessment of the environmental impacts of different water uses on NSAS; and, assessment of socioeconomic conditions for the oases, and their direct and indirect relationship to the ecosystem.

Keywords: Groundwater; IWRM; Transboundary aquifer

1. Introduction

The majority of the Libyan land is categorized as arid to hyper-arid. About 90% of the land is desert characterized by low rainfall rates, diurnal temperature variations, poor soils, and seasonal winds. Groundwater accounts for 97% of total water abstracted for different uses. The available figures indicate that the county's total water abstraction is about 6.5 billion cubic meters per year (GWA, 2006) and (NWRE, 2017).The dependence on the Nubian Sandstone Aquifer System (NSAS) mostly occurs in the middle and eastern parts of the country, while other regions of the country depend on other groundwater basins. Many settlements are dependent on for The NSAS for domestic water purposes and for irrigation in agriculture projects which provide crops to the residents in the NSAS area

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as well as the rest of Libya. The country's political conflict and uprising have led to a disruption of the water management system and to a difficulty in monitoring and managing water resources. This research discusses the current situation of the NSAS aquifer in Al Kufra Oasis. The NSAS (Fig. 1) is the world's largest known fossil water aquifer system. It is located in the eastern end of the Sahara Desert and spans the political boundaries of four countries in north-eastern Africa. The NSAS covers a land area spanning over 2.2 million km^2, including north-western Sudan with an extension of 376.000 km^2, north-eastern Chad with an extension of 235.000 km^2, south-eastern Libya with an extension of 760.000 km^2, and most of Egypt with approximately 80% and extension of 826.000 km^2 (Ahmed, 2013).

2. Geology of Al Kufra

Desio (1935) introduced the term Kufra/Al-Kufrah as the general name to all geological sequences, where the greater part composed of quartzitic sandstones, which form the area of Al-Kufrah group or series. The sediments of the Al-Kufra basin are mainly continental cross-bedded sandstone intercalated with argillaceous clays and shale (Klitzch, 1970) that corresponds to the "Nubian Sandstone" in the southeastern part of Libya. The Nubian sandstone of the Al Kufra basin has a maximum thickness of 900 m and includes mainly cross-bedded sandstone, intercalated with clays and shales. Table 1 illustrates the general stratigraphic geological succession of the Al Kufra basin (Salama and El Ebaidi, 2016)

3. Groundwater resources of Al Kufra

3.1. Aquifers

Two aquifer systems are known to exist in the Kufra basin; the as the Nubian sandstone aquifer; the lower is the Paleozoic aquifer system upper one is the Mesozoic (Triassic-Jurassic-Lower Cretaceous) known (Cambrian, Ordovician, Silurian and Devonian) (Bakhbakhi, 2010). The thickness of the Paleo-Mesozoic aquifers (Cambrian to Lower Cretaceous) exceed 3,000 m at the center of the Kufra basin and consists of continental sandstones with clay and shale intercalations. According to Jones (1969), Kufra Basin covers an area of 245,000 km^2, and an available resource from storage in the groundwater reservoir of the basin is in the order of 25,000 km^3 of good quality water.

The lower Mesozoic aquifer consisting of layers of loose sand, silt, and mud, with fewer sandstones and some other sedimentary rocks and divided into (Salem, 1996):

Shallow aquifer
Water level of this aquifer extends from depths of 5–60 m, where it does not exceed 60 m below ground surface and the total dissolved solids (TDS) ranges from 300–8,000 ppm.

Fig. 1. NSAS location map (IAEA, 2013).

Table 1
General sedimentological succession of the Kufra basin (Salama and El Ebaidi, 2016)

Age	Formations & approximate max. thickness (m)	Lithology & depositional environment
Recent/Pleistocene	100 m	Sandstone and Sabkha deposits
Lower Cretaceous	Nubian Sandstone (900 m)	x-bedded sandstone, shale and conglomerates
Carboniferous	800 m	Continental sandstones
Devonian	Tadrart Sandstones (100 m)	Massive, continental x-bedded sandstones with fossil plant marginal marine deposits
Silurian	Tanezzuft Shales Acacus Sandstones (90 m)	Sandstones, marine with fossils. dark shale and silty with fossils
Ordovician	Gargaf Group (700 m)	x-bedded sandstones with some silty shale (continental/marginal marine deposits
Pre-Cambrian	Basement	Folded metamorphic and granitic igneous rocks

Table 2
Type and number of crops (GAALMR, 2018)

Olive	Palm	Almond	Apple	Citrus fruits	Grape	Figs	Other types
446,279	1,484,990	3,797	5,060	18,509	163,604	37,733	139,385

Deep aquifer
Starts from a depth of 60 to 800 m; the TDS of this aquifer ranges from 300–4,500 ppm.

The high values of TDS in both aquifers are remarkable in some localities due to the existence of an old sabkah.

3.2. Current situation of the water use

The total abstraction from NSAS in Libya estimated at about 1,020.7 Mm^3 per year for all water uses (NWRE, 2017). The increase in freshwater demands for domestic, agricultural and industrial purposes corresponds to the increase in population. Currently, about 964,100 inhabitants living in 74 human settlements are dependent on the NSAS for domestic use and for agricultural production. The agriculture abstraction is estimated at about 504 Mm^3 per year, utilized in about 7,011 farms with different crops as provided in Tables 2–4. As for industrial use, the oil industry represents the main consumer which use water for oil production. The amount of water abstracted for industrial purposes is estimated from the available data at about 130 Mm^3 per year.

The water use for agricultural purposes in Al Kufra Oasis is the largest when compared with other uses, as shown in Table 5. The unaccounted for water in the water supply network is considered high, where remarkable frequent explosions noted in the main and secondary pipelines, due to the weakness of the current network. In addition,

Table 3
Type and production in tons for harvest (GAALMR, 2018)

Wheat	Barley	Cane	Animal feed	Beans
37,920	34,364	4,255	95,747	180

Table 4
Type and number of cattle (GAALMR, 2018)

Sheep	Goats	Camels
238,291	91,609	47,106

Table 5
Number of wells, pumping and towing rates for Kufra area (GAALMR, 2018)

Use	Project name	Abstraction Mm^3/ year	Aquifer	Depth (m)
Agriculture	Al Kufra production project	176	Deep	250–300
	Al Kufra settlement project	32	Deep	450
	Palm Project	33	Shallow	50–120
Domestic and Industrial	Private farms	75	Shallow	50–150
	Domestic and water bottling industry	26	Deep	250–450
Total		342		

most of the main and secondary pipelines are being violated when passing through private farms by illegal connections, as well as by several new residential neighborhoods which are built randomly out of the main urban plan and do not have public facilities.

3.2.1. Groundwater levels

The data of groundwater levels in Al Kufra region were collected from monitoring wells (Ahweej et al., 2017) as shown in Table 6 and mapped using geographical information system and superimposed by the main land use in the oasis, as illustrated in the Figs. 2 and 3. In the year 2005, the average depth to water level was about 17.55 m, with the lowest at 2.35 m at the southwestern part of the oasis, while in the urban and agriculture projects areas; the depth to water level reached 40.25 m. In 2015 the average water level was 23.07 m, where the lowest water level was 4.4 m at the southwestern part of the oasis, while in the urban and the agriculture projects areas water level depth reached 51.18 m. The drawdown in groundwater levels in Al Kufra area in 10 years is presented in Fig. 4 where the average drop of the water level is about 5.54 m, where it is noted that there is a significant decline in the water level at the urban area and Al Kufra agricultural production project, which recorded the highest value of drawdown, estimated at 15.2 m.

3.2.2. Groundwater quality

According to the results of the chemical analysis of water samples in the region (Table 7) (Ahweej et al., 2017), the total dissolved solids of the groundwater aquifer ranged from 172 to 900 ppm. The map of total dissolved salts (TDS) shows increasing values in urban area and the agriculture projects areas in comparison with other areas of the oasis (Fig. 5). There are two possible interpretations for this salinity increase. The first is that the increase in salinity

Table 6
Depth to water levels in monitoring wells

Well no	Water Level meter Year 2005	Water Level meter Year 2015	Drawdown meter
PZ-O4	13.54	18.72	5.18
PZ-6	25.86	36.74	10.88
PZ-8	2.35	14.14	11.79
PZ-O8	5.00	14.89	9.89
PZ-9	25.04	26.56	1.52
PZ-O9	30.28	29.96	0.32
PZ-11	6.59	21.68	15.09
PZ-13	35.98	51.18	15.20
PZ-14	29.62	35.19	5.57
PZ-15	17.80	29.31	11.51
PZ-16	32.10	42.19	10.09
PZ-17	6.30	13.32	7.02
PZ-18	12.88	23.61	10.73
PZ-19	10.80	12.19	1.39
PZ-25	10.82	13.06	2.24
PZ-26	22.22	25.85	3.63
PZ-28	28.31	29.84	1.53
PZ-30	19.85	21.05	1.20
PZ-32	22.64	24.85	2.21
PZ-33	40.25	41.00	0.75
PZ-35	3.77	4.40	0.63
PZ-37	13.54	16.50	2.96
2311	7.50	9.21	1.71
PZ-2232	8.97	10.87	1.90
PZ-2122	6.86	10.40	3.54
PZ-O4	13.54	18.72	5.18
Average	17.55	23.07	5.54
Minimum	2.35	4.40	0.32
Maximum	40.25	51.18	15.20

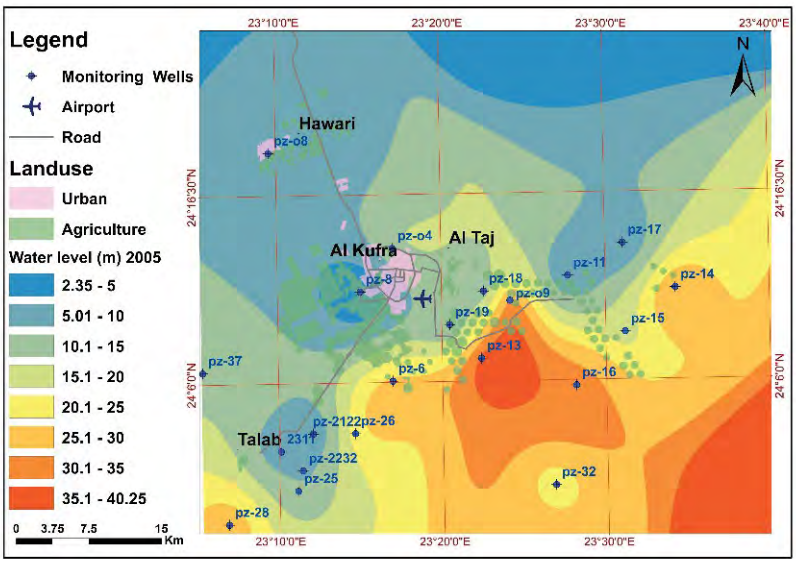

Fig. 2. Depth to water level map year 2005.

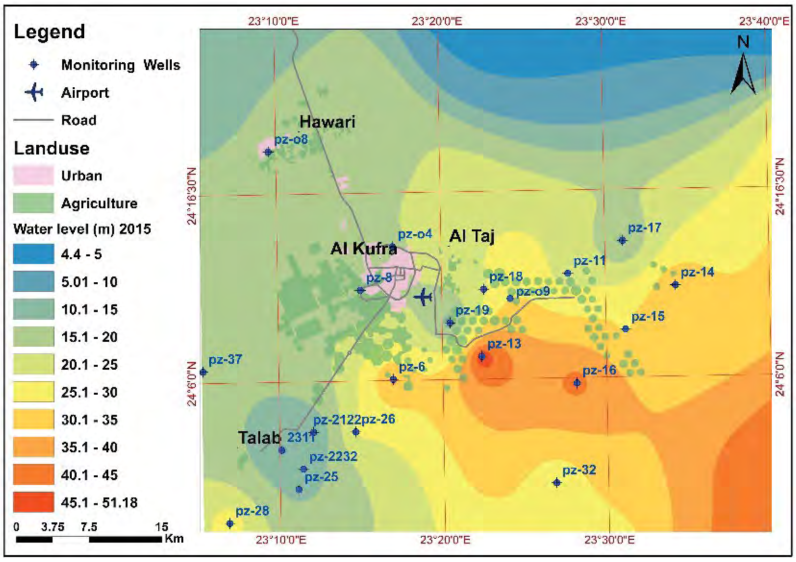

Fig. 3. Depth to water level map year 2015.

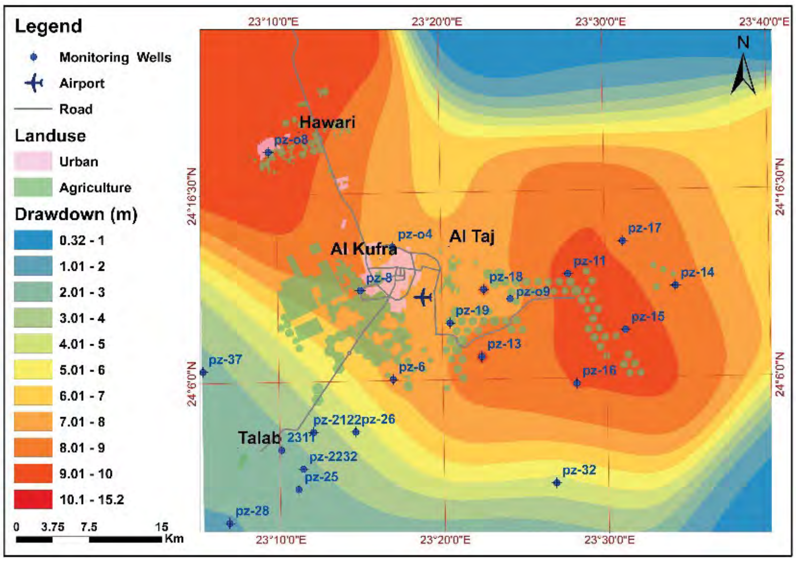

Fig. 4. Drawdown in groundwater level map.

is due to saltwater migration due to heavy abstraction, and the second is that increased salinity is a result of anthropogenic surface activities represented in irrigation return flow and wastewater return flows, where most of the city's neighborhoods and suburbs do not have sewage collection networks to groundwater. There are no major changes in the suitability of groundwater to agriculture Piper's and Wilcox diagram as illustrated in Figs. 6 and 7.

3.2.3. Groundwater management

Most of the government water institutions in Libya were established through decisions from the Ex-Ministerial Council. After the political change in 2011, the government in 2012 established the Ministry of Water Resource to be the highest water resources authority responsible in Libya to supervise and administrate all the water institutions. After two years, the Ministry of Water Resource' name was changed to the National Water Resources Establishment with the same tasks. Water institutions were characterized by administrative instability, and overlaps in responsibilities, in addition to the centralized approach in the management.

The responsibilities and tasks of the water institutions in Al Kufra Oasis can be summarized as follows (WSP 2011; GCWW 2018; JA 2018):

- *The General Water Authority (GWA)*

Formed in 1972 and responsible mainly for ground water resources exploration, monitoring, supervision on the drilling of the water, and ground water regulation.

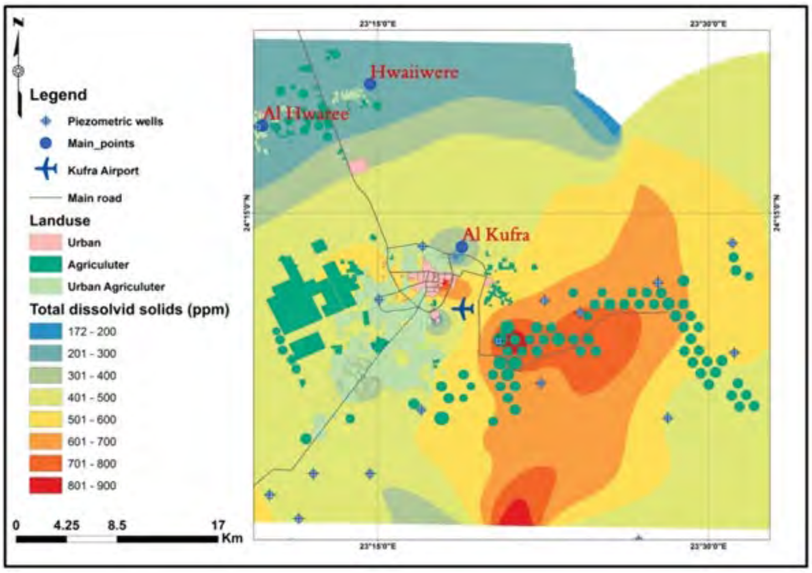

Fig. 5. Total dissolved solids map.

Table 7
Results of the chemical analysis of water samples

Well No	pH	TDS (ppm)	Bicarbonate mEq	Chloride mEq	Sulfate mEq	Calcium mEq	Magnesium mEq	Sodium mEq	Potassium mEq
1	6.8	387	0.7	2.1	1	1.2	0.7	1.74	0.16
2	6.78	387	0.7	2.2	1.21	1.3	0.9	1.74	0.17
3	6.83	172	0.7	0.7	0.52	0.7	0.4	0.7	0.12
4	6.84	660	0.8	5.1	1.63	1	1.3	5	0.23
5	6.78	823	0.7	6.6	2.5	1	1.5	6.52	0.78
6	6.87	612	0.7	3.9	2.47	1.2	1.7	3.91	0.26
7	6.98	537	0.6	3.4	2.07	1	1.6	3.26	0.21
8	6.94	365	0.6	2.1	1.18	1	1.1	1.61	0.17
9	7.08	704	0.6	5.4	1.78	1.3	1.2	5	0.28
10	7.17	237	0.7	1.3	0.74	1.1	0.5	1	0.14
11	7.1	211	0.7	0.5	1.22	1	0.5	0.82	0.1
12	7.1	260	0.7	1.2	0.88	0.7	0.6	1.3	0.18
13	6.99	233	0.65	1.2	0.86	0.7	0.6	1.22	0.19
14	7.07	401	1	2.1	0.92	1.3	0.9	1.65	0.17
15	7.04	512	0.8	3.3	1.64	0.9	0.9	3.69	0.25
16	6.96	343	0.7	1.9	0.85	1	0.8	1.48	0.17

- *The General Company for Water and Wastewater (GCWW)*

Established in 1996 and responsible mainly for water supply, construction, operation, maintenance of transmission, distribution networks, water pumping stations, and control centers, to ensure the provision of better services to the users of them. In addition to the construction, operation, and maintenance of drainage systems and related treatment plants, filtration, pumping, and monitoring.

- The Joint Authority for NSAS (JA)

An authority has been established in 1989 between the signed countries of Libya, Egypt, Sudan, and Chad under the name "Joint Authority for the Study and Development of the Nubian Sandstone Aquifer Waters" The Authority has been established to carry out the following objectives:

- Study, develop, and invest water resources in the Nubian Sandstone Aquifer System and strengthen the regional corporation between member states.
- Protection and maintenance thereof and nationalizing their use and harnessing them for searing the overall economic and social development.

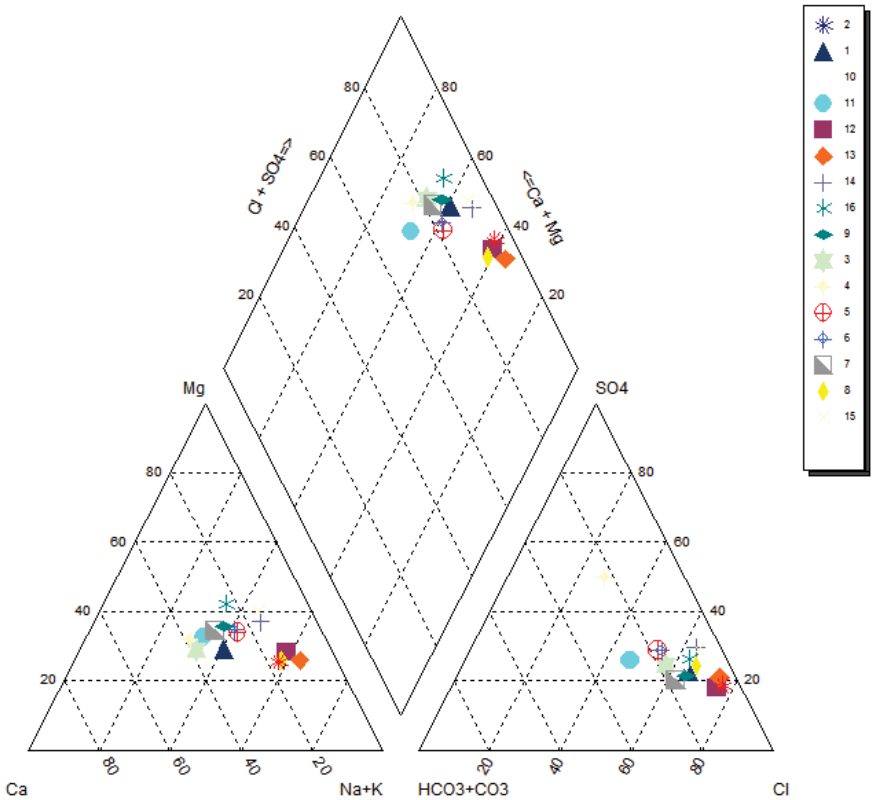

Fig. 6. Piper's diagram.

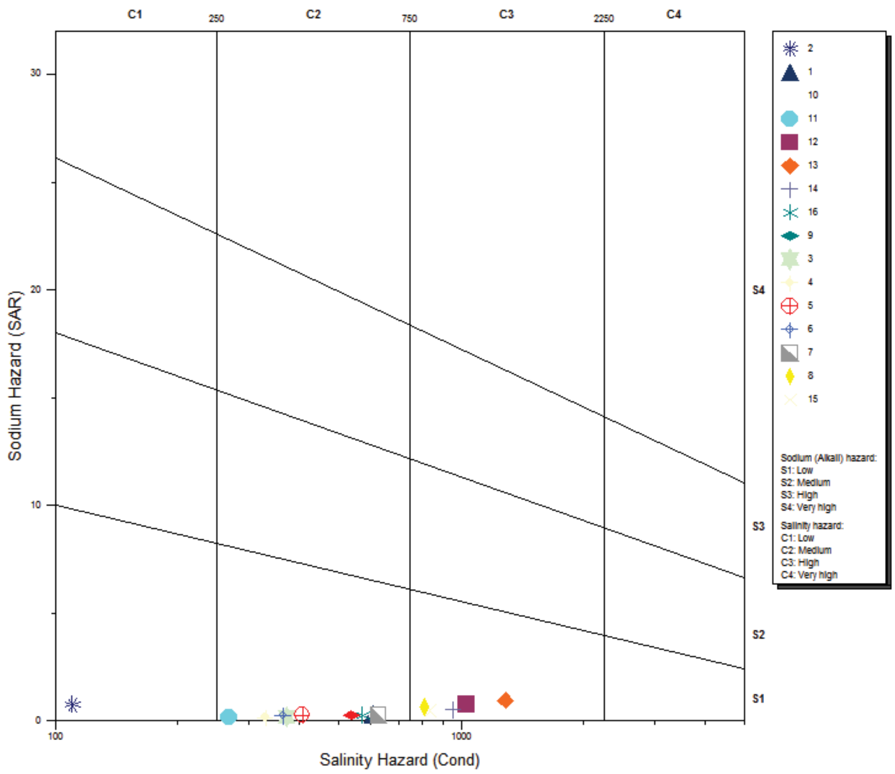

Fig. 7. Wilcox diagram.

- Development in the participant countries and the formulation of a regional strategic action plan for the sustainable utilization of the Nubian Sandstone Aquifer System and create a rule for the formulation of a regional development strategy.

These institutions suffer from the lack of highly qualified water professionals in the region, due to the public relatively low salaries, which limited income that the state paid, this has made most specialists to move to the private sector or to join other institutions outside the oasis. Furthermore, current institutions face multiplicity of mandates and conflict of interests, monopoly, in addition to inadequate enforcement of legislation and complete absence of law enforcement instruments, and lack of policies and strategies.

GCWW is the only institution largely operating and facing many challenges and difficulties, some of which are the problems of the old water networks and the explosion of transmission pipeline, and absence of sewage treatment, in addition to the violations of water utilities. However, the company suffers from the lack of adequate financial coverage to perform its tasks as required.

GWA introduced in 2006, policies and strategies concerning the delineations of risk areas for groundwater utilization, and unfortunately they did not put into practice due to the political circumstances of the country those also limits the monitoring and implementations Moreover, the GWA has a limited representation in the area in terms of the presence of specialists, offices, and laboratories to monitor and prepare hydrogeological studies, which is needed to raise awareness and ensure the implementations of the policies and the strategies in the region.

The JA is only linked to water governors and main water stakeholders at the national level in Libya. It needs to be linked with academia. The countries participating in the Commission shall bear the Commission›s budget in equal proportions for each of them. JA is needed to be reformed at the national by

- Increasing qualified staffing
- Enhancing monitoring system
- Upgrading the information systems, and support it with modern technologies
- Supporting national capacity building programs

Also, the JA needs more political support at the national level through organizing meetings, conferences, and workshops for demonstrating its activities at the national and regional levels to ensure the political commitment that will be the driver to financial support by the national government. Furthermore, there is a need for restructuring the JA in a way that allows the increase of experts and staff to ensure more geographical engagement for the areas of NSAS at the national level. Moreover, there is no participation of NGOs especially those specializing in water and environmental issues as well as the lack of water awareness activities Table 8 presents an inventory of the components of the enabling environmental indicators and institutional arrangement in the Al Kufrah Oasis.

4. Conclusion and recommendations

The NSAS is a valuable water resource in Libya, but it not managed properly and is associated with negative impacts, which might have dire consequences on the water security in the country. Currently, uncontrolled increasing water demands, driven by population growth and urbanization and agricultural activities, have led to water revels drop and quality degradation of the NSAS. Therefore, there is an urgent need for management interventions to stop this trend and ensure the sustainability of the aquifer in serving the socio-economic development needs of Libya. Moreover, assessment and analysis of the current institutional structure for water resources management in Al Kufra oasis indicate that the water challenge is probably a governance and management challenge rather than a technical one. The results of the assessment of the current water management system in Al Kufra Oasis can be summarized as follows:

- Centralized planning and financing and limited financial resources.
- Tasks overlap of water institutions, lack of coordination, and organizational instability.
- Inadequate institutional capacity at regional and local levels and limited experience in integrated water resource management (e.g., insufficient consideration of the socio-economic dimensions).
- Inadequate stakeholders participation.
- socio-economic dimensions are not involved in the current scheme of the management

Table 8
Enabling environmental indicators and institutional arrangement

Indicator	Unit	Year: 2018
Water resources policies based on IWRM principles	Yes/No	No
Water institutions	Number	3
Inter-institutional integration	Yes/No	No
Stakeholder participation	Yes/No	No
Existence of a supreme national authority	Yes/No	Yes
Application of laws to violators of the Water Law	Yes/No	No
Academies that provide training in the field of water in the region	Number	0
Awareness and water awareness activities per year	Number/YEAR	0

- Limited capacities in water management and lack of skilled labour to cope with future challenges.
- Lack of organized approach of awareness.
- limited monitoring system and lack of data quality.

These issues should be taken into consideration for the proper management of this precious resource. The following are the recommended actions that will need to be implemented in order to achieve an effective and sustainable water management system:

- Addressing issues that support institutional integration and engagement of stakeholders to enhance their cooperation in the field of water resources and ecosystem management. Thus, to ensure aspects of socio-economic aspects of engagement for future planning and assessment are scaled up relative to their direct and indirect relationship of the ecosystem.
- Evaluation of the current status of the NSAS beneath the main oases in terms of groundwater quality and quantity where the drawdown might have consequences which need to be investigated. Also, the salinity increase may be due to saltwater migration as a result of heavy abstraction or the increased salinity resultant from anthropogenic surface activities represented by irrigation return flow wastewater return flows since most of the city's neighbourhoods; and, suburbs that do not have sewage collection networks, necessitates the immediate implementation of a monitoring programme.
- Assessment of the environmental impacts resulting from differential water usage on NSAS and increasing knowledge about the ecosystem and its challenges. For example, the impact of the drawdown of the water level on the ecosystem of the oases can affect the growth of palm trees, and other desert species. The development of dry water bodies such as small sabkha, which leads to the migration of certain living species that thrive on them in addition to land subsidence resulting from groundwater obstruction.
- Investigating the institutionalization programme of capacity development and building to support the rational and equitable management of the NSAS.

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Assessment of the Groundwater at Ali Al-Garbi area, Iraq using Geochemical modeling and Environmental isotopes

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ABSTRACT

Geochemical modeling and environmental isotopes (deuterium, oxygen-18, and tritium) were used to determine the hydrogeochemical evolution and the main factors controlling the groundwater chemistry in Misaan, South of Iraq. Groundwater samples were collected and analyzed for major ions at 20 sites for two periods in 2016. Moreover, 6 rainfall samples were collected to determine local meteoric water line. The main water types are Ca-SO_4, which is the dominate type for two periods, while a few wells were (Na-SO_4) or (Mg-SO_4) dominate. All available $\delta^{18}O$ and δD data for the study area are plotted to the global meteoric water line (GMWL) and Local meteoric water line (AMWL). They indicated to the meteoric origin of all waters. They are exposed to evaporation before entering the aquifer. Using PHREEQC, Geochemical modeling was conducted to calculate mineral saturation indices for all water samples. These results show that dissolution of dolomite, gypsum, halite and siderite and precipitation of calcite, Sylvie and hematite are the main chemical reactions in the first period, whereas there are no specific reactions can be shown in the second period. Hydrogeochemical evolution of groundwater as modeled with NETPATH-WIN, the inverse geochemical modeling results showed that the main reaction controlling the groundwater quality is Dedolomitization process (dolomite dissolution driven by anhydrite dissolution and calcite precipitation).

Keywords: Geochemical modeling, Environmental isotopes, Groundwater geochemical evolution, Iraq.

1. Introduction

WATEQ4F program mainly calculates the saturation indices (S.I), which developed by Ball and Nordstrom (1991). PHREEQC V.3 2016 can be used to calculate saturation indices, ionic strength and the distribution of aqueous species; it was issued by Parkhurst (1995). One of the most programs applied widely in geochemical modeling is NETPATH software, developed by Plummer et al., (1991). Later, those models were upgraded in according development of computer systems. The natural isotopes (stable & unstable) contributes in many applications of hydrological, hydrogeological and geochemical sciences, which give evidence about of water sources, quality, and ages of water, in addition to recharge and movement of groundwater (Verhagen et al, 1992). The first studies on isotopes techniques in water were involved of precipitation and seawater. The first study was about survey on variations in concentration rate of ^{18}O, after that followed by a study about variation ^{2}H rate in natural waters, the variations of ^{18}O in global precipitation scale, involving a discussion in great detail on the meteorological patterns (Friedman, 1953; Dansgaard, 1960). Many hydrological studies use the stable isotopes (^{18}O, ^{2}H) to determine the origin, recharge mechanisms and hydraulic connection of water molecules in groundwater. Isotopes can be divided into two types (Peters et al, 2005) This study is the first work in Ali Al-Gharbi district that comprises geochemical evolution of groundwater and environmental isotope in this area, there are many studied, which are related to geology, geomorphology, hydrogeology and hydrogeochemistry of the groundwater or neighboring area.

The purpose of this study has been to use environmental isotope techniques and a geochemical modeling to make better studies and clear image for groundwater type in

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quaternary aquifer. This includes calculate Saturation index and ionic strength to determine geochemical evolution in quaternary deposits of study area, also determine chemical reaction dominate on groundwater in study area. Draw of the Amarah Meteoric Water Line (A.M.W.L) using stable isotopic technique (^{18}O & ^{2}H) in rainwater samples and linking it with the Global Meteoric Water Line (G.M.W.L). Identify the variation of isotopic content in water then determine age of groundwater by tritium ^{3}H. Locate the evaporation and origin of salinity in groundwater using stable isotopes ^{18}O.

2. Study area discretion

The study area is district that is called Ali Al-Gharbi and located in the northeastern of Missan province, the area of study about (760 km^2), (Fig. 1). The topography elevation ranges from (0–160 m). The surface is relatively flat in the central part of the area and bounded by Hemrin hills in the north-eastern near of the Iran. The surface elevations from north-east to south-west of the study area for district of Ali Al-Gharbi are decrease. The topographic elevation is derived from the Digital Elevation Model (DEM) produced by (USGS), (Fig. 2). The geological characteristics of study area are by the Rocks of uppermost Miocene and Pliocene are slope towards the Mesopotamian plain from the foothills along the Iraqi-Iranian border on the east. The rocks are buried under the Mesopotamian plain by thick layer deposits of Pleistocene and Holocene age (Buday and Jassim, 1987). The study area is covered with several sediments such as fluviatile, lacustrine, and Aeolian sediments of recent age (Barwary, 1993). The study area is Composed from different types of Quaternary deposits mainly sand and alluvium deposits of recent and sediment of Pleistocene sequence. The sediments characterized of Quaternary are finer grained and unconsolidated than the underlying Mukdadiya and Bai Hassan Formations (Bellen et al., 1959; Naqib, 1967; Al-Siddiki, 1978). Many deposits such as Alluvial fan, depression fill, sheet runoff deposits, and Aeolian deposits are the major units in the study area (Al-Jaburi, 2005). The tectonic setting of study area was the largest part is within of eastern most units the stable shelf (Mesopotamian Zone). The study area bounded in the north -east by the high folded zone that represented in the Hemrin hills (Khalaf et al., 1985 in Jassim and Goff, 2006; Bashu, 2002).

3. Hydrogeologic settings

Aquifer system in study area is subdivided into two aquifers: shallow aquifer (unconfined), deep aquifer (confined). These aquifers are separated by less permeable layers the hydraulic characteristics of which are unknown. The hydraulic connection between aquifer units is possible. Unconfined aquifer is shallow in nature. The sediments are sand (fine, medium) with little layer of silt and clay represents the main component of this unit and some of wells contain a gravel. Many dug wells in the study area penetrate this unit of aquifer and extract water; these Dug wells are with irregular diameters. Most of rainfall recharge goes to this part of aquifer; water quality is change depended on surface salt washing process. Confined aquifer is deep and found only in the eastern part of the area. This aquifer is limited extent in the study area and consists mainly of mixture of gravel and sand (sandy gravel), gravel and clay (clayey gravel) with significant amount of silt in some parts of the

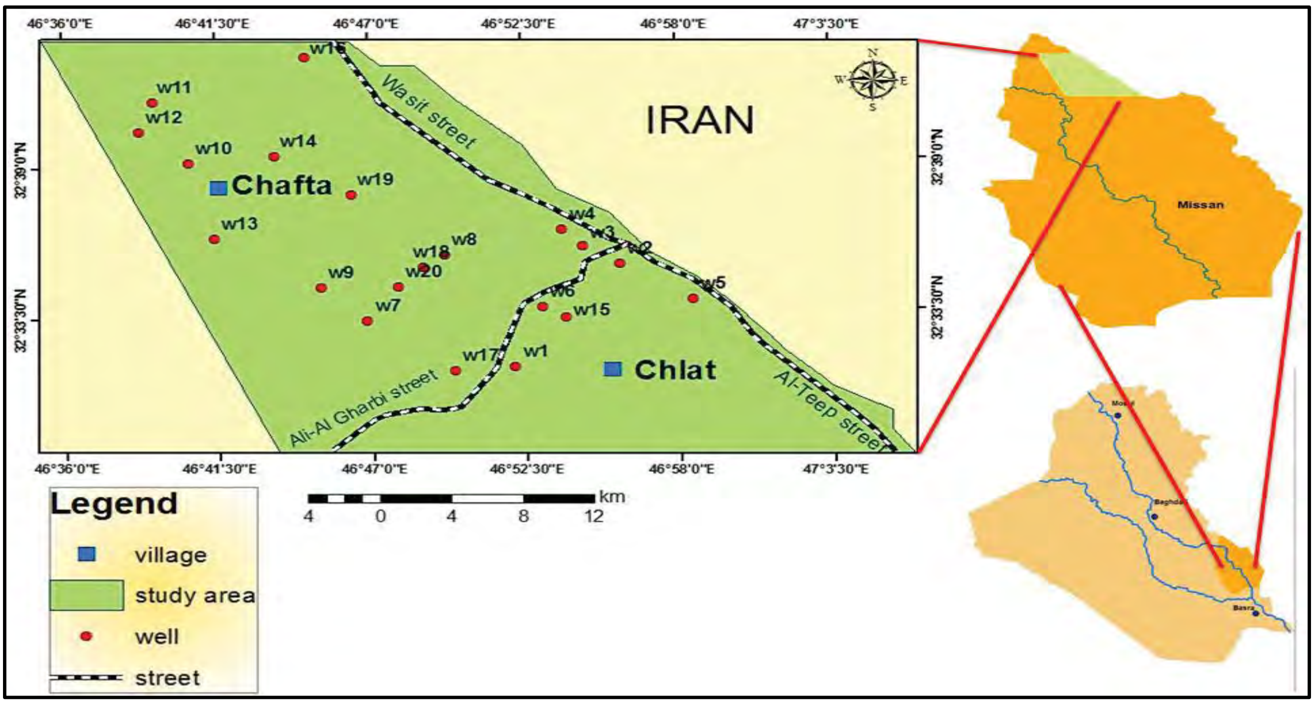

Fig. 1. Location Map of study area.

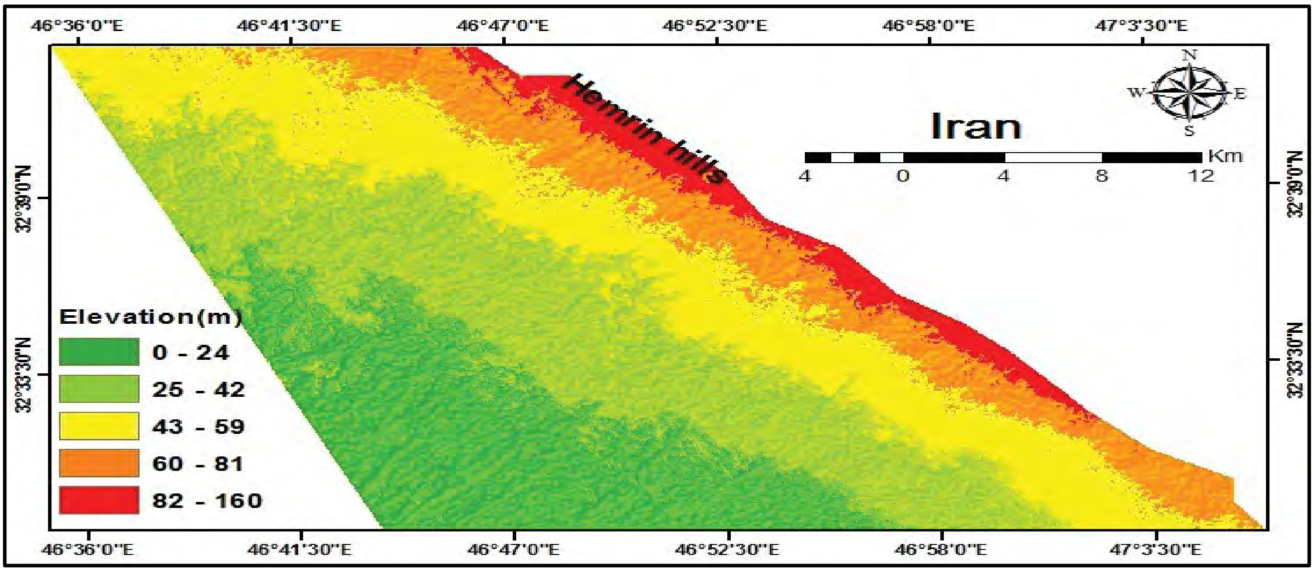

Fig. 2. Digital elevation's models of study area.

aquifer. Hydraulic conductivities values quaternary deposits in the study area are acquired from previous studies such as Al-Jaburi (2005). But no mention of the method used to get these values is given. The value of hydraulic conductivity for quaternary deposits between (0.5–5.3) m/day (Fig. 3). These values are less than other deposits, this may be because of.

4. Methodology

4.1. Hydrogeochemical modeling

Mass transfer along flow paths and geochemical reactions that control on water were modelled for (20) wells during two period of study area. The new software computer code, NETPATH, these soft were estimate any change in mass transfer between any waters bodies when equipollent constraints are placed on reactive phases of initial water and product phases of final water chemistry. Saturation index (S.I) is index used in hydrogeochemical studies. It indicates the saturation status of minerals in the groundwater system and then determines the rock type which is in contact with groundwater. It has been defined through equation. So, the minerals in the aqueous phase are equilibrium status, supersaturation or undersaturation based. We can calculate the ionic activity from equation, and after that calculate the activity coefficient (γ) by (Debye – Huckel) equation. The mineral saturation indices used to construct reaction models by PHREEQC V.3 (Parkhurst and Appelo, 2013). The Partial pressure of CO_2 is important

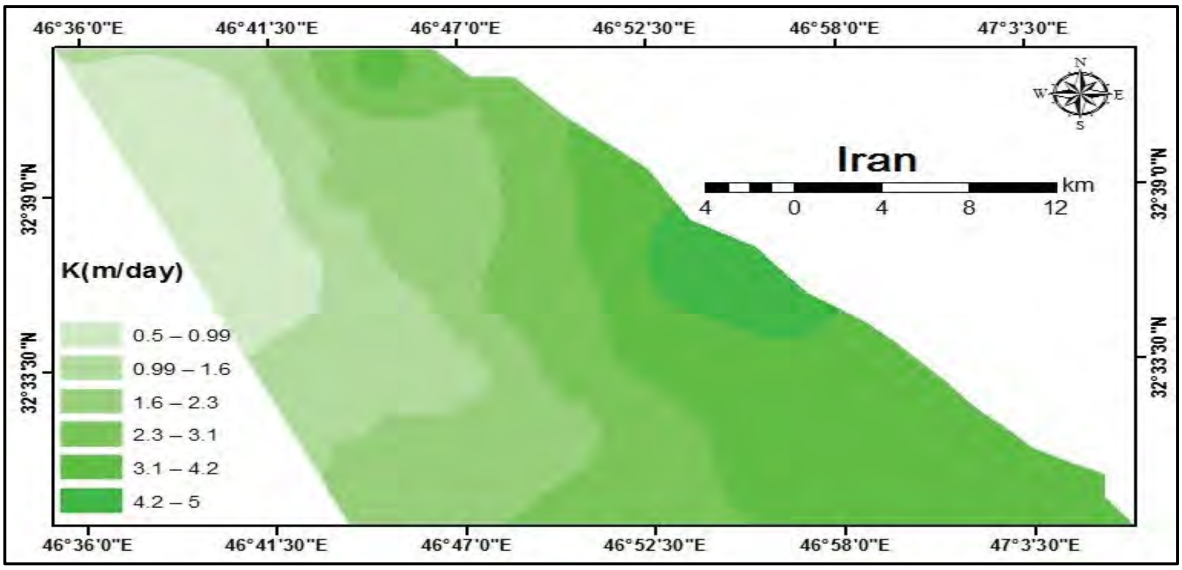

Fig. 3. Hydraulic conductivity of study area modify after Al-Jaburi (2005).

factor because it is control on chemistry system of natural water (carbonate – water). The reaction path models are based on the principle of mass balance transfer of chemical reactions needed for detailed calculations. One of the most important reaction flow paths for models is the evolutionary trend models along flow paths. These models provide important information on geochemical processes and (water-rock) interaction system. NETPATH uses chemical mass balance, (electron & isotope) mass balance equations with inverse geochemical modeling techniques (Plummer, 1984; Parkhurst and Plummer, 1993).

4.2. Isotope

Stable isotopes are a powerful research tool in geology and environmental science (Andrews, 2006; Basak et al., 2009; Barros et al., 2010). The interest of stable isotopes in groundwater is that the two isotopes should display identical chemical behavior in the environment. Slight variations in isotopic abundance are caused by small differences in reactivity of the different isotopes.

For stable isotopes (^{18}O, ^{2}H) of waters, the standard adopted is Vienna- Standard Mean Ocean Water (V-SMOW) (Clark and fritz, 1997; Cook and Herczeg, 1999; IAEA, 2006). δ (‰) is indicate to ratio of sample and a standard, when the sample is enriched in heavy isotopes, the values (δ) will be positives, while if the sample is depleted in heavy isotopes, the values (δ) will be negative.

In the present study, the isotopes (^{2}H, ^{18}O and T) content in water of studied area was evaluated by collected (10) groundwater samples and (6) samples for rainwater. All samples were analyzed at the laboratories of isotopes in Ministry of science and technology (Iraq).

5. Results and Discussion

5.1. Hydrogeochemical results

The reaction between groundwater and aquifer minerals plays a significant role in water quality, which is also useful in understanding the genesis of groundwater (Ghalib, 2017). Chemical analysis of groundwater for two periods measuring the concentrations of major caution whose (Ca^{+2}, Mg^{+2}, Na^{+}, K^{+}) and the concentration of major anion (Cl^{-}, SO_4^{2-}, NO_3^{-}, HCO_3^{-}), and measurement of total dissolved salts (TDS) by evaporation inside the electric oven, also measurement electrical conductivity (EC) Table 1. The chemical data of groundwater (20) samples are used to calculate the saturation indices. Carbonate minerals and sulphate are taken in consideration based on the major ion's contents in groundwater. Later, the reaction path model (mass transfer) is activated through selected lines flow path. Table 2 shows us the log PCO_2 for two periods. Log PCO_2 has range from (–1.18) to (–1.86) in dry period, while in wet period range from (–1) to (–2.48), this range of log PCO_2 is normal.

Ionic strength values give us important indicator to knowledge the behavior of solutions and solubility amount. The increase of values (Ionic strength) refers the total dissolved solid (TDS) increase; show us positive relationship between the ionic strength and the total dissolved solid. Also, it has positive relationship with the electrical conductivity (EC). The correlation coefficient between ionic strength and total dissolved solid (0.77) in the dry period and (0.85) in the wet period, this indicates a strong relationship between them (Fig. 4) as shown Table 2. Lower value appears in eastern part of study area for wells (w2, w3, w5) of confined aquifer, and increased value toward western part (discharge area).

The saturation indices of carbonate phases of groundwater in the study area are oversaturated during the wet period (w18, w20) for Calcite. It is found that the saturation S.I (Calcite) > S.I (Aragonite) > indices S.I (Dolomite) for two period. This is interpreted as due to dominant contents of Ca^{+2} in the lithological facies. Also, there is abundance of Mg^{+2} associated with Ca^{+2} to precipitate calcite in the groundwater phase. Gypsum values (S.I) are oversaturated found in all wells except (w2, w3, w5, w10, w14, w17, w20) for dry period, while found in wells (w1, w6, w7, w12, w13) for wet period, gypsum values (S.I) decrease because

Table 1
Statics chemical analysis for two periods of study area

		Dry period					Wet period		
Well NO.	Unit	Min.	Max.	Ave.	Stan. Dev.	Well NO.	Max.	Ave.	Sta. Dev.
EC	(μs/cm)	619	7,660	4,302.3	1,812.64	EC	4,938	3,287.9	1,298.12
TDS	mg/L	400	5,800	3,048	1,334.57	TDS	3,900	2,479.7	1,039.87
pH		6.2	6.7	6.4	0.14	pH	6.99	6.79	0.25353
T	(C°)	27	30	28.6	0.80	T	26.3	23.71	1.588
Na^{+}	mg/L	25	1,135	482.6	306.15	Na+	1,240	821.35	341.08
K^{+}	mg/L	3	52.5	16	13.08	K+	29	9.92	7.98
Ca^{+2}	mg/L	104	1,100	738.8	279.40	Ca^{+2}	960	601.76	253.67
Mg^{+2}	mg/L	10	550	298.8	156.82	Mg^{+2}	450	219.59	125.11
Cl^{-}	mg/L	70	1,372	934.6	389.38	Cl^{-}	1,180	818.53	355.3
SO_4^{-2}	mg/L	300	3,050	2,070.1	793.10	SO_4^{-2}	2,850	1,647.6	680.29
NO_3^{-}	mg/L	1.9	30.59	11.2	9.45	NO_3^{-}	27	10.54	9.29
HCO_3^{-}	mg/L	40	204	126.4	55.09	HCO_3^{-}	200	115.44	49.48
Fe^{+2}	mg/L	0.23	0.86	0.5	0.19	Fe^{+2}	0.73	0.44	0.178

Table 2
Ionic strength & Log PCO_2 for two periods

Well No.	Aquifer type	Dry period EC	TDS	Ionic strength	Log PCO_2	Wet period EC	TDS	Ionic strength	Log PCO_2
–	–	(µs/cm)	(mg/L)	–	–	(µs/cm)	(mg/L)	–	–
w1	unconfined	7,660	4,000	0.107	–1.233	4,240	3,800	0.085	–1.557
w2	confined	792	510	0.013	–1.542	787	400	0.013	–2.133
w3	confined	808	600	0.022	–1.48	1,020	700	0.02	–2.033
w4	confined	3,383	2,600	0.097	–1.588	2,870	2,400	0.086	–1.92
w5	confined	619	400	0.016	–1.586	610	500	0.015	–2.477
w6	unconfined	3,200	2,500	0.111	–1.512	2,730	2,100	0.091	–1.002
w7	unconfined	6,340	5,800	0.131	–1.18	4,450	3,900	0.12	–1.499
w8	unconfined	5,270	4,800	0.122	–1.644	3,800	3,100	0.097	–1.692
w9	unconfined	5,140	3,850	0.104	–1.197	–	–	–	–
w10	unconfined	4,340	3,100	0.118	–1.3	–	–	–	–
w11	unconfined	4,900	3,800	0.093	–1.339	–	–	–	–
w12	unconfined	4,467	3,900	0.11	–1.523	3,900	3,100	0.098	–1.873
w13	unconfined	5,790	3,700	0.118	–1.367	4,450	3,600	0.103	–1.764
w14	unconfined	5,130	4,120	0.097	–1.453	4,160	3,100	0.088	–1.852
w15	unconfined	4,443	2,466	0.088	–1.861	3,900	2,140	0.076	–2.351
w16	confined	3,383	2,600	0.103	–1.387	2,600	2,200	0.084	–2.076
w17	unconfined	5,620	3,242	0.091	–1.55	4,938	2,930	0.084	–2.317
w18	unconfined	4,170	3,000	0.098	–1.207	3,550	2,646	0.086	–1.703
w19	unconfined	4,740	2,871	0.094	–1.304	3,740	2,600	0.077	–1.726
w20	unconfined	5,850	3,100	0.093	–1.266	4,150	2,940	0.084	–1.694

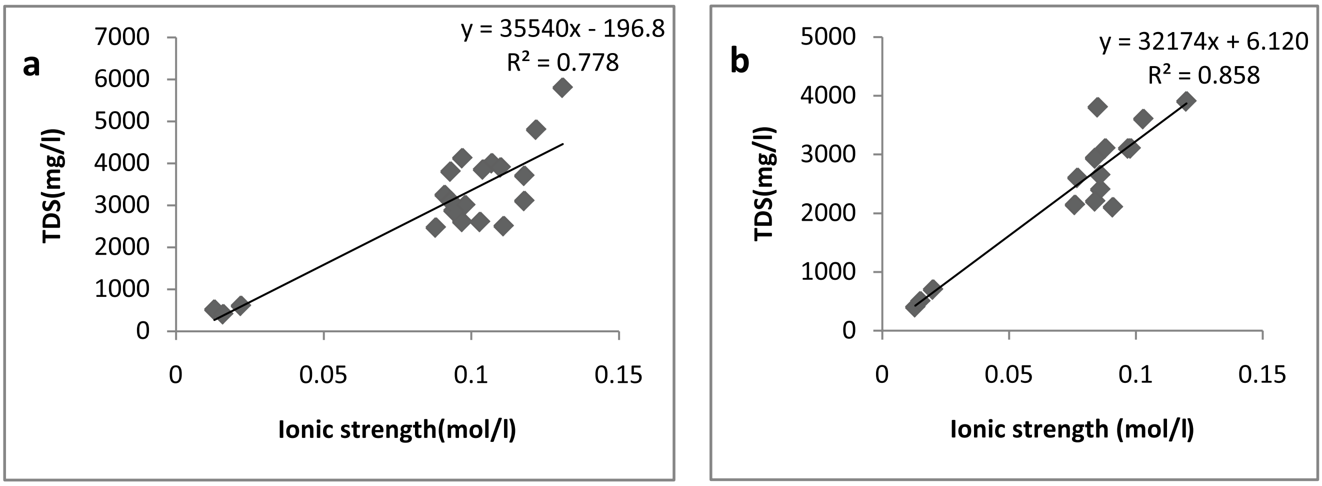

Fig. 4. TDS and ionic strength relationship for in the study area, (a) dry period and (b) wet period.

of amount of water recharge. Anhydrite values (S.I) are undersaturated in groundwater within dry and wet periods. Saturation indices of them are SI (Gypsum) >SI (Anhydrite), gypsum is dissolved more than anhydrite. Iron minerals are found in clay minerals. The deposition of these minerals in the study area is very high. The results of S.I. for hematite and goethite are high value which shows that the solutions are over saturation for both periods (dry and wet) in study area except (w8) in wet period because of amount of water recharge. Halite (NaCl) is found in many current evaporative deposits. The deposition of this minerals in the study area are very low, Table 3. The results of S.I for halite are low value which shows that the solutions are under saturation for both periods (dry and wet).

Carbonate minerals show us transient variations. That is, for dolomite, calcite and Aragonite there is an overall upward trend in PCO_2 values during the two periods, which indicates the deposition carbonate minerals with decrease

Table 3
Saturation index (S.I) for two period

Well No.	Calcite	Aragonite	Dolomite	Siderite	Gypsum	Anhydrite	Hematite	Goethite	Halite
Dry period									
w1	–0.44	–0.58	–1.08	–1.29	0.14	–0.07	5.29	1.42	–5.07
w2	–1.68	–1.83	–4.02	–2.08	–1.08	–1.29	4.03	0.87	–6.80
w3	–1.29	–1.43	–3.00	–1.61	–0.73	–0.93	5.07	1.24	–6.97
w4	–0.50	–0.64	–0.93	–1.50	0.04	–0.16	6.09	1.75	–5.32
w5	–1.72	–1.86	–3.34	–2.09	–1.07	–1.28	4.31	0.86	–6.92
w6	–0.42	–0.56	–0.90	–1.71	0.16	–0.04	5.53	1.40	–5.14
w7	–0.56	–0.70	–0.96	–1.47	0.07	–0.13	4.93	1.17	–4.61
w8	–0.41	–0.55	–0.99	–1.62	0.12	–0.09	6.06	1.81	–4.58
w9	–0.35	–0.49	–0.65	–1.32	0.05	–0.15	5.36	1.46	–5.02
w10	–0.31	–0.45	–0.38	–1.28	0.00	–0.21	5.85	1.70	–4.82
w11	–0.19	–0.33	–0.68	–1.34	0.20	0.00	5.81	1.68	–5.52
w12	–0.01	–0.15	0.06	–0.90	0.02	–0.18	7.45	2.50	–5.09
w13	–0.28	–0.42	–0.61	–1.10	0.08	–0.13	6.34	1.95	–4.69
w14	–0.38	–0.52	–0.56	–1.35	–0.14	–0.34	6.21	1.88	–4.86
w15	–1.00	–1.14	–2.33	–1.79	0.02	–0.18	5.85	1.63	–4.94
w16	–0.69	–0.83	–1.25	–1.69	0.02	–0.17	5.01	1.14	–5.19
w17	–0.98	–1.12	–2.29	–1.66	–0.06	–0.26	5.40	1.33	–4.76
w18	–0.29	–0.43	–0.74	–1.60	0.02	–0.18	4.92	1.17	–4.94
w19	–0.19	–0.33	–0.55	–1.40	0.02	–0.19	5.62	1.59	–5.07
w20	–0.20	–0.35	–0.29	–1.14	–0.12	–0.33	6.06	1.81	–5.25
Wet period									
w1	–0.24	–0.38	–0.99	–1.33	0.01	–0.21	6.24	2.02	–5.08
w2	–1.02	–1.16	–2.70	–1.82	–1.07	–1.29	6.88	2.36	–6.93
w3	–0.52	–0.66	–1.42	–1.53	–0.88	–1.11	7.08	2.68	–6.97
w4	–0.11	–0.25	–0.14	–1.15	–0.05	–0.27	7.94	2.89	–5.39
w5	–1.20	–1.34	–2.37	–1.34	–1.11	–1.33	8.51	3.32	–6.98
w6	–1.10	–1.25	–2.66	–2.33	0.08	–0.15	1.14	–0.10	–5.14
w7	–0.37	–0.51	–0.64	–1.35	0.06	–0.16	5.90	1.98	–4.73
w8	–0.36	–0.51	–0.94	–1.20	–0.04	–0.27	6.62	2.51	–4.73
w12	0.19	0.04	0.21	–0.76	0.03	–0.20	8.35	3.39	–5.13
w13	–0.03	–0.18	–0.16	–0.84	0.00	–0.23	7.78	3.09	–4.80
w14	–0.18	–0.33	–0.16	–0.78	–0.22	–0.45	8.40	3.27	–4.90
w15	–0.73	–0.87	–1.77	–1.42	–0.06	–0.29	7.81	3.05	–5.11
w16	–0.21	–0.36	–0.47	–1.06	–0.03	–0.26	8.05	3.24	–5.41
w17	–0.41	–0.55	–1.19	–1.06	–0.09	–0.32	8.88	3.51	–4.83
w18	0.04	–0.11	–0.05	–1.18	–0.10	–0.32	7.25	2.62	–5.00
w19	–0.23	–0.37	–0.47	–1.14	–0.16	–0.39	7.04	2.66	–5.17
w20	0.10	–0.04	0.29	–0.77	–0.16	–0.38	8.13	3.06	–5.29

of PCO_2. Sulphates minerals show us overall upward trend in PCO_2 values during the two periods.

The mass transfer of selected mineral phases (mmol/kg H_2O) for the existing flow paths is given in Table 4. Depending on chemical analyzes entered, mineral phases to determine chemical reaction along flow path of study area for two periods, has been getting two models for each flow path and chosen one model suitable with the chemical results and mineral phases. Flow path 1 shows different time evolution between dry and wet period, and the reaction products are calcite and dolomite. In wet period they are transformed form dolomite to calcite, and other minerals are soluble minerals. Calcite mineral sedimentation occurs three flow path, flow path 2 has similar to flow path 1 and, for two period calcite and sylvite precipitate along flow path. Flow paths 3 Show difference than other flow path,

Table 4
Mineral phases for each flow path

Mineral phases	Calcite	Dolomite	Halite	Sylvite	Gypsum	Hematite
Flow path No						
F1(dry)	5.13	–2.44	10.05	0.10	2.66	0.00
F1(wet)	–22.33	12.20	51.80	0.50	31.01	0.01
F2(dry)	–20.91	10.11	8.17	–0.26	9.31	0.00
F2(wet)	–17.97	8.69	5.33	–0.16	11.87	0.00
F3(dry)	–1.34	0.54	3.53	–0.01	1.13	0.00
F3(wet)	–2.70	1.30	8.63	0.14	4.12	0.00
F4(dry)	3.16	–1.90	–1.63	–0.07	–3.04	0.00
F4(wet)	3.05	–1.80	–1.26	–0.06	–2.79	0.00

calcite, sylvite and hematite precipitate in dry period while wet period dissolution all minerals just calcite precipitate. Flow path4 show only calcite precipitate and dissolution the remaining minerals. Generally, there is change in the calculated mass transfers of selected minerals, and we can be seen as a "characteristic reaction" that dominates the field.

5.2. Isotope results

Six rain water samples are collected during three month, December, 2015 and January, February 2016. The results for all isotopes are expressed in δ record as per mil deviation from internationally accepted standard V-SMOW (Vienna standard mean ocean water). The changes of δ^{18} O and δ^2H in rainwater throughout Iraq are due to rainfall intensity (amount effect) and are attributed to passage of air mass from the Mediterranean Sea. (Kattan, 1997). The results are reported in negative numbers because they are showing how much less ^{18}O isotopes are present compared to the ocean water. The low negative numbers indicate heavier water with a higher concentration of ^{18}O, whereas the high negative numbers signify lighter water where more of the ^{18}O has been precipitated out.

In Missan for district of Ali al Gharbi, δ^{18}O and δ^2H relationship for all the samples data during the observation periods of December, 2015 and January, February 2016, may define initial Amarah meteoric water line (AMWL) which fits with the relation below a regression line coefficient R^2 = 0.94 as shown in Fig. 5.

$$\delta D = 7.51\ \delta^{18}O + 10.82 \quad (1)$$

The equation defines the Local (Missan) Meteoric Water Line (LMWL). The slope of the line (7.51) is slightly different from the slope of GMWL (8) and interception (10.82), because of the varying climate conditions. The Slope (7.51) shows that no evaporation occurred during precipitation (Scholl, 2011). The slope of the regression line for the relationship between (δ^{18}O–δ^2H) in rainwater is <8, Fig. 5, which is the climate characteristic is a semi-arid (Geyh et al., 1998). The slope of the linear regression is less than the GMWL and (δ^{18}O and δ^2H) relationship provides a good characterization of air mass origin (Al-Charideh, 2011).

Many factors such as evaporation, condensation, and melting, freezing, chemical and biological process affect in heavy isotopes (Craig, 1961; Povinec et al, 2008; Al-Paruany, 2013). Generally, fresh water wells supply in study area is limited due to scarce precipitation, high evaporation and salinity. For evaluation the groundwater resource in the study area requires determination of origin of groundwater, water age, salinity, and interaction between the surface and groundwater, if found surface water in study area. Stable isotopes composition in groundwater samples in study area,

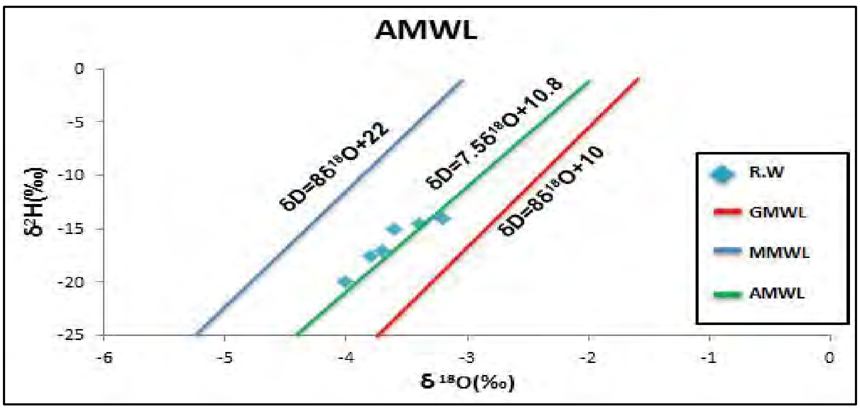

Fig. 5. LMWL for Missan (Ali Al-Gharbi) during the observation periods December 2015 and January, February 2016.

ranges from (–3.55 ‰) to (–2.19 ‰) $\delta^{18}O$ with the average (–3.01) in the dry period, and(–4.7 ‰) to (–2.22 ‰) $\delta^{18}O$ with the average (–3.35) in the wet period and from (–16.2 ‰) to (–8.23 ‰) $\delta^{2}H$ with the average (–12.54) in the dry period, while the ranges from (–19‰) to (–11.3 ‰) $\delta^{2}H$ with the average (–14.18) in the wet period.

The results of stable isotope in groundwater ($\delta^{18}O$, $\delta^{2}H$), that have proved the isotopes content in the groundwater samples have no remarkable trend of seasonal isotopes change. Also, the average values of ($\delta^{18}O$, $\delta^{2}H$) in groundwater of the study area are relatively low compared with rainwater samples. The variation in stable isotopes signature of water in study area is caused mainly by natural evaporation, change of stable isotopes content in rain water and mixing. Depended on distribution for all sample in two periods on $\delta^{2}H$ and $\delta^{18}O$ diagram, we have two groups in study area, Fig. 6. the first group (A) includes the wells (W2, W3), this well located in east part of study area (confined part). The stable isotopes composition in this group ranges from (–3.98) to (–4.7) for $\delta^{18}O$ with the average (–4.31) and from (–14.7) to (–21.2) for $\delta^{2}H$ with the average (–17.4). The second group (B) is represented mainly by the remaining wells, the isotopic concentration in this group ranges from (–3.23) to (–2.18) for $\delta^{18}O$ with the average (–2.74) and from (–12.9) to (–10.2) for $\delta^{2}H$ with the average (–11.81), this value are relatively low compared with that of the first group. According all above, we have two wells in group (A) belong in confined part and other wells in group (B), this indicates presence hydraulic connection and mixing processes between confined and unconfined part.

The relationship between ($\delta^{18}O$ /$\delta^{2}H$) in groundwater is plotted as seen in Fig. 11. the distribution of the samples of groundwater in the study area is located between the

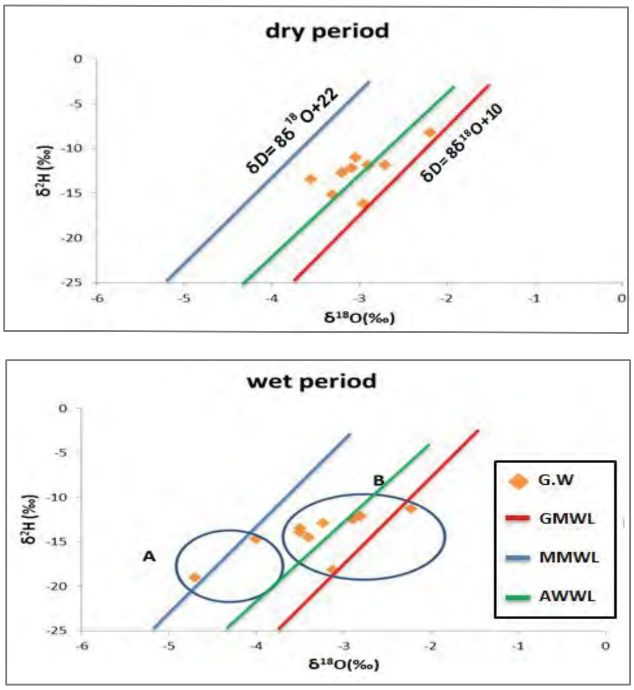

Fig. 6. diagram ($\delta^{2}H$–$\delta^{18}O$) of groundwater sample for study area.

GMWL and MMWL, which that the evaporation is not an influential factor this indicates that groundwater in this study, where recharge water comes from the precipitation. This suggested that stormwater rapidly infiltrates processes throughout quaternary sediment and the highly permeable deposits in the recharge areas. The variation in the isotopic composition in all points indicates that groundwater is affected by different degree of evaporation (Kattan, 2006; Ghalib, 2014). The groundwater in the Quaternary Sediments probably recharged from Mediterranean precipitation and continental water of meteoric origin. The stable isotope similarity between the two aquifers is probably related to the hydraulic interconnection between confined and unconfined aquifer. This indicates that Water from the confined aquifers is more depleted in the stable isotope ratios, suggesting a cooler climate at the time the water was recharged. The stable isotopes content decreases from the north western part towards the south eastern part of studied area which indicates poorly modern recharge.

Stable isotopes ($\delta^{18}O$, $\delta^{2}H$) are successfully and suitable method for determine the mechanisms of groundwater salinity, also estimate origin of salinity (IAEA, 2010; Al-Charideh, 2010). The Sources of salinity are from the dissolution processes, the isotopic concept is not changes in the composition of (δ18O, δ2H) based on sources of salinization. The changes in stable isotopic composition ($\delta^{18}O$, $\delta^{2}H$) under mixing or evaporation processes are sensitive (IAEA, 2010, Al-Charideh, 2010).

6. Conclusion

Study area (Ali Al-Gharbi) approximately 760 km^2 covering the north east of Missan Province of Iraq. The topographic map elevation (DEM) is between (0–160) m, high elevation is Hemrin hills. The sediments of study area are quaternary deposits. Calculation results of saturation indices of mineral phases indicate that there are changes in these values in the study area for two periods. Major minerals such as calcite, dolomite, gypsum and sylvite show significant spatial and temporal changes and no significant change in other minerals. Also, the calculations show us precipitation and dissolution processes of minerals in study area. The situation in wet period shows a significant difference compared to December dry period. The complex flow path system affects both of the precipitation and dissolution rates, and will be heterogeneous distribution of the above process. PCO_2 has an important role in saturation control of some carbonates; submit to atmospheric effects in free aquifer (partly open system). The different trends of PCO_2 with all minerals also explain the complex structure of the aquifer. The results of flow path reactions are various both in two periods, also the nature of these reactions is different during working (periods) with time. The processes both of dissolution and precipitation of carbonate minerals often influence in the control of chemical composition changes. Reaction path models show that there are different chemical reactions related to selected flow paths for two periods. The main sedimentation mineral was calcite, while dolomite dissolved except the flow path 4. Gypsum and halite reactions have same behavior for both (precipitation & dissolution) results, while hematite and sylvite are various in precipitation/dissolution. According to these facts, the basic reaction for two periods can be explained as follows

Dolomite + Gypsum + Halite → Calcite + Hematite + Sylvite

The applied models are the dominant geochemical process of d-dolomitization involving dolomite, gypsum and halite dissolution and calcite precipitation of groundwater in study area.

Confined part located in eastern part of study area and most of sediment of this aquifer is gavel, while unconfined part located in western part of study area and most of sediments are sand with silt. The hydraulic connections between the aquifers in middle part of study area. According to stable isotope data δ18O and δD, most wells of groundwater are of meteoric origin and exposed to evaporation, also presence hydraulic connection between to water type. Stable isotopes are explaining that recharge groundwater undergoes significant evaporation through it transit to the aquifer. The variation in the isotopic composition in all points indicates that groundwater is affected by different degree of evaporation. The Stable isotopes for all samples of groundwater are located between GMWL and MMWL, this indicate that these samples are mixture of two types. Amara meteoric water line (AMWL) is near to GMWL and away from MMWL, this indicates climate of study area is affected by Arab Gulf climate.

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Strategic water reserve using aquifer recharge with desalinated water in Abu Dhabi Emirate

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ABSTRACT

United Arab Emirates (UAE) as well as other countries in arid region mainly relay on desalinated water for domestic water supply. The challenges facing UAE, however, is the vulnerability of desalination plants to pollution and emergency conditions. There should be available alternatives for reserving freshwater sources for emergency and peak demand conditions. Aquifer storage and recovery (ASR) technique has been proposed as a cost-effective large water storage alternative that can help to meet the needs of domestic sector in crisis/emergency situations. ASR technique is used to store excess desalination water during non-peak hours for recovery during emergency or peak hours. In an attempt to capture, store and redistribute desalinated water and to regulate the quality, quantity, timing and distribution of water flows, Abu Dhabi Emirate started in 2002 to study and evaluate the construction of ASR pilot project in western region. The initial target injection of pilot ASR facilities is to store 2.5 MIGD using five injection wells and one infiltration basin. Desalinated water is infiltrated into a desert dune sand aquifer using "sand-covered gravel-bed" recharge basins. In this study, we evaluate the hydrogeological and hydrogeochemical stratification of the (sub)oxic target aquifer, and water quality changes of DSW during trial infiltration runs. A three dimensional model was developed to assess the impact of hydrologic and operational parameters and factors on the recovery efficiency of the pilot ASR experiment. The model was integrated with geodatabase tool to produce an easily updateable model. Results from this study demonstrate the interaction between hydrologic and operational parameters on the predictions of recovery efficiency. The pilot observations and modeling results demonstrate that in scenario A recovered water quality still complies with Abu Dhabi's drinking water standards (even up to 85% recovery).

Keywords: Three-dimensional modeling; Geodatabase; Visualization; Artificial recharge; Water supply; Abu Dhabi

1. General background

Aquifer storage and recovery (ASR) involves the injection of freshwater in an aquifer through wells or infiltration basins for the purpose of creating a subsurface water supply that is recovered at a later time, to meet seasonal, long-term, emergency, natural crises or other demands (Pyne, 2007). United Arab Emirates (UAE) as well as other Gulf Cooperation Council (GCC) Countries mainly relay on desalinated water as the main source of fresh water for domestic, sustainable development and security of their communities. Moreover, desalination is still considered as very expensive source of water compared with other natural resources. Research and development, new ideas, and improved technologies are all needed to explore new approaches that are more cost-effective to desalinate water. It has been argued that the best long-term solution for the water crises in the domestic sector is to build a network of large-scale desalination plants. The problem faced by the GCC countries, however, is the vulnerability of desalination plants to pollution, natural crises, and emergency conditions. The possible alternatives for reserving fresh water sources for emergency and peak demand conditions are: (1) to increase ground reservoirs and distribution network storage capacity or (2) using a groundwater ASR system. It has been proved that increasing the capacity of the ground reservoirs and network is very expensive and not environmentally friendly. One solution is to store this

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water in groundwater aquifers using aquifer storage and recovery technique. For example, the maximum stored water in the ground reservoirs and distribution network is enough only for 24 h, except in Saudi Arabia and Kuwait, where it is 3 and 5 d, respectively (Fig. 1; Dawoud 2008). Thus, in any crisis or emergency, the stored water will not be enough to cover the demand. ASR has been explored in diverse settings worldwide (Bichara 1974; Khanal 1980; Bouwer et al. 1990; Calleguas 2004; Artimo et al. 2008).

Aquifer storage and recovery is used to overcome the groundwater depletion and unavailability of strategic fresh water reserve (Heilweil 2005), store and recover groundwater (Lowe 2005), provide seasonal and long-term storage, and regulate and improve water quality (Topper et al. 2004). It is particularly useful as a purification method for surface and wastewaters (Rüetschi and Wülser 1999; Brissaud 2003; Al-Katheeri 2007). Artificially recharged water can be introduced into aquifers in various geological settings, such as river basins (Lowe et al. 2003), fractured sandstone bedrock (Heilweil 2005), and esker aquifers (Artimo et al. 2003).

In an arid country such as the Emirate of Abu Dhabi with no permanently existing natural surface water and limited groundwater resources, artificial recharge and storage of surplus desalinated water in aquifers can play a major role in the management of water resources. Due to the absence of large storage reservoirs, desalination plants producing fresh water for urban supply are forced to operate at sub-optimal conditions. Thus, artificial recharge of groundwater and storage of freshwater is deemed necessary and promising technology for meeting seasonal peak demand and offset periods of water deficit due to long-term emergency and natural crisis conditions. Also, it will help to manage the daily and seasonal fluctuations in desalination water production and consumption as the production of desalination plants is constant and the demand is not constant. The excess amount of produced desalinated water during the non-peak hours could be stored in aquifers.

The success of the ASR scheme is normally measured in terms of recovery efficiency, which is defined as the percentage of water injected into a system in an ASR site that fulfills the targeted water quality when recovered. The recovery efficiency is controlled by a wide variety of factors including ambient hydraulic gradient; aquifer permeability, porosity, heterogeneity, thickness, and confinement; ambient groundwater density and quality; injected water density and quality; ASR operation (Bear, 1979; Merritt, 1985; Missimer et al., 2002; Reese, 2002). For example, aquifer transmissivity, the product of permeability and aquifer thickness, must be high enough to permit injection under reasonable pressures and to allow for high flow recoveries. However, if the transmissivity is too high, injected water can migrate excessively (sometimes beyond the capture zone of the ASR well) and in turn reduce recovery efficiencies.

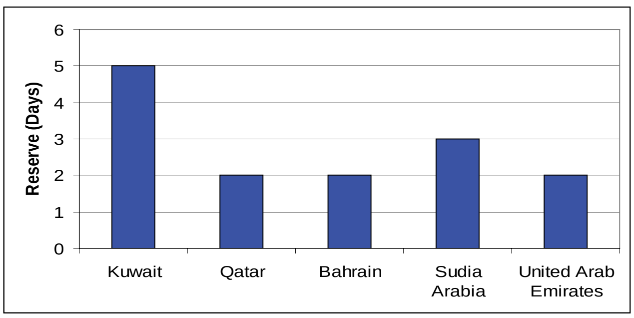

Fig. 1. Storage capacity for emergency water in GCC countries (Dawoud, 2008).

In Abu Dhabi, the pumping test evaluations revealed a range of the transmissivity from some 100 to 3,000 m²/d, with an average of 1,065 m²/d and a median of 950 m²/d. The lower values mostly refer to wells, in which the deeper section of the aquifer was tested. The calculated geohydraulic conductivity varies between 2 and 106 m/d with an average of 27 m/d and a median of 28 m/d as shown in Table 1. Therefore, the optimum transmissivity is within a limited range depending on desired pumping rates and recovery efficiencies (Missimer et al., 2002). In most hydrologic settings, the simplistic "underground storage tank" conceptual model applied to ASR system may have limited utility. Multiple processes including physical, chemical and biological, which can degrade water quality and quantity, control the ASR efficiency. Groundwater models can play an important role in the assessment of ASR scheme. Development of good calibrated modeling tool enables a variety of approaches concerning characterization of aquifer that will host artificially recharged groundwater. Collection and management of primary hydrologic data are key factors to successful characterization of any ASR system. Optimum injection and recovery rates are a function of site-specific conditions. The applications of developing geodatabases combined with geographic information systems (GIS) and three dimensional (3-D) modeling tools have been applied in models of regional scale (Kolm 1996; Russell et al. 1996; Kassenaar et al. 2004; Ross et al. 2005; Thorleifson et al. 2005; Cools et al. 2006) and at local scale (Shah 2004). Three-dimensional modeling tool is needed to build consistent conceptual model for groundwater flow (Shafer et al. 2006)

Table 1
Values of transmissivity and geohydraulic conductivity for the study area (derived from pumping test evaluation)

Well No.	Transmissivity (T)		Geohydraulic conductivity (kf)	
	(m²/d)	(m²/s)	(m/d)	(m/s)
GWA-141	1,050	1.2E-02	19	2.2E-04
GWA-144	250	2.9E-03	6	7.1E-05
GWA-148B	500	5.8E-03	13	1.5E-04
GWA-151	900	1.0E-02	22	2.6E-04
GWA-153	830	9.6E-03	16	1.8E-04
GWA-156	800	9.3E-03	28	3.3E-04
GWA-164	245	2.8E-03	6	6.5E-05
GWA-172	140	1.6E-03	5	5.9E-05
GWA-177	1,200	1.4E-02	45	5.2E-04
GWA-178	1,500	1.7E-02	38	4.4E-04
GWA-215B	2,500	2.9E-02	51	5.9E-04
GWA-240	950	1.1E-02	28	3.2E-04

to simulate the movement of artificially recharged water through the unsaturated zone building the fresh water bubble and the interaction of native water in the aquifer system with fresh injected water. In Abu Dhabi Feflow package was used for simulating the groundwater flow in the study area.

2. Sit selection

The success of the pilot project is mainly dependent on the selection of the most suitable site. To select the most suitable location for the ASR pilot experiment, Abu Dhabi Emirate (Fig. 2) was divided into 10 × 10 km squares. A site selection suitability index was developed including all factors affecting the success of the ASR. GIS was used to overlay various layers and calculate the site suitability index and evaluate and propose an initial array of potential ASR site locations. The suitability index was based on the premise of maximizing ASR effectiveness while minimizing any attendant impacts (Fig. 3). Multiple planning factors were used for the evaluation of ASR feasibility in Abu Dhabi Emirate including the availability of recharge water in terms of quantity and quality, topography, cost of required surface facilities and infrastructures, aquifer native groundwater quality, unsaturated aquifer thickness, aquifer extent and boundary conditions, and aquifer hydraulic parameters. From this analysis, it was found that northern Liwa area is the most suitable site for the pilot ASR project (Fig. 4).

The following advantages for the water supply system of the Emirate of Abu Dhabi are obvious in case of the northern Liwa area would be developed and utilized in the way described above:

- The geological settings and relative remoteness of the northern Liwa area offer a vast natural storage capacity and an excellent protection of naturally and artificially recharged water resources from environmental influences at the surface. In comparison, man-made storage facilities with a comparable capacity would be almost impossible to build and to maintain;
- A deep-seated underground reservoir utilizing natural sand formations as storage with a possible extension of up to 400 km^2 and with sufficient aquifer thickness and unsaturated depth to groundwater table is hardly vulnerable as a whole against environmental hazards and vandalism.
- The mixture of the artificially recharged desalinated seawater and the native existing fresh groundwater will improve quality of the resource and presumably favorable hydrochemical conditions. Huge volumes of the existing fresh groundwater (salinity of up to 1,000 ppm) could then meet the international WHO-Drinking Water Standard.
- Such a groundwater enhancement project in the northern Liwa area would be an essential back-up water supply for the Emirate of Abu Dhabi. The proposed system can cope with seasonal consumption peaks as well as emergency situations easily

The current investigations mainly focus on the water supply of the City of Abu Dhabi. Yet, any provision scheme for other urban or agricultural areas is possible, depending on the water balance the supplier wants to achieve through abstraction and injection. The artificially recharged groundwater

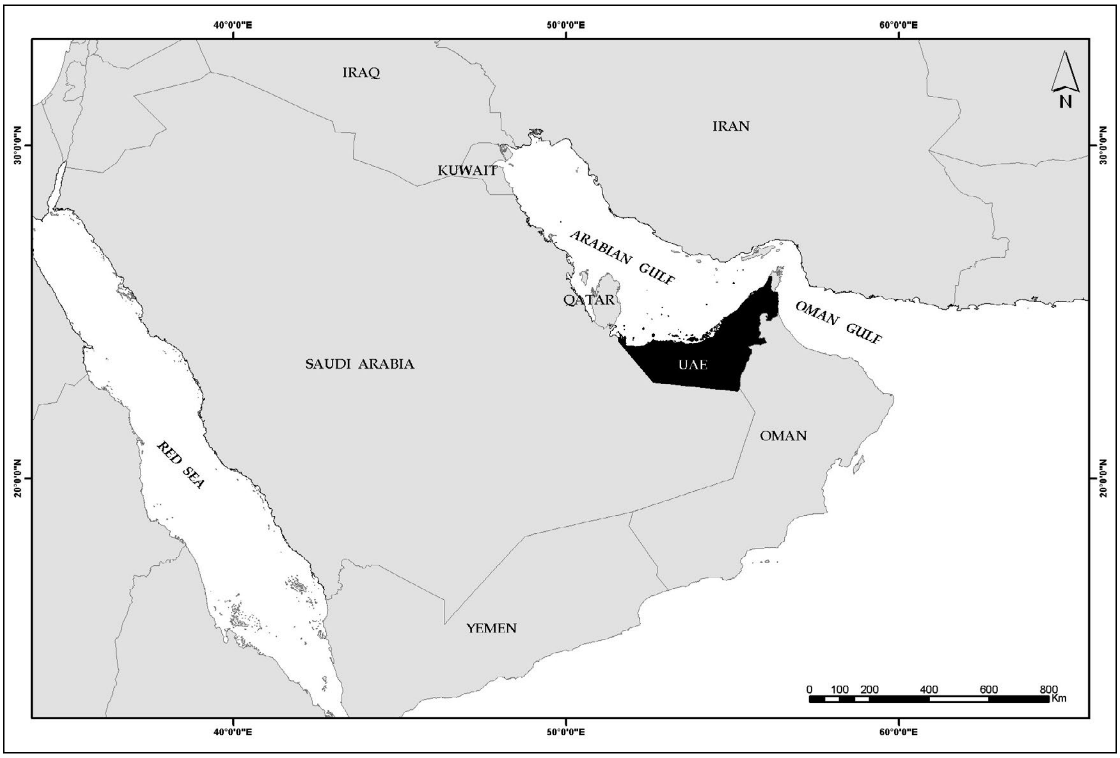

Fig. 2. General location map for Abu Dhabi Emirate.

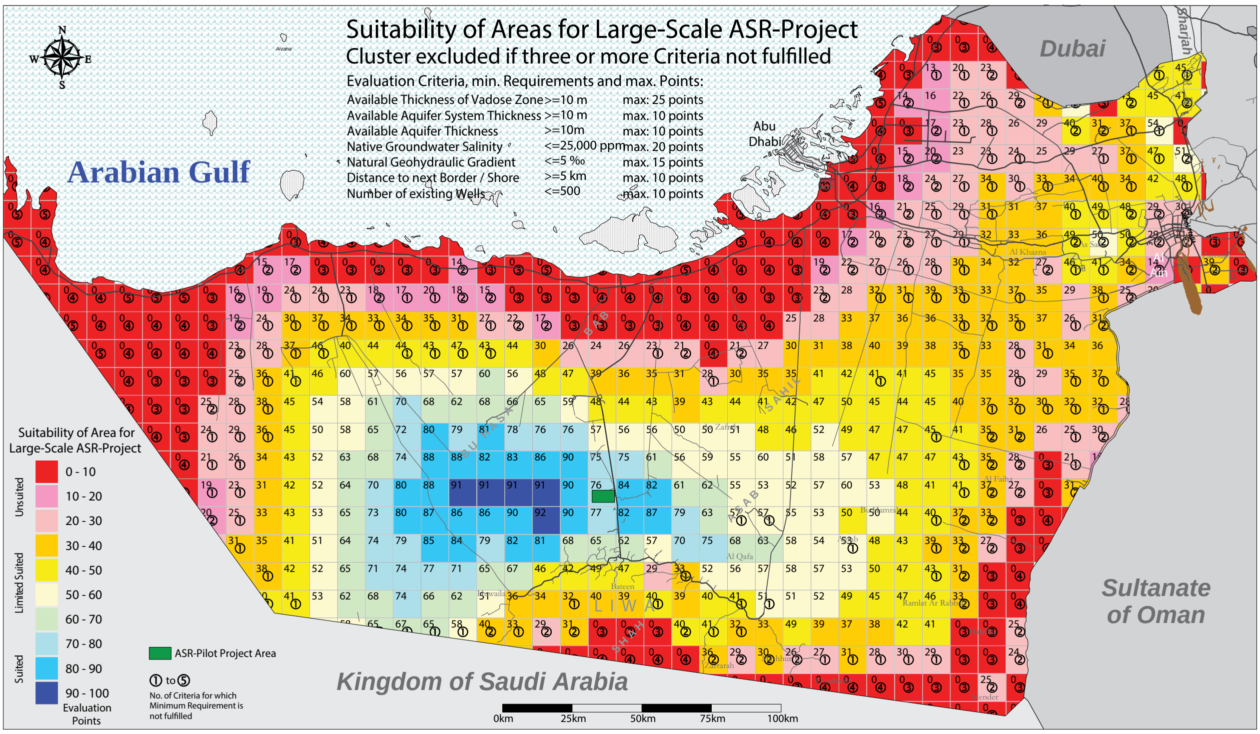

Fig. 3. Development of site suitability index.

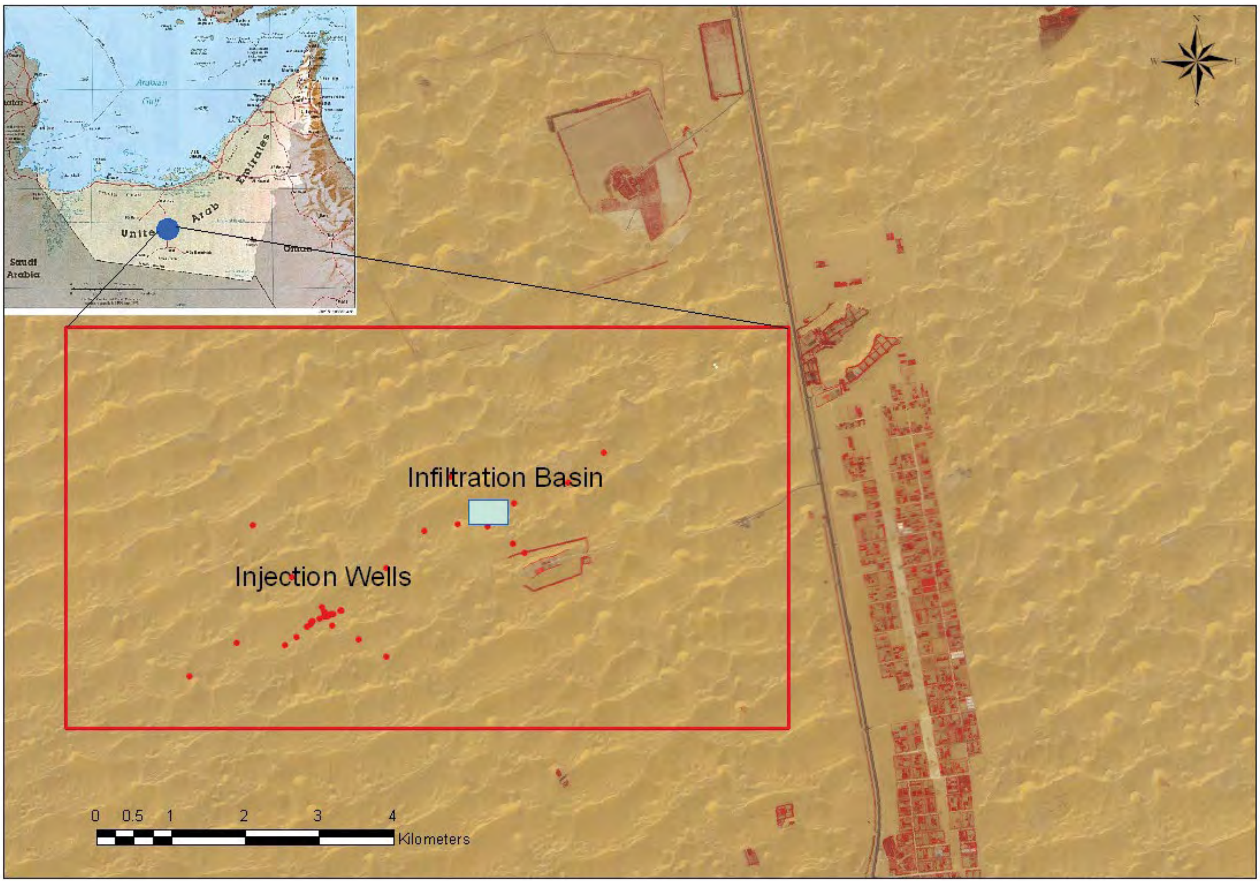

Fig. 4. Selected site for ASR pilot project (Northern Liwa).

resource in the northern Liwa area could be considered as the strategic drinking water reserve of the Emirate of Abu Dhabi for future generations.

3. Hydrogeological assessment

3.1. Lithology and aquifer system geometry

To assess the aquifer geometry and the stratifications, geodatabase populated with the information collected from 43 wells drilled within the study area and 140 existing wells around it. As the injection of fresh water will be in shallow groundwater, the depth of most selected wells is less than 150 m and is not penetrating the deep aquifer. However, four boreholes were drilled deeper than 490 m. In consequence, more detailed lithologic information is available for the uppermost layers of the stratigraphic sequence of the region. Two main stratigraphic units have been encountered:

- *Quarternary unit:* Holocene and Pleistocene eolian fine to medium sands and interdunal deposits. The thickness of this unit varies between 100 and 150 m, depending on the topographic height of the respective location within the study area.
- *Tertiary unit:* mudstones, evaporites and clastics of Miocene age. This unit has a thickness of over 350 m and has not been completely penetrated by any project well.

The Quarternary unit may be divided into two subunits. The upper unit is characterised by the predominance of well-sorted, fairly loose eolian dune sands with occasional intercalations of fine-grained, slightly cemented interdunal deposits. In the lower subunit of the Quarternary, these interdunal deposits prevail. They consist of caliche horizons with traces of organic matter, siltstones and even marls that may be interpreted as playa lake sediments and give evidence of more frequent pluvial periods in the Pleistocene. The Tertiary unit can also be subdivided into an upper unit, consisting of mudston layers and evaporites (gypsum, anhydrite, dolomite) of the Lower Fars Formation, and a lower subunit that is marked by the predominance of clastic sediments (sandstones, siltstones), that are intercalated with layers of mudstones and anhydrite. Table 2 summarizes the upper stratigraphic sequence in the study area as revealed by the project boreholes. The approximate spatial distribution of the stratigraphic units is shown in the hydrogeological cross-sections (Fig. 5).

The boundary between the Quarternary upper unit (aquifer) and the Quarternary lower unit (aquitard) is not clearly defined and cannot be easily correlated between boreholes. However, a significant increase of slightly cemented interdunal deposits is generally noticed around 60 m + MSL. Below this depth, the formation is still fully saturated, but does not contribute significant amounts of groundwater to wells, due to its relatively low permeability. This part of the formation is thus considered as an aquitard. A very significant lithological and hydrogeological boundary is the one between the Quarternary lower unit (aquitard) and the Tertiary upper unit (aquiclude). This boundary is defined by the first occurrences of evaporites of the Lower Fars Formation and marks the bottom of the aquifer/aquitard system. As shown in the hydrogeological cross-sections, in the study area, this interface is encountered at a depth of around 30 m-MSL. The static groundwater level is encountered between 104 m + MSL and 107 m + MSL. Hence, the average thickness of the main aquifer is about 40 to 50 m.

Table 2
Upper stratigraphic sequences in the study area

Unit	Subunit	Description
Quaternary Unit	Upper subunit	Eolian, loose fine to medium sand
Holocene + Pleistocene)	Lower subunit	Interdunal deposits (caliche, silt, marl and sand
Tertiary Unit	Upper subunit	Mudstone and evaporites of the Lower Fars Formation
Miocene	Lower subunit	Miocene clastics (sandstones, mudstones, anhydrite)

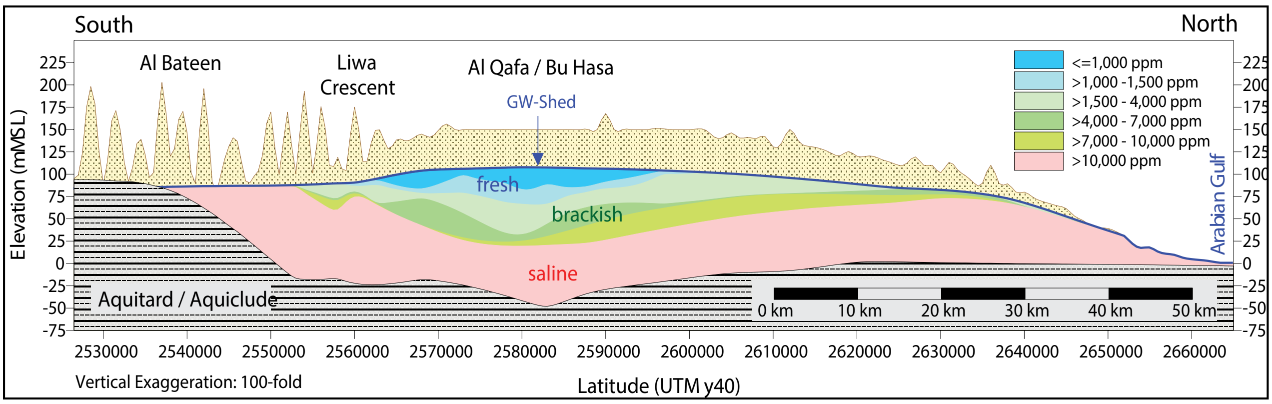

Fig. 5. Hydrogeological cross-section for the selected area.

The entire aquifer/aquiclude system exhibits a total thickness of around 130 m.

3.2. Groundwater flow

Generally, in geohydraulic terms, the Western Region of the Emirate of Abu Dhabi is separated by a major groundwater divide, running approximately from east to west. It passes the greater Liwa area some 20 to 30 km north of the Liwa Crescent. All shallow to medium deep-seated groundwater north of it flows to the north, towards the Arabian Gulf as the receiving body, while all groundwater south of it flows southerly to Saudi Arabia. There, huge Sabkha areas, much lower in elevation than the central part of the Western Region, function as a discharge area, where tremendous groundwater volumes constantly evaporate. The study area is located exactly along this major groundwater divide. The measured groundwater level in December 2001 was between 103.6 m + MSL and 107.2 m + MSL, with an aerial average of 106 m + MSL (Fig. 6). From the highest geohydraulic head in the central part of the eastern half of the study area, groundwater flows naturally radial to the adjacent areas under a maximum geohydraulic gradient of 0.5‰. The calculated natural velocity of groundwater movement ranges from 1 to 10 m/a. Although the geohydraulic gradient is comparatively low, the groundwater flow system is a dynamic one, which cannot be maintained without a driving force. Groundwater abstraction by discharging wells modifies the current flow pattern only locally; its effect on the large-scale groundwater flow is still negligible.

3.3. Aquifer hydraulic parameters

To calculate the aquifer hydraulic properties within the study area, 23 pumping tests were carried out between October 2001 and February 2002. Analyzing the results of these pumping tests gave more detailed information regarding:

- *Geohydraulic parameters* (such as transmissivity, geohydraulic conductivity and storage coefficient of the aquifer)
- *Well performance characteristics* (well capacity, well efficiency)
- *Groundwater quality* (general hydrochemical composition, vertical salinity profile and possible dependency of the quality on the discharge rate).

The calculated geohydraulic conductivity varies between 2 and 60 m/d with an average of 27 m/d and a median of 28 m/d and the calculated transmissivity ranges from 100 to 3,000 m²/d, with an average of 1,065 m²/d and a median of 950 m²/d. The lower values mostly refer to wells, in which the deeper section of the aquifer was tested. The storage coefficient was obtained only for those pumping tests, where additional piezometers in the vicinity of the tested well could be monitored. However, the determined values strongly depend on the test duration. For the 2-d lasting test, an

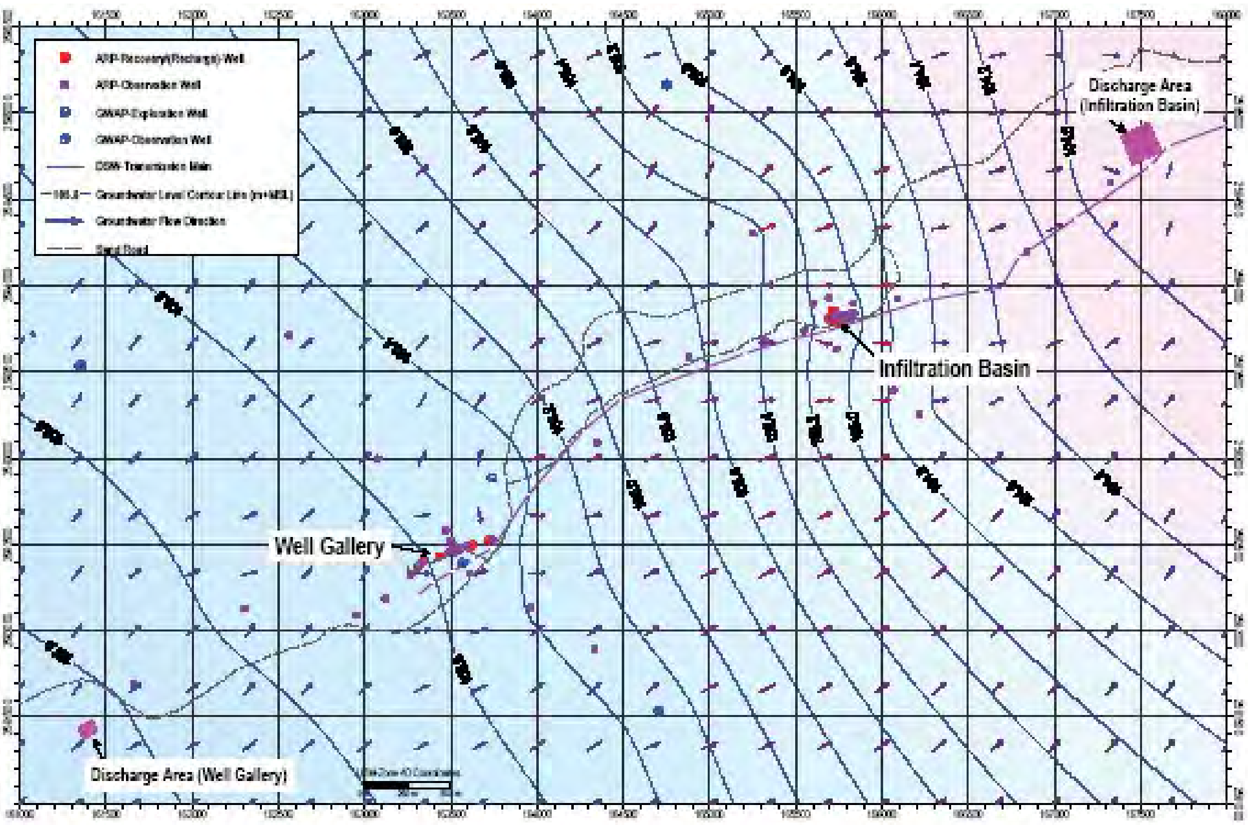

Fig. 6. Groundwater levels contour map (before injection, 2001).

average storage coefficient of $S = 0.16$ was calculated, while the 10-d lasting test finally gave the higher value of $S = 0.32$. The projected short to medium-term yield of the tested wells is comparatively high and ranging from 40 to 250 m³/h with an average of about 130 m³/h (GTZ/DCO 2002).

3.4. Field infiltration tests

In order to obtain information on infiltration rates and vertical geohydraulic conductivity, one well infiltration test and four tank infiltration tests were conducted. The results of the infiltration test indicated that the infiltration rate per m² ranges from 0.77 to 0.49 m³/h. The evaluated vertical hydraulic conductivity in the vadose zone ranged from 1.6 10^{-4} to 2.5 10^{-4} m/s, indicating an approximately 40% lower conductivity value than that of the horizontal hydraulic conductivity.

3.5. Evaporation column tests

Evaporation has to be considered as an essential part in the artificial recharge project and needs to be surveyed precisely. Evaporation from bare soils occurs by capillary rise of soil water up to the evaporation front, at certain soil depth, followed by molecular diffusive water vapour transport through the dry soil layer above. For bare soil conditions and certain depths of groundwater table, the following evaporation rates are reported (Table 3).

This indicated that direct evaporation from the groundwater body is negligible beyond a depth to the groundwater table of about 5 m. Here, less than one mm/a of evaporation has to be considered. If the capillary fringe does not reach the ground surface, evaporation occurs mostly as transport of water vapour. In order to obtain long-term groundwater evaporation data, two holes have been drilled with a diameter of 26″ down to 50′, and a bottom sealed 21½″ steel conductor pipe was installed. An impermeability test of the 21½″ steel casing was conducted followed by the installation of a 2‴ pipe inside the monitoring well. The steel casing was filled up with sand and afterwards water was pumped from a tank through the 2″ pipe into the well until the sand was saturated and the water level reached the top of the 21½″ casing. The impact of temperature, humidity and wind speed was correlated with the evaporation and possible recharge in the capillary zone. The test results and obtained data indicated that significant evaporation from the Liwa Aquifer could only occur in zones of very shallow groundwater table (<1 m). Literature evaporation data support these preliminary results and observations.

3.6. Groundwater quality

Complete hydrochemical analyses were carried out for 400 wells. The evaluation of the hydrochemical and hydroisotopical composition of the groundwater within the study area is based on 40 groundwater samples, 37 samples of which have been collected from wells, mostly at the end of the long-term constant discharge pumping test. Furthermore, three samples of the very shallow groundwater were taken from excavations. The analyzed total dissolved

Table 3
Evaporation rates of sands (after Kontny 1993)

Depth of groundwater table (m bgl)*	Mean depth of groundwater table (m bgl)*	Groundwater evaporation (mm/a)	
		Coarse sand	Fine sand
0–5	2.5	2.18	6.91
5–10	7.5	0.53	0.79
10–15	12.5	0.28	0.38
15–20	17.5	0.20	0.24

*m bgl = Meter below ground level.

Table 3
Salinity-related classification of groundwater samples

TDS (ppm)	Classification	Samples
≤1,000	Freshwater (World Health Organization WHO)	28
>1,000–1,500	Freshwater	7
≤1,500	Freshwater (Local UAE-Standard	35
>1,500–4,000	Slightly brackish	3
>4,000–7,000	Medium brackish	1
>7,000–10,000	Strongly brackish	0
>10,000–25,000	Slightly saline	1
>25,000–50,000	Medium saline	0
>50,000–100,000	Strongly saline	0
>100,000	Brine	0

solids (TDS) of the 40 groundwater samples ranged from 348 to 12,314 ppm. The number of samples according to the applied groundwater salinity classification is shown in Table 3.

In terms of mineralization, as much as 70% of the analyzed samples meet the limit of the WHO-Drinking Water Standard and almost 90% of the analyzed samples are fresh, according to the local standard (TDS: ≤1,500 ppm). Deeper screened wells produce groundwater of higher salinity: three samples are slightly brackish (>1,500 to 4,000 ppm), one is medium brackish (>4,000 to 7,000 ppm) and another one is slightly saline (>10,000 to 25,000 ppm). As sodium is the dominant cation, and chloride is the prevailing anion, hydrochemically, the tapped groundwater can be characterised as "alkaline water, predominantly chloridic". The calculated content of sodiumchloride (salt) as the major dissolved mineral phase ranges from 77 to 7,169 ppm with a median value of 431 ppm.

4. Conclusions

In Abu Dhabi emirate, two recharge schemes using injection wells and infiltration basins were used for injecting the desalinated water into the shallow groundwater aquifer system. Recovery cycles results indicated that under the given conditions the recovery ratios ranged between 85% and 90% were physically recovered. At the end of 250 d lasting period of constant recharge, the lateral migration of the outer injected freshwater body was only 0.2 m/d. For 75% recovery ratio, the recovered water salinity will be up to 430 ppm, and for 85% recovery ratio, the recovered water salinity will be up to 485 ppm. Both schemes proved to function perfectly. However, in contrast to the infiltration basin scheme, for the dual-purpose wells of the well gallery scheme there are indications of reducing injection and abstraction capacity over time due to clogging effects. Moreover, considering the local hydrogeological conditions, the infiltration basin conception is advantageous as it is easier to operate and maintain. It was recommended to use recharge basin in the full scheme project.

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Connectivity between aquifers: evidence from $^{87}Sr/^{86}Sr$ ratio and from stable isotopes case study of Oman

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ABSTRACT

Isotope techniques are powerful tools in hydrological studies such as determination of groundwater age, recharge source, groundwater mixing etc. The aim of this study is to identify physico-chemical processes that control groundwater in North Oman. We have collected several groundwater samples in North Oman from different geological units namely the tertiary formations, Hajar super group (HSG) formations and ophiolite which comprise different aquifers. All groundwater samples were analyzed for strontium $^{87}Sr/^{86}Sr$ ratio and environmentally stable isotopes ($^{18}O/^{16}O$ ($\delta^{18}O$) and $^{2}H/^{1}H$ ($\delta^{2}H$)). The analysis of the stable isotopes data ($\delta^{2}H$ and $\delta^{18}O$) suggests (1) a groundwater recharge to the ophiolite from the HSG and from direct infiltration and (2) groundwater in the tertiary formations formed from meteoric and evaporated waters. The different aquifers have shown variable $^{87}Sr/^{86}Sr$ ratio that ranges between 0.70840 and 0.70864 for the ophiolite aquifer, 0.70776 and 0.71141 for groundwater from the Tertiary aquifer and from 0.70798 to 0.70938 for the groundwater from the HSG aquifer. The relationship between $^{87}Sr/^{86}Sr$ ratio and 1/Sr indicates aquifers' inter-connectivity and suggests recharge from the HSG into the ophiolite. Groundwater of the Tertiary aquifer is from two main reservoirs: (1) a reservoir generated by a mixture of groundwater from the ophiolite and HSG aquifers and (2) a reservoir generated by a direct infiltration of rainwater and its interaction with evaporites.

Keywords: Isotopes; Mixing; Recharge; Strontium; Aquifer

1. Introduction

The renewability of groundwater, which comprises the main water resources in arid areas, is vital for development plans and sustainability. Increasing water demand has greatly stressed the water resources causing resources depletion, deterioration of water quality and aquifer hydraulic properties and encourages seawater intrusion in coastal areas.

Isotopes are found to be very powerful tools to investigate aquifer interrelations, surface water and groundwater interactions and infiltration through the soil zone. In previous studies, hydrological investigations of groundwater in Oman using isotopes revealed mixing and interactions between deep and shallow waters (McCarthy et al., 1992; Horst et al., 2007; Nakaya et al., 2007; Makni et al., 2013) but did not distinguish those between different types of aquifers. Among isotopes, ^{18}O and ^{2}H are the most commonly used to determine such hydrological information including the sources of recharge and groundwater mixing.

The D/H and $^{18}O/^{16}O$ ratios in precipitations vary according to elevation and distance from the ocean. The D/H and $^{18}O/^{16}O$ ratios in water may also sometimes change within the aquifer due to evaporation and exchange and mixing processes between waters and interaction with rocks. Such approaches are commonly used for hydrological purposes (Yeh et al., 2009, Saka et al., 2013).

Although the application of stable isotopes in hydrological studies has been carried out intensively, most of these studies were focusing on individual aquifers and rarely consider geological diversity (Davisson et al., 1999; Petrella and Celico, 2013; Saka et al., 2013; Swarzenski et al., 2013).

In the current study, we are using D and ^{18}O and strontium isotopes to investigate the hydrogeology of terrains

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characterized by diversified geology. The better understanding of such hydrogeology is necessary for well informed management plans and future development. The water sustainability management is highly dependent on mapping the pathways of groundwater in each aquifer and identifying the mixing processes.

This study is carried in order to (1) characterize the isotopic composition of groundwater from North Oman and investigate the evaporation effect and (2) investigate the connectivity between groundwater from different aquifers.

1.1. Study area

The study area covers a total geographical area of about 82,259 km^2 (Fig. 1). It is bounded by Oman Sea from the North with an extending coast of about 300 km up to United Arab Emirates (UAE) border. The mean monthly temperature in the mountainous area varies between 4.6°C and 17.6°C while in the plains and coastal areas it was reported between 18.9°C and 35.7°C (Al Abri, 2009). The average rainfall calculated for North Oman is about 100 mm. The mean annual

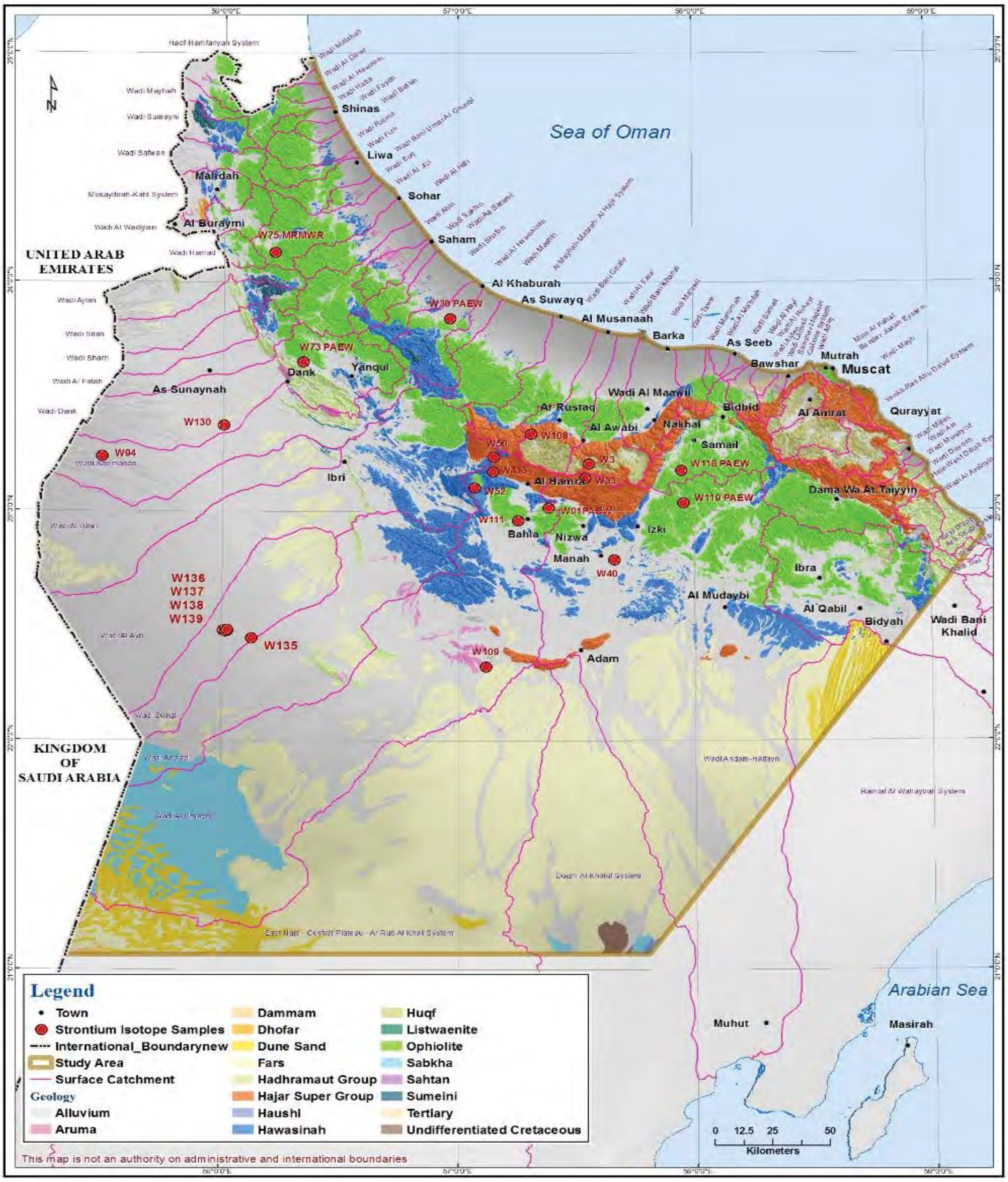

Fig. 1. Geology of Oman and sampling locations.

evaporation rates have been found to be 2,359 mm in the mountainous area (Jabal Shams station) in the summer time and drops to about 1,500 mm in winter time while it is about 2,260 mm in the plain area (MRMWR, 2006).

The study area is characterized by diversified geology that extends from Precambrian to recent. It comprises in general five main rock sequences, Hajar super group (HSG, carbonate rocks about 270–90 Ma age), Hawasina Formation (consolidated ancient seafloor sediments about 270–90 Ma age), ophiolite (igneous rocks), Tertiary (shallow marine carbonates about 65–2 Ma age) and recent alluvial deposits (Glinne, 2005; Al Abri, 2009). In the core of the Jabal Akhdar that represents the highest elevation, metamorphosed rocks of pre-Permian age are reported (Glinne, 2005).

2. Materials and methods

2.1. Sampling and analytical methods

Several samples were collected from groundwater hosted in ophiolite and limestone (Fig. 1). Samples were filtered through 0.45 μm diameter and analyzed for $^{18}O/^{16}O$ and $^{2}H/^{1}H$ and Sr isotopes. Analysis of oxygen $^{18}O/^{16}O$ and $^{2}H/^{1}H$ for most of samples were determined in Ottawa University, faculty of science, Earth Science G.G. Hach Isotope laboratories and in Environmental Isotope Laboratory ETLAB at University of Waterloo in Canada by laser absorption spectroscopy using a Los Gatos Research (LGR) Isotopic Water Analyzer (IWA-35d-EP) Model 912-0026. Routine precision for hydrogen is +/–1 per mil. Routine precision for oxygen is +/–0.25 per mil. The results are reported with respect to International Atomic Energy Association (IAEA), international standard Vienna standard Mean Oceanic Water (VSMOW) and expressed in delta values, δ, in units of per mil relative variation with respect to VSMOW:

$$\delta = \text{Rsample} - \frac{\text{Rstandard}}{\text{Rstandard}}$$

where Rsample is the ratio of the heavy to the light isotope measured for the sample and Rstandard is the equivalent ratio for the standard.

Analysis of Sr isotopes was carried in the Ottawa University, faculty of science, Earth Science G.G. Hach Isotope laboratories and some in Environmental Isotope Laboratory ETLAB at University of Waterloo in Canada.

3. Result and discussion

3.1. Stable isotopes

For the discussion of results, groundwater samples are divided according to the type of their aquifer rocks (Table 1). The investigated groundwater is from the following aquifers: ophiolite, limestone of Hajar super group (HSG) and limestone of tertiary. The plot of δD vs. $\delta^{18}O$ is discussed relative to the Global Meteoric Water Line defined by Craig (1961) (Fig. 2), and to Northern Oman Meteoric Water Line (NOMWL; $\delta 2H = 5\delta^{18}O + 10.7$) and the Southern Oman Meteoric Water Line (SOMWL; $\delta 2H = 7.2\delta^{18}O–1.1$) suggested by Weyhenmeyer et al. (2002). The stable isotopes data ($\delta^{18}O$ and δD) have been used for investigation of interactions

Table 1
Stable and Sr isotopes in groundwater from ophiolite, Hajar super group (HSG) and tertiary aquifers

	Ophiolite					HSG					Tertiary			
	Sr	$^{87}Sr/^{86}Sr$	$\delta^{18}O$	δD		Sr	$^{87}Sr/^{86}Sr$	$\delta^{18}O$	δD		Sr	$^{87}Sr/^{86}Sr$	$\delta^{18}O$	δD
	mg/L		(per mil SMOW)			mg/L		(per mil SMOW)			mg/L		(per mil SMOW)	
W19 PAEW	0.27	0.70844	−1.55	−2.05	W3 PAEW	0.74	0.70938	−3.96	−20.2	W94	6.87	0.70841	−1.62	−11.9
W73 PAEW	0.49	0.70853	1.45	2.76	W33 PAEW	0.61	0.70858	−3.90	−20.2	W130	1.22	0.70861	−1.62	−6.9
W75 MRMWR	0.01	0.70799	−1.39	−10.44	W49 PAEW	1.74	0.70846	−1.00	−6.1	W135	17.32	0.70785	−2.78	−13.67
W80 PAEW	0.57	0.70864	−0.06	−2.07	W50 PAEW	2.42	0.70837	−2.61	−14.6	W136	15.55	0.70784	−2.56	−10.61
w91PAEW	0.37	0.70863	−0.68	−4.84	W52 PAEW	0.67	0.70806	−2.48	−11.6	W137	15.86	0.70785	−2.64	−10.36
W111	0.23	0.70853	−0.64	−3.16	W108	0.67	0.70855	−2.95	−17.0	W138	85.8	0.71141	−2.11	−20.83
W118 PAEW	0.1	0.70809	0.29	0.92	w109	7.55	0.70832	−1.38	−6.6	W139	28.16	0.70776	−2.60	−13.17
Average	0.29	0.71000	−1.212	−5.63	W113	0.01	0.70798	−0.55	−1.79	Average	24.3971	0.70853	−1.63	−10.26
Min	0.01	0.70799	−4.72	−24.01	Average	1.80125	0.70846	−2.38	−11.47	Min	1.22	0.70776	−4.44	−21.33
Max	0.57	0.70864	1.45	2.76	Min	0.01	0.70798	−4.16	−20.23	Max	85.8	0.71141	−0.16	−1.79
SdV	0.19	0.00020	1.077	4.91	Max	7.55	0.70938	−0.52	−1.79					
					SdV	2.28	0.00040	1.137	5.99					

between different aquifers as well. The approach employs the relationship between δ^{18}O and δD which is used to highlight the groundwater mixing between relatively unaffected waters and those being influenced by evaporation and/or by mixing with other water sources.

The isotopic composition of groundwater from the ophiolite aquifer ranges from –24 to 2.73.0‰ V-SMOW for δD and from –4.72 to 1.45‰ V-SMOW for δ^{18}O. The δ ^{18}O and δ D in groundwater samples is referenced to LMWLs previously defined by Weyhenmeyer et al. (2002) in addition to GMWL (δD = 8 δ^{18}O + 10, Craig, 1961).

Most of groundwater samples collected from the ophiolite aquifer during this study plots between NOMWL and SOMWL (Weyhenmeyer et al., 2002) and shows an evaporation effect indicated by a slope of 3.8 and intercept of –0.96 (Fig. 2).

The isotopic composition of the groundwater from HSG aquifer ranged from –20.2 to –1.79.0‰ V-SMOW for δD and from –4.16 to –0.52 ‰ V-SMOW for δ ^{18}O.

The δD–δ^{18}O relationship showed that most of wells plot close to GMWL with a slight deviation which defines the following regression equation: δD = 5δ^{18}O + 0.57 (Fig. 2).

The deviation of waters of the few wells from the GMWL indicates an effect of only slight evaporation. However water of most wells plot near the SOMWL rather than near to NOMWL.

The isotopic composition of groundwater from Tertiary aquifer ranged from –21.33 to –1.79‰V-SMOW for δD and from –4.44 to 0.16‰V-SMOW for δ^{18}O. The δ^{2}H – δ^{18}O relationship for all water samples showed that there are two groups of groundwater (1) those which plot on the GMWL, and (2) those which have undergone evaporation and which plot in two parallel distributions (Fig. 2).

3.2. Sr isotopes

The concentrations of Sr in groundwater collected for this study from ophiolite range from 0.1 to 0.57 mg/L much lower than that measured by Lanphere et al. (1981) in rocks from Samail ophiolite (about 87 to 278 ppm).

Although the Sr concentration in groundwater remain lower than that measured in the Samail ophiolite rocks, the ^{87}Sr/^{86}Sr ratio about 0.7084 to 0.7086 (Table 1) is higher than ^{87}Sr/^{86}Sr ratio measured in rocks from ophiolite rocks (about 0.7028 to 0.7040) by McCulloch et al. (1981) and Lanphere et al. (1981). Indeed the relationship between ^{87}Sr/^{86}Sr and 1/Sr is considered to identify the different sources of Sr in waters of this aquifer (Fig. 3). Although the difference between ^{87}Sr/^{86}Sr of different wells is not significant (about 10%), it is clear that Sr in groundwater of ophiolite aquifer is yielded from two main sources (1) one with high concentration of Sr and slightly high ^{87}Sr/^{86}Sr and (2) the other with low Sr concentration and slightly lower ^{87}Sr/^{86}Sr. The source 1 may reflect meteoric waters with an effect of evaporation. The source 2 can be apparented to young waters which have interacted with limestone of HSG which were deposited during Cretaceous.

The ^{87}Sr/^{86}Sr ratio in waters collected from Tertiary aquifer varies from 0.70776 to 0.708612. Like waters from ophiolite, groundwater from Tertiary aquifer exhibit small variations of ^{87}Sr/^{86}Sr ratio and large variations in the Sr concentrations.

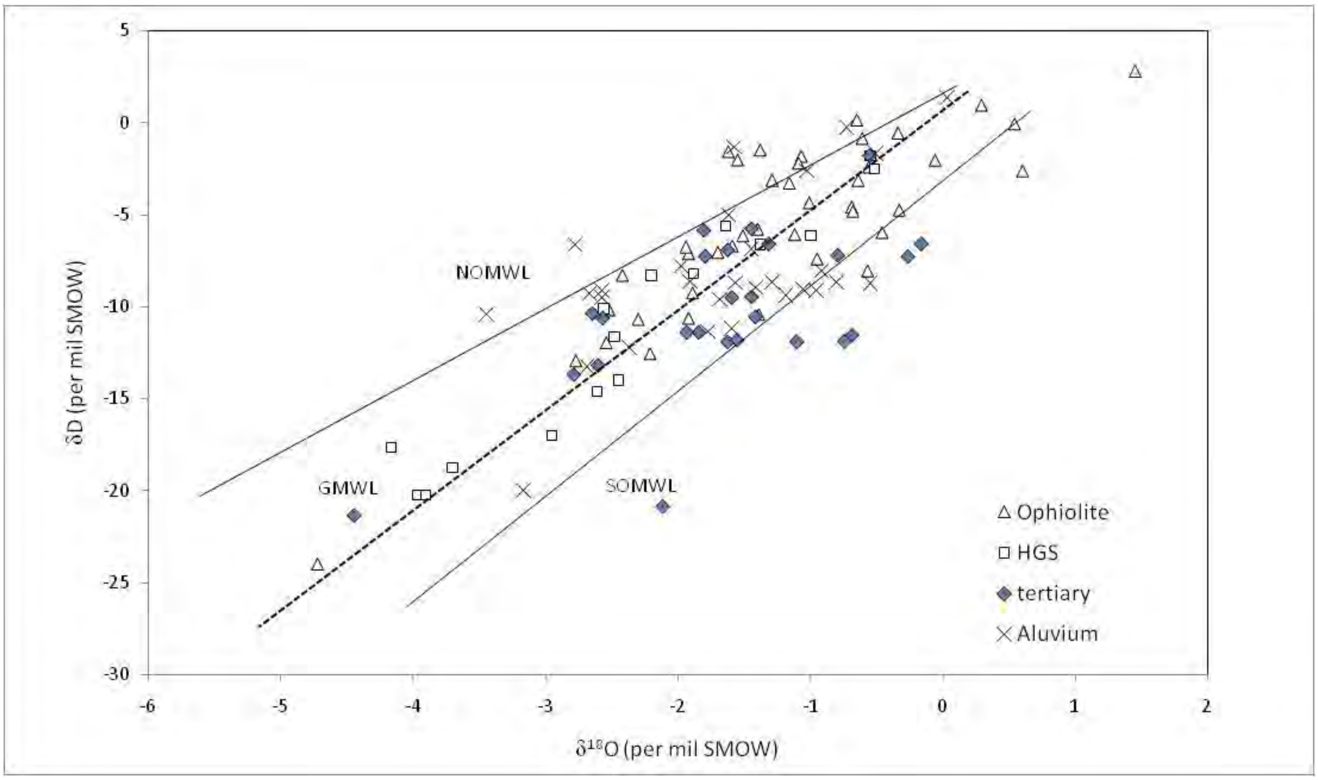

Fig. 2. δD–δ^{18}O diagram for groundwater from different aquifers.

Sr isotopes data of groundwater from Tertiary aquifer indicates two main reservoirs, (1) one with low $^{87}Sr/^{86}Sr$ and high Sr concentration and (2) one end member with slightly higher $^{87}Sr/^{86}Sr$ and low Sr concentrations (Fig. 3).

The endmember with higher concentration in Sr and lower $^{87}Sr/^{86}Sr$ ratio can correspond to evaporite rocks which have been identified in tertiary formation while the more radiogenic endmember (2) may correspond to infiltration of waters from ophiolite aquifer. These infiltrated waters are characterized by isotopic signature yielded from limestone of HSG.

The $^{87}Sr/^{86}Sr$ ratio in waters collected during this study from HSG aquifer vary from 0.70798 to 0.70858 while the Sr content is about 0.01 to 7.6 mg/L. The plot of $^{87}Sr/^{86}Sr$ vs. 1/Sr of groundwater samples collected from HSG aquifer involves mixing between at least 3 end members (Fig. 3). These various water source endmembers consist of: 1) waters with high Sr concentration and low $^{87}Sr/^{86}Sr$ (Figs. 3 and 2) waters with high $^{87}Sr/^{86}Sr$ and low concentration and 3) waters with low Sr concentrations and low $^{87}Sr/^{86}Sr$.

The endmember 1 can be related to dissolution of carbonates while endmember 2 seems to be related to silicate minerals. The endmember 3 is likely apparented to infiltrated rainwater which does not reflect neither an effect of evaporation nor an important interaction with carbonate rocks.

3.3. Connection between different aquifers

The groundwater interaction between different aquifers can be determined using the variation of δD vs. $\delta^{18}O$ and Sr isotopes.

The δD and $\delta^{18}O$ in groundwater from the HSG aquifer is more homogeneous when compared with other aquifers. The karstification in the HSG, its location in the high altitude with anomalous rainfall and less evaporation (cool climate) accelerates the percolation to the aquifer and therefore the isotopic signature remains unaffected. Groundwater moves from the HSG through fractures and faults to feed the other aquifers resulting in mixing of groundwater. This is a slower process compared with percolation to the HSG. Therefore, considerable variation of δD and $\delta^{18}O$ values characterizes groundwater from the ophiolite. Groundwater from tertiary plot between waters hosted in ophiolite and those in HSG indicating that the recharge of tertiary is a mixing between these waters (ophiolite and HSG). These mixing waters may discharge to other groundwater hosted in ophiolite aquifer, those which are enriched in $\delta^{18}O$.

Comparison between $^{87}Sr/^{86}Sr$ data of waters from all aquifers (Fig. 3) shows that the lowest $^{87}Sr/^{86}Sr$ ratio and the highest concentration of Sr characterize waters from Tertiary aquifer (deeper than wells in the other aquifers) while the lowest Sr concentration was measured in waters from ophiolite.

Although the recharge processes to each aquifer do not look similar, the sources of recharge to different aquifers seem be connected. The location of HSG samples in the center of all samples collected from the other aquifers support the suggestion of discharge of waters hosted in HSG to all aquifers. Among groundwater hosted in HSG (in the recharge zone), there are wells which plot near tertiary, and other wells plot near ophiolite.

The similarity of $^{87}Sr/^{86}Sr$ of waters in ophiolite with those hosted in HSG reflects a short residence time of waters

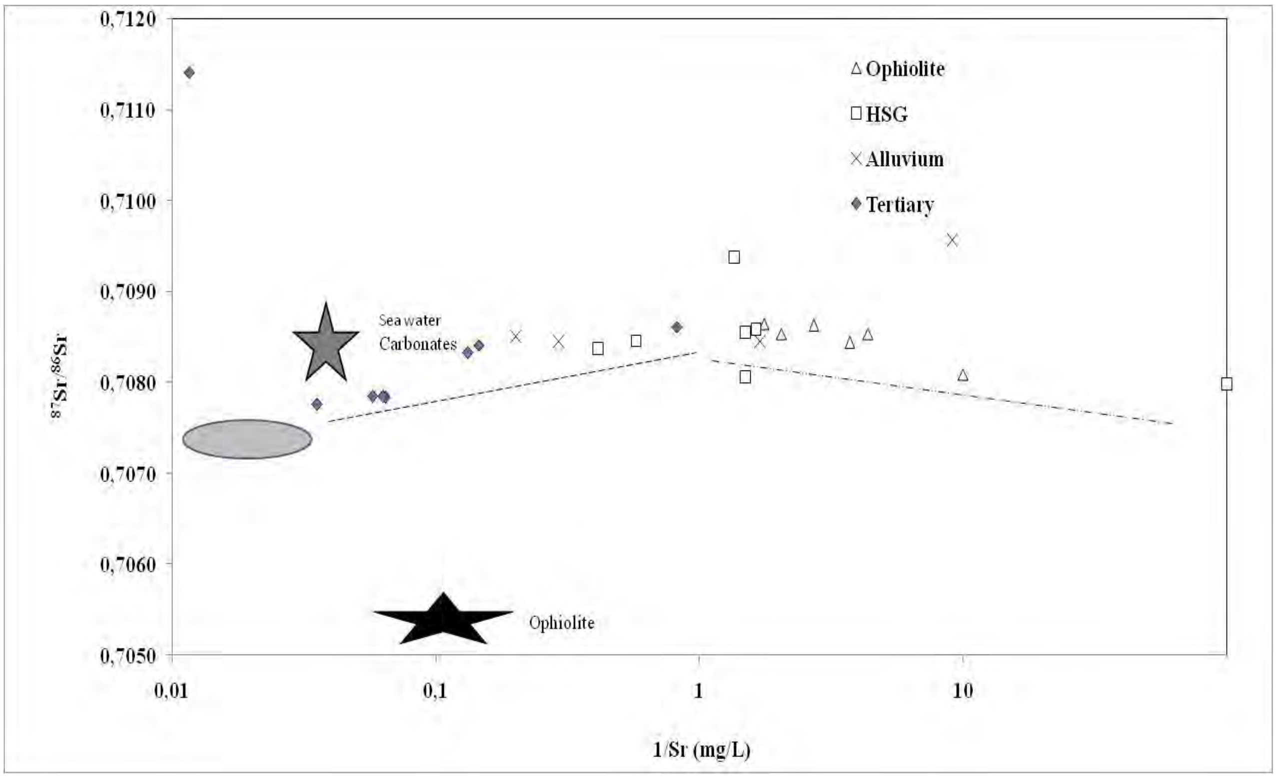

Fig. 3. Variations of $^{87}Sr/^{86}Sr$ ratio vs. 1/Sr.

in ophiolite. Moreover because of their low solubility degree, ophiolite interaction with waters does not influence the $^{87}Sr/^{86}Sr$ ratio of water. It is clear that the source of recharge to ophiolite waters consists in waters from HSG. A possible discharge of waters from ophiolite to waters in Tertiary aquifer can be an explanation of similarity of $^{87}Sr/^{86}Sr$ ratio measured in waters of ophiolite with that in waters from one endmember of Tertiary aquifer (the endmember with high $^{87}Sr/^{86}Sr$).

4. Conclusion

Based on stable isotopes:

- Waters in Tertiary aquifer are a mixture between waters from a shallow source apparented to ophiolite and a deep source apparented to HSG.

The source of groundwater and the connectivity between aquifers has also been shown using $^{87}Sr/^{86}Sr$ ratio vs. 1/Sr plot which indicates that:

- Waters from ophiolite are recharged from HSG
- The waters from Tertiary formation are recharged from two main sources: (1) waters with high $^{87}Sr/^{86}Sr$ are recharged from a possible mixture between waters from HSG and waters from ophiolite and (2) waters with low $^{87}Sr/^{86}Sr$ reflect the interaction of waters with evaporite rocks.

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Managed aquifer recharge (MAR) in coastal aquifers, in brackish and saline groundwater

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Summary

Managed aquifer recharge (MAR), the intentional recharge of water into an aquifer, has been generally shown to work in different geological settings – in soft and hard rock aquifers, porous and fractured media, and under confined and unconfined conditions. The origin of the source water for MAR applications depends on local water availability, and to date many successful MAR schemes apply water from alternative sources, for example, desalinated seawater or treated sewage effluent. An adequate treatment of the water prior to recharge, and hydrochemical mixing reactions and water–rock interactions within the aquifer after recharge have to be considered for all MAR applications regardless of their scope. The application of MAR for water storage in coastal aquifers in saline or brackish groundwater poses additional challenges: The mixing of the recharge water with native brackish and saline groundwater, either in the aquifer or during abstraction may render the abstracted water unfit for most intended purposes. Therefore, the aim of MAR applications under such conditions must be to recover the recharged water with little mixing.

Members of the SUBSOL project – bringing subsurface water solutions to the market – financed by the European Commission, have modified conventional MAR techniques to make them more efficient in saline or brackish groundwater settings. The so called subsurface water solutions (SWS) provide different building blocks to minimize the mixing of freshwater with the native groundwater: Multiple partially penetrating wells can be used to control the upward movement of freshwater bubbles caused by buoyancy, smart configurations of interception wells can be applied to prevent upcoming of saltwater during freshwater abstraction, and automated control units are utilized to optimize pumping schemes.

In the framework of the SUBSOL project, further exchanges have been developed between the SUBSOL consortium and institutions from GCC countries. The GCC countries are one of seven regions where so called "regional assessments" were conducted to evaluate the potential of SWS. Besides hydrogeological and technical matters, a number of other issues are included in these studies. One aspect is the regional perspective, whether subsurface solutions are considered as suitable tools in the repertoire of the water management schemes. Another aspect is the regulatory framework, especially the legislation on water – for example, regulations on injection, abstraction and quality of water. Based on preliminary assessments, first positive results give way to the hope that the regional studies in the GCC countries will help to establish a solid base for common future projects.

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Using satellite rainfall data to estimate direct flow

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ABSTRACT

The main objective of this paper is to develop methodology for obtaining basin hydrological data for the Blue Nile sub-basins; as well to establish different types of data bank for the Blue Nile River Basin (BNRB). Data scarcity has been regarded as a huge problem in modeling the water resources of the Blue Nile River Basin. Satellite rainfall data together with the evapotranspiration have been used to calculate the runoff data. However, in data-scarce regions such as in a transboundary basin, remote sensing data could be a valuable option for hydrological predictions when ground rainfall stations are not available; as well as the remote sensing data can be used to fill gaps in the ground rainfall stations. The satellite rainfall data for all Blue Nile sub-basins were downloaded in a monthly basis for the period 1980–2010 from the Global Weather Data for the National Centres for Environmental Prediction (NCEP) from its website (www.globalweather.tamu.edu). This data were modified with the actual measured rainfall from near gauge stations for the period 1993–1999 by using a weighting factor depending on the distance between satellite data, by using inverse equation and the distances between the middle of sub-basins and the first and second nearest measured rainfall stations, respectively, the modified satellite rainfall data have been found. The selection of the boundary coordinates is used for each sub-basin to set the nearest rainfall satellite station in the middle of each sub-basin and, this is done by using the global weather and Google earth capability. The relation between modified rainfall data and the satellite rainfall data has been found. Different types of input data are used in the WEAP model after being modified and calibrated, such as satellite rainfall data, ET_{ref}, effective precipitation, and crop coefficient K_c in the upper Blue Nile basin. The study area has been divided into 16 sub-basins. WEAP model has been applied to the whole Blue Nile basin, keeping the monthly values of K_c same among the different sub-basins for the whole simulated period of 1980–2010. The observed stream flows, using rainfall-runoff relationship, have been simulated with the measured flows by using WEAP model at the four river gauging stations (El-deim, Giwiasi, Hawata and Khartoum) in a monthly time step yielded reasonable values. By evaluating the Blue Nile River Basin at the calibration period (1980–1995) in a monthly time step, the NSE, r^2, and d results for the Blue Nile River at the gauging stations showed a very good model performance.

Keywords: Satellite; Rainfall; Blue Nile River; Flow

1. Introduction

The Nile River, with a length of 6,825 km [1], is the longest river in the world. It comprises of three major tributaries, the Blue Nile; the White Nile, and Atbara river. The White Nile River starts its journey from the Great lakes region of Central Africa to the north. While the Blue Nile starts its journey from Lake Tana in Ethiopia. The Atbara River starts its journey from Ethiopian high lands till it joins the Main Nile river just upstream Atbara in northern Sudan. The Blue Nile River and White Nile River meet in Khartoum, capital of the Sudan, forming the Main Nile River which flows northwards through Sudan, Egypt, and drains finally into the Mediterranean Sea [1]. The 11 countries that share the Nile River Basin are Burundi, Democratic Republic of Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, and Uganda.

Geographically, the BNRB is a transboundary water source shared by Ethiopia and Sudan; nonetheless Egypt is the most benefiting country from its water resources [2].

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The importance of the BNRB can be represented in the huge percentage of its water contribution to the mean Main Nile River flow (51.61%), while it is also unique on its wide seasonal variation in its discharge and problems of erosion upstream (i.e., lost more than 250 million m^3 of topsoil) and sedimentation downstream (i.e., silt accumulation in the reservoirs) [3].

2. Satellite rainfall data

The satellite rainfall data have many applications in applied climatology and biogeochemical modeling, as well as in hydrology and agricultural meteorology. The satellite rainfall data are available through the International Water Management Institute is World Water and Climate Atlas (http://www.iwmi.org), as well as it available at the website of the Climatic Research Unit (http://www.cru.uea.ac.uk).

The satellite rainfall data for all Blue Nile sub-basins were downloaded in a monthly basis for the period 1980–2010 from the Global Weather Data of the National Centers for Environmental Prediction (NCEP) from its website (www.globalweather.tamu.edu). This data were modified with the actual measured rainfall from nearby gauge stations for the period 1993–1999 by using weighting factor depending on the distance between satellite nodes, by using inverse equation number 1. All the modified rainfall data for the 16 Blue Nile River sub-basins were found, as described in Figs. 1–16. The selection of the boundary coordinates is used for each sub-basin to set the nearest rainfall satellite node to the middle of each sub-basin and, this was done by using the global weather and Google earth capability.

$$R_m = \frac{\frac{1}{X^2}}{\left[\frac{1}{X^2+\frac{1}{Y^2}}\right]} \times R_{\text{mst1}} + \frac{\frac{1}{Y^2}}{\left[\frac{1}{X^2}+\frac{1}{Y^2}\right]} \times R_{\text{mst2}} \quad (1)$$

where X: distance (in km) between the nearest satellite rainfall node to the middle of the sub-basin and the first nearest measured rainfall station to the middle of the sub-basin.

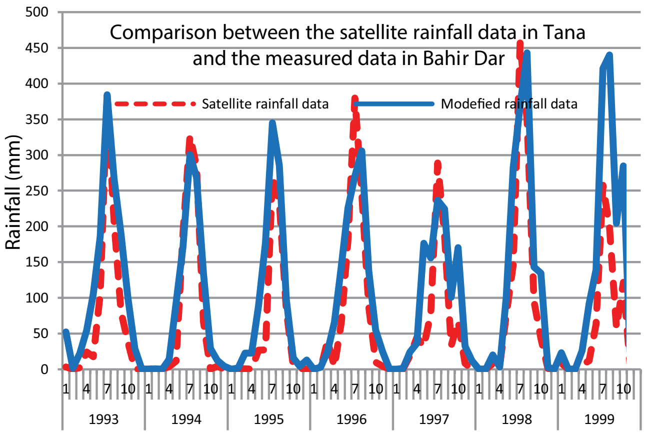

Fig. 1. Adjusted satellite rainfall data for Tana sub-basin.

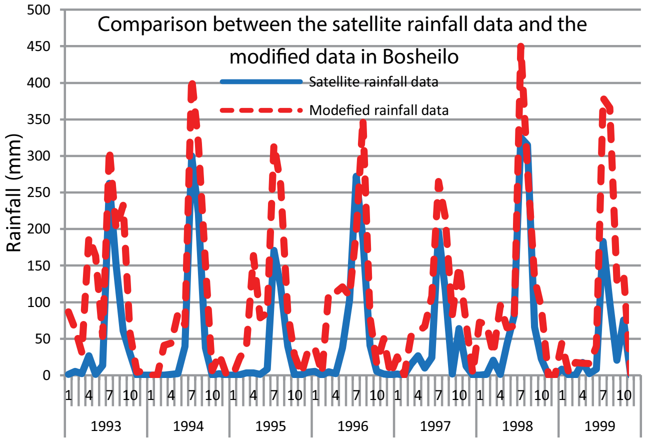

Fig. 2. Adjusted satellite rainfall data for Bosheilo sub-basin.

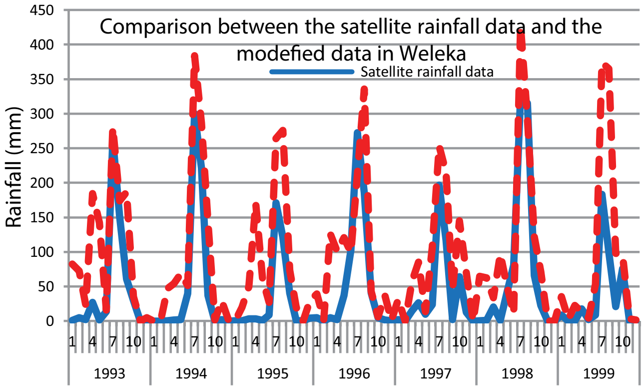

Fig. 3. Adjusted satellite rainfall data for Weleka sub-basin.

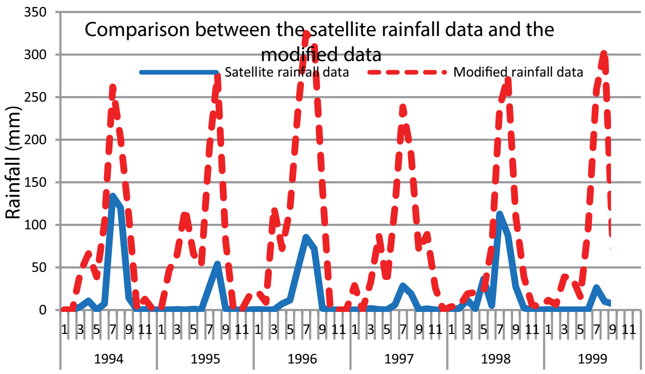

Fig. 4. Adjusted satellite rainfall data for Jemma sub-basin.

Y: distance (in km) between the nearest satellite rainfall node to the middle of the sub-basin and the second nearest measured rainfall station to the middle of the sub-basin.

R_{mst1}: measured rainfall in the first nearest station

R_{mst2}: measured rainfall in the second nearest station

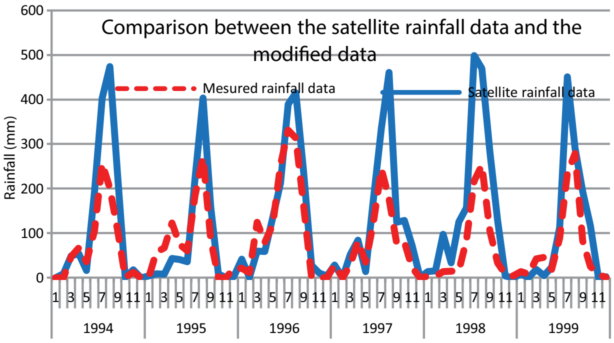

Fig. 5. Adjusted satellite rainfall data for Muger sub-basin.

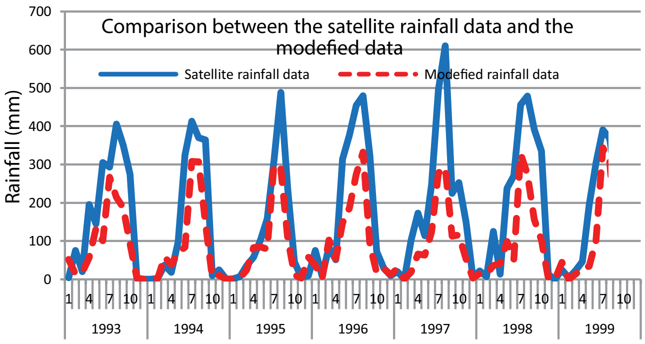

Fig. 6. Adjusted satellite rainfall data for Guder sub-basin.

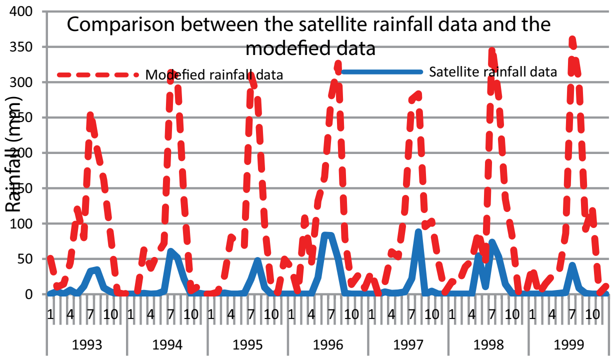

Fig. 7. Adjusted satellite rainfall data for Finchaa sub-basin.

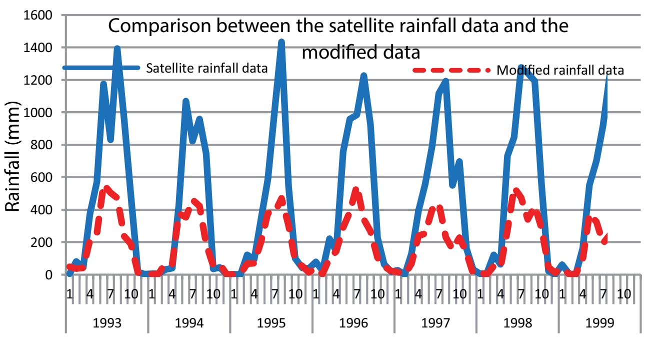

Fig. 8. Adjusted satellite rainfall data for Didessa sub-basin.

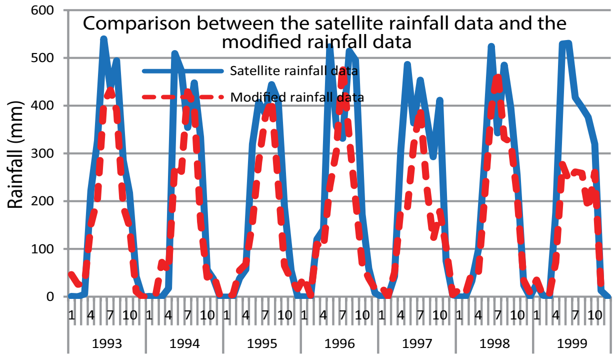

Fig. 9. Adjusted satellite rainfall data for Dabus sub-basin.

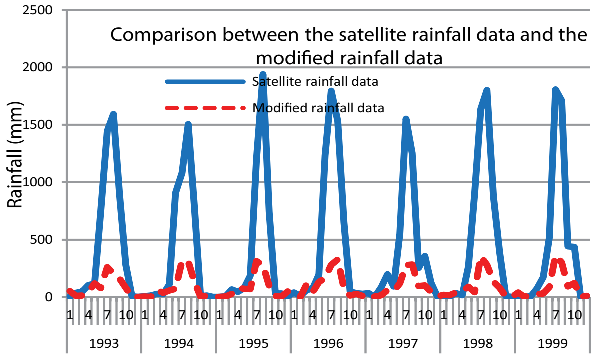

Fig. 10. Adjusted satellite rainfall data for South Gojam sub-basin.

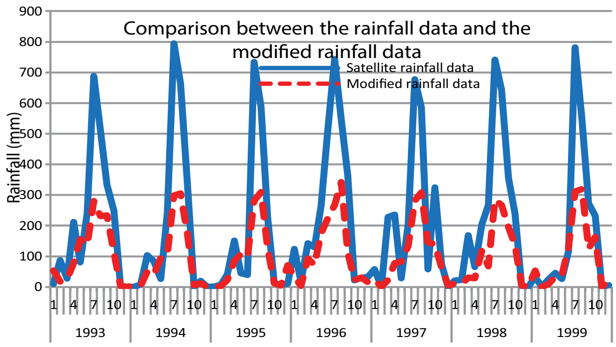

Fig. 11. Adjusted satellite rainfall data for North Gojam sub-basin.

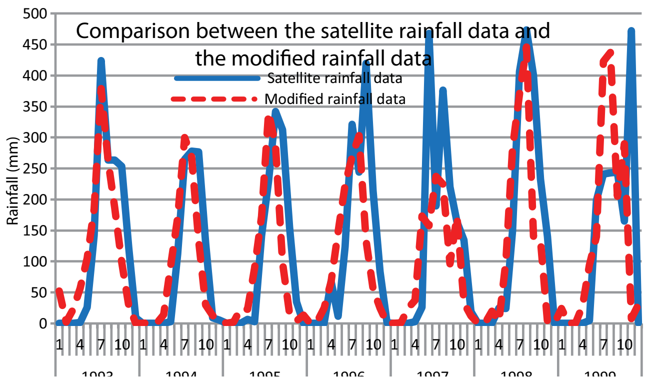

Fig. 12. Adjusted satellite rainfall data for Rahad sub-basin.

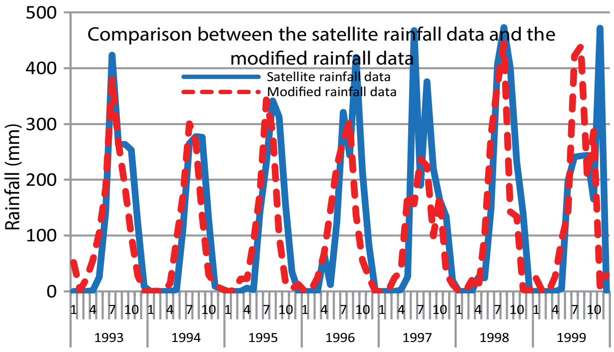

Fig. 13. Adjusted satellite rainfall data for Dinder sub-basin.

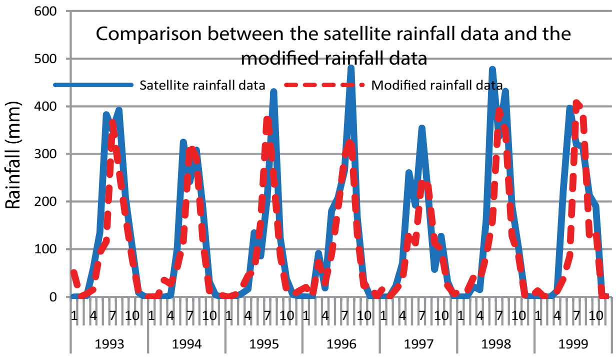

Fig. 14. Adjusted satellite rainfall data for Beles sub-basin.

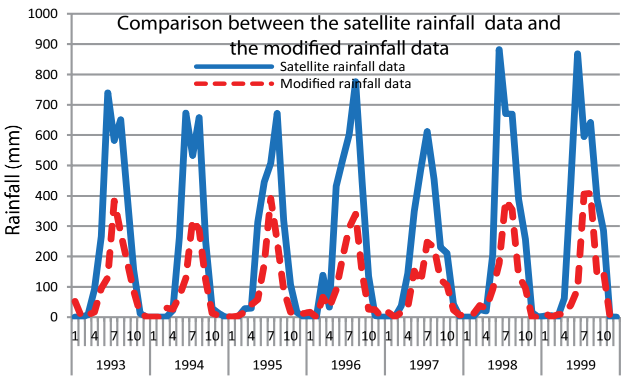

Fig. 15. Adjusted satellite rainfall data for Wonbera sub-basin.

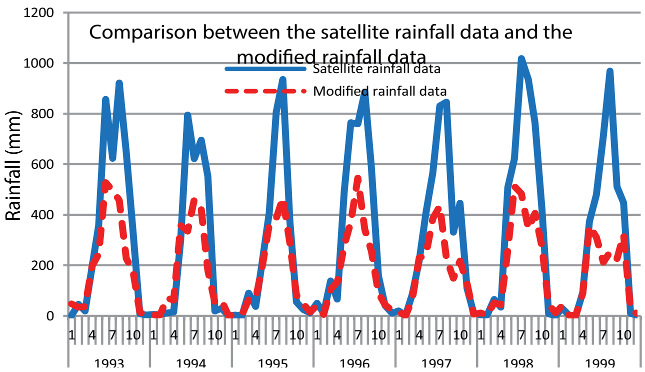

Fig. 16. Adjusted satellite rainfall data for Anger sub-basin.

R_m: modified rainfall for the nearest satellite rainfall station, which represents the rainfall for the middle of sub-basin.

Based on the average monthly ET_{ref} data for the whole Blue Nile Basin [3] and the average annual ET_{ref} data for each sub-basin, the monthly data ET_{ref} for each sub-basin can be found. The monthly ET_{ref} for each sub-basin have been found by multiplying the value of the average monthly of ET_{ref} of the selected sub-basin by the value of the average annual of ET_{ref} of the selected sub-basin divided by the total annual ET_{ref} for the whole Blue Nile Basin.

3. Water balance equation

The water balance equation for the BNRB on monthly basis can be written as (Tekleab, 2010):

$$\frac{ds}{dx} = P - Q - E - L \tag{2}$$

where:

$\frac{ds}{dx}$ is storage change per time step (mm/month).

P is the precipitation (mm/month).
Q is the total monthly runoff (mm/month) depth.
E is the actual monthly evaporation (mm/month).
L is the total loss (such as deep percolation and interception losses).

By assuming storage, fluctuations are negligible over monthly time scale, the water balance equation can be reduced to [4]:

$$P - Q - E - L = 0 \tag{3}$$

$$Q = P - E - L \tag{4}$$

4. Runoff estimation

A comprehensive effort has been made to download the rainfall satellite data from 1980 to 2010 in monthly basis at all of the Blue Nile sub-basins. The simplified rainfall runoff method has been used to determine the contribution of each tributary to the BNRB. The runoff from each BNRB sub-basins are estimated by using the rainfall-runoff simplified method, which considers that each sub-basin within a catchment have different climate data.

$$Q = f\left(P, \mathrm{ET}_{ref}\right) \tag{5}$$

$$Q = P \times A \times f_1 - \mathrm{ET}_{ref} \times \left(A \times f\right) \times K_c \times f_v - L \tag{6}$$

where:

Q is the total monthly discharge (Million m^3/month).
P is the total monthly modified satellite rainfall (mm/month).

A is the sub-basin area.

f_1 is the percentage of each sub-basin area that will be wetted by rainfall.

ET_{ref} is the monthly average evapotranspiration for a reference land class.

K_c is the crop coefficient.

f is the represents the adjusted factor for real and average of ET_{ref}.

f_v is the percentage of the vegetation cover.

L is the loss (=0).

5. Simulation MODEL (WEAP)

In order to test WEAP model's ability and to simulate runoff in the basin, the record was split into two parts. The data for the first 16 years (1980–1995) were used to calibrate the runoff, where the second 15 years (1996–2010) are used for validation process. To determine the adjusted factor for real evapotranspiration for each sub-basin on monthly basis during calibration step, a trial and error procedure with a range of logical values and actual existing was used (average value for the whole Blue Nile Basin), thus the evapotranspiration can be generated.

The WEAP model data have been simulated with the measured stream flows in the four main stations (Eldeim, Giwasi, Hawata, and Khartoum) and it shows a very good performance for the 16 sub-basins of the Blue Nile Basin. The Nash and Sutcliffe efficiency ENS was applied for monthly flow for the period (1980–1995) was found 89% in the Eldeim station, while for the verification period (1996–2010) it was found to be 80%. The model performance was tested also by percentage bias (PBIAS) at Eldeim station at the calibration period which gives (–18.72) a negative value which indicates overestimation simulated data at Eldeim station. As well as other efficient criteria, such as coefficient of determination (r^2) and the index of agreement (*d*) are also considered to test the model performance, where it was summarized in Table 1. Thus the model shows high accuracy in all its tested stations. As well, the model was tested for its efficiencies at the validation period (1996–2010; Table 2).

6. WEAP setup for Blue Nile river basin and simulations

Stockholm Environment Institute (SEI) developed the WEAP model, which was used to evaluate and manage water resources projects. The WEAP model essentially performs different demand calculation methods, such as rainfall-runoff method.

The WEAP model has been selected to be applied as one of the research methodology for its huge advantages, such as easy to use; free 2-year license for research work; its ability for simulation of a wide range of data, rainfall, runoff, and other hydrological data.

A WEAP model was set up for BNRB between Sudan and Ethiopia. The model used different sources for input data and information to establish a transboundary water resources management for the BNRB countries. In particular, the models were required to address different questions to secure sustainability of water resources management in the BNRB.

Long-term monthly total values (January to December) for the research period (1980–2010) as well as total annual values for both water availability and demand were used in the modeling.

The WEAP model first configured to simulate the current situation '1980–2010'. As well as, the research used five different scenarios to assess the situation in the future.

Due to the limitation (availability) of the input data in the WEAP model, that is, 'rainfall' from satellite website for the period 1979 till 2010 from website (www.globalweather.tamu.edu), and easy to calibrate these data with the measured data, the research used the period 1980 to 2010 as a research period.

Table 1
Model efficiencies at selected stations at the calibration period (1980–1995)

Station	River	Nash–Sutcliffe efficiency (NSE) %	Coefficient of determination (r^2) %	Index of agreement (*d*) %
Eldeim	Blue Nile	89	95	97
Giwasi	Dinder	96	98	99
Hawata	Rahad	88	95	97
Khartoum	Blue Nile	67	88	92

Table 2
Model efficiencies at selected stations at the validation period (1996–2010)

Station	River	Nash-Sutcliffe Efficiency (NSE) %	Coefficient of Determination (r^2) %	Index of agreement (d) %
Eldeim	Blue Nile	80	90	95
Giwasi	Dinder	62	84	85
Hawata	Rahad	86	93	96
Khartoum	Blue Nile	72	88	93

7. Analysis and results

The research used the satellite website to download the monthly rainfall data for all Blue Nile sub-basins for the period 1980–2010. Then the satellite rainfall data were modified with the actual measured rainfall stations for the period 1993–1999. Figs. 17–19 show the comparisons between the satellite rainfall data at the middle of Tana sub-basin and the nearest measured rainfall data before (that are Gonder and Bahir Dar stations) and after modification, by using weighting distance factor.

Before the modification, the Nash efficiency was 76%, where after modification the efficiency has been found as 94%, which gives more reliable rainfall data.

8. Water resources projects before Roseires heightening

The current water resources projects demand data were collected from data provided by Sudan Ministry of Water Resources, Irrigation and Electricity, Ministry of Water and Energy (Ethiopia) and agencies or from previous studies, where there is some information obtained from direct contact with responsible and research engineers. The gathering data include different information regarding water flow through the turbines and water required for irrigation in monthly values.

The research makes different assumptions, regarding irrigation return flows, consumption, maximum monthly flow percentage of demand (withdrawal), loss from system (return flow).

The research used Eq. (1) to calculate monthly time series runoff from all Blue Nile sub-basin. As well as, the research used a joint calibration to calibrate the rainfall runoff model for flow time series. The research considered each sub-basin, within the model domain to find realistic parameters. The adjusted factors of evapotranspiration in monthly basis, for all the 16 sub-basins, have been used to evaluate the efficiency of the WEAP model (at Eldeim station), at Giwasi (Dinder), Hawata (Rahad) and finally the WEAP model performance has been evaluated for all the Blue Nile basin (at Khartoum station; Fig. 20).

In order to test WEAP model's ability and to simulate runoff in the basin, the record was split into two parts.

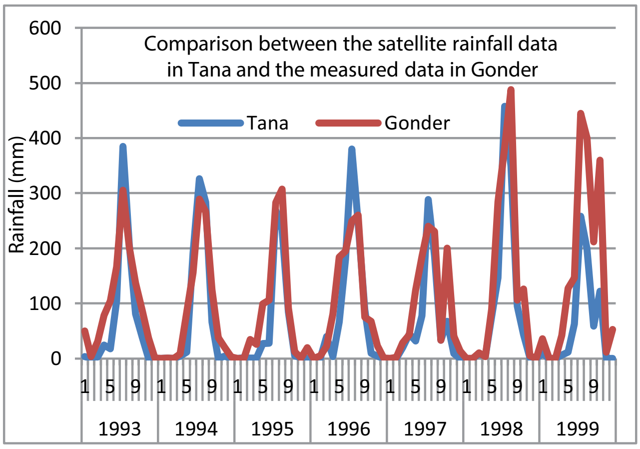

Fig. 17. Comparison between the satellite rainfall data at middle of Tana sub-basin and Gonder rainfall station (before modification).

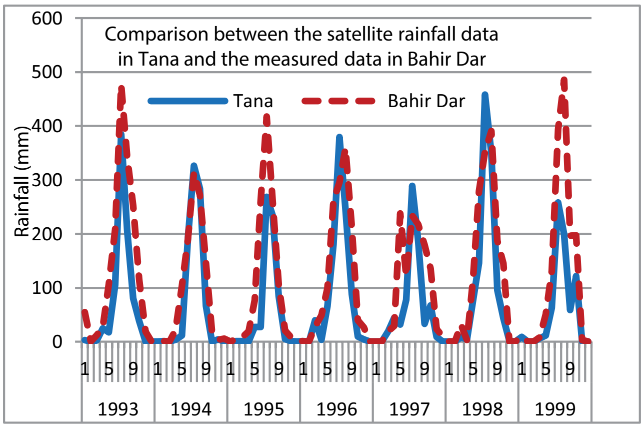

Fig. 18. Comparison before modification, satellite rainfall data at middle of Tana sub-basin and Bahir Dar rainfall station.

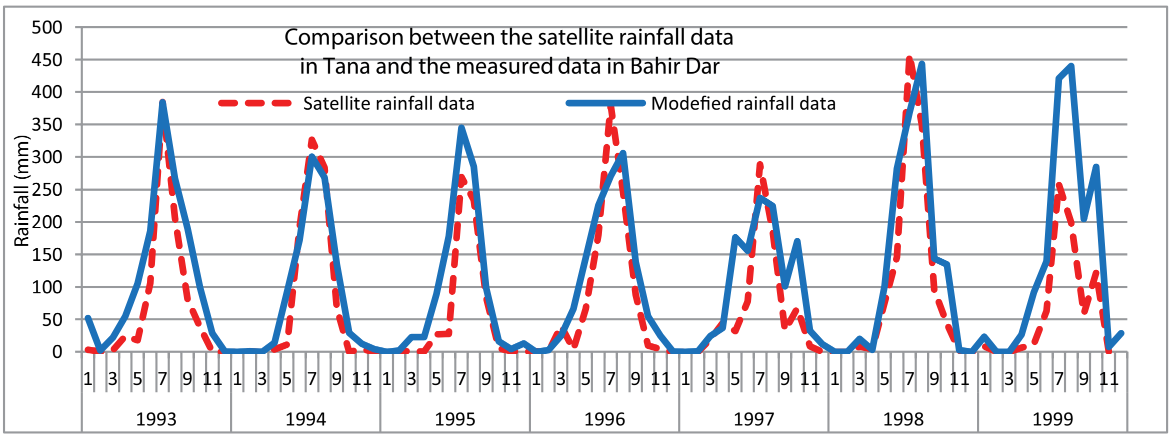

Fig. 19. Comparison after modification between satellite rainfall data at middle of Tana sub-basin and at the Gonder and Bahir Dar rainfall stations.

The data for the first 16 years (1980–1995) were used to calibrate rainfall and runoff purposes, where the second 15 years (1996–2010) are used for validation.

The WEAP model data have been calibrated and validated against the historical stream flow data, by using different types of efficiencies, in the four main stations (Eldeim, Giwasi, Hawata and Khartoum), as it can be seen in Tables 3 and 4.

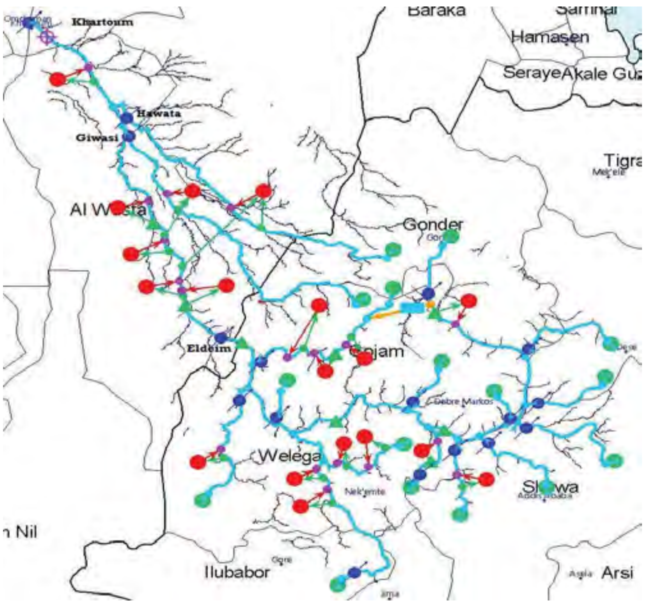

Fig. 20. Schematic of the BNRB in the WEAP model.

During the calibration period (1980–1995), the WEAP model efficiency was calculated using Nash and Sutcliffe method (ENS) for monthly flow prediction in Eldeim station and was found to be 89% (as in Table 3), while for the verification period (1996–2010) it was found as 80% (Table 4). The model performance was tested also by using percentage bias (PBIAS) method at Eldeim station for the calibration period which gives (–18.72), where the negative value indicates there was an overestimation simulated data at Eldeim station; as well as other efficient criteria such as coefficient of determination (r^2) and the index of agreement (d) are considered to test the model performance, as it was summarized in Tables 3 and 4. Thus the model shows high accuracy in all the tested stations, where it was suggested that the WEAP model has high degree of efficiencies during the calibration and validation periods, thus it can be used for future analysis for flows in Eldeim station and other gauged (Giwasi, Hawata, and Khartoum); as well as the model can be used at any ungauged stations. Table 5 and Fig. 21 show the proposed future structural scenarios and expected result obtained by WEAP model, respectively.

9. Discussion

In 2011, the Blue Nile Basin countries consumed about 7,803 Million m^3/year (196.9 Million m^3 for Ethiopia, and 7,606.2 Million m^3 for Sudan) to satisfy irrigation requirements. At the same time, the production of the hydropower from the Blue Nile Basin reaches at the current status 513 MW (218 MW benefits by Ethiopia, and 295 MW benefits by Sudan), where it reaches up to 9,493 MW in 2031

Table 3
Model efficiencies at selected stations at the calibration period (1980–1995)

Station	River	Nash–Sutcliffe efficiency (NSE) %	Coefficient of determination (r^2) %	Index of agreement (d) %	PBIAS
Eldeim	Blue Nile	89	95	97	O.E.
Giwasi	Dinder	96	98	99	O.E.
Hawata	Rahad	88	95	97	O.E.
Khartoum	Blue Nile	67	88	92	O.E.

O.E.: overestimation values.

Source: Prepared by the researcher.

Table 4
Model efficiencies at selected stations at the validation period (1996–2010)

Station	River	Nash-Sutcliffe Efficiency (NSE) %	Coefficient of Determination (r2) %	Index of agreement (d) %	PBIAS
Eldeim	Blue Nile	80	90	95	O.E.
Giwasi	Dinder	62	84	85	U.E.
Hawata	Rahad	86	93	96	U.E.
Khartoum	Blue Nile	72	88	93	O.E.

O.E.: overestimation values.

U.E: underestimation values.

Table 5
Proposed future scenarios

Scenario number	Scenario code	Description
Scenario 1	S – 1	This scenario considered construction of Tana-Beles and Roseries Dam Heightening (TBRDH), considering all projects in Current situation, for the period 2011–2016
Scenario 2	S – 2	This scenario considered construction of Grand Ethiopian Resilience Dam (GERD), considering all projects in S-1, for the period 2017–2023
Scenario 3	S – 3	This scenario considered construction of Karadobi Dam with others future irrigation projects, considering all projects in S-2, for the period 2024–2030
Scenario 4	S – 4	This scenario considered construction of Mendaya dam, considering all projects in S-2, for the period 2024–2030, as parallel scenario to S-3
Scenario 5	S – 5	This scenario considered construction of all projects in S-3 and S-4, for the period 2031–2040

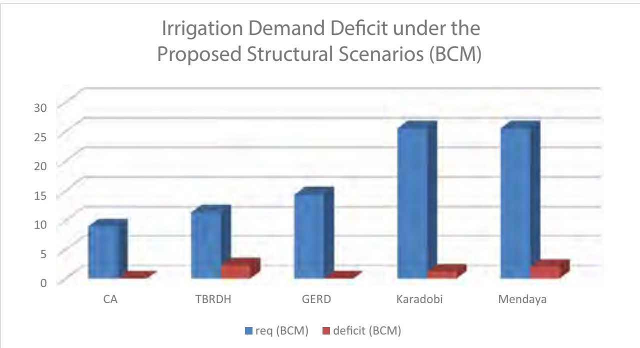

Fig. 21. WEAP results for selected structural scenarios for irrigation water requirements.

(9,148 MW utilized by Ethiopia, and 345 MW utilized by Sudan).

In setting WEAP for Blue Nile River Basin (WEAP_BNRB), it is required to define the priority order in the systems for all water resources projects, and for filling reservoirs and generating hydropower. The research gave a high priority for hydropower production in Ethiopia (=1) and lower in Sudan (2), whereas the research gave higher priorities for irrigation in Sudan (=1) and lower in Ethiopia (=2).

Regarding Scenario (S-1), there are irrigation demands deficit for Gezira and Sennar-Khartoum and for other irrigation projects, which can be due to the increased amount of the Roseries storage after heightening, especially due to the increase in the top of inactive (volume in reservoir not available for allocation), which was increased from 30.1 Million m^3 (in the current situation 2010) to 172.4 Million m^3.

One of the main research contributions is the establishment of different types of data bank for the BNRB, independent of the intervention of the human being, especially for the transboundary river basin and hence not waiting for data sharing protocol which may take a long time to be realized.

Regarding Scenario (S-2), there are unmet demands to satisfy the irrigation requirement, especially in 2017, due to the first filling of the reservoir [5]. There are only 9% irrigation demand deficit for Gezira scheme, and 7.8% for Sennar-Khartoum schemes. Also, there is 18.7% unmet demand for irrigation project in Finchaa which is due to the proposed extension of the project. This simulation has been made by giving a less priority to reservoir filling (priority = 3). At the same time, the research assumes high hydropower priority (=1), when comparing with the other demands.

Regarding (S-3), it has been noticed that there are no unmet irrigation demands for Gazira and all other Sudanese irrigation projects except for the whole future irrigation projects (i.e., Kenana-1, Kenana-II, Kenana-III, Kenana-IV) with about 9%. For Ethiopian irrigation projects, it has been noticed that there is 83% unmet demand for Lower and Upper Beles irrigation water projects.

Regarding Scenario (S-4), it has been noticed that there are no unmet irrigation demands for Gazira and all other Sudanese irrigation projects except for the whole Future irrigation projects (i.e., Kenana-1, Kenana-II, Kenana-III, Kenana-IV) with about 15.6%. For Ethiopian irrigation projects, it has been noticed that the whole water requirement for Lower and Upper Beles irrigation water projects is unmet.

Regarding Scenario (S-5), it has been noticed that there are no unmet irrigation demands for Gazira and all other Sudanese irrigation projects except for the whole Future irrigation projects (i.e., Kenana-1, Kenana-II, Kenana-III, Kenana-IV, Dinder, Roseries, Rahad-II and Rahad-III) with 40%, where the total water requirements are 9.43 BCM. For Ethiopian irrigation projects, it has been noticed that there is about 24% unmet demand for Lower and Upper Beles irrigation water projects.

Regarding Scenario (S-5), the research also examined the Blue Nile River Basin by changing the GERD reservoir-filling priority to be something of less priority (=3). It has been noticed that in this case there are no unmet irrigation demands for all the Sudanese irrigation water projects.

10. Conclusion

Rainfall-runoff relationship is a tool to predict the river discharge. Based on the mathematical relationship and assumptions in the rainfall-runoff relationship for the BNRB, a simplified rainfall-runoff relationship was used to predict the monthly flows.

Different water management models exist, but WEAP model has been selected to adapt current and future analysis regarding water resources projects.

The Blue Nile River has 16 major sub-basins, with a total basin area of 203,665 km^2, and average annual flow of about 51.61% when comparing with the annual flow of the Nile River for the simulation period (1980–2010). This large percentage reaches up to 72% of the Nile River flow in the flood period (July, August and September).

The satellite rainfall data for all Blue Nile sub-basins were downloaded in a monthly basis for the period 1980–2010 from the Global Weather Data website for the National Centers of the Environmental Prediction (NCEP; www.globalweather.tamu.edu).

The satellite rainfall data were modified with the actual measured rainfall from nearby gauge stations for the period 1993–1999 by using a weighting factor depending on the distance between satellite data.

The selection of the boundary coordinates was used for each sub-basin to set the nearest rainfall satellite station in the middle of each sub-basin and, this was done by using the global weather and Google earth websites.

The research used the satellite rainfall data for all Blue Nile sub-basins which was downloaded on a monthly basis for the period 1980–2010 from the Global Weather Data. The downloaded satellite rainfall data were modified with the actual measured rainfall from the nearest available gauge station. Using the below simplified rainfall-runoff relationship, the research obtained the runoff in monthly time steps for each Blue Nile sub-basins at its outlet utilizing the capability of WEAP.

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Rainfall-runoff estimation and comparative analysis using SCS method based on GIS

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ABSTRACT

Accurate estimation of runoff and sediment yield amount is not only an important task in physiography but also important for proper watershed management. Watershed is an ideal unit for planning and management of land and water resources. Direct runoff in a catchment depends on soil type, land cover and rainfall. Of the many methods available for estimating runoff from rainfall, the curve number method (SCS-CN) is the most popular. The curve number depends upon soil and land use characteristics. This study was conducted in the Kaam watershed in north western Libya using remote sensing and GIS. SCS-CN method has been used for surface runoff estimation for five sub-watersheds of Kaam. The soil map, land use and slope map were created in the GIS environment, because the curve number method is used here as a distributed model, it is necessary to obtain information on a large number of sub-catchments in the basin. Therefore, remote sensing and GIS techniques were used. The major advantage of employing GIS in rainfall -runoff modelling is that more accurate sizing and catchment characterization can be achieved. Furthermore, the analysis can be performed much faster, especially when there is a complex mix of land use classes and different soil types, Landsat satellite image was used to obtain ground cover information. The thematic layers such as the soil map, elevation map, rainfall map and ground cover map were created in Arc GIS 10.3. Then was set the values of Curve numbers in the study area, and by applying the SCS-CN method, the results showed that the surface runoff ranged from 94 to 165 mm in the study area, when rainfall rates were received from 204.07 to 284.6 mm. To find the relationship between rainfall and runoff rates, the straight line equation was used, That was found there a strong correlation between runoff and precipitation rates. The value of the determination coefficient was 73% and the correlation coefficient between them 85%. Through these results, the study recommends taking advantage of runoff rates by reserving them at collection of sub basins and then using them for agricultural purposes in the vicinity. This would be better than reserving water from the total area of the basin, which is 2,283 square kilometres, and then will evaporate or infiltrate before reaching the dam lake.

Keywords: GIS; SCS method; Rainfall-Runoff; Watershed; Land use

1. Introduction

The determination of the runoff value is necessary for designing dams, reservoir management, and prediction of risks and potential losses caused by flooding. Also, determining amount of the runoff is very important in projects related to sediment and erosion processes. Surface runoff and sediment losses are the two important hydrologic responses from the rainfall events occurring over the watershed systems (Gajbhiye et al. 2014c). Rainfall generated runoff is very important in various activity of water resources development and management such as a flood control and its management, irrigation scheduling, design of irrigation and drainage network, hydro power generation, etc. (Mishra et al. 2013). A watershed is an area covering all the land that contributes water after rainfall occurs to a common point. Watershed management programme is mainly for conservation and development of natural resources, where most

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of the watersheds in Libya are ungauged, having no past records of the rainfall-runoff process. There are several flow estimation methods for ungauged catchments such as rational method, SCS-curve number method, cook's method and unit hydrograph method. The Soil Conservation Service developed curve number method for predicting direct runoff or infiltration from rainfall excess of ungauged watershed. Soil and land use parameters which control surface runoff can be evaluated and mapped significantly through Landsat Thematic Mapper (Sharma et al. 1992). Curve Number method (SCS-CN) is one of the most widely used approaches for fast and accurate calculation of the basin surface runoff. This approach involves the use of a simple empirical formula and readily available tables and curves. Also, this method has been used more and provides accurately automatic runoff prediction by connected with the geographical information system (GIS). In recent decades, most researchers have considered the use of GIS (Patil. 2008). Remote sensing and GIS techniques are widely used in the determination of spatial distribution of the catchments ecosystem characteristics and their impact on catchments hydrology (Takeli et al. 2006, Sharma et al. 2001). GIS, which has been designed to restore, manipulate, retrieve and display spatial and non-spatial data, is an important tool in analysis of parameters such as land use/land cover, soils, topographical and hydrological conditions. To carry out resource monitoring and assessment of area of interest, information derived through remote sensing data has to be merged or integrated with database in GIS, Thus the remote sensing along with GIS application aid to collect, analyse and interpret the data rapidly on large-scale intermittently and is very much helpful for watershed planning (Sharma et al. 2014c; Gajbhiye 2014). Conventional methods of runoff estimation using SCS model are time consuming and error prone. Thus, remote sensing and geographical information (GIS) techniques are being increasingly used, as all the factors of SCS model are geographic in character. Due to geographic nature of these factors of SCS runoff model can easily be modelled into GIS data.

2. Materials and methods

2.1. Study area

Kaam Basin located within the coastal areas to the west of Libya, which is one of the large basins where rainwater accumulates, where the storage capacity has about 111 m^3. The catchment area has about 2,283 square kilometres, as well as the average height above sea level of about 283.5 m, the basic purpose of its establishment is a reservation rainwater and floods which amounts to an average of about 15 million m^3 a year, which was to go to the Mediterranean without the benefit of them. Fig. 1 shows the location map of study area.

2.2. Data source

Digital map of the soils Libyan study covers the area from previous studies (agricultural mapping project, the Ministry of Agriculture, 2006) at a scale of 1:1,000,000. Digital map land cover of the study area from previous study (agricultural mapping project, the Ministry of Agriculture, 2006) at a scale of 1:250,000. Digital Elevation Model at a resolution of 30 m was used to extract the sub-watershed, Arc Map 10.1 software was used for creating, managing,

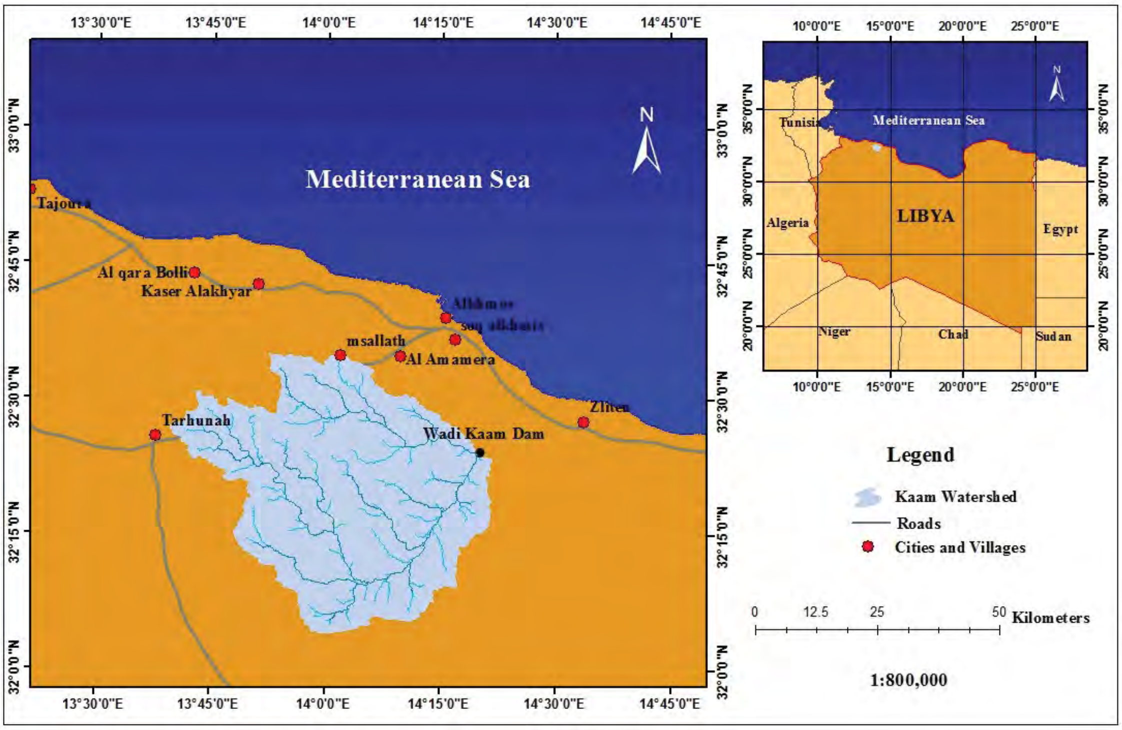

Fig. 1. Location of the study area.

and generating different layer and maps. The Microsoft Excel was used for mathematical calculation.

2.3. Methodology

Preparation of various thematic maps by ArcMap10.1 soil map of the study area, drainage map, slope map and land use/land cover map.

2.3.1. Soil map

Soils were classified according to the sub-watershed hydrological soil groups (HSG) of the US Department of soil conservation, as in Table 1, There are main two types of soil in the present study area which comes under the hydrologic soil group A, B.

2.3.2. Elevation map

The use of geographic information systems software Arc map 10.1 for the analysis of Digital Elevation Model and to obtain a topographic characteristic of the sub-watershed and drainage network extraction and slope. Fig. 2: shows the Hydrology Model.

Table 1
Hydrological soil groups

Texture	HSG
Sandy, loamy, sandy loam	A
Silt loam or loam	B
Sand clay loam	C
Clay loam, silt clay loam, sandy clay, silt clay, or clay	D

2.3.3. Curve number map

To create the CN map, the soil map and land use map were uploaded to the Arc GIS. The soil map and land use map were selected for intersection, after intersection a map with new polygon representing the merged soil-land map. The appropriate CN value for each polygon of the soil-land map was assigned.

$$\text{CN} = \left(\sum \frac{(\text{CN}_i \times A_i)}{A} \right) \tag{1}$$

where,

CN = weighted curve number.
CN_i = curve number from 1 to 100.
A_i = area with curve number CN_i.
A = the total area of the watershed.

2.3.4. Determination of rain distribution by Thiessen method

The average precipitation over the study area was calculated from rainfall data from period by Theissen polygon method using the following equations:

$$P_{\text{Average}} = \frac{P_1 \times A_1 + P_2 \times A_2 + P_3 \times A_3 + \cdots}{A} \tag{2}$$

where:

P_A = precipitation in polygon A.
A_1 = Area of polygon 1.
A = the total area of the watershed.

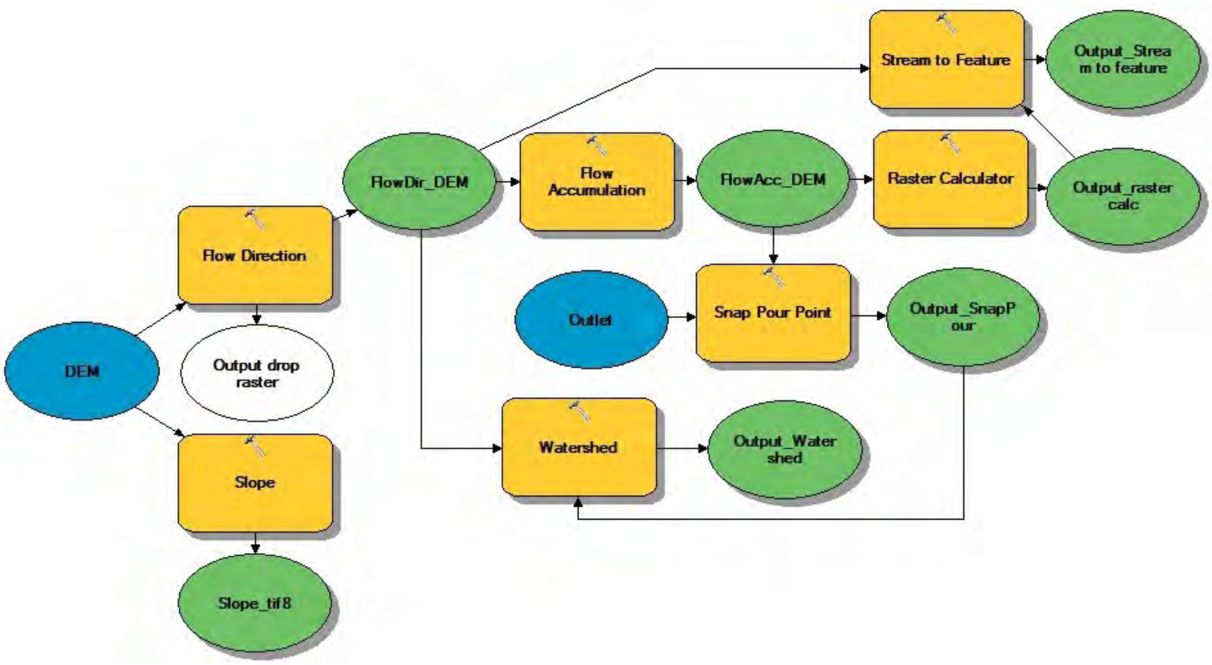

Fig. 2. Hydrology model.

2.3.5. *Estimation of runoff depth using SCS model*

SCS method estimates the runoff according to rainfall and characteristics of basins. So it is appropriate for estimating runoff where there is no station for the flow measurement in the basin. The SCS empirical method proposed by the US Soil Conservation Service is widely used for estimating direct runoff. The SCS method that is also well known as curve number method is based on water balance. The following equation is used for estimating runoff:

$$Q = \frac{\left(P - 0.2S\right)^2}{\left(P + 0.8S\right)} \quad (3)$$

Eq. (1) is true for $P > Ia$, otherwise the estimated runoff to be zero. Initial retention (Ia) is in fact part of the precipitation that does not participate in the runoff and is considered equal to Ia = 0.2 S in SCS:

$$S = \frac{25{,}400}{\text{CN}} - 254 \quad (4)$$

where,

Q = runoff depth (mm).
S = maximum recharge capacity.
CN = curve number.
P = rainfall depth (mm).

3. Results and discussion

To apply this method to Kaam catchments, the available land use and soil type maps were processed using GIS techniques. To determine the HSG, the USDA soil texture must be known. This can be determined according to the percentage of sand, silt, and clay. Table 2 Classifies the HSG by its USDA soil texture. In the GIS-based SCS-CN method, the CN and average rainfall values were used as inputs to compute yearly runoff for various curve numbers, the

Table 2
Calculation of Weighted Curve Number for AMC II

Area%	Area/km^2	CN	HSG	Land use
0.33	7.71	67	A	Irrigated plants
0.15	3.51	78	B	
18.35	419	49	A	Plants pain fed
3.88	88.71	69	B	
1.42	32.53	63	A	Barren rocks
1.83	41.91	77	B	
1.06	24.28	77	A	Barren soils
1.62	37.05	85	B	
0.41	9.45	77	A	Urban area
0.13	3	85	B	
64.16	1465	68	A	Herb plants
6.28	143.40	79	B	

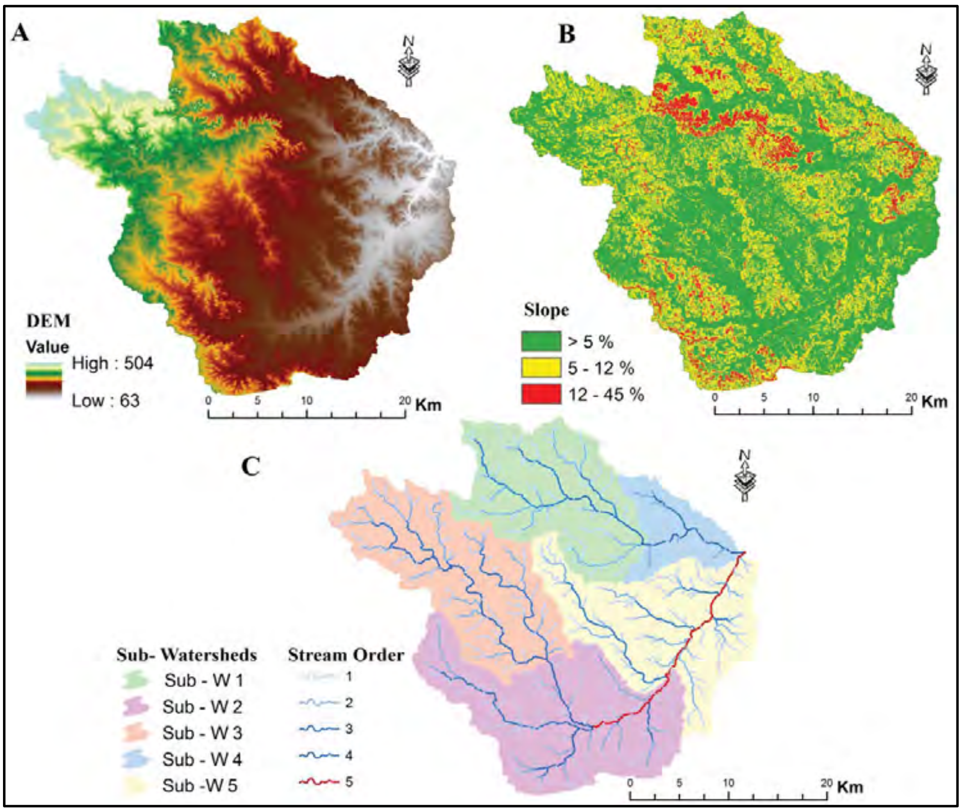

Fig. 3. A (DEM map), B (slope map) and C (sub-watershed map).

individual composite curve number was computed for all study area for AMC II condition using Eq. (1). Fig. 4 shows hydrological soil group, land use/land cover, CN map of Kaam sub-watershed.

SCS developed soil classification system that consists of four groups, which are identified as A, B, C and D according to their minimum infiltration rate. CN values were determined from HSG and AMC of the watershed. For the present study, average condition (AMC II) is selected foe study area. Runoff curve numbers for AMC II. Different layers of land use/land cover, soil, HSG were added in attribute table using union tool in ArcGIS 10.1. The result obtained from union attribute was used to compute weighted area curve number of the study area. Calculated value of CN is 88.14 (taking CN = 65) in Table 2.

Runoff mapping: runoff potential has been estimated using Soil Conservation Service (SCS) model. Maps for various parameters have been generated and finally a map showing variation in annual runoff potential has been prepared. Fig. 5 shows rainfall map, runoff map, runoff coefficient map, of Kaam sub-watershed.

SCS-CN method has been used for surface runoff estimation for five sub-watersheds of Kaam and the parameters of all sub-watersheds shown in Table 3.

The weighted CN value of sub-watershed 1, 2, 3, 4, and 5 comes to be 64,58, 63, 68, and 70, respectively. The runoff value for sub-watershed 1, 2, 3, 4, and 5 to be 165.07, 129.78, 94.57, 163.75, and 122.63, respectively. It can be inferred from Table 3. There is no provision for runoff monitoring in Kaam watershed; therefore this method could be used to find out the runoff. Thus the generated curve numbers may be used for prediction of runoff from an ungauged watershed. To using 20 years rainfall data from 1980 to 2000 runoff has been calculated for five sub-watersheds and graphs was drawn.

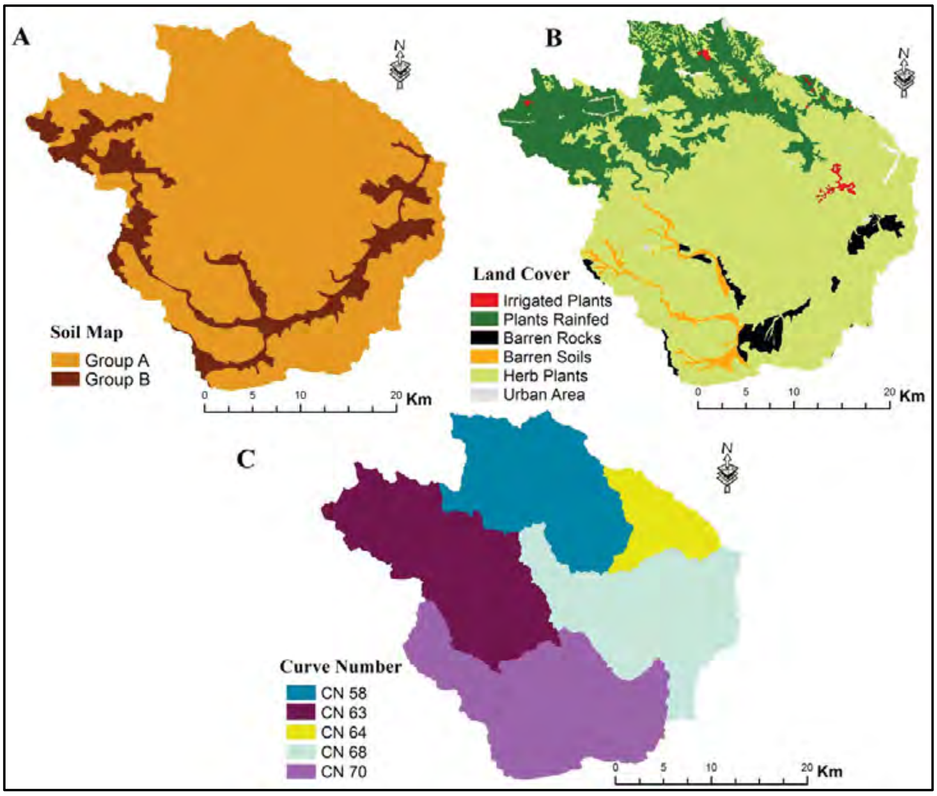

Fig. 4. A (hydrological soil group), B (land use/land cover map) and C (CN map).

Table 3
Average rainfall - runoff depth of kaam sub-watershed for season (1980–2000)

Sr.no	Sub-watershed	Area (km^2)	Storage coefficient (S) mm	CN	Rainfall (mm)	Runoff (mm)
1	Sub1	153	141.6	64	284.60	165.07
2	Sub2	460	182.4	58	268.35	129.78
3	Sub3	547	147.6	63	204.07	94.57
4	Sub4	516	114.6	68	264.39	163.75
5	Sub5	602	106.2	70	212.10	122.63

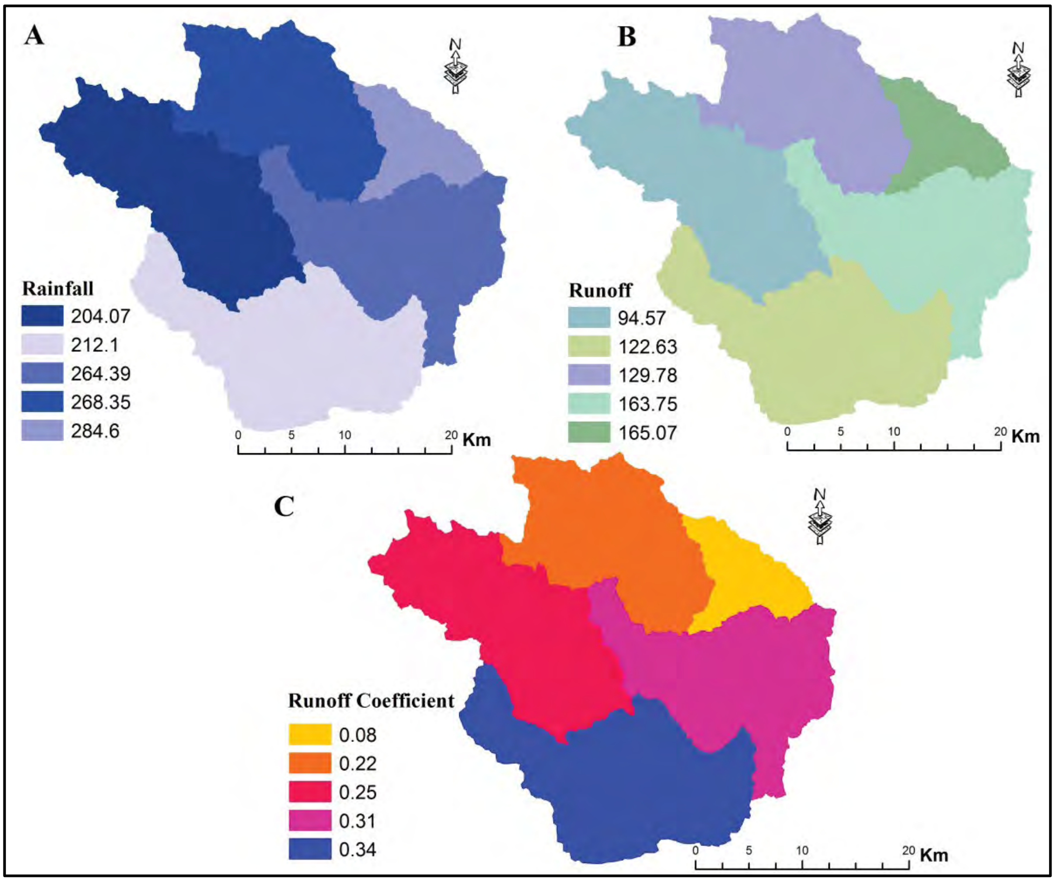

Fig. 5. A (rainfall map mm), B (runoff map mm) and C (runoff coefficient map).

Fig. 6 showing bar chart yearly variation of rainfall-runoff rate for five sub-watersheds in Wadi Kaam for 20 years 1980 to 2000.

To check the performance of curve number method, the calculated yearly runoff and the daily rainfall data were plotted using MS Excel to develop the relationship between them used to find the correlation coefficient of the data, the relationship between rainfall-runoff is shown in Fig. 7. The figure indicates that rainfall and runoff are strongly correlated with correlation coefficient (*r*) value being 0.855.

4. Conclusions

The estimation of runoff using GIS-based SCS curve number method can be used in watershed management

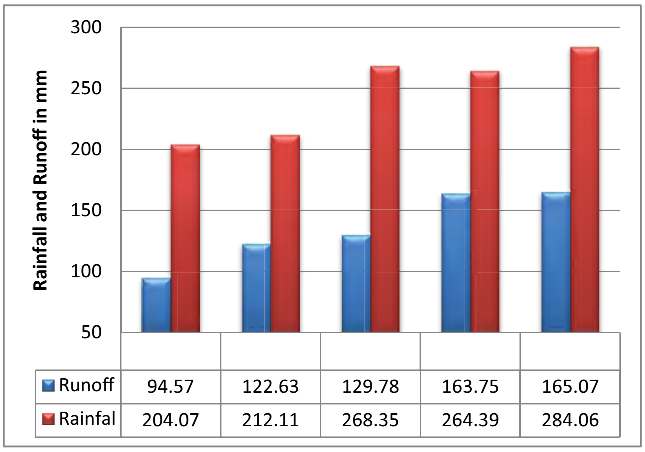

Fig. 6. Graph of rainfall-runoff rate for five sub-watersheds of period 1980–2000.

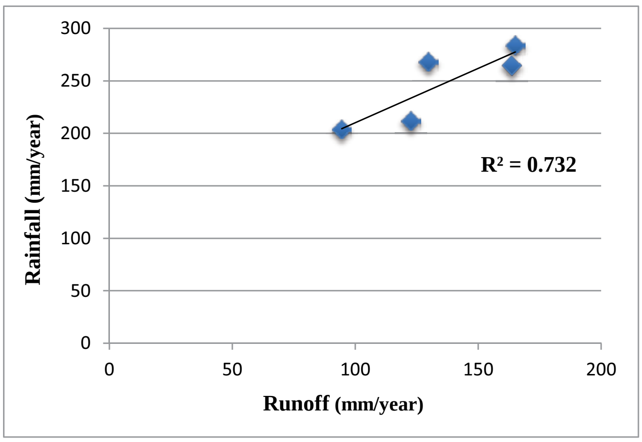

Fig. 7. Relationship between Average Rainfall and Runoff from (1980–2000).

effectively. All the factors in SCS model are geographic in character. Due to the geographic nature of these factors, SCS runoff model can be easily modelled into GIS. The study demonstrates the importance of remotely sensed data in conjunction with GIS to derive the model parameter to estimate surface runoff from the ungauged watershed. Results obtained clearly shows the variation in runoff potential with different land use/land cover and with different soil conditions. Based on the digital database creation, conservation techniques such as percolation pond, check dam, etc., can be recommended for better management of land and water resources for sustainable development of the watershed. In the present study, the process of runoff computation using SCS-CN model in GIS environment has been presented. Remote sensing and GIS with application of SCS-CN model proves to be a powerful tool for runoff estimation. Land use planning and watershed management can be done effectively and efficiently using SCS-CN number method with GIS. The SCS-CN method is a widely used method for estimating the surface runoff volume for a given rainfall event. The major advantage of employing GIS in rainfall-runoff modelling is that more accurate sizing and catchment characterization can be achieved. Furthermore, the analysis can be performed much faster, especially when there is a complex mix of land use classes and different soil types.

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Automatic calibration of arid rainfall-runoff model for Wadi Thara Western Kingdom of Saudi Arabia

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ABSTRACT

Input parameter calibration to rainfall-runoff models is the most critical stage of the overall flood modeling processes, where the input parameters values are adjusted to make the simulated flood hydrographs fit the corresponding records. Wadi Thara (275 km^2) in the Western Kingdom of Saudi Arabia (KSA) is selected and hourly rainfall data are extracted from the paper charts. Five-minute observed runoffs are analysed and ASTER Digital Elevation Model (DEM) with 30-m pixel size is processed to compute automatically the morphometric parameters and to extract the geometric features of the catchment. hydrological soil group map and land cover/land use (LCLU) map are developed to estimate the excess rainfall using composite SCS curve number (SCS-CN). Clark unit hydrograph (Clark-UH) time of concentration approach is used to transform the excess rainfall to flood hydrograph. Four parameters are chosen for calibration, which are SCS-CN, initial abstraction (I_a), Clark-UH time of concentration (T_c) and Clark storage coefficient (R). Nine observed runoff events are selected for modeling; seven different events are chosen for parameter calibration and two for parameter validation. This study focuses on calibrating the peak flow only, which is one of the most critical hydrograph characteristics in rainfall-runoff modeling in arid regions. Calibration process produced exact peak flow for five out of seven events and one event with very close match (–2.6% of change). On the average parameters, calibrations for SCS-CN, I_a, T_c and R are 81.6, 11.0 mm, 3.81 h and 1.88 h, respectively, where R is the most highly variable parameter with 139% coefficient of variation. The reason behind this variation may be because of the local search algorithms usage, which produce local minimum objective function and assign optimized value to the parameter that is not in existence, also the selected hydrological methods are lumped, where the spatial rainfall variation and the other input parameters are not taken into consideration. In the validation process, the four average calibrated parameters are used to validate two events, the first event produced a peak flow with –50% change, which can be considered as relatively high, while the second event resulted in a peak flow with –6.0% change). The value of calibrated parameters is very valuable and can be used in the future for the same and similar catchments. More optimization module applications may be needed with global search algorithm and multiple objective functions to enhance the estimated parameters in future studies.

Keywords: Automatic calibration; Parameter optimization; Rainfall runoff model; Arid regions; Kingdom of Saudi Arabia; Wadi Thara

1. Introduction

The input parameters calibration to the rainfall-runoff models is the most critical stage of the overall flood modeling processes. Unfortunately, these input parameters are usually highly variable in space and difficult to estimate properly for ungauged catchments (Yang et al., 2018). For Wadi systems with runoff gauging station (gauged catchments), the calibration techniques help to optimize (enhance) the parameter estimation. The optimization process adjusts the input hydrological model parameters to produce a flood hydrograph simulation that closely matches the observations (Duan et al., 2003). Historically, parameter optimization techniques back to the start of digital revolution in the 1960s of the previous century (i.e., Rosenbrock, 1960, Nelder and Mead 1965).

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Nowadays, parameter optimization can be achieved automatically using computer capabilities (Todini and Biondi, 2017). Calibration techniques can be categorized in different approaches, by the objective function, the optimization techniques can be divided into single or multiple objective functions, and by the search algorithms into local or global search. In this paper, Hydrological Engineering Center – Hydrological Modeling system (HEC-HMS) software by Corps of engineers in US Military is used, and HEC-HMS is commonly used to simulate the surface runoff hydrograph based on basin rainfall and the physiographical characteristics.

Several methods are available in HEC-HMS to develop surface response basin simulation. In this study, soil conservation services curve number (SCS-CN) method (Soil Conservation Services, 1985) is used to compute the effective rainfall (excess rainfall), while Clark synthetic unit hydrograph (Clark-UH) method is selected and the time of concentration (T_c) equation developed by Arizona Department of Transportation (ADOT, 1993) is implemented. These two methods are categorized as lumped empirical approaches and usually used in single event rainfall-runoff modeling (Feldman, 2000).

Optimization module of HEC-HMS software has 12 different objective functions "Goodness-of-fit Index" (Scharffenberg, 2016), which all are single objective function and none of them are multi-objective function. Two search algorithms are available in HEC-HMS, which are univariate-gradient search and Nelder and Mead algorithms (Skahill, 2016). Both search algorithms are local and none of them is global. Several attempts have been made for using optimization module of HEC-HMS software in rainfall-runoff modeling in Arab arid regions (Hammouri and El-Naqa, 2007, Abushandi and Merkel, 2013, Laouacheria and Mansouri, 2015, El-Alfy, 2016, Skhakhfa and Ouerdachi, 2016, Derdour, et al. 2017, Rahman, et al. 2017).

The aim of this study is to investigate the optimization of four input parameters to rainfall-runoff models for peak flow discharges calibration in Wadi Thara Western of Kingdom of Saudi Arabia (KSA).

2. Study area

Wadi Thara is an upper sub-basin of Wadi Allith, which drains into the Red Sea, located in Tihama Escarpment Mountains of the Arabian shield on the western cost of the Kingdom of Saudi Arabia (KSA) with about 200 km south of Jeddah city, and administratively located within Makkah Province. Wadi Thara is located in the west of the main catchment with an area of about 275.5 km^2. It lies between 40°11′E and 40°25′E longitudes and 20°39′N and 20°50′N latitudes (Fig. 1).

In 1986 Ministry of Agriculture and Water (MAW) in KSA (currently Ministry of Environment, Water and Agriculture) conducted an intensive field survey and laboratory analysis to determine the soil types (Ministry of Agriculture and Water, 1986). It was found that Wadi Thara consists mainly of two soil types: rock outcrops and alluvial deposits. Rock outcrops are mainly lithic and Typic Torriorthents complex, extremely steep gravelly and loamy soils, which have in steep to extremely steep side slopes in mountainous uplands. Alluvium deposits contain mainly deep, very cobbly sandy and sandy soils.

Wadi Thara can be considered mainly as arid range land. The vegetation cover in the rock outcrops consists of about 20% shrubs and 5% grass. The vegetation cover in the alluvial deposits consists of about 25% trees and 20% shrubs. There are no farms or villages in Wadi Thara and only insignificantly very small and scattered houses are found near the main channel.

3. Methodology

3.1. Runoff computation approach

Rainfall-runoff modeling is presented to simulate the flash flood discharge (hydrograph) using the hourly rainfall data and physiographic characteristics of the catchment as input to the model. Hydrologic Engineering Center–Hydrologic Modeling System (HEC-HMS) software is used for flash flood simulation and parameter optimization.

Two hydrological computation processes are usually employed to develop the flood hydrograph simulation, namely, excess rainfall using loss methods and direct runoff transformation by synthetic unit hydrograph (UH) methods. In this study, SCS-CN method (Soil Conservation Service, 1986) is used to compute the effective rainfall (excess rainfall), while Clark-UH method is used to compute the direct runoff hydrograph. SCS-CN method is based on mapping of land cover/land use (LCLU) and hydrological soil groups (HSG). The other parameters of SCS-CN method such as potential maximum retention (S) can be calculated easily, which is a measure of the watershed ability to abstract and retain storm rainfall, and initial abstraction (I_a), the equations for computing storage (S) and initial abstraction (I_a) for SI units can be given as follows (Mishra and Singh, 2013)

$$S = \frac{25,400 - 254\text{CN}}{\text{CN}} \quad (1)$$

$$I_a = 0.2S \quad (2)$$

Finally, the effective rainfall (or excess rainfall) depth (R_e) can be estimated by the following expression,

$$R_e = \frac{\left(P - 0.2S\right)^2}{\left(P + 0.8S\right)} \quad (3)$$

where P is the accumulated rainfall depth at time (t).

Direct runoff hydrograph process is the method to transform excess rainfall to point runoff hydrograph. Synthetic UH (SUH) methods are usually used to compute the direct runoff. SUH uses the watershed characteristics to compute travel time parameter, which influences the shape and peak of runoff hydrograph. Usually this parameter can be expressed as lag time or time of concentration (T_c), which is indications of the response time at the outlet of the watershed for the rainfall event. In this study, Clark-UH method is selected and the T_c equation by Arizona Department of Transportation (ADOT, 2014) is adapted for mountainous terrain, which can be expressed as:

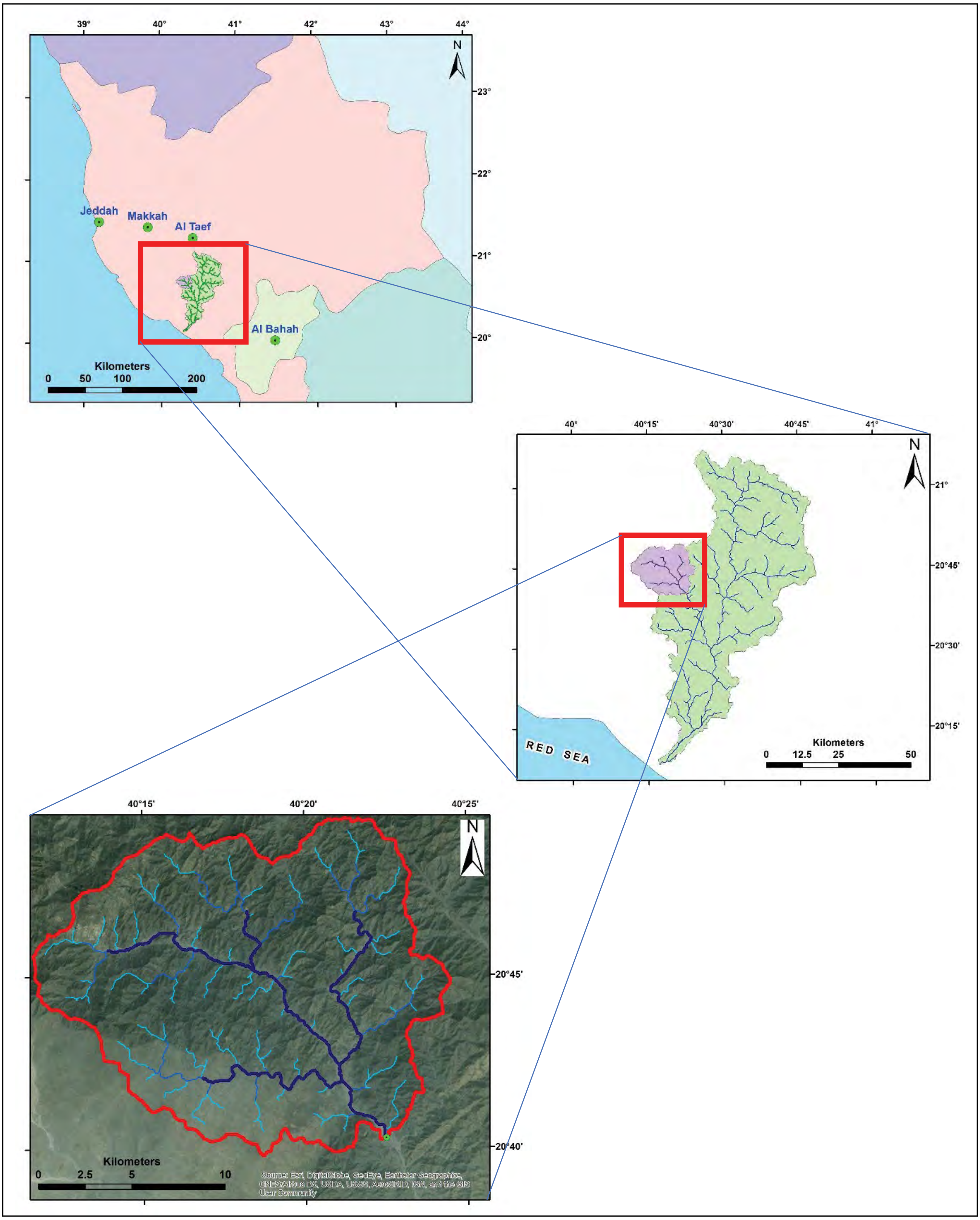

Fig. 1. General location of study area.

$$T_c = 2.4 \times A^{0.1} \times L^{0.25} \times L_{Ca}^{0.25} \times S^{-0.2} \quad (4)$$

where T_c is the time of concentration in hours,

A is the catchment area in square miles,

L is the length along main channel from outlet to upstream boundary in miles,

L_{Ca} is the length along main channel from outlet to point opposite to centroid in miles.

S is the slope along main channel from outlet to upstream boundary in feet/mile.

The catchment storage coefficient, R, can be computed as;

$$R = 0.37 \times T_c^{1.11} \times L^{0.8} \times A^{-0.57} \quad (5)$$

3.2. Calibration process approach

Parameters estimation can be optimized via automatic calibration. In rainfall-runoff modeling, usually the hydrological process parameters (i.e., SCS-CN and Clark-UH) are selected for calibration and validation depending on the methods used. In this study, the goal of automatic calibration process is to specify reasonable values for the input parameters that produce the best computational fit to observed peak flow. HEC-HMS optimization module is used and four input parameters are selected for calibration, which are SCS-CN, I_a, T_c and R.

Parameter estimation optimization process starts with selection the objective function. Since the most critical value for rainfall-runoff in arid regions is the peak flow, the percentage error in the peak (PEP) objective function is selected, which is the absolute value of the difference between observation and simulation flood peak discharges in percentage. This objective function ignores the entire hydrograph ordinates except for the single peak flow value and can be expressed as follows:

$$Z = 100\left|\frac{Q_p(\text{Simulated}) - Q_p(\text{Observed})}{Q_p(\text{Observed})}\right| \quad (6)$$

where Z is the objective function that needs to be minimized, Q_p (observed) is the observed peak flow of the hydrograph event, and Q_p (simulated) is the simulated peak flow resultant from optimized parameters.

The second step in optimization process is to select the search algorithm for minimizing the objective function and finding optimal parameter values. In this study, both search algorithms are used. Two parameters are needed for the search algorithm, which are tolerance value that should be very small (i.e., 0.001) and maximum number of iterations as high as possible (i.e., 1,000). Mathematical description of these two search algorithms is out of the scope of this study.

The next step in optimization process is to specify the constraints on the search, which sets the range of feasible and acceptable parameter limits (or boundaries), where the search outside of these boundaries is not acceptable.

The last step in the optimization process is to select the initial estimates of the parameters. As with any search, the better these initial estimates (the starting point of the search), the quicker the search will yield a solution. In this study, the estimated parameter from previous sections will be used as initial value.

The observed dataset is sub-divided into two groups, the first group of events are for calibration (≈ 80% of the dataset) and the second group for validation (≈20% of the dataset), where the average calibrated (optimized) parameters are used in the validation process.

The most critical hydrograph characteristic is the peak flow discharge in most rainfall-runoff modeling in arid regions. This study focuses on calibrating the peak flow.

4. Results and discussions

4.1. Geomorphological and morphometric analysis

One of the most important steps in rainfall-runoff modeling is the extraction of geomorphological features (basin boundary, drainage network) and computation of the morphometric parameters (catchment area, channel length, channel slope) of study area, which can be achieved by automatic techniques such as the GIS software and DEM.

In this study, DEM developed by Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 2 (GDEM V2) is processed at 30 m pixel size using Aquaveo Watershed Modeling System (WMS) software (Aquaveo, 2014). It is found that the catchment area of Wadi Thara is about 275.5 km^2, and it has three main tributaries (streams) flowing from north west to south east, which are Dilimah stream in the eastern part of the Wadi, main Thara stream in the middle, and Tabshu stream in the western part of the Wadi. Fig. 2 shows the DEM of Wadi Thara with the automatically delineated boundary and extracted drainage network, while Table 1 presents the automatically computed morphometric parameters.

4.2. Rainfall and runoff data analysis

Wadi Thara contains two recording rainfall stations, J-235 in the upper part of the sub-catchment, and J-237 inside the catchment near the outlet. Thiessen polygons for these rainfall stations are developed automatically by GIS capabilities of Aquaveo Watershed Modeling System package (WMS), where the inputs are the boundary of the sub-catchment and the location of two rainfall stations. It is found that the effective area ratio for station J-235 and station J-237 are 52% and 48%, respectively.

As the paper charts are not available for most of recording rainfall stations, hourly rainfall records in tabular form are used instead. For this reason, rainfall time interval is set to 1 h (60 min) for modeling, but shorter rainfall intervals could not be developed. Strom events that produced runoff flows as mentioned in the next section are selected and presented in Table 2. It can be shown that almost all the selected rainfall storms occurred in the afternoon period except for 19 December 1985 and rainfall duration is less than three hours for most of the storms.

The paper charts of Wadi Thara runoff station (J-416) at the catchment outlet are examined and the selected runoff events are analyzed and processed to produce

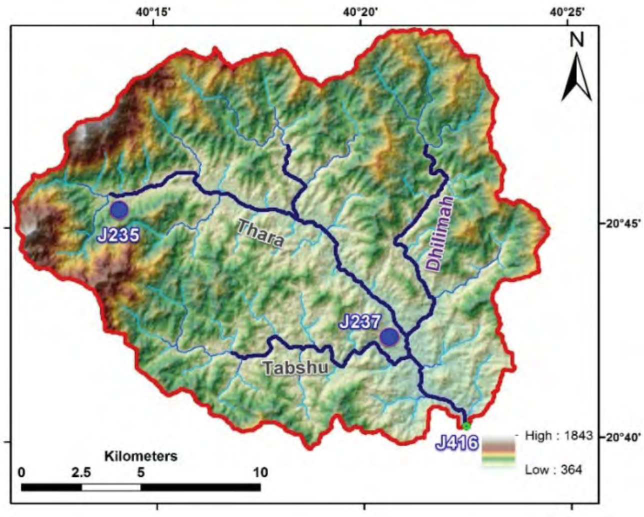

Fig. 2. ASTER DEM and automatically extracted drainage system of Wadi Thara.

Table 1
Automatically computed morphometric parameters from ASTER GDEM

Morphometric parameter	Value
Basin Area (km^2)	275.5
Total stream length (m)	94,735
Basin (overland) slope (%)	35.93
Main channel length (m)	29,660
Main channel slope (%)	4.6
Shape Factor "or circularity" (mi^2/mi^2)	1.64
Sinuosity	1.31
Perimeter (m)	103,403
Mean elevation (m)	740
Average stream slope (m/m)	0.022
Drainage density (km/km^2)	0.34

Table 2
General characteristics of selected storm events

Event No.	Date	Weighted average rainfall depth (mm)	Duration (hr)	Start time
1	25/11/1984	16.6	2	14:00
2	05/09/1985	10.6	2	14:00
3	18/09/1985	11.8	3	15:00
4	19/12/1985	9.2	2	00:00
5	02/03/1986	38.6	3	14:00
6	30/07/1986	54.9	3	15:00
7	14/01/1987	6.9	2	16:00
8	07/08/1987	17.5	5	15:00
9	09/08/1987	17.7	3	16:00

Table 3
Selected hydrograph characteristics (in historical order)

Event No.	Runoff date	Runoff peak (m^3/sec)
1	25-Nov-84	73.4
2	05-Sep-85	26.0
3	18-Sep-85	26.4
4	19-Dec-85	22.3
5	2-Mar-86	49.3
6	30-Jul-86	210
7	14-Jan-87	60.0
8	8-Jul-87	63.0
9	8-Sep-87	44.0

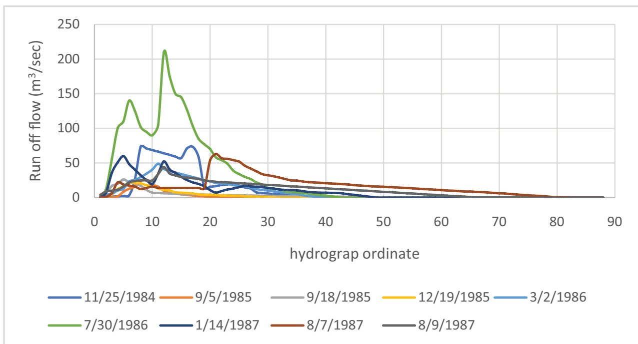

Fig. 3. Selected observed run off hydrograph of Wadi Thara.

runoff ordinates at 5-min intervals. Only 17 significant run-off events are recorded in the paper charts, from which only 9 suitable events are selected for modeling. Table 3 presents runoff peak discharges of these selected nine runoff events extracted from the paper charts. Fig. 3 shows these runoff hydrographs (with timeless ordinates). It is noticed that the peak flow of these nine floods are less than 100 m^3/s (except event in 14th July 1986) and four events appeared with peak flows more than 50 m^3/s.

4.3. Computing runoff volume and flood hydrograph

From Section 2, it was noticed that Wadi Thara has mainly one LCLU feature, which is in arid ranges with desert shrub that can take SCS-CN between 63 for HSG type A and 88 for HSG type D. There are two soil types in Wadi Thara, namely, rock outcrops (81% areal coverage), which represents hydrological soil group type D and alluvial deposits (19%), which represents hydrological soil group type A. The computed composite SCS-CN is found as 83.3.

From the composite SCS-CN, the storage of Wadi Thara is computed using Eq. (1) leading to about 51.0 mm. The initial abstraction is computed by Eq. (2), which is about 10.2 mm. These values are inputs into the rainfall-runoff model to compute the effective rainfall (runoff volumes).

For the flood hydrographs computation, the Clark time of concentration (Clark-T_c) is selected using ADOT equation for mountainous desert regions. Four input parameters are necessary for T_c, which are computed automatically from DEM using Aquaveo WMS software. It is found that the Clark-T_c for Wadi Thara is about 4.16 h, while R coefficient is about 2.23 h.

HEC-HMS software is used to compute the flood hydrographs. Table 4 presents the percentage difference between observed and uncalibrated peak flows, which range from –124% up to +142%, where 78% of values have positive difference (underestimation), the percentage change ranges from –83.2% up to 323.2%, where most of values are in decrease. These results show the importance of rainfall-runoff modeling calibration process in arid regions.

4.4. Calibration and validation

The runoff hydrograph dataset is sub-divided into two main groups, seven runoff events are selected for parameter calibration and two runoff events (the first and the last events) for parameter validation. Table 5 shows the two categories of runoff event and the selected events for calibration and validation.

Four input parameters (SCS-CN, I_a, T_c and R) are used for enhancing the simulated peak discharge flow hydrographs. Already estimated parameters in Section 4.3 are used as initial values. Running the HEC-HMS optimization module for the selected seven events using the input values as mentioned in the previous section produced the calibrated hydrographs given in Fig. 4. It can be seen from Table 6 that six (out of seven) calibrated peak flows are almost exactly the same as the observed one, while event 14th Jan. 1984 failed to produce close peak with –55.7 % difference. The reasons behind this failure may be due to using of local search algorithm.

Calibration process also shows that the average of the optimized SCS-CN, I_a, T_c and R parameters are 81.6, 11.0 mm, 3.81 h and 1.88 h, respectively, where R is the most highly variable with 139% coefficient of variation. These optimized values are used in the validation process for the two selected validation events, which are 25th Nov 1984 and 9th Aug 1987.

In the validation stage, the first and last events are chosen and then the average optimized parameters are used. Validation process results are shown in Table 7, which presents the percentage difference and percentage change between the peak flow observation and the validation. For the 25th Nov 1984 event, the percentage difference and change are 67.4% and –50.4%, respectively, which can be considered as relatively high, while for the 9th Aug 1987 event they are 6.6% and –6.6%, respectively, which are insignificant. Fig. 5 shows the observation and the computation flood hydrographs from the validation process. There are several reasons behind these variations and high errors in the validation process, including the limited number of events available for calibration, the highly variable calibrated parameters, usage of local (non-global) search methods for calibration, etc.

Table 4
Comparison between observed and uncalibrated peak hydrographs for Wadi Thara

Events	Observed	Uncalibrated	% Diff.	% Change
19,841,125	73.4	36.5	67.2	–50.3
19,850,905	26	17.1	41.3	–34.2
19,850,918	26.4	17.7	39.5	–33.0
19,851,219	22.2	14.7	40.7	–33.8
19,860,302	49.1	207.8	–123.6	323.2
19,860,730	210	388.1	–59.6	84.8
19,870,114	60	10.1	142.4	–83.2
19,870,807	63	37.6	50.5	–40.3
19,870,809	44	41.6	5.6	–5.5

Table 5
Selected observed runoff events for calibration and validation (in peak flow ascending order)

Runoff date	Runoff peak (m^3/s)	
19,841,125	73.4	Validation Calibration
19,850,905	26	Calibration
19,850,918	26.4	Calibration
19,851,219	22.2	Calibration
19,860,302	49.1	Calibration
19,860,730	210	Calibration
19,870,114	60	Calibration
19,870,807	63	Validation
19,870,809	44	Validation

5. Conclusions

The main aim of this paper is parameter optimization for the peak flow discharge calibration in Wadi Thara (275 km^2), Western KSA. Seven runoff flows observations are considered for calibration, while two for validation. In the calibration process, the average optimized parameters, SCS-CN, I_a, T_c and R are 81.6, 11.0 mm, 3.81 h and 1.88 h, respectively. Six out of seven calibrated events produced almost exactly the same peak flow as observation, while one ended at underestimation with –55% of change. The reason behind this variation may be that HEC-HMS has only local search algorithms, which produce local minimum objective function and assign optimized value to the parameter that is not in existence. The structure of the lumped hydrological model can also be another reason, where the spatial rainfall variation and the other input parameters are not taken into consideration. In the validation process, the average optimized parameters are applied for other two observed events. The first validated event produced very close peak flow with –6.4% of change, while the second validated event failed to produce a good match to peak flow observation, where the percentage of change was –50.4%. There are several reasons behind this including the limited number of events selected for calibration and the high variability in resultant optimized parameters. In the future, more optimization module applications are necessary with global search algorithm to enhance the parameters estimations. The resultant optimization estimations of Wadi Thara parameters can be used for future simulations and also for similar catchments.

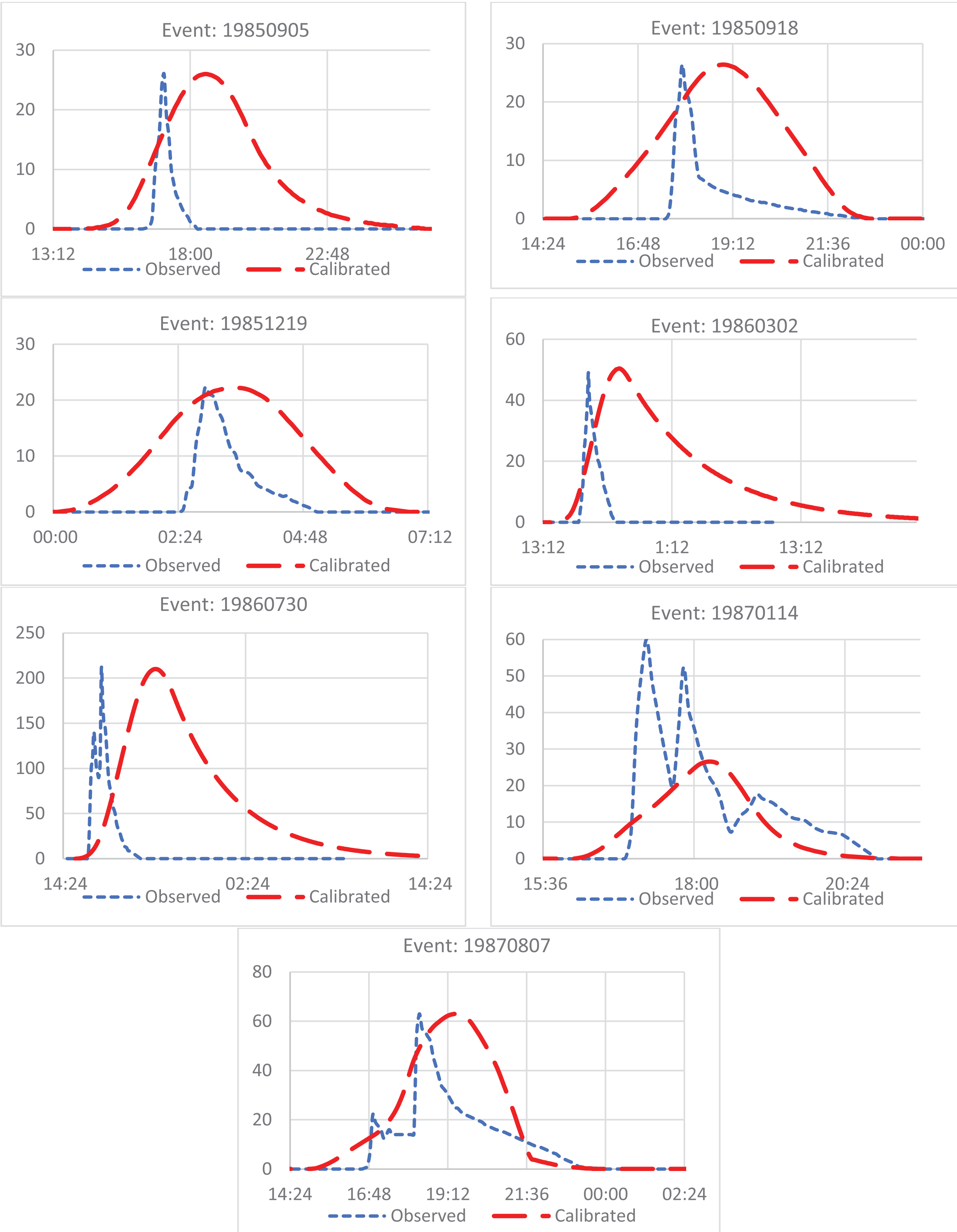

Fig. 4. Observed and calibrated hydrographs of Wadi Thara.

Table 6
Observed and calibrated peak flows of Wadi Thara

Events	Observed	Calibrated	Diff.	% Diff.	% Change
19,850,905	26	26	0	0.0	0.0
19,850,918	26.4	26.4	0	0.0	0.0
19,851,219	22.2	22.2	0	0.0	0.0
19,860,302	49.1	50.4	1.3	–2.6	2.6
19,860,730	210	209.9	–0.1	0.0	0.0
19,870,114	60	26.6	–33.4	77.1	–55.7
19,870,807	63	63	0	0.0	0.0

Table 7
Results of validation process for the two selected events

Event	Peak flow (m^3/s)		GOF tests		
	Observed	Validated	Diff.	% Diff.	% Change
19,841,125	73.4	36.4	–37	67.4	–50.4
19,870,809	44	41.2	–2.8	6.6	–6.4

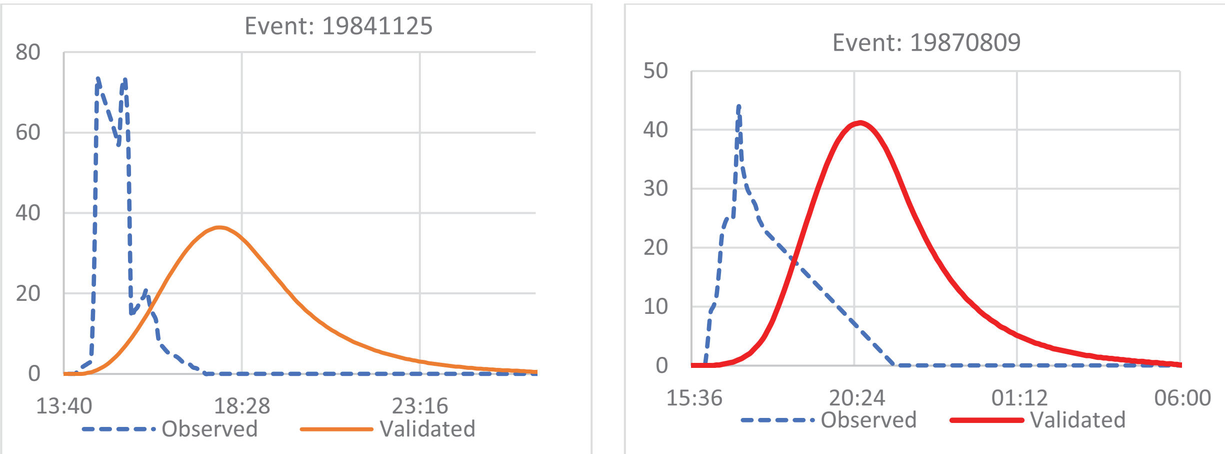

Fig. 5. Observed and the flood hydrographs computed from validation process.

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جمعية علوم وتقنية المياه
Water Sciences and Technology Association

العلاقة بين وجود الآبار أعلى أمهات الأفلاج واستدامة تدفق الفلج (دراسة تحليلية لفلج الخطمين وفلج الملكي)

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الملخص:إن فترات الجفاف الطويلة التي قد تستمر لعدة سنوات تؤكد الحاجة إلى إدارة فعالة للموارد المائية تمكن من تخزين المياه والاستفادة منها في المستقبل وهذا هو جوهر فكرة الأفلاج التي تعد نمطاً من الأنماط التقليدية للاستخدام في سلطنة عمان. فكان لهذه الأفلاج الدور الفاعل في تكوين التجمعات السكانية المنتشرة في ربوع المستدام للمياه السلطنة والتي لا تزال قائمة إلى الآن. ونظراً لما سببته ندرة الأمطار وقلة اهتمام الأهالي بالأفلاج من انخفاض منسوب مياه الأفلاج وحدوث جفاف عام شمل الكثير من الأفلاج، جاءت فكرة حفر الآبار لتعزيز العجز المائي لهذه الأفلاج ولتلبية الاحتياجات القائمة عليها ولكن جاء ذلك على حساب التدفق الطبيعي للفلج.

بالرغم من كون الآبار المساعدة للأفلاج هي الحل الوحيد لحياة واستمرار تدفق الفلج إلا أن هناك العديد من السلبيات التي تخلفها الآبار وفي هذه الورقة تم التطرق إلى تأثير وجود الآبار أعلى وداخل إحرامات أمهات الأفلاج واستدامة تدفق الفلج لفلجين من الأفلاج بمحافظة الداخلية (فلج الخطمين وفلج الملكي)، حيث اثبتت النتائج بانخفاض تدفق فلج الملكي بسبب كثرة الآبار المحيطة بأم الفلج مقارنة مع فلج الخطمين.

ان الحفر العشوائي للآبار ساهم في انخفاض المخزون الجوفي من المياه والذي بدوره يشكل تأثيراً مباشراً على تدفق الفلج، فكان لا بد من سن التشريعات والقوانين التي تحمي هذه الأفلاج من النضوب والحد من الحفر العشوائي لهذه الآبار والضخ الجائر من قبل الآبار الخاصة، هذا فضلاً عن أن كثرة الآبار يشكل ضغطا كبيرا على المخزونات الجوفية على حساب مصادر مائية أخرى قد تكون أكثر أهمية. ولتفادي مثل هذه المشاكل لا بد التقليل من حفر الآبار على أن تكون وفق معايير ثابتة وحسب حالات معينة بحيث تتخذ لتنفيذها طرق وخطوات مدروسة حتى تكون نتائج ذلك مضمونة وخالية من المشاكل ومقللة من الأعباء والضغط على الخزان الجوفي.

الكلمات الدالة:

الأفلاج ، الآبار ، التدفق الطبيعي للفلج ،المخزون الجوفي.

Presented at the 13th Gulf Water Conference – Water in the GCC: Challenges and Innovative Solutions. 12–14 March 2019, Kuwait

المقدمة:

إن المياه من أعظم نعم الله على خلقه، ووجودها يعني وجود الحياة بكافة أشكالها، وقد تضاعفت أهمية المياه في العصر الحاضر كونها أصبحت تشكل حجر الأساس لنجاح واستمرار أي تنمية في البلدان المتقدمة والنامية على حد سواء.

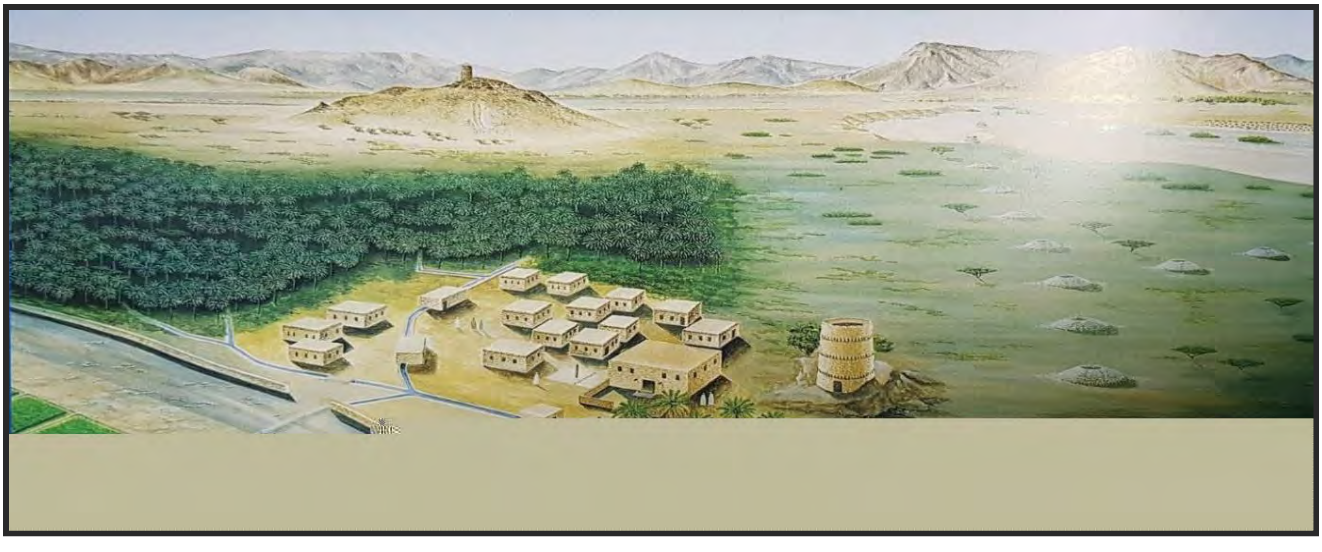
تعتبر الأفلاج من أهم مصادر المياه بالقرية العمانية منذ القدم وهي إحدى أهم الموروثات التراثية بالسلطنة، وتنبع هذه الأفلاج من بطون الجبال ثم تنحدر في مجار تشبه الشلالات وتخترق الهضاب وتشق السهول لمسافات طويلة حاملة الحياة إلى الأرض بنشر الخضرة والنماء من حولها، فكان لهذه الافلاج الدور الفاعل في تكوين التجمعات السكانية المنتشرة في ربوع السلطنة والتي لا تزال قائمة إلى الآن.

وما ان طل التقدم الحيوي وخيم ظلاله على البشرية وبعد أن برزت مشكلة زيادة الكثافة السكانية في المجتمعات المحلية والفجوة التي تتسع باضطراد بين العرض والطلب على الماء مع تعاضد عوامل أخرى جفت الكثير من الأفلاج فكان لزاماً وتضاعف حاجة الإنسان إلى الماء لجميع الاستخدامات وأصبحت الافلاج لا تفي الزراعات القائمة عليها. إيجاد بدائل أخرى تساعد في إبقاء ما تبقى من هذا الرمز العماني الأصيل.

تكوين الفلج وانواعه:

نظام الفلج هو عبارة عن نظام متكامل للفلج يتكون من الفلج ومنطقة الاحتياج ، وقد يتكون نظام الفلج من فلج واحد ومنطقة احتياج واحدة وقد يحوي نظام الفلج أيضاً اكثر من فلج واكثر من منطقة احتياج ترتبط فيما بينها بطريقة معينة لتوزيع المياه .

يتكون الفلج من قناة رئيسية ممتدة من منبع الفلج وهو ما يعرف محلياً ب « أم الفلج» وقد تكون القناة تحت الأرض أو سطحية تبعاً لنوع الفلج، وتمد إلى القرى لمسافات قد تطول أو تقصر تبعاً لموقع الفلج والقرى التي ترويها، وتقوم هذه القناة بنقل المياه إلى القنوات الفرعية التي غالباً ما تكون داخل القرية (الشكل رقم (**1**)).

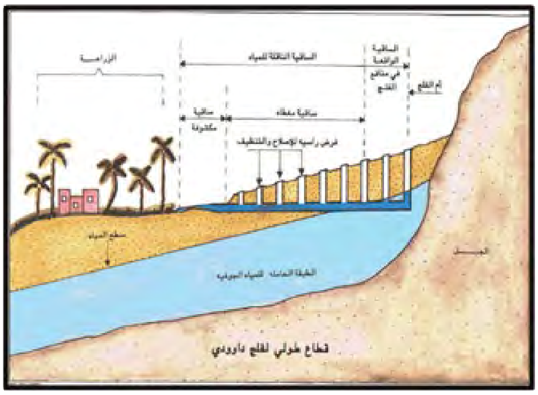


الشكل رقم (1): نظام الفلج واستخداماته حيث تشق قناته الرئيسية من مصدر الفلج في الجبال أو الوديان وباتجاه منطقة الاحتياج

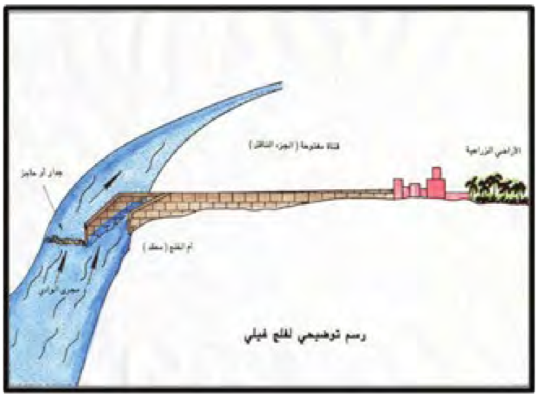
وقد صممت هذه القنوات الرئيسية على نمط فريد من نوعه حيث روعي في التصميم عاملان أساسيان هما تقليل التكلفة المالية وعدم استعمال أجهزة آلية لنقل المياه. ومن هذا المنطلق يلاحظ أن جميع القنوات الرئيسية تكون منحدرة بدرجة

معينة لتضمن انسياب المياه طبيعياً عن طريق الجاذبية الأرضية ابتداءاً من مصدر المياه الجوفية حيث تصل مندفعة إلى القرية وتتشعب عبر القنوات الصغيرة لتروي بساتين القرية وأشجارها وتسقي سكانها. [1]

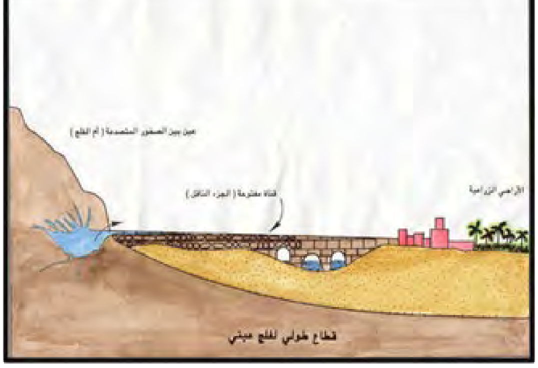
<u>تنقسم الأفلاج في سلطنة عمان إلى ثلاثة أنواع</u>[2] :-



أ- **<u>أفلاج عدية (داوودية) :</u>** وهو ذلك الفلج الذي يستمد مياهه على عمق كبير من سطح الأرض وغالباً يستمر تدفقه دون تأثير كبير بفترات المحل(الجفاف) ويستمر جريان المياه بها على مدار العام ، ويتواجد هذا النوع من الأفلاج في أعلى السهول وتتميز هذه الأفلاج بطولها حيث يصل إلى أكثر من 12 كيلو متر، ولها سواعد (روافد) تغذية بالماء تصب فيها وقد تصل في بعض الأحيان إلى مائة ساعد أو أكثر، وتمثل هذه الأفلاج حوالي 45٪ من إجمالي عدد الأفلاج بسلطنة عمان (الشكل رقم (2)). **الشكل رقم (2): مقطع طولي للأفلاج الداوودية**



ب- **<u>أفلاج غيليـــــــــة:</u>** وهو الفلج الذي يستمد مياهه من غيول الأودية أو من المياه السطحية الجارية على سطح الأرض أو من المياه تحت السطحية بالقرب من سطح الأرض في مجاري الأودية أو على سفوح الجبال، وهي أفلاج موسمية لا يستمر جريانها إلا في فترات معينة مرتبطة بالمياه الجوفية القريبة من السطح ومياه الأمطار، وفي السنوات الشحيحة بالأمطار تجف معظم هذه الأفلاج ، أما أطوالها تتراوح بين 100 متر و 2 كيلو متر. وهذا النوع من الأفلاج يتواجد بمناطق عديدة بشمال عمان ، ويحتل مانسبته حوالي 50٪ من إجمالي عدد الأفلاج بالسلطنة (الشكل رقم (2)). **الشكل رقم (2): مقطع طولي للأفلاج الغيلية**

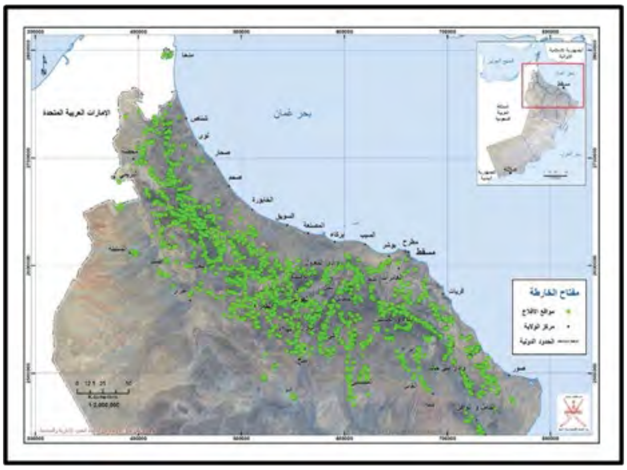


ج- **<u>أفلاج عينية</u>** : وهي عبارة عن عيون تنبع من قمم وسفوح الجبال وتنساب منها المياه في قنوات مكشوفة ، وتتدفق مياه هذه الأفلاج من عمق الطبقات الجيولوجية المتكونة من الأزمنة الساحقة ، وتختلف جودة المياه من عين لأخرى نتيجة للتراكيب الجيولوجية التي تنبع منها، كذلك تختلف درجة حرارة المياه نتيجة لعمق المصدر الجوفي فتكون مياهها في بعض الأحيان حارة وتصلح في كثير من الأحيان لعلاج بعض الأمراض مثل الروماتزم ، ويوجد بالسلطنة العديد من العيون أشهرها عين الثوارة بولاية نخل وعين الكسفه بولاية الرستاق وعين أرزات في جبل القرا بمحافظة ظفار (الشكل رقم (4)).

الشكل رقم (4): مقطع طولي للأفلاج العينية

الأسباب الرئيسية لجفاف الأفلاج:

اعتمدت سلطنة عمان منذ القدم اعتماداً كلياً على نظام الأفلاج في الزراعة، كما أن الآبار اليدوية رغم محدودية دورها وحجم انتشارها فإنها تستخدم بشكل أساسي لتعزيز الأفلاج في حالات انخفاض تدفقاتها بحيث تقل عن الاحتياجات الزراعية والسكانية ولازال نظام الأفلاج التقليدي حتى الآن من أهم المصادر التي تعتمد عليه السلطنة في تأمين يبلغ عدد الأفلاج في سلطنة احتياجاتها المائية حيث يشكل حوالي 30٪ من مصادر الموارد المائية الحالية في السلطنة. عمان 4112 فلجاً، يتركز معظمها في شمال عمان (الشكل رقم (5))، منها 3017 فلجاً حياً و 109 فلجاً ميتاً [3]. هناك العديد من العوامل التي ساهمت في جفاف الأفلاج وتوقفها عن الجريان، وتتلخص هذه الأسباب [4]:



- قلة الهطول المطري.
- الحفر العشوائي للآبار العميقة في نطاق أمهات الأفلاج وذلك قبل سن القوانين المنظمة لذلك.
- الاستنزاف الجائر للمياه من الآبار.
- الصيانة العشوائية للأفلاج بدون ضوابط فنية.
- قلة اهتمام الأهالي بالأفلاج بسبب ارتباطاتهم المدنية الحديثة. **الشكل رقم (5): توزيع الأفلاج في سلطنة عمان**

وبالرغم من ذلك فإنه يوجد نسبة كبيرة من هذه الأفلاج لا تزال تنبض بالحياة. من هذا المنطلق سعت الحكومة في تدارك جفاف الأفلاج وتولي الجهات المختصة في سلطنة عمان الأفلاج اهتمامها البالغ وتبذل جهوداً لتحسين أدائها باستخدام الطرق التالية: -

- صيانة وتأهيل الأفلاج المنهارة حسب الأسس الفنية الصحيحة.
- تمديد الفلج من الأم فصاعداً إذا لم يواجه هذا التمديد المشاكل الفنية الاجتماعية.
- حفر الآبار المساعدة للأفلاج.

الآبار المساعدة للأفلاج [4]:

يظهر دور الأفلاج في سلطنة عمان بارزاً في المحافظة على النمط الاجتماعي للقرية العمانية لما يوفره من أسباب الحياة للبيئة الزراعية ذات المحاصيل المختلفة وأهمها النخيل والتي ترتبط ارتباطاً وثيقاً بتاريخ الإنسان العماني على مدى التاريخ، فكان لهذه الافلاج الدور الفاعل في تكوين التجمعات السكانية المنتشرة في ربوع السلطنة والتي لا تزال قائمة إلى الآن.

إلا أن مشكلة زيادة الكثافة السكانية في المجتمعات المحلية والفجوة التي تتسع باضطراد بين العرض والطلب على الماء مع تعاضد عوامل أخرى جفت الكثير من الأفلاج ونقص تدفق البعض الآخر وأصبحت الافلاج لا تفي بالزراعات

القائمة عليها وأصبحت الزراعات والنخيل مهددة بالانقراض وتضاعفت حاجة الإنسان إلى الماء لجميع الاستخدامات، فكان لزاماً إيجاد بدائل أخرى تساعد في إبقاء ما تبقى من هذا الرمز العماني الأصيل.

من هذه النقطة برزت فكرة البحث عن المياه في الأعماق البعيدة حيث المخزونات الجوفية ذات الإنتاجية العالية عن طريق حفر الآبار المساعدة الأفلاج مع العلم أن هذه الفكرة ليست وليدة الحاضر بل كانت موجودة فيما سبق متمثلة في الآبار المفتوحة الجماعية التي كانت تستخدم أيضاً لري النخيل والزارعات الأخرى أوقات الجفاف وانخفاض تدفق الفلج.

البئر المساعدة للفلج إما أن يكون بئر مفتوحة أو على هيئة ثقب ولا تختلف عن الآبار الأخرى سوى انها مخصصة لري الزراعات القائمة على الفلج وتوزع مياهها من قبل الأهالي حسب العرف المتبعة في توزيع مياه الفلج.

أهمية الآبار المساعدة:

أن حفر الآبار المساعدة تعتبر العلاج الأخير للفلج فالكثير من مشاريع الآبار المساعدة ساهمت بدور كبير وفعال في المحافظة على الزراعات القائمة عليها مما جعل الكثير من الأفلاج تعتمد اعتماداً كلياً على آبارها المساعدة حتى في أيام الخصب مثل فلجي المبعوث والمفجور بولاية عبري وفلج البسياني بولاية بهلاء وأفلاج البريمي وصعراء وفلج القابل بولاية البريمي(٤).

كما توجد أفلاج كثيرة لا تزال على قيد الحياة إلا أنها تحتاج لدعم مائي يتم تعويضه عن طريق الآبار المساعدة.

المعايير الحالية المتبعة لحفر الآبار المساعدة :

- جفاف الفلج وعدم استجابته للصيانة والتمديد .
- النقص الحاد في تدفق الفلج وعدم استجابته للصيانة والتمديد وعدم تلبيته للاحتياجات الزراعية القائمة عليه .
- تلوث الفلج بالمواد الهيدروكربونيه .

سلبيات الآبار المساعدة للأفلاج :

بالرغم من كون الآبار المساعدة للأفلاج هي الحل الوحيد لحياة واستمرار تدفق الفلج إلا أن هناك العديد من السلبيات الكثيرة التي تخلفها الآبار المساعدة للأفلاج[٤] والتي نختصرها في النقاط التالية:

- ارتفاع الضخ من المخزون الجوفي على حساب الأفلاج والمصادر الأخرى مما يشكل عبء آخر على المخزون الجوفي.
- الاستنزاف الجائر للمخزون الجوفي يصعب تعويضه في ظل ندرة الأمطار.
- استصلاح أراضي زراعية جديدة وزراعة زراعات موسمية غير التي كانت تروى بالفلج مما يؤدي إلى ارتفاع معدلات الضخ المحددة خاصة في حالة وجود آبار مساعدة ذات إنتاجية عالية.
- الاستمرار في زراعة الزراعات الموسمية حتى في حالة نقص المياه على حساب الزراعات المستديمة كالنخيل.
- اعتماد الأهالي كليا على تدفق الآبار المساعدة مما يؤدي إلى إهمالهم الأفلاج وعدم الاهتمام بصيانتها وبالتالي إلى اندثارها.

تأثير وجود الآبار أعلى وداخل إحرامات أمهات الأفلاج وتدفق الفلج نموذج للدارسة (فلج الخطمين والملكي بمحافظة الداخلية):

تم إدراج فلج الخطمين وفلج الملكي ضمن خمسة أفلاج عمانية بلائحة التراث العالمي من قبل لجنة التراث العالمي التابعة لمنظمة التربية والعلوم والثقافة (اليونسكو) في اجتماعها الثلاثين المنعقد بجمهورية ليتوانيا وذلك تعبيراً عن المكانة الدولية لهذا النظام المائي الفريد الذي يشكل موروثاً حضارياً أبدعه العمانيون منذ ما يزيد على ألفي عام [5].

إن هذه الأفلاج التي تم إدراجها بالقائمة العالمية تعتبر ذات تاريخ عريق من حيث القدم وتتميز بوجود الكثير من المعالم الأثرية على جوانب قنواتها مثل أبراج المراقبة والحصون والبيوت الأثرية.

لا يقتصر إدراج هذه الأفلاج بسجل التراث العالمي على قناة الفلج بل يشمل مواقع هذه الأفلاج وما تحتويه من آثار ومبان ومزارع وصناعات وجميع الأنشطة القائمة بالموقع (الأشكال رقم (6 ، 7)).

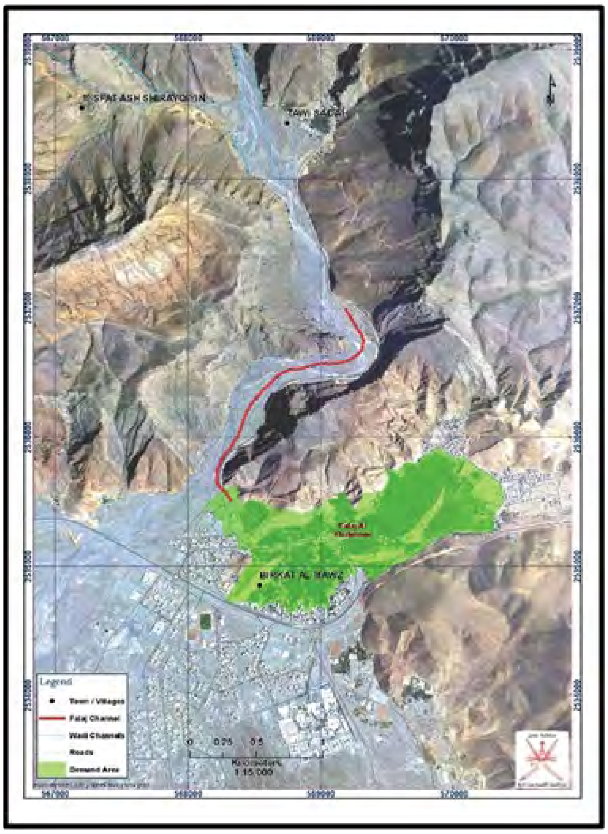
الشكل رقم (6) (فلج الخطمين): مسجد اليعاربة الاثري ويمر بمحاذاته فلج الخطمين و حصن بيت الرديدة الذي يمر فلج الخطمين بداخل اسواره.

الشكل رقم (7) (فلج الملكي): حارة النزار الاثرية تعلو غار جرنان وإحدى أزقة حارات إزكي الاثرية تفضي لبوابة منزل قديم.

فلج الخطمين

يعتبر فلج الخطمين من الأفلاج الداوودية بالمنطقة الداخلية، ويتراوح متوسط تدفقه حوالي٢٠٠لتر/ثانية، وتبلغ الموصلية الكهربائية لمياه الفلج حوالي(440 ميكروسمنز/سم)، والرقم الهيدروجيني (7,16) ودرجة الحرارة (30 درجة مئوية)، يبلغ إجمالي طول الفلج من الأم وحتى الشريعة حوالي2410متراً، ويبلغ عمق أم الفلج حوالي 7,15متر، ولا توجد سواعد متفرعة من الفلج وأهم الأودية المغذية للفلج هو وادي المعيدن[1].

الشكل رقم (8): فلج الخطمين وانقسام مياهه عند الشريعة



وينبع فلج الخطمين من سفح الجبل الأخضر ثم يمضي في سواقيه على ضواحي القرية بما يشبه الحلقة الدائرية، ملتفا حول المساحات الزراعية، وأهم ما يميز هذا الفلج هو طريقة انقسام مياهه عند الشريعة (الشكل رقم (8)) إلى ثلاث قنوات كل منها ينال نصيباً متساوياً من المياه فعند رمي ثلاث كرات متساوية قبل نقطة الانقسام، تذهب كل كرة في قناة مما يدل على براعة التصميم الهندسي للفلج [1].

<u>وصف الموقع والمنطقة التي يرويها</u>[1]:

يقع فلج الخطمين بنيابة بركة الموز التي تعد إحدى قرى المنطقة الداخلية الشهيرة بضواحيها ومعالمها الاثرية، حيث تتمازج معاً في رسم لوحة بديعة لمدينة عمانية جميلة.

تقع أم الفلج على الإحداثيات (0569288) شرقا (2336777) شمالا، أما الشريعة تقع على إحداثيات (2535269) شرقاً (2535269) شمالاً.

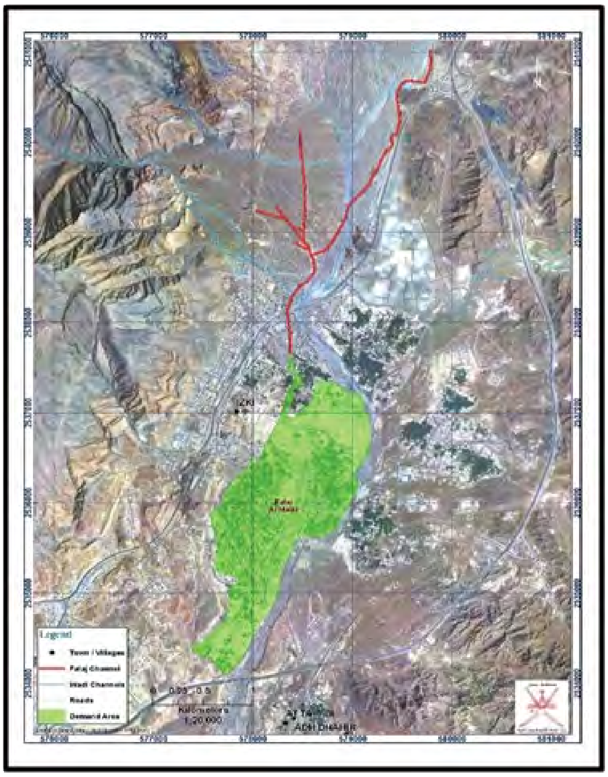
ينقسم استخدام الفلج إلى استخدامات زراعية وأخرى منزلية وتقدر المساحة الكلية لمنطقة الاحتياج (1004,340) متراً مربعاً وتقدر المساحة المزروعة ب 723124 متراً مربعاً (الشكل رقم (9)). وقد تم تقسيم مجرى الفلج عند مدخل البلدة إلى ثلاث أقسام متساوية بحيث يذهب أحد الأقسام إلى ري المزارع التابعة للأهالي أما القسمان الآخران فيعودان للالتقاء في مجرى واحد وهما مخصصان لري الأراضي الزراعية التابعة لبيت المال الذي تملكه الدولة. **الشكل رقم (9): موقع فلج الخطمين والمنطقة المروية**

<u>فلج الملكي</u>[1]:

يعتبر فلج الملكي من الأفلاج الداوودية وأقدم أفلاج المنطقة الداخلية، حيث تعود تسميته بهذا الاسم إلى مالك ابن فهم الأزدي، ويصل تدفقه إلى 200 لتر/ الثانية، تبلغ الموصلية الكهربائية لمياه الفلج حوالي (764.5 ميكروسمنز /سم) والرقم الهيدروجيني = (7.82) ودرجة الحرارة = 37 درجة مئوية.

يعتبر من أكبر أفلاج السلطنة من حيث عدد السواعد حيث يبلغ عدد سواعده (17) ساعداً وهو أطول فلج على مستوى المنطقة الداخلية، حيث يبلغ الطول الإجمالي لسواعده 14875 متراً ، معظم قنوات الفلج مغطاة وتمر تحت الأرض على أعماق مختلفة. **الشكل رقم (10): قنوات فلج الملكي**

وتشتهر المنطقة التي يقع فيها الفلج بوجود حارتين قديمتين وهما حارة نزار وحارة اليمن وبهما بيوت ومبان أثرية تقليدية. وتتفرق قناة الفلج إلى قسمين يروي القسم الأول منطقة نزار وأما الآخر فيروي منطقة اليمن (الشكل رقم (10))، وكان فلج الملكي فيما مضى يروي مساحات كبيرة من بساتين النخيل، ولكن نظراً للظروف المناخية التي تمر بها المنطقة من حيث قلة الهطول المطري بالإضافة إلى الضغط الشديد للخزان الجوفي المغذي للفلج نتيجة للتوسع العمراني، فقد أدى إلى تناقص تدفق الفلج خاصة في فترات الجفاف وقد تم تزويد الفلج بعدة آبار مساعدة تصب في شريعة الفلج لتعزيز تدفقه.



وصف الموقع والمنطقة التي يرويها:

يقع فلج الملكي بولاية إزكي وهي إحدى ولايات محافظة الداخلية ويعتبر من اهم المعالم السياحية بالموقع.

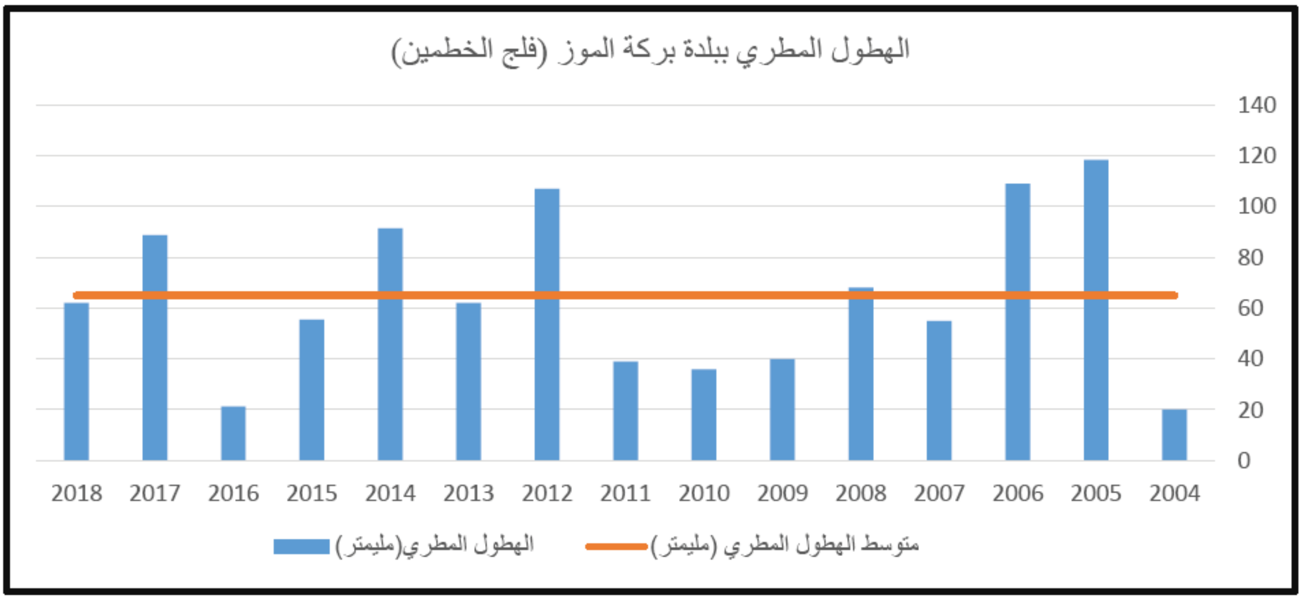
تقع أم فلج الملكي على الإحداثيات (057736) شرقاً (2514896) شمالاً بينما شريعة الفلج على الإحداثيات (0578197) شرقاً (2537266) شمالاً.

يبلغ إجمالي مساحة منطقة الإحتياج (157.273.9) متر مربع، أما المساحة المزروعة التي يرويها الفلج فتبلغ حوالي (113.237.2) متراً مربعاً (الشكل رقم (11)).

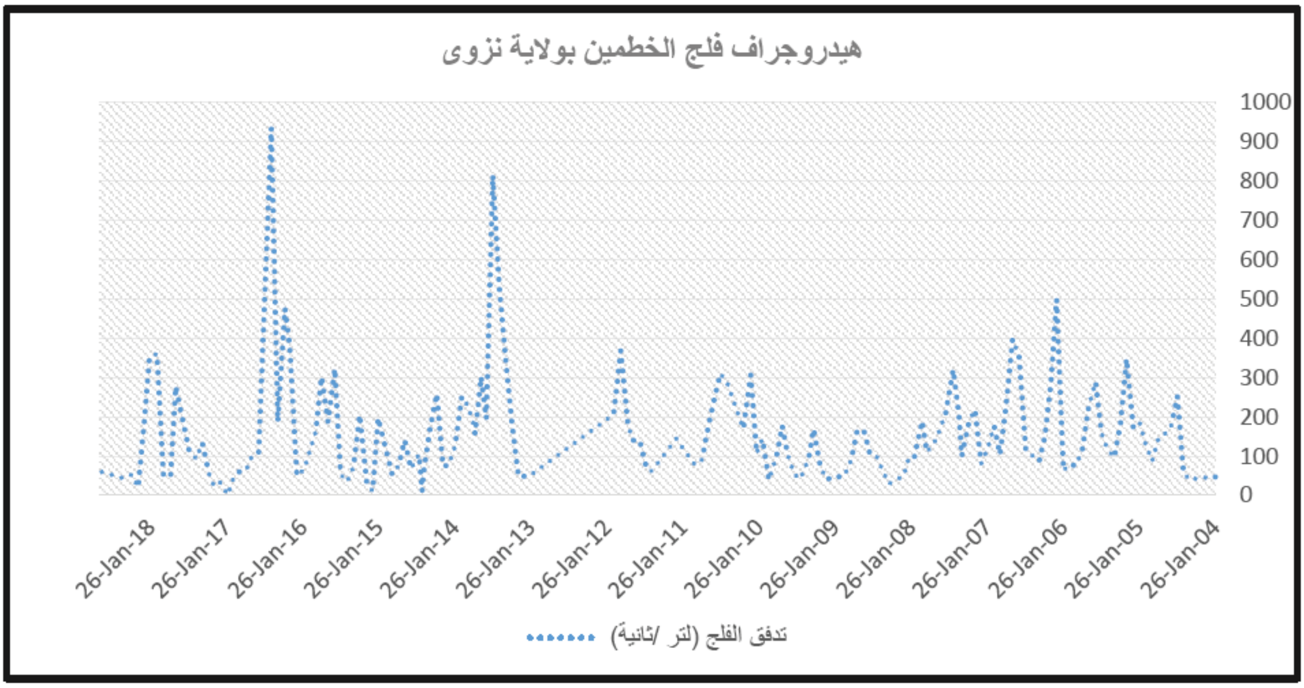
الشكل رقم (11): موقع فلج الملكي والمنطقة التي يرويها

معدلات الهطول المطري وتدفق فلج الخطمين بولاية نزوى:

تم تسجيل معدلات الهطول المطري في محطة الأمطار التي تقع في ولاية بركة الموز بالقرب من فلج الخطمين خلال الفترة من عام 2004 م ولغاية عام 2018 م حيث بلغت أعلى معدلات الهطول المطري حوالي 118.5 مليمتر في عام 2005 م، وبلغ متوسط الهطول المطري خلال تلك الفترة حوالي 64 مليمتر كما تم تسجيل معدلات تدفق الفلج خلال تلك الفترة كما هو موضح بالأشكال رقم (13,12).

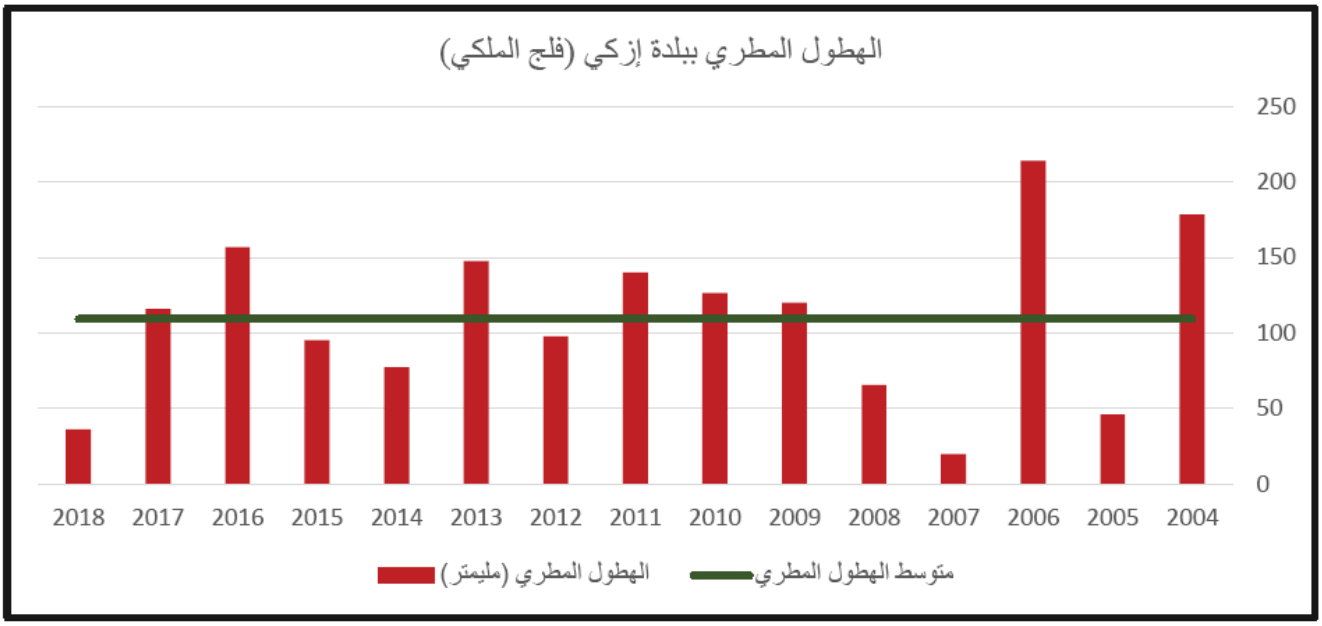


الشكل رقم (12): معدلات الهطول المطري ببلدة بركة الموز خلال الفترة بين عام 2004 م وعام 2018 م [5]

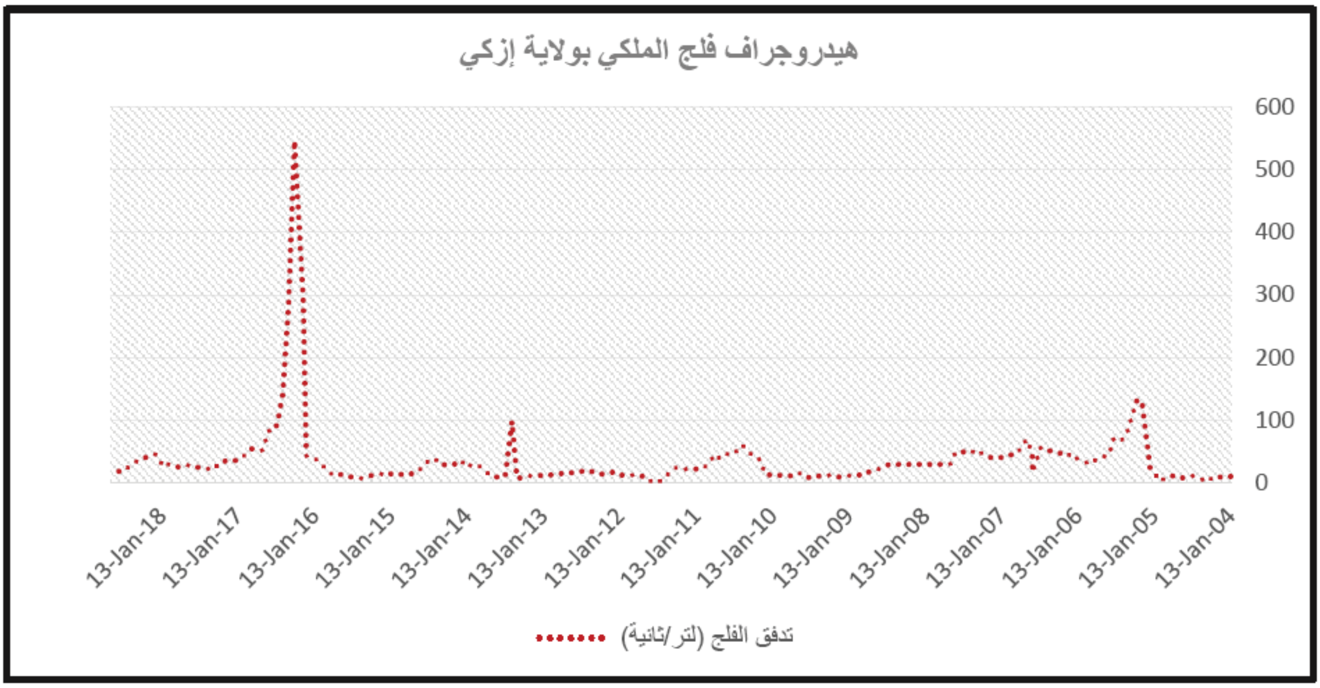


الشكل رقم (13): هيدوجراف فلج الخطمين خلال الفترة بين عام 2004 م وعام 2018 م[5]

أما فيما يتعلق بمعدلات الهطول المطري في محطة الأمطار التي تقع في ولاية إزكي بالقرب من فلج الملكي خلال الفترة من عام 2004 م ولغاية عام 2018 م حيث بلغت أعلى معدلات الهطول المطري حوالي 214 مليمتر في عام 2006 م ، وبلغ متوسط الهطول المطري خلال تلك الفترة حوالي 109 مليمتر كما تم تسجيل معدلات تدفق الفلج خلال تلك الفترة كما هو موضح بالأشكال رقم (14و 15).



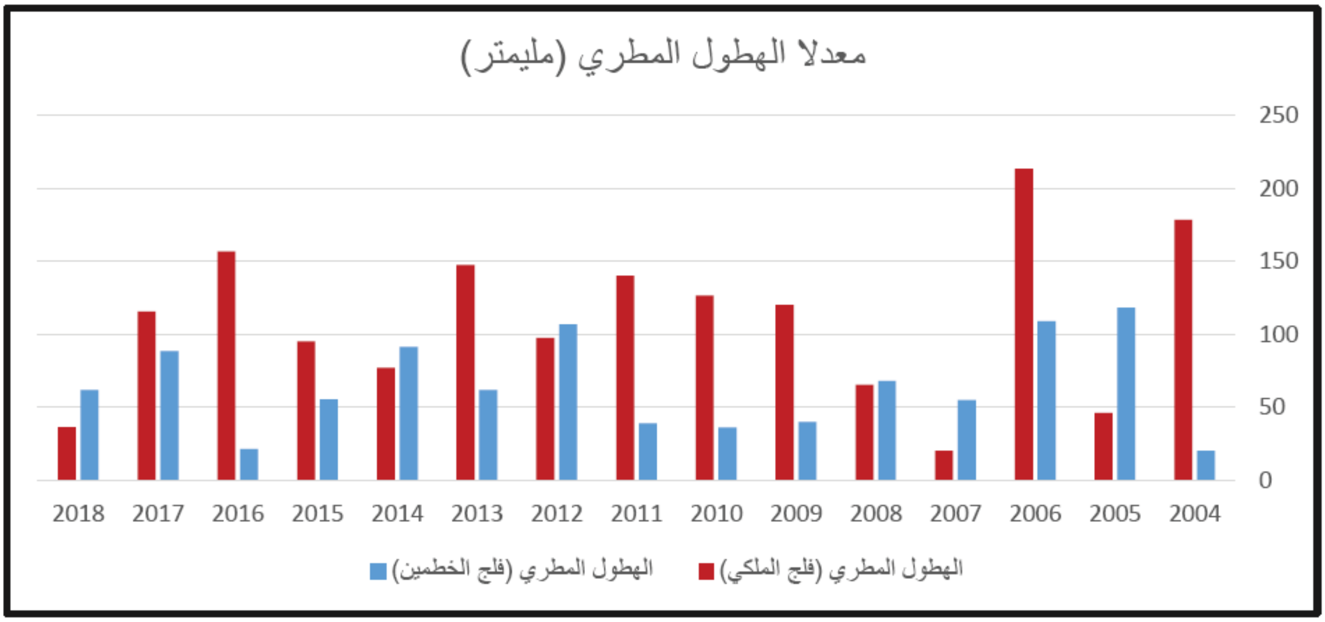
الشكل رقم (14): معدلات الهطول المطري بولاية إزكي خلال الفترة بين عام 2004 م وعام 2018 م [5]



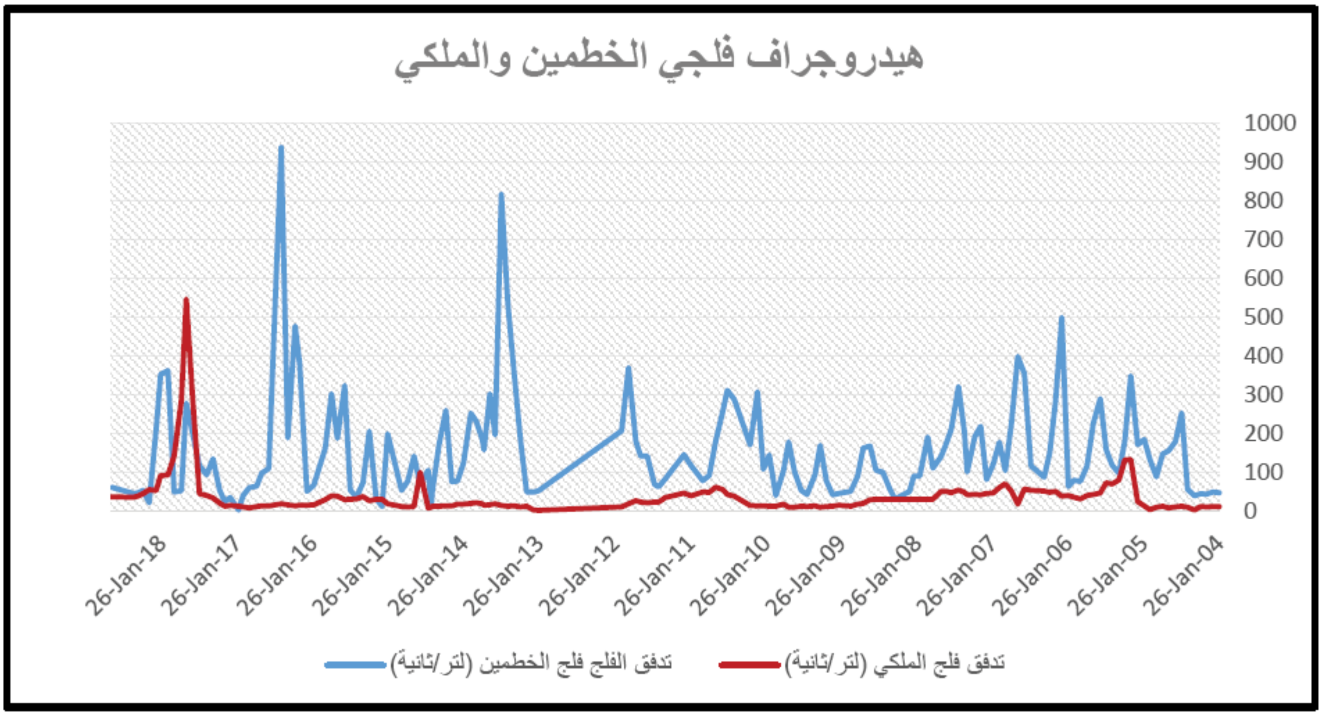
الشكل رقم (15): هيدروجراف فلج الملكي خلال الفترة بين عام 2004 م وعام 2018 م[5]

ومن خلال دمج هذه البيانات المتعلقة بالفلجين ومقارنتها ببعضها يتضح لنا بأن معدلات الهطول المطري أعلى بكثير في ولاية إزكي منها في ولاية نزوى ببلدة بركة الموز إلا أن تدفق فلج الخطمين أعلى من تدفق فلج الملكي كما هو موضح بالشكلين (16،17).

ويعود هذا السبب إلى وجود عدد كبير من الآبار داخل إحرامات وأعلى أم فلج الملكي والتي يصل عددها إلى حوالي 120 بئراً مما يساهم بإنخفاض المخزون الجوفي في منطقة التغذية لأم الفلج ، ومقارنة ذلك بفلج الخطمين فيوجد فقط عدد 30 بئراً داخل إحرامات أم الفلج وعدد بئرين فقط أعلى الام.



الشكل رقم (16): معدلات الهطول المطري ببلدتي إزكي وبركة الموز خلال الفترة بين عام 2004 م وعام 2018 م



الشكل رقم (17): هيدروجراف فلجي الملكي والخطمين خلال الفترة بين عام 2004 م وعام 2018 م

المراجع :

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2- موارد المياه في سلطنة عمان ، وزارة البلديات الإقليمية وموارد المياه ٢٠٠٨م.

3- إحصائيات وقوائم الأفلاج في سلطنة عمان ، وزارة موارد المياه ، مشروع حصر الأفلاج ،٢٠٠٠.

4- الآبار المساعدة للأفلاج ، وزارة البلديات الإقليمية وموارد المياه ، ٢٠١٥م.

5- بيانات الهطول المطري وتدفق الأفلاج ، دائرة مراقبة المياه الجوفية والسطحية، وزارة البلديات الإقليمية وموارد المياه.

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Improving the irrigation quality of Kuwait native shallow groundwater using phytoremediation technology

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ABSTRACT

In Kuwait, shallow groundwater is used mainly for irrigation purposes. This groundwater is, however, brackish with TDS values ranging from 4,000 to 15,000 mg/L. Also, this groundwater is normally subjected to industrial and agricultural pollution increasing the concentration of heavy metals, nitrogen compounds and salt ions. The aim of this paper is to illustrate through field experiments that the roots of the Reeds plants (which are common in Kuwait) are capable to improve the efficiency of irrigation by reducing the concentration of some pollutants in the native groundwater in Kuwait. Two basins were constructed in the fields of KISR premises then Reeds plants were allowed to grow up under climatic conditions of Kuwait until they were 2.5 m tall. Then the Reeds plants were irrigated with native shallow groundwater from Kuwait aquifers. Samples of inflowing irrigating water and outflowing water from the bottom of the basins were taken over a period of 3 months. The water quality between the two waters was compared. The results show that the Reeds roots are capable of reducing the concentration of salt ions by about 70%, and removing completely heavy metals from the irrigating groundwater and hence improving the irrigation efficiency considerably.

Keywords: Phytoremediation; Reeds roots; Salts ions and heavy metals

1. Introduction

Pollution of groundwater resources and upper ground soil in Kuwait due to intensive industrial and agricultural activities has reduced the efficiency of native groundwater to irrigate crops (Aliewi and Al-Khatib 2015 and Afzal et al. 2014). A relatively new technology known as phytoremediation has emerged as a solution to remediate both soil and groundwater for better irrigation (Dhanwal et al. 2017). Phytoremediation is a suitable treatment technology for different pollutants that include heavy metals (Mohan et al. 2015 and Ahmadpour et al. 2015), organic, inorganic compounds, salts (Gerhardt et al. 2017) and hydrocarbons pollutants (Almansoory et al. 2015, Brynhildsen and Rosswall 1997, Kim and Owens 2010 and Lakra et al. 2017). The technology was also used (Doni et al. 2015, Singh 2017 and Kamusoko and Jingura 2017) to illustrate that it is capable of removing both heavy metals, organic and inorganic pollutants in addition to total petroleum hydrocarbons. Wu et al. 2017 and Mahar et al. 2016 showed that bioremediation of plants and soil fertility can be improved. Moreover, phytoremediation is a cost-effective method of treatment (Wan et al. 2016 and Vose et al. 2000). In many cases phytoremediation is a better solution than "pump and treat" solutions (Vose et al. 2000, Carman and Crossman 2000 and Black 1995).

Phytoremediation, however, has some limitations in some environmental applications (Filippis 2015) such that the technology is suitable only for locations that are well suited for plant growth. The high concentration of contaminants is toxic to the plants and in these locations the technology is not applicable (Raskin et al. 2000). In order for the technology to be successful, the depth to contaminants should not be great. It should be within 20 feet of the ground surface in order for plant roots to be able to treat them (Smith 1997 and Schnoor et al. 1995). Phytoremediation is also controlled by the suitability and growth rate of the plants. Table 1 presents the contaminants type and the plants used for each one.

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Table 1
Examples of plants in phytoremediation (Smith 1997)

Plant	Contaminant	Use
Indian mustard greens	Heavy metals	Removes Pb, Cr, Cd, Zn and Cu from soil.
Goosefoot	Salt pollution from petroleum production	These salt-resistant weeds have cleaned up oil-patch areas ravaged by brine spills.
River Reeds	Runoff from airplane de-icing agents	In tests, the reeds rapidly broke down glycol antifreeze into water and CO_2.
Desert Reeds	Salts and heavy metals	Remove heavy metals and reduce the concentration of salts ions.
Poplar trees	TCE, petroleum, atrazine, other groundwater contaminants	These deep-rooted trees have been used to halt the spread of contaminated groundwater.
Kochia and Multiflora rose	Herbicide spills at agrichemical dealer lots	Used in combination, the tumble weed such as Kochia plant and the woody Multiflora rose halt the spread of herbicides.
Sunflowers	Radionuclides	Shown to remove uranium from water and have been successfully used at sites contaminated from the Chernobyl disaster.

The aim of this paper is to use the indigenous Reeds Plants as phytoremediation technology to examine its capability to enhance degradation of the pollutants and hence increase irrigation efficiency. Kuwait is chosen as the study area because it suffers from water scarcity and infertility of agricultural lands.

2. Technical approach

Phytoremediation is the use of many treatment mechanisms using plants (Chappell 1998 and Van Deuren et al. 2002). In this paper, a polluted beach well at KISR's premises was planned to be treated by Reeds plants. The native groundwater of this well was analyzed chemically at KISR laboratories and the results are presented in Table 2. Reeds plants were first implanted (in the fields of KISR) and irrigated with freshwater for about 6 months to allow them to grow up naturally. After that the Reeds plants were irrigated with polluted groundwater from the beach well using a closed basin in the field. Then the basin in Fig. 1 was flooded with polluted groundwater from the beach well to investigate the treatment efficiency of the roots of the Reeds in a way to detect any change in the concentration of pollutants between the native water and the outflow taken from the sampling point shown in Fig. 1. The volume of the portion of the field basin that was effective for the roots experiment as 2.31 m^3 (the root zone in this experiment is 1.5 m).

Table 2
Chemical analysis of the original sample (native groundwater)

Parameter	Unit	Original sample
TDS	mg/L	11,675
Cl	mg/L	4,148
SO_4	mg/L	2,862
Na	mg/L	2,720
K	mg/L	40.8
NH_4	mg/L	10.1
NO_3	mg/L	115
F	mg/L	2.3
Li	mg/L	0.23
Ca	mg/L	796
Mg	mg/L	354
Fe	µg/L	7.96
Zn	µg/L	15.1
Cr	µg/L	4.18
Co	µg/L	0.53
Cu	µg/L	3.1
Al	µg/L	71.32
Cd	µg/L	1.1

3. Results and discussion

The suitability of the concentration of ions in irrigation water for plant growth is presented as follows:

- Lithium (Li) is toxic for plants. It affects the mobility of nutrients from soil to plants. Lithium sources come mainly from Li industrial activities (Hull et al. 2014) and disposal of Li batteries (Al-Thyabat et al. 2013). Li reduces the plant growth by altering metabolism in plants(Shahzad et al. 2016). Therefore, reducing Li will help the growth of plants.
- Fluoride (F) influences the metabolic effects of plant growth. A water fluoride level of 1.5 mg/L can be toxic to plants (Swarup and Dwivedi 2002).
- Heavy metals can cause significant reduction in plant growth. The heavy metals that have the most toxic effect are Cd, Cu, Zn and Cr (Athar and Ahmad 2002). The following limits (Rowe and Abdel-Magid 1995) should not be exceeded in irrigating water to reduce toxic effects and to improve irrigation efficiency: Al (5–20 mg/L); Cd (0.01–0.05 mg/L), Cr (0.1–1 mg/L); Co (0.05–5 mg/L), Cu (0.2–5 mg/L), Fe (5–20 mg/L), F (1–1.5 mg/L), Zn (2–10 mg/L) and Li (< 2.5 mg/L).
- Freshwater can easily be absorbed through the roots without problems, but brackish water faces difficulties to do that. Salinity can limit plant access to soil water by increasing the osmotic strength of the soil solution.

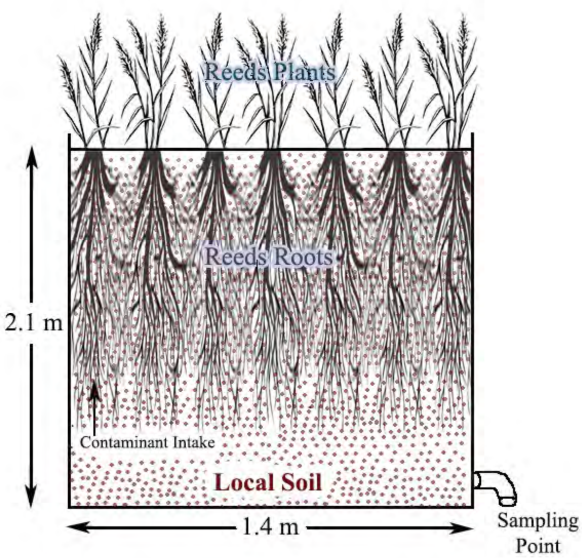

Fig. 1. Basic design of Reeds roots experiment in the field.

In Kuwait, hotter weather requires more energy from plants to absorb water. The following limits (Rowe and Abdel-Magid 1995) are favorable limits for good quality water to irrigate with: TDS < 960 mg/L; Cl < 140 mg/L; K < 10 mg/L; Na < 50 mg/L; SO_4 < 400 mg/L).

- NH_4 should be in the range (15–30 mg/L) and NO_3 around 50 to 100 mg/L (Rowe and Abdel-Magid 1995).

The native groundwater was analyzed chemically and showed that the type of this water is brackish with domination of Na-Cl-SO_4 salt ions. That means the salt is dominating this water which makes it difficult to irrigate with TDS value of 11,675 mg/L which is substantially above the limit of 960 mg/L (Rowe and Abdel-Magid 1995). Also the chemistry of the original water shows that Cl = 4,148 mg/L which is >140 mg/L, SO_4 = 2,862 mg/L which is >400 mg/L, Na = 2,720 mg/L which is >50 mg/L and K = 40.8 mg/L which is >10 mg/L. It should be noted that using the roots of Reeds plant is not intended to bring down the concentration of these ions to the limit of their use but the aim is to illustrate that these roots can reduce considerably the concentration of these ions to improve irrigation efficiency and productivity. The concentration of NH_4 in the original sample is 10.1 mg/L which is less than the limit of 15 mg/L and for NO_3 is 115 mg/L which is greater than the limit of 50–100 mg/L. The concentration of Li in the original sample is 0.23 mg/L < 2.5 mg/L and F is 2.3 mg/L which is greater than the limit of 1.5 mg/L. High concentration of salts affects plant growth by limiting the uptake of calcium and increasing the adsorption of sodium and potassium, resulting in a disturbance in the cationic balance within the plant. The roots of the Reeds plants were used to investigate the reduction of salts in the native polluted groundwater which is an alkaline water with SO_4–Cl salts domination. By Reeds roots treatment, the type of water changed to earth alkaline water with less SO_4 salts domination. The results of reducing the concentration of salts are presented in Table 3 and some of them are shown in Fig. 2. The reductions in the TDS, SO_4, Cl and K values for the same period of time in the experiment were substantial as shown in Fig. 2 for Cl ion. It is believed that the roots have big surface area and strong ability to absorb pollutants by the roots and to precipitate them from the irrigating water within the soil zone.

Table 3
Concentration of salt ions (mg/L) after using Reeds roots

Elapsed time (weeks)	Na^+	Cl^-	SO_4^{2-}	K^+	TDS
Original	2,720	4,148	2,862	40.8	11,675
4					
8	925	1,740	793	18.04	11,632
10	838	1,519			
12	805	1,430	644	10.5	4,024

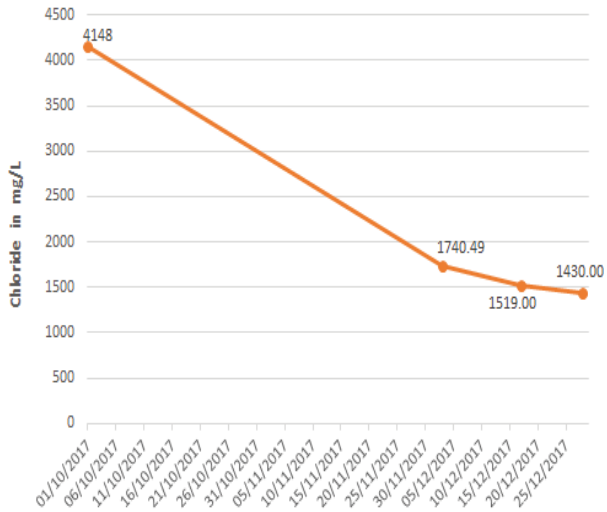

Fig. 2. Reduction of chloride by Reeds roots.

Table 4
Concentration of N compounds (mg/L) after using Reeds roots

Elapsed Time (weeks)	NH_4^+	NO_3^-
Original	10.1	115
4		
8	0.67	<0.1
10	0.24	<0.1
12	<0.1	<0.1

Irrigation water high in N can cause quality problems in crops. The existence of NH_4 as an example at higher concentrations than 30 mg/L is phytotoxic (Király et al. 2013). It took the Reeds roots 2 to 3 months to remove NH_4 and NO_3 ions from the polluted groundwater (Table 4). The Reeds roots transform the inorganic nitrogen from the irrigating groundwater into plant biomass, thereby removing the constituent from groundwater (Rowe and Abdel-Magid 1995). In this study, NH_4 and NO_3 were removed completely. However, N is needed for plant growth, therefore, good fertilizers and

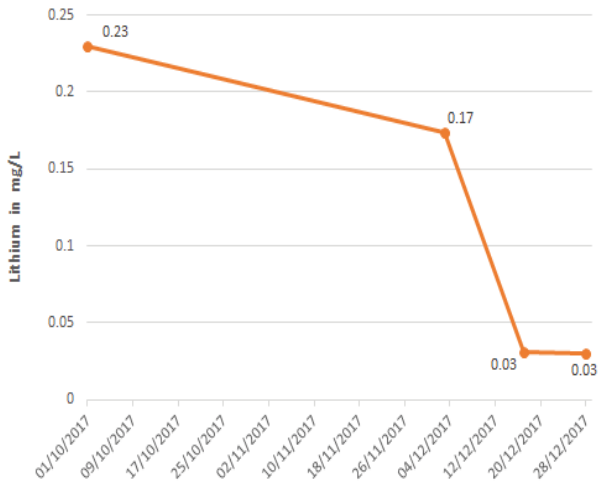

Fig. 3. Reduction of Li concentrations by Reeds roots.

irrigation management can help solve these problems (Rowe and Abdel-Magid 1995). Regardless of the crop, nitrates should be credited toward the fertilizer rates in general.

The experiments carried out in this paper shows that the Reeds roots almost removed (90% to 100% reduction) the concentration of F and Li ions (Fig. 3).

The Reeds roots reduced Co, Cd, Cr, Zn and Fe by almost 100% within a period of about 3 months. They reduced the concentration of Al and Cu by 53% and 39%, respectively (Table 5).

For heavy metals, the Reeds roots act as "hyper-accumulators" to absorb large amounts of metals (such as Zn, Ni and Cu) and concentrate them in the plant roots. Therefore, the Reeds roots are successful in removing heavy metals from polluted groundwater.

4. Conclusions

This paper has illustrated with evidence that Reed plants are capable of effectively removing contaminants from the polluted shallow groundwater in Kuwait. The reduction percentage of contaminants concentration in Kuwait native and polluted groundwater is presented in Table 6. In this study, the phytoremediation process was proved to be successful through roots of the Reeds plants to reduce the concentrations of contaminants (salts ions, nitrogen compounds and heavy metals). Table 6 shows that the roots of the Reeds plants can significantly reduce (Cl, Na, K and SO_4) by about 66%–78%. Also, the TDS value was reduced by the roots by 66%. The Reeds plants were capable of removing the nitrogen compounds (nitrates and ammonium ions) with 100% complete reduction. However, N is needed (within limits) for plant growth, therefore, good fertilizers and irrigation management can help solve these problems. Nitrates should be kept for irrigation purposes in Kuwait in the region of 50 to 90 mg/L. Fluoride ion concentration was reduced by about 86% while the roots removed the concentration of lithium completely. The concentration of the heavy metals in the native polluted groundwater (Table 6) is below the international standards (Rowe and Abdel-Magid 1995) but this research illustrates that the roots of the Reeds plants are capable to remove completely Cd, Co, Zn and Fe. The reduction of the concentrations of the heavy metals (of Al, Cu and Cr) by the roots of the Reeds plants was 53%, 39% and 89%, respectively.

Table 5
Concentration of some heavy metals (μg/L) after using Reeds roots

Elapsed time (weeks)	Fe	Al	Zn	Cd
Original	7.96	71.32	15.1	1.1
4				
8	<0.01	35.94	15.1	<0.1
10	<0.01			
12	<0.01	33.51	<0.2	<0.1

Table 6
Summary of reduction of specific pollutants by Reeds roots

Parameter	Unit	Original sample	Roots outflow	Reduction
TDS	mg/L	11,675	4,024	66%
Cl	mg/L	4,148	1,430	66%
SO_4	mg/L	2,862	644	78%
Na	mg/L	2,720	805	70%
K	mg/L	40.8	10.5	74%
NH_4	mg/L	10.1	<0.1	100%
NO_3	mg/L	115	<0.1	100%
F	mg/L	2.3	0.32	86%
Li	mg/L	0.23	0.03	100%
Fe	μg/L	7.96	<0.01	100%
Zn	μg/L	15.1	<0.2	100%
Cr	μg/L	4.18	0.47	89%
Co	μg/L	0.53	<0.1	100%
Cu	μg/L	3.1	1.88	39%
Al	μg/L	71.32	33.51	53%
Cd	μg/L	1.1	<0.1	100%

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Improving water use efficiency of crops for sustainable agriculture in dry lands

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ABSTRACT

Improving water use efficiency in agriculture especially in dry countries is the dire need of the day. Oman has limited groundwater and in many places it is saline water. Therefore, various approaches could be used to improve plant productivity in saline dry lands. One approach to overcome the limitation of plant growth due to shortage of water and soil drying could be to promote root growth for efficient uptake of water from greater soil volume. Ethylene is a plant hormone that is involved in the regulation of many plant physiological responses especially under stress conditions. Water stress has been extensively associated with elevated release of endogenous ethylene by the plant which results in root growth inhibition dramatically. Therefore, there are certain plant growths promoting rhizobacteria (PGPR) which contain a unique enzyme that decreases ethylene in the inoculated plant roots. The main aim of this project was to isolate and evaluate plant growth promoting rhizobacteria for increasing plant growth and water use efficiency of crops. Moreover, different compost could enhance the growth of bacteria and save water for better growth. For this purpose, different bacteria were isolated from saline soil of Barak, Oman. The best bacteria that gave better growth in saline media were selected. The best two bacteria were reproduced and used for field trials. They were compared with two bio-stimulants (Stimpo and Regoplant) and grown in three different composts (Kala, Growers and Al-Mukhasib). The study was done in greenhouse using radish and okra plants grown in pots and irrigated with freshwater and saline (4 dS/m) treated waste water.

Plant showed the best growth under freshwater irrigation compared with saline water. This happened due to salinity stress that affected water and nutrients movements from the soil to the plant. All used composts positively affected plant growth. However, Kala compost gave the best growth and productivity even under saline irrigation. The most important thing was how bacteria and bio-stimulants could improve plant growth and give significant effect especially under saline conditions. It was observed that Regoplant was good and gave better results for plant growth (plant height, fresh weight and fruit weight) with freshwater irrigation compared with saline condition. Whereas, Stimpo and bacteria showed positive effect under saline condition and they supported plant growth much better than Regoplant. However, Stimpo is still chemical compound and could have some side effects with long-term applications. Therefore, bacteria could be the best option for improving plant growth under saline conditions because it is from nature and could adapt with soil-water-plant conditions. Using these bacteria under Oman saline condition will improve the growth and productivity of different plants that could not survive under saline conditions.

Keywords: Enriched compost; Plant growth promoting rhizobacteria; Bio-fertilizers; Organic fertilizer

1. Introduction

Plant growth promoting rhizobacteria (PGPR) are comprised of diverse taxa of bacteria that commonly inhabit the rhizosphere or the interior of plant root tissues (Glick et al., 1995). PGPR enhance plant growth through several mechanisms, including solubilization of phosphorus and iron, phytohormone production, suppression of pathogens,

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and by lowering stress-ethylene concentrations in the rhizosphere (Glick et al., 2007; Dutta and Podile, 2010). Among these traits, suppression of ethylene production is one of the most important for alleviation of plant stress caused by drought, salinity, chemical toxicities. There are certain PGPR which contain a unique enzyme, ACC-deaminase that hydrolyses ACC and decreases ethylene in the inoculated plant roots. It is well documented that inoculation of seed/plant with these PGPR increases growth of inoculated plants. Better root growth can result in greater water use efficiency through exploiting greater soil volume. This ACC-deaminase biotechnology has been found very effective in increasing crop yields under different stress conditions such as drought, soil salinity, heavy metals, etc. on sustainable basis in many countries such as Canada, USA, India, Pakistan, China and Vietnam. However, it is very essential to evaluate this biotechnology under harsh climate, saline soils and arid environment such as Oman.

Another strategy to enhance water use efficiency could be by improving water holding capacity of the soil. Compost could be a good candidate for this because it could not only increase water holding capacity of the soil but also improve other physicochemical and biological properties of different soils. Composting offers the most sensible and economic way to handle organic waste materials which create environmental problems, and at the same time it produces a high quality and inexpensive soil amendment. Through composting, the undesirable features of these materials (heavy metals and organic compounds, pathogens, odor, wider C:N ratio, etc.) can be changed to desirable characteristics. In general, finished composts are highly regarded for their ability to improve soil health and plant growth. The efficacy of the compost could be further enhanced if the essential nutrients required by the plants and other biological substances are added to the applied compost.

In Oman, agricultural production is highly dependent upon the availability of suitable irrigation water. Water is a very precious commodity and all efforts are required to increase the productivity per unit of water applied. Water scarcity in agriculture sector is becoming an extremely serious problem in hampering the crop yields (Abdelrahman et al., 2011). The problem of water scarcity is very serious in Oman and average rainfall is less than 125 inches per year (FAO, 2013) which is often below the required amount for many crops.

As global climate change is predicted to make rainfall more erratic, there is a pressing need to improve crop production and water use efficiency. For this purpose different physical, chemical and biological approaches could be used to produce more biomass per unit of water. Therefore, many engineering and other management practices are being investigated to improve the water use efficiency of the agricultural systems in Oman (Luedeling et al., 2005). Application of enriched compost and PGPR for improving yield of crops and physical, chemical and biological properties of soils has been investigated in other countries (Shahzad et al., 2008) but application of this technology under the arid environment needs to be evaluated. The integrated application of both the PGPR and enriched compost could be more beneficial with improvement in plant growth, yield and water use efficiency of crop under the harsh climatic conditions of Oman. Therefore, the aim of the study was to evaluate the combined effect of applying PGPR containing ACC deaminase and enriched compost in improving plant growth and water use efficiency of crops.

2. Methodology

Indigenous PGPR was isolated from the rhizosphere of crops grown under saline conditions in Barak area, Oman, and was screened for plant growth promotion under axenic conditions. Three composts (Kala, Growers and Al-Mukhasib) were selected from different commercial sources, characterized for their physicochemical and biological properties. All three composts were enriched with nutrients and biologically active substances. Then the efficacy of both PGPR and enriched compost were evaluated under pot experiment irrigated by fresh and saline waters. To get clear comparisons, two bio-stimulants (Stimpo and Regoplant) were used and their effects were compared with local bacteria.

2.1. Greenhouse experiment

Okra and radish seeds were inoculated with four types of bio-stimulants (bacteria 1, bacteria 2, stimpo and regoplant). All seeds were planted for germination in plastic trays filled with peat-moss. The seeds were left to grow for 3 weeks and germination rates were recorded.

Seedlings were transplanted to greenhouse in pots filled either with Kala or Growers or Al-Mukhasib composts (50% sand:50% compost). Pots of different composts and crops were irrigated either with freshwater or saline treated wastewater (4 dS/m). Around 200 pots were prepared with 4 pots per treatment as shown in Fig. 1.

During the experiment, different measurements were taken as following: soil salinity, soil moisture content, chlorophyll content (SPAD meter) and Okra plant height, fruit number and weight. Finally both crops were harvested. Soil samples for all treatments were taken within 10 cm depth. Soil and plant samples were analyzed in soil and water lab for some physico-chemical analysis.

3. Results and discussions

3.1. Soil moisture content

Soil moisture content usually depends on soil/compost types and plant growth and consumption. Fig. 2 shows the average soil moisture content of Mukasab, Growers and Kala composts. Soil moisture content was approximately equally distributed in all Growers compost treatments compared with other two composts, whereas, it varies with different treatments of Kala and Mukasab. For bacteria treatments, it can be seen that control and Regoplant had more moisture content in all three composts; whereas, bacteria 1, bacteria 2 and stimpo had lower values. Differences in moisture contents between different treatments could mean that plant was absorbing water and the evapo-transpiration losses depend on plant health and compost physical properties.

Fig. 1. Pots of different composts irrigated with fresh and saline waters.

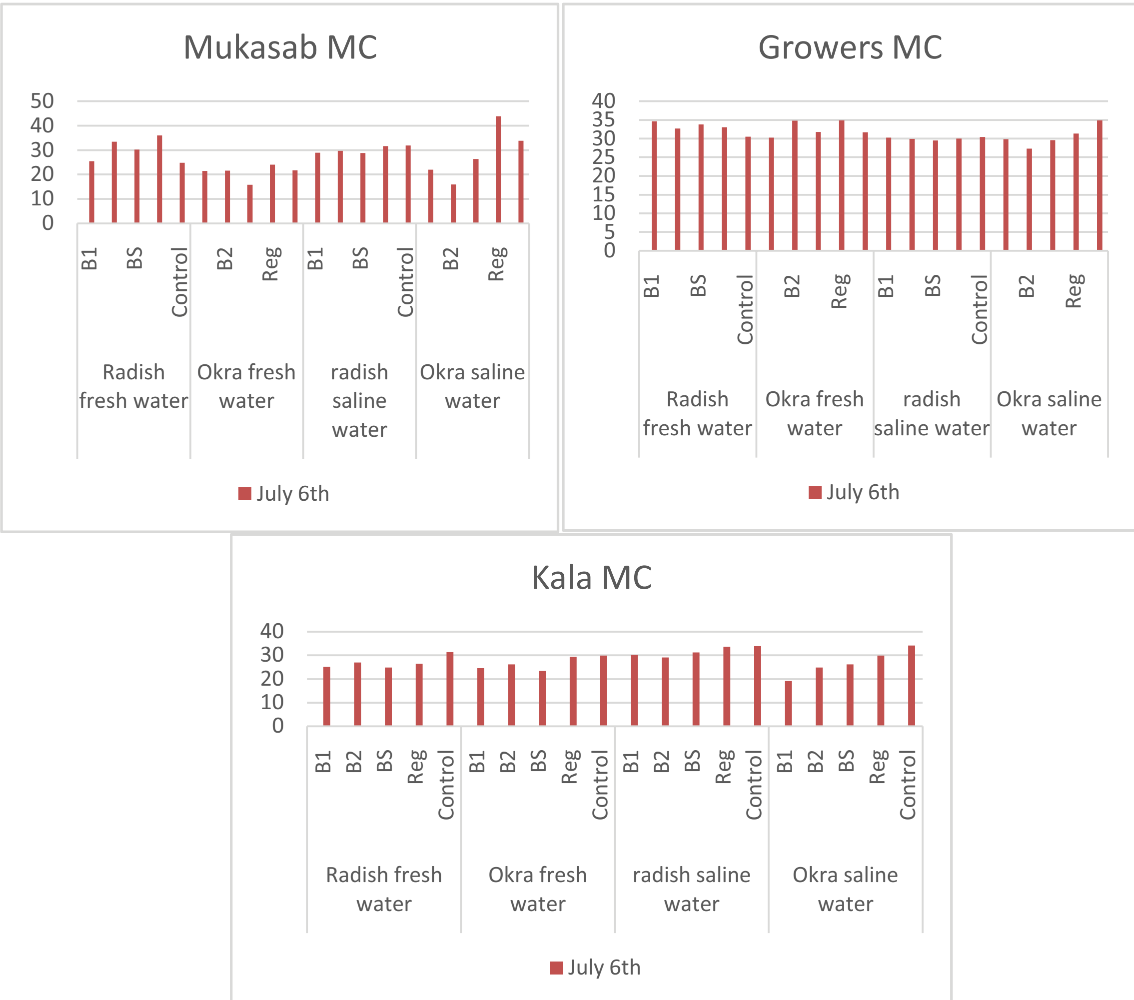

Fig. 2. Soil moisture content under different treatments.

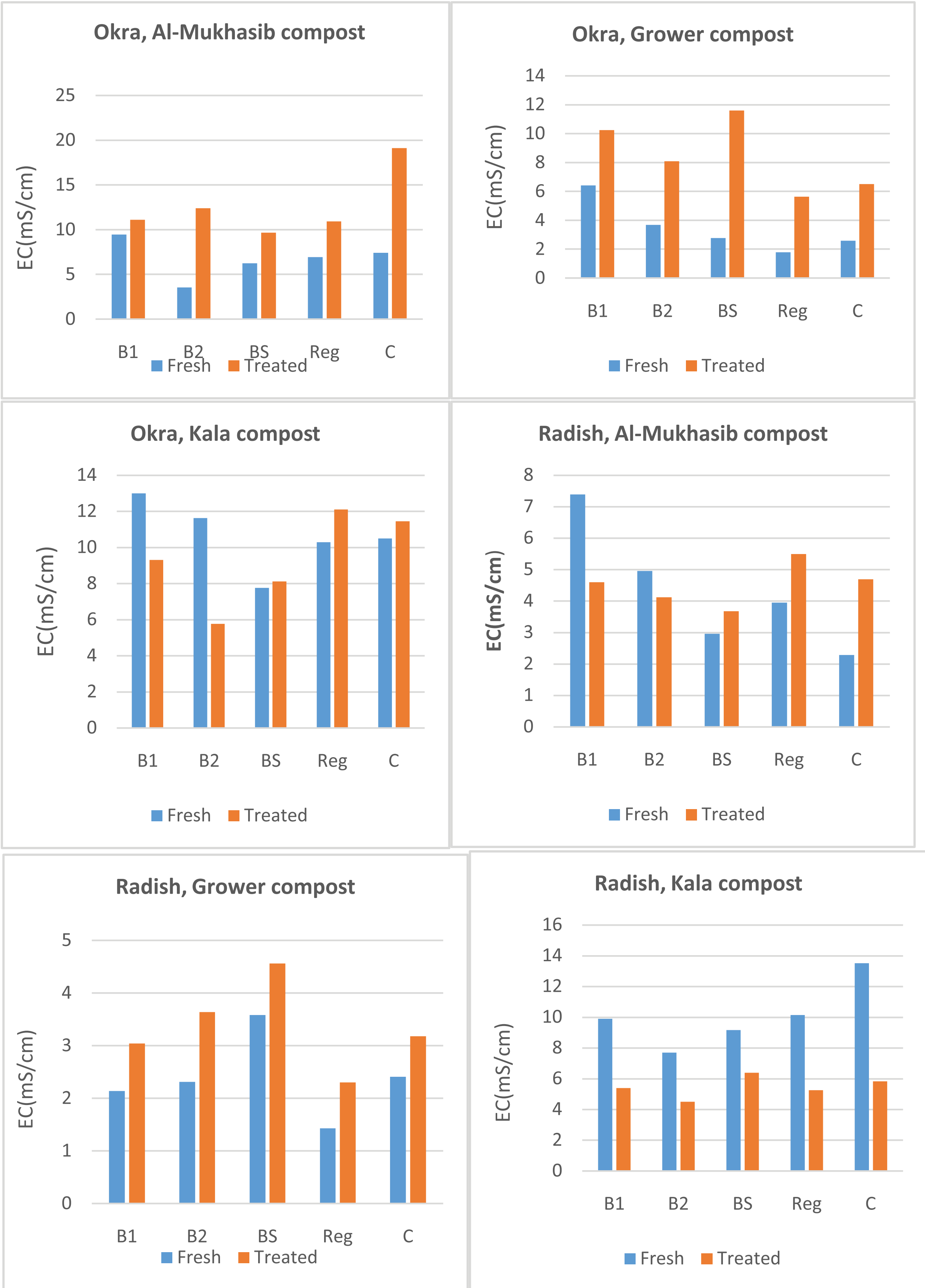

Fig. 3. Soil salinity as affected by different treatments.

3.2. Soil salinity (ECe)

Soil salinity could increase or decrease with time depending on original salts, salts added, consumed or leached down the profile. In case of saline irrigation, it is expected that soil salinity increases more than freshwater irrigation which can be seen clearly with both crops in Fig. 3. Irrigation amount, soil and compost water holding capacity could increase or decrease leaching process and affect salts accumulated in the soil. At the end of the study (Fig. 3), it can be seen that Kala compost had higher salinity values compared with other composts which could mean that Kala compost was continuously releasing nutrients to the soil solution and feeding the plants. The most interesting thing is that bacteria 1 and 2 were more active under Kala compost and helped in decreasing soil salinity under saline treatments. This finding needs extra investigation.

3.3. Chlorophyll content

Chlorophyll is an indicator for green color which is usually related to the nitrogen absorbed by plant. From Fig. 4, it can be seen that Kala compost gave the highest values for chlorophyll content which mean that Kala could have more nitrogen compared with other composts. Moreover, saline treatments had negative effect on chlorophyll content which mean plant cannot absorb nitrogen when soil salinity is high.

3.4. Okra height

As shown in Fig. 5, it can be seen that Kala compost was the heights compared with other composts. Plant grown under freshwater irrigation got better results than saline conditions. However, Bacteria 2 was more active in supporting Okra growth compared with other treatments. Bacteria 1, Bacteria 2, stimpo have good height in both fresh and saline water irrigation. However, Regoplant was good in fresh water irrigation but not in saline water irrigation and control have the lowest height in fresh and saline water irrigations.

3.5. Okra fruit weight

Plant productivity is the most important thing for the farmer and consumer. Okra fruits were highly affected by

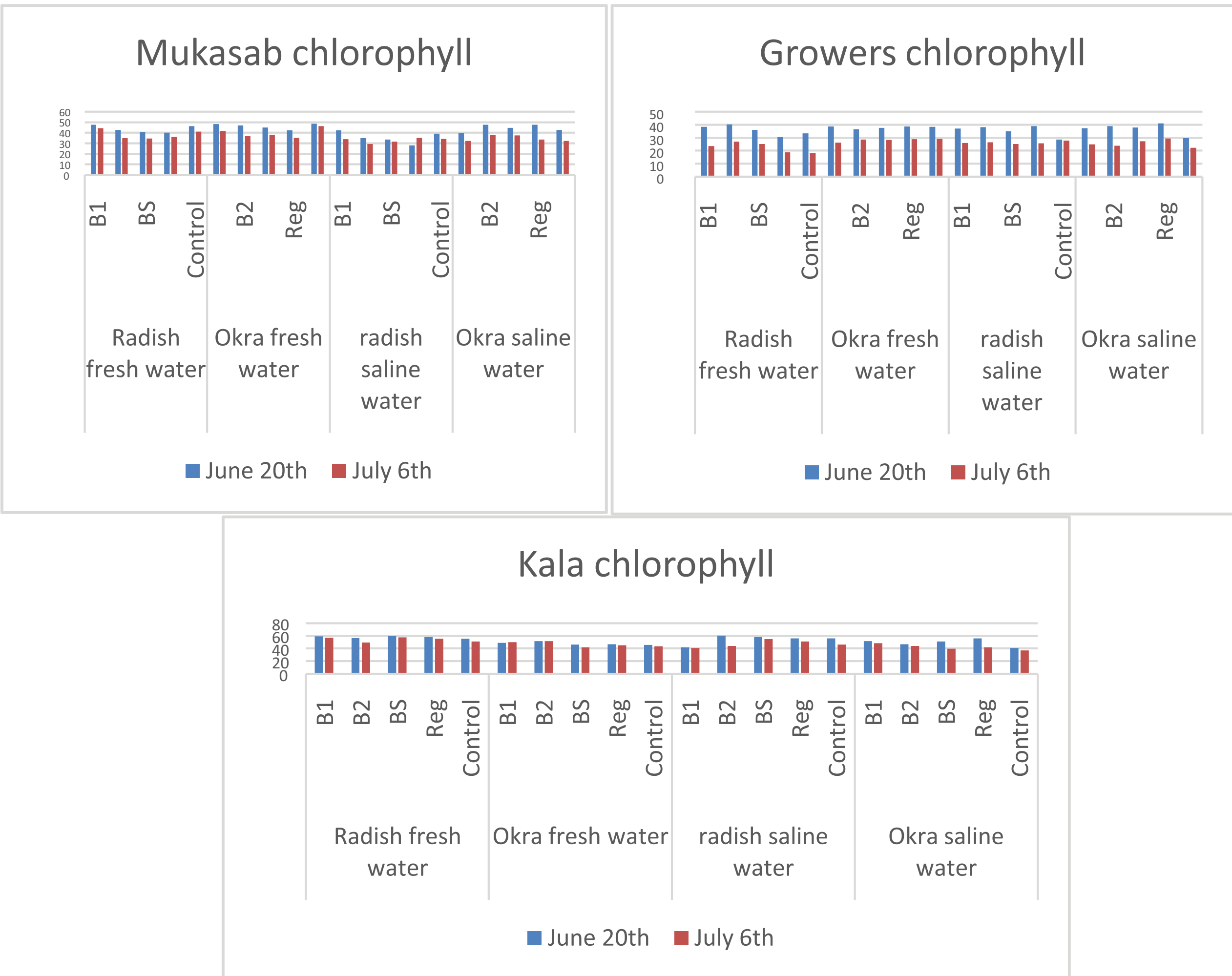

Fig. 4. Chlorophyll content as affected by different treatments.

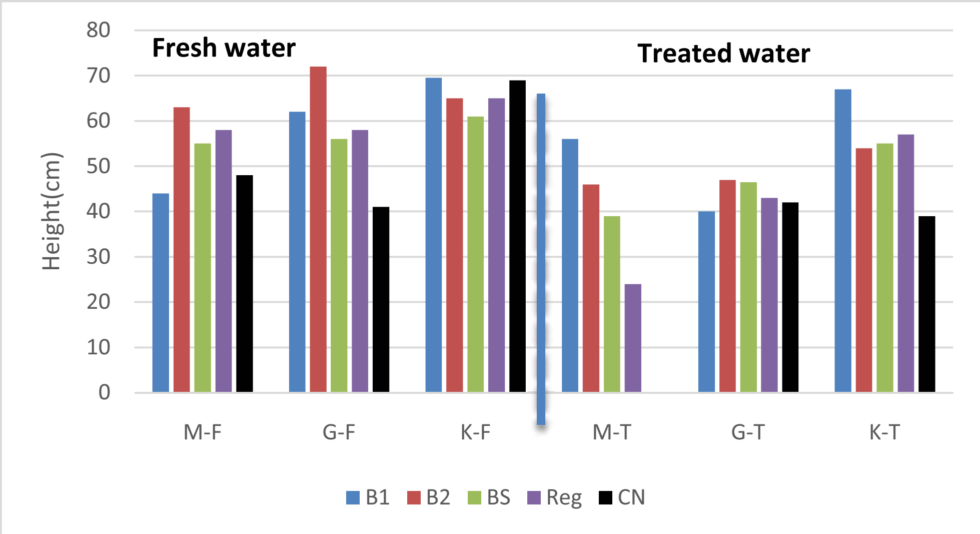

Fig. 5. Okra height as affected by different treatments.

fresh-saline irrigation followed by compost type and finally with bacteria treatments (Fig. 6). Salts present in irrigation water suppressed okra productivity and gave zero or low fruits compared with freshwater irrigation.

Compost was the media supporting plant growth. Therefore, it looks like that Kala compost was the best compost that gave the highest productivity of okra fruits compared with other composts. The most interesting thing is that bacteria 1 and 2 gave the best productivity within all composts. It seems that native bacteria were supporting plant growth by improving nutrient absorbance and reducing salinity stress.

Regoplant and control showed no fruits production under saline treatments compared with freshwater irrigation; whereas, stimpo, bacteria 1 and bacteria 2 gave good amount of fruits under both qualities of water. The highest fruit weights were with Kala compost as clearly shown in Fig. 6 and bacteria 1 was the best. In general, treatments with B1, B2 and BS were adding values to the plants by improving productivity and reducing soil and water stresses.

3.6. Radish fresh weight

Radish is a short growing crop. Therefore it could be a fast indicator for short-term effects or stress. From Fig. 7, it can be seen that water salinity and type of compost were the main parameters that affected radish productivity. There was a big difference in Radish productivity between three composts in which Kala got the highest values followed Mukasab and finally Grower. Moreover, there was a clear effect of water salinity within each compost where salts suppressed radish growth.

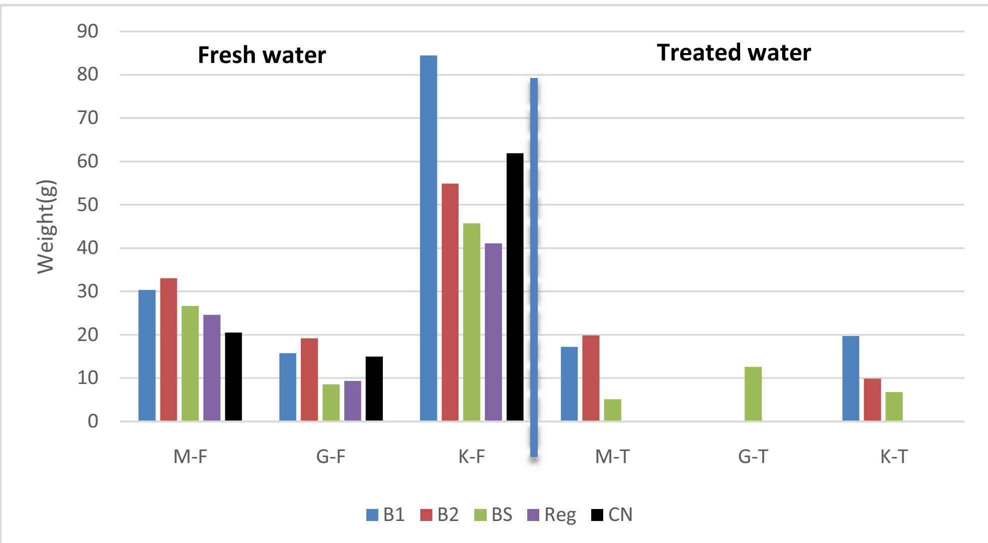

Fig. 6. Okra fruit weight as affected by different treatments.

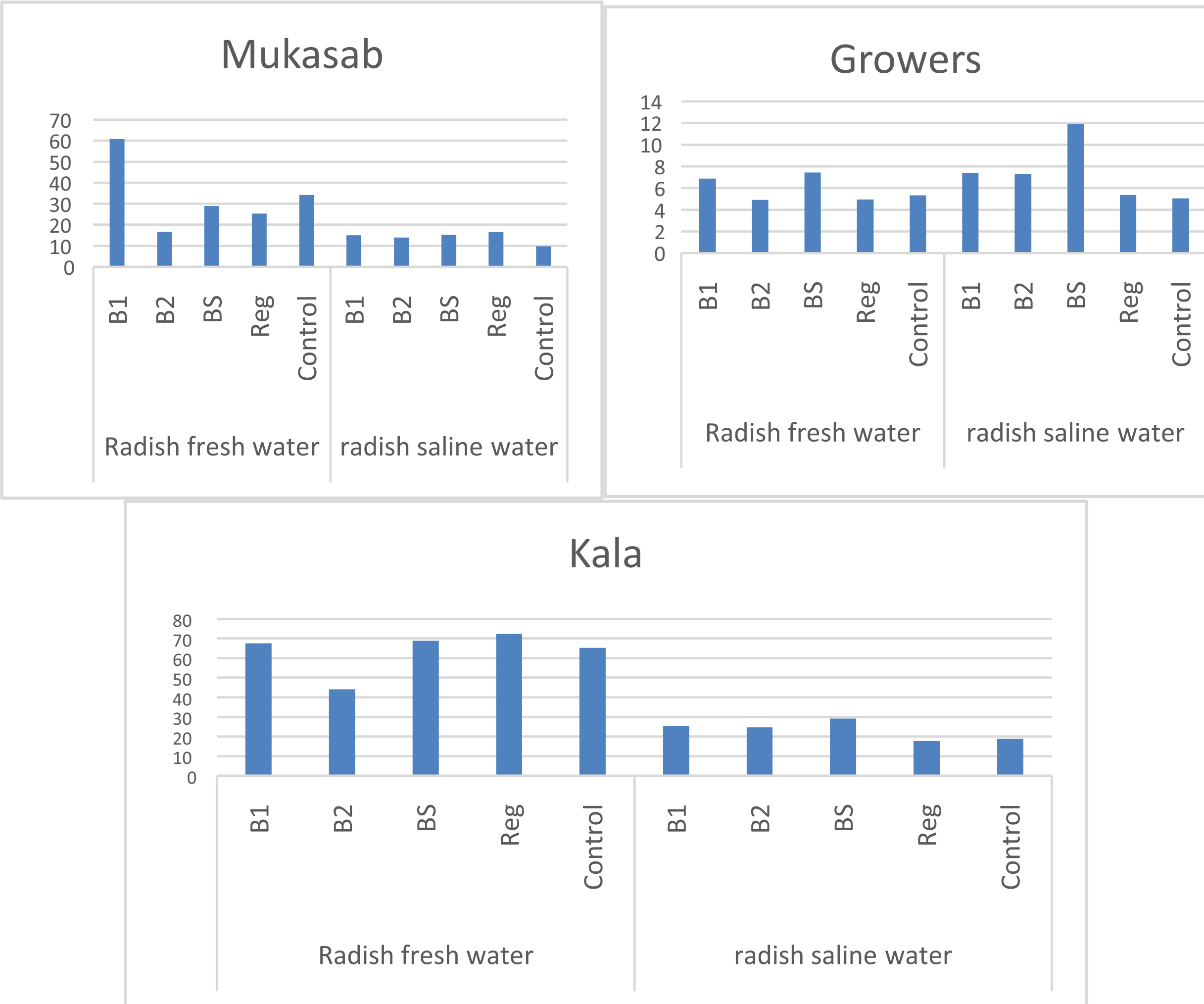

Fig. 7. Radish fresh weight as affected by different treatments.

For bacteria treatments, bacteria 1 was the best followed by bio-stimulants treatments. This finding is confirming what was found with Okra crop which mean bacteria 1 is the best for Oman saline conditions.

4. Conclusion

Plant growth can be affected by different parameters such as salts, organic matter and bacterial activities. From this study, it was found that soil salinity was the major parameter that affected plant growth and productivity. Application of different composts and bacteria had a role in supporting plant growth and its productivity.

For the composts application, it was found that Kala compost was the best compost in creating good environment for plant growth by providing more water and nutrients in root zones compared with Mukasab and Grower composts. In addition it was enhancing bacterial growth by providing almost all needed parameters for better bacterial growth.

Bacteria obtained from Oman environment (native bacteria) was the best bio-stimulants in which it gave the best data for plant growth even under saline conditions; whereas, other bio-stimulants vary and gave lower support for plant compared with native bacteria.

In general, regoplant was a good agent under normal conditions but not in saline soils. Stimpo and plant growth promoting rhizobacteria (bacteria 1 and 2) did well under saline condition. However, bio-stimulant was not a native product and could not work well under Oman harsh conditions. Therefore it cannot be recommended for future application. However further studies should be done to evaluate that. Plant growth promoting rhizobacteria (bacteria 1 and 2) were native bacteria adapted to saline and hot conditions. It is the best for salt-affected soils in Oman. However, more research should be done to elaborate its mechanisms and understand the best growth condition for them so better plant growth can be found under Oman salt-affected soils.

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Water saving in arid irrigated lands: a comparison between different irrigation techniques adopted under date palms in the Tunisian Oasis

Latifa Dhaoudi, Tunisia

ABSTRACT

Water irrigation resources scarcity combined with the problem of poor quality of most of these resources known by their high salinity, present a great threat for the oasis agriculture sustainability. Hence, improvement of water saving technologies is imperative to ensure the better oasis productivity. The main objective of this work is to identify the efficiency of the irrigation technique for date palm trees through the assessment of irrigation technologies newly introduced by a few farmers in some of the Tunisian oasien regions. The three irrigation techniques, which were evaluated by applying the same volume of water irrigation under date palm trees, are the bubbler, the mini diffuser and the subsurface drip irrigation systems. The irrigation assessment showed that the uniformity in water irrigation distribution of the soil after irrigation is around 90% for the three techniques. The water irrigation losses after irrigation were 42, 63 and 72 mm, respectively, by bubbler, by mini diffuser and by subsurface drip irrigation. The irrigation water application efficiency is the best for the bubbler irrigation (62%). The water use productivity is also the highest for the bubbler (0.66 kg/m^3); in addition to the desalination efficiency which was 63% . The results of this study showed that the bubbler irrigation system is the most efficient technique which will be the best technology practice under date palm trees in the Tunisian Oasis conditions.

Keywords: Tunisian Oasis; Date palm; Bubbler irrigation; Mini diffuser; Subsurface irrigation

1. Introduction

The agricultural sector consumes from 70% to 72% of the total world water resources (Ahmed et al., 2012). In arid and semi-arid regions, the consumption of these resources is the biggest. In some countries, it could account for more than 80% of the total annual water consumption (Alamoud, 2012; Mumtaz Khan et al., 2012). In this current situation, the challenge is to find the ways to ensure the food security in these regions. In this context, it is necessary to improve irrigation and water use efficiencies in order to get higher crop productivity and agricultural sustainability.

Date palm trees are crops which can provide food and nutrition for people and they have been the major agricultural crop in the oases of Algeria, Egypt, Iran, Libya, Morocco, Oman, Saudi Arabia, Tunisia, United Arab Emirates and Yamen which are largely arid countries. These fruit trees cope in an excellent way with the arid climate but they are dependent on irrigation because they need enough amounts of water to sustain growth through keeping all metabolic processes intact, and produce marketable fruit (MKV carr 2012; Mumtaz Khan et al., 2012). Deglet Nour date palm cultivar is one of the most high quality commercial and popular dates in Tunisia (third place of food products nationally) and in the world but in this decade the fruit quality is endangered by the effects of the climate change and the absence of adaptation strategies.

The Tunisian oases are located in four main regions: Tozeur, Kebili, Gabes and Gafsa. These oases are in the Sahara Mediterranean bioclimatic floor, on top floor, varying mild winter. This climate is characterized by low and erratic rainfall, contrasting temperatures and climate rather than irregular winds. The average annual rainfall is less than 100 mm in Tozeur and Kebili and it exceeds 150 mm in Gafsa and Gabes. The highest temperatures are recorded in continental regions, highly influenced by the Sahara. The average maximum temperatures recorded in the regions of Tozeur, Kebili and Gafsa are, respectively, about 40.4°C, 42.2°C and 38°C. As for the region of Gabes, the maximum average temperatures are, respectively, around 32.7°C and 36.8°C.

Evaluating the water resources in the oasis zones, we can say that they reach a total of 551,700,000 m^3/year against an estimated operating 645.88 Mm^3/year, or 117% over-exploitation. All aquifers are over-exploited with different degrees. The sheet of terminal complex (TC) is the most over-exploited with a rate of 129%. The oasis of Kebili

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region recorded the highest rate of exploitation with 157% and 172%, respectively, for the TC and CI (continental inter-calary). So the main problem of oases agriculture is water scarcity and its worsening quality. In addition to that, the distribution of water irrigation done according to the system of the water rotation to different farmers has been conducted according to pre-established areas and has not been conducted according to the real water needs of crops. On each antenna, there are series of irrigation terminals each irrigates a set of plots (3–4 ha). The irrigation period lasts from 10 to 14 h/ha, irrigation rate of 90 to 120 mm/rev water. This irrigation method practice can reduce and damage the irrigated land productivity (Tyagi et al. 2005). So we are facing a serious oasis ecological problem. That is why, in order to ensure the oasis sustainability, it is necessary to develop irrigation systems under date palms. The flood irrigation system which is the most widespread in traditional production oasis is not efficient compared with the modern one such as, surface drip irrigation, bubbler and subsurface one (Alamoud, 2012; Dhaouadi et al., 2015). In 2014, Bourziza Rquia et al. showed that subsurface drip irrigation (SDI) is an efficient technique, which allows the sustainable irrigation under date palm in arid areas. Al-Subaiee et al. in 2013 demonstrated that bubbler irrigation method has been proved as a very efficient one judging by producing higher vegetative growth. In Tunisian oases, the use of the SDI and the bubblers under date palms is limited in spite of both the evolution of palm date areas and the absence of the irrigation scheduling programs caused by water scarcity conditions.

Several oasian farmers have been aware of the necessity to modernize their irrigation methods in order to ensure their future income sources and their food security.

The aim of this work is to identify the best efficient irrigation system under the date palm. It consists mainly of an evaluation of the different irrigation techniques that are currently applied under date palms in the Tunisian oases, namely irrigation by mini diffuser, by bubbling and by drip subsurface irrigation.

2. Materials and methods

The experiments were carried out in oasis plot which is located in the slope of Chott El Jerid in the north-west of the ancient oasis of Déguache (33° 59′28.27′′N, 8° 14′16.44′′E) knowing that El Jerid is located in the south-west of Tunisia. Our study area belongs to the Saharan domain that is characterized by a fairly flat relief except in its eastern part where the North chain chotts are situated. This region has the highest summer humidity rate and the nature of the soil is favorable to the plantation of the date palm (Namsi, 2008)

The experimental plot has an area of 4 ha irrigated with different water qualities (well water, water association) for many years by basin irrigation system (5 L/s). Starting from 2012, a gravitational irrigation was implemented under palms for a surface of 1 ha where the bubbler has been adopted (360 L/h), and the water irrigation has been uniquely from the well (12 L/s). This water has been drawn from well of filling a basin. Irrigation, by these three different irrigation systems (bubbler, mini diffuser and subsurface drip irrigation) was assessed.

The experiments focused on the following aspects:

- Physico-chemical characterization of irrigation water.
- Hydrodynamic characterization of the soil of the study plot.
- Study of the root distribution of date palms.
- Monitoring the moisture soils for different irrigation systems.

2.1. Irrigation water quality

Water samples were taken from irrigation drilling. Temperature, pH and electrical conductivity of these samples were measured using portable devices. The major elements were measured in the laboratory using standard methods such as volumetric method for bicarbonate ions, total hardness, calcium, magnesium and chloride. The colorimetric method was used for sulfates and nitrates. The sodium adsorption ratio (SAR), which measures the risk of sodisation complex adsorbent, was calculated using the following formula in which concentrations are expressed in (meq/L; Hanson et al., 2006):

$$\mathrm{SAR} = \frac{\mathrm{Na}^+}{\sqrt{\dfrac{\mathrm{Ca}^+ - \mathrm{Mg}^{2+}}{2}}} \quad (1)$$

2.2. Soil texture

The samples, which have suffered the particle size analysis, were taken from four horizons (0–30, 30–60, 60–90 and 90–120 cm). It was limited to five sampling profiles: four at the vertices and one at the middle of the study plot. The results were used to identify the soil texture by the mean of the USDA chart (United states Department of Agriculture; De Forges et al., 2008).

2.3. Bulk density

Soil samples verifications were carried out from a pit (1.2 m × 1.2 m) in slices 0–30, 30–60, 60–90 and 90–120 cm; these undisturbed samples were transported to the laboratory with the aid of the cylinders of a non-disturbed auger. Knowing the constant dry weight of the samples to 105°C and the capacity of cylinders, we measured the soil bulk density of the experimental plot.

2.4. Infiltration

The experimental study of water infiltration into the ground at the field scale was performed by double-ring infiltrometer. The result of cumulative infiltration test over time allowed the determination of water infiltration law for the experimental plot soil by Philip equation (1966):

$$i(t) = \frac{1}{2} s t^{-0.5} + A \quad (3)$$

$$\mathrm{A} = \frac{\gamma s_2}{r} + \frac{(2-b)}{3} \times k(h_0) \quad (4)$$

$$K(h_0) = q(h_0) - \frac{4bs_2}{\pi r} \quad (5)$$

q (h_0): infiltration flow in steady state (from infiltration curve), s: sorptivity, r: radius of the inner ring 30 cm, b = 0.55, $\gamma = 4b/\pi = 0.7$.

The experimental infiltration study allowed to identify the hydraulic conductivity at saturation K_s.

2.5. Soil water content characteristics

The objective is to identify the function of the water retention curve which is described according to Van Genuchten (1980) as:

$$\theta(h) = \theta_r + \frac{(\theta_s - \theta_r)}{\left(1 + |\alpha h|^n\right)^m} \quad (2)$$

where $\theta(h)$ is the water content at pressure head h, θ_r is a residual water content which is usually fitted to measured data, θ_s is the water content at saturation which is usually not fitted but taken as the measured total porosity. α, n and m are parameters without physical meaning describing the shape of the function; m is usually fixed as $m = 1-1/n$.

In this work, the Richards Pots were used (Set PF-meter ceramic plate, basic standard set) to determine θ_{cc} the water content at field capacity and θ_{pf} the water content in the permanent wilting point. Using these parameters by the Hydrus-1D; θ_r, θ_s, α, n and m were easily evaluated.

This experimental study allowed to predict the hydraulic conductivity function (Mualem, 1976; Van Genuchten, 1980):

$$K(h) = K_s S_e^{\lambda}\left[1 - \left(\left(1 - S_e^{\frac{1}{n}}\right)^m\right)\right]^2 \quad (3)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (4)$$

λ is the connectivity parameter 0.5 and S_e is the effective saturation.

2.6. Root profile

It is evident that knowing where roots are located and their concentrations on the soil layers increases the production system efficiency when cultural practices are wisely applied under-tree area such as irrigation and fertilization (Bauer et al., 2003).

The root distribution at the experimental site was studied on soil profiles 0.5 m, on 1 m and on 2 m radium from the tree. Soil and root-samples have been taken every 0.20 m layer until 1.20 m depth.

2.7. Assessment of irrigation

To analyze the distribution of water in the soil before and after irrigation, we adopted the following steps: experiments had begun in the experimental plot with a first irrigation, the duration of which was about 5 h for bubbler, subsurface and mini diffuser and basin system; these durations are practiced by farmers in the study area. Monitoring soil moisture was observed before and after irrigation for four successive irrigations every 10 d. The monitoring of moisture and water stocks in the study plot was performed by gravimetric method.

Two other durations have been tested for the case of bubbler irrigation technique, namely 9 and 4.5 h with monitoring the soil moisture before and after every irrigation. Using an auger, soil samples have been taken from different depths ranging from 20 to 120 cm for multiple profiles following the irrigation technique and the tested duration. All these measures have allowed us to determine both the irrigation performance indicators:

Uniformity Christiansen CU (Heermann et al. 1990):

$$\mathrm{CU}(\%) = 100 \times \left(1 - \frac{\sum|\theta_i - \theta\mathrm{moy}|}{\sum\theta_i}\right) \quad (5)$$

Irrigation efficiency (Burt et al. 1997):

$$\mathrm{IE} = \frac{\text{vol. irrig. water beneficially used}}{\text{vol. irrig. water applied-a storage of irrig. Water}} \times 100\% \quad (6)$$

3. Results and discussion

3.1. Zone characterization

3.1.1. Irrigation water quality

The analysis in Table 1 presents the water irrigation quality in the experimental field. The SAR value that was evaluated by Eq. (1) is 6.37. This value is less than 10 so the risk of sodium accumulation in the soil is minimal (N'DIAYE et al. 2010).

Table 1
Physical and chemical composition of water irrigation for experimental plot

	Water drilling		
T (°C)	25.3		
pH	7.46		
Electrical conductivity (ms/cm)	3.38		
Dry residue (mg/L)	1.91		
Ion concentration	mg/L	Mmol/L	Meq/L
Calcium	152.8	3.82	7.64
Magnesium	78.04	3.21	6.42
Sodium	3.89	16.91	16.91
Potassium	23	0.58	0.58
Bicarbonate	352	5.77	5.77
Sulfate	427	4.44	8.89
Chlorure	568	16	16
Nitrate	8.7	0.14	0.14

Fig. 1. Localisation of the study plot. (A): the study area. (B): the experimental plot.

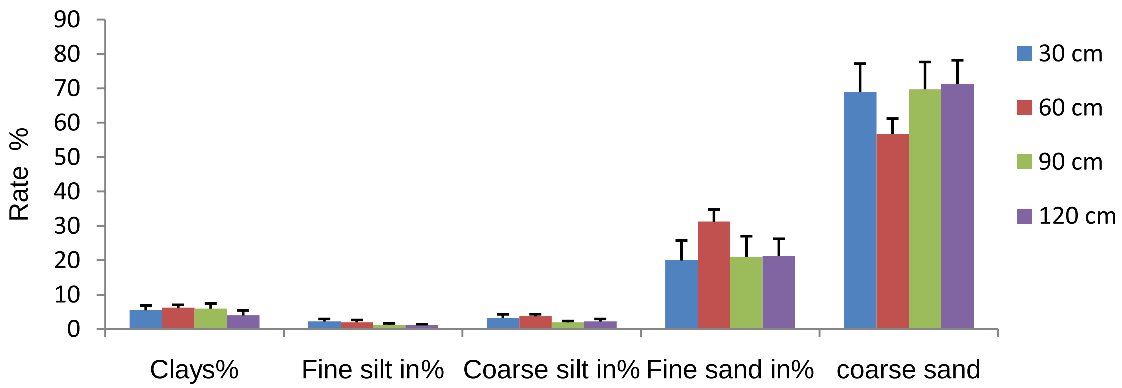

Fig. 2. Soil texture of the study plot per depth.

3.1.2. Soil texture

3.1.3. Bulk density

The curve of Fig. 3 shows that the bulk density is slightly varying depending on the depth. The maximum value is about 1.46 g/cm^3 for the depth of 90 cm. The average is in order to 1.44 g/cm^3.

3.1.4. Infiltration

According to Philip's Eq. (2) and the following figure, the infiltration law of the experimental plot soil is as follows:

$$i(t) = 0.17t^{-0.5} + 27 \quad (5)$$

And $K_s = 1,\ 9.10^{-3}$cm/s.

3.1.5. Soil water content characteristics

The results in Table 2 were used to establish Eqs. (2)–(4) characterizing the soil of the experimental plot:

The water retention curve function:

$$\theta(h) = 0.04 + \frac{0.4}{\left(1 + |0.062 \times h|^{1.679}\right)^{0.404}} \quad (6)$$

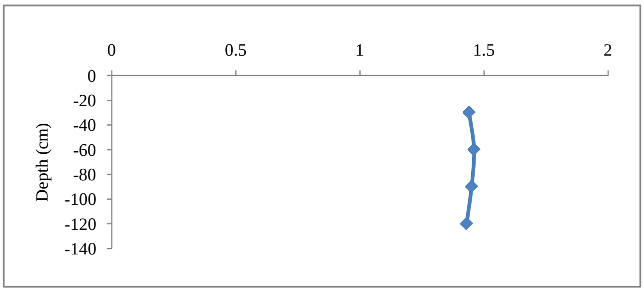

Fig. 3. Soil bulk density of experimental plot.

The hydraulic conductivity function:

$$K(h) = 6.8 S_e^{\lambda}\left[1-\left(\left(1-S_e^{0.595}\right)^{0.404}\right)\right]^2 \quad (7)$$

where:

$$S_e = \frac{\theta - 0.04}{0.4} \quad (8)$$

3.1.6. Root date palm distribution

The expérimental study of root distribution showed that the majority of the roots (approximately 90%) were located between 0.4 and 1.2 m. knowing that Leyron in 2000 (Jrad, 2012) showed that the region between 0.9 and 1.5 m is occupied by the nutrition roots which present the high proportion of root system.

Fig. 5 presents the spatial distribution of roots in the soil depending on the depths and distances from the palm trunk. Root equal percentage curves in the soil was drawn by the software SURFER 9.

4. Monitoring soil water content

4.1. Drip subsurface irrigation

The irrigation duration, which was about 2.7 h of irrigation, adopted this technique that lasts 2.7 h. The initial average water content was about 7%. It oscillates between 6% and 9%; values slightly above θ_{pf}, which is higher than the water content θ_{pf} (6%). At the end of irrigation, the maximum water content is 20%; in the average it was 17%. Soil moisture gradually decreases over time to reach 14% 48 h after the end of irrigation. It is an average grade value that is greater than the average moisture content at the field capacity θ_{cc} (11%). The moistened radius at the end of the irrigation was about 120 cm whereas the average water contents were 9% and 18%, respectively, for the whole profile and around the point of emission. The average water content is 9%, and the average water content next to the emitter is 18%.

4.2. Mini irrigation diffusers

The irrigation practiced by this technique lasted 3 h. The initial average water content was slightly higher (7%)

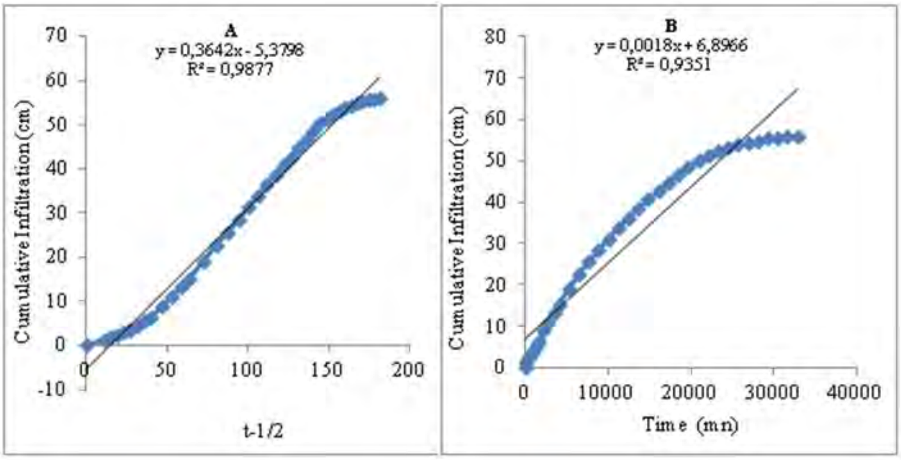

Fig. 4. (A): Sorptivity, (B): hydraulic conductivity at saturation K_s.

Table 2
Adjustment parameters of the relation θ (*h*) according to van Genuchten Model (1980)

Depth cm	θ_{cc} (cm³/cm³)	θ_{pf} (cm³/cm³)	θ_s (cm³/cm³)	θ_r (cm³/cm³)	*A* cm⁻¹	*n*	*m*
0–30	0.12	0.07	0.41	0.04	0.0602	1.600	0.375
30–60	0.11	0.06	0.41	0.04	0.0612	1.608	0.378
60–90	0.07	0.04	0.40	0.04	0.0585	2.009	0.502
60–120	0.08	0.05	0.41	0.04	0.0574	2.003	0.501
0–120 cm	0.10	0.06	0.41	0.04	0.062	1.679	0.404

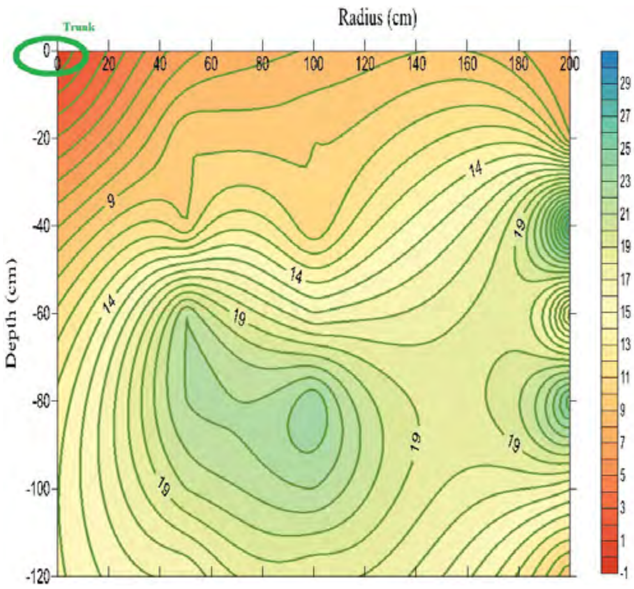

Fig. 5. Space distribution of date palm roots in the soil.

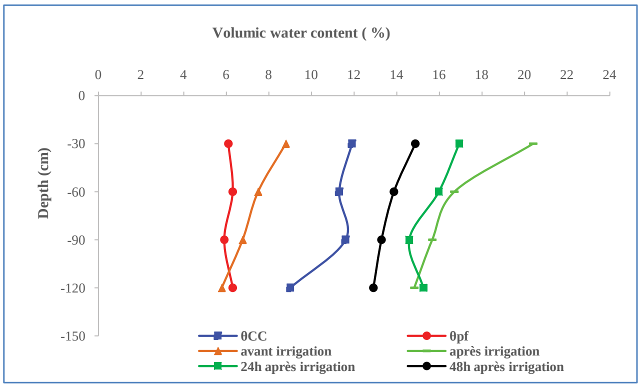

Fig. 6. Water profile in the soil after irrigation by drip subsurface system.

than the water content θ_{pf} (6%). The maximum value (9%) was recorded at the 0–30 cm horizon (Fig. 7). Just at the end of the irrigation, the soil moisture varies between 15% and 17% depending on the depth. Over time, the decrease in moisture content was regular and remarkable over the entire root depth. After 48 h, the minimum average water content is about 13%, which is higher than the average moisture content at the field capacity θ_{cc} (11%). At the end of irrigation, the water content, compared with the mini-diffuser emitter, is 17% knowing that the radius of the wet front is 110 cm whereas the average value of the soil moisture is 14% in all the root depth.

The water stock, immediately after irrigation, was greater (about 194 mm) than its field capacity value (132 mm). So the losses were 62 mm.

4.3. Bubbler irrigation system

With this technique, the irrigation lasted 5 h. The initial average water content did not exceed 7%. Just after

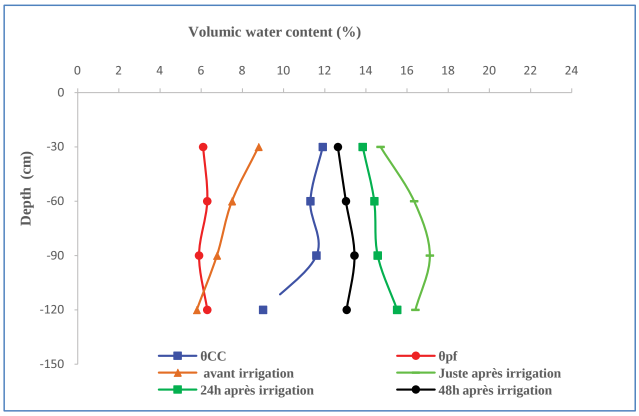

Fig. 7. Water profile in the soil after irrigation by mini-diffuser system.

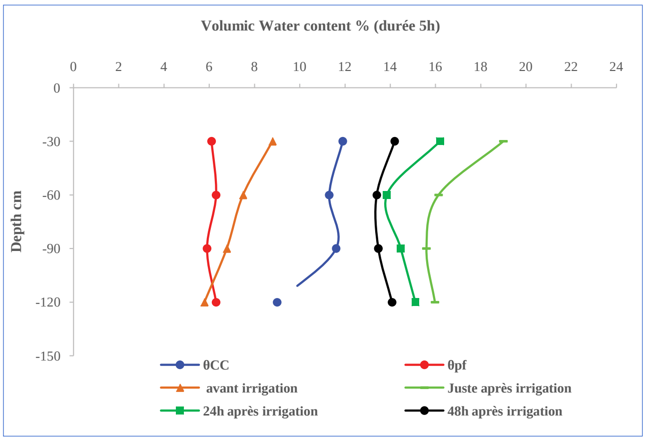

Fig. 8. Water profile in the soil after irrigation by bubbler system.

irrigation, the minimum humidity was about 16%; value greater than θ_{cc}. At the end of irrigation, the moistened ray was 170 cm. Average water content was 19% close to the bubbler but decreased to 14% at mid-distance between bubblers. The distribution of moisture in the root zone is homogeneous and decreases steadily with time. Indeed, before irrigation, it does not exceed 7%. On the other hand, just after irrigation, it reached 21% (60 cm from the bubbler) but it did not exceed 10% at the edge of the wetting front (at 140 cm from the bubbler). On the scale of the root profile, it reached 17%. After 48 h, this decrease was more remarkable (14%) although it remains higher than θ_{cc}. Just after irrigation, the moistened ray on the soil surface was greater (140 cm) than the spacing between the two dabblers of the same palm.

4.3.1. Efficiency of water irrigation application

The efficiency of water application for the various techniques adopted varied among 57%, 36% and 30%, obtained, respectively, for drip irrigation, drip subsurface irrigation and by mini diffusers. These low efficiencies obtained, values can be explained by the low soil water retention capacity and the relatively high doses of the low soil water

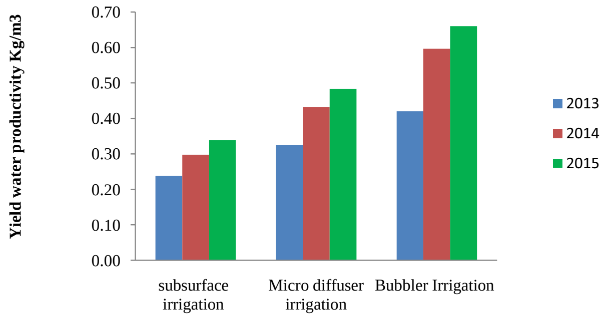

Fig. 9. Yield productivity of the three irrigation systems.

reserves, which has resulted in the excessive loss of water percolation.

4.3.2. Yield water productivity

The analysis results showed that for the year 2013, the average yields per palm tree were not significantly different and did not differ significantly between the three irrigation techniques adopted. 42 kg/tree were obtained. In 2015, production increased to 63, 59 and 66 kg/palm in irrigation by mini diffusers, subsurface and bubblers, respectively. During the years 2014 and 2015, the irrigation technique that gave the best yield is bubbler irrigation. In 2011, Talat Farid Ahmed proved that localized surface irrigation was more cost-effective than underground localized irrigation in an Al-Gassim palm grove (Saudi Arabia). This result did not agree with the work that was done by Al-Amoud (2006), on the drip subsurface irrigation under date palm in the same region (Al-Gassim, Saudi Arabia), which recommended that the technique of drip subsurface irrigation applied by farmers can promote better production compared with other localized surface techniques and the increase in production can reach 50% compared with the other localized techniques.

5. Conclusion

The main objective of this work is to identify the efficient irrigation system under palm date in Tunisian oasis conditions. Following tentative conclusions can be drawn:

- Good uniformity was observed. It exceeds 85% for the three techniques adopted in this test.
- Measurements of soil moisture after the irrigation test using the three localized irrigation techniques show that bubbler water application efficiency is 57% while it is 36% and 30%, respectively, for drip subsurface and mini-diffuser techniques.
- During the years 2014 and 2015, the bubbler irrigation technique gave the best yield, an average of 62 kg/palm. During 2015, the efficiency of the lowest water use is obtained by underground irrigation, that is, 0.34 kg/m^3. The most important efficiency is that recorded by bubbler which is of 0.66 kg/m^3.
- Improvement of bubbler irrigation system uses under date palm will be necessary and the key to save irrigation water resources in Tunisian oasis.

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Improvement of water and energy use in sprinkler irrigation under semi-arid conditions

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ABSTRACT

This study aims to assess the impact of sprinkler irrigation performance on the energy requirements of solid-set sprinkler irrigation systems. For this purpose, a methodology to evaluate the energy requirements for solid-set sprinkler systems was proposed. Experimental and simulated irrigation data were used to analyze the impact of water application efficiency on the energy required to distribute water on soil surface. Results show that the decrease in the water application efficiency from 81% to 69% due to deep percolation losses over the potato irrigation season greatly increases the water distribution energy (34.4%) with an increase in the energy cost (kWh per ton) of 22.4% as well as a reduction of 18% in the water use efficiency. Results indicate also that improvement of water application efficiency of irrigated tomato from 74.1% (day irrigation) to 86.8% (night irrigation) induced a reduction in the energy cost (kWh per ton) of 22.8% although the net seasonal irrigation depth for night time was larger than that for day time due to the decrease in wind drift and evaporation losses.

Keywords: Sprinkler irrigation; Energy; Application efficiency; Water distribution

1. Introduction

For the majority of the Mediterranean countries, scarcity of water resources, the ever-growing water demand and the increase in irrigation acreages make of rational water use a major concern. This objective may be achieved using pressurized irrigation systems (sprinkler and drip irrigation). Playán and Mateos (2006) indicated that improvement of the irrigation performance depends on the appropriate choice of the equipment according to the soil and climate characteristics, water availability and socio-economic conditions. According to Keller and Bliesner (1990), distribution uniformity, wind drift and evaporation losses (WDEL) as well as application efficiency are the prominent performance factors in the design and management of sprinkler irrigation systems. Clemmens and Dedrick (1994) indicated that when appropriately designed and managed, sprinkler irrigation systems can reach irrigation efficiency greater than 80%. Burt et al. (1997) reported that sprinkler irrigation performances are affected by climatic and technical factors such as wind speed, operating pressure, sprinkler characteristics and sprinkler spacing. Under sprinkler irrigation, the farmer is often faced to an economic dilemma. Indeed, under-irrigated areas results on a reduction of crop yield and inputs (fertilizers, phytosanitary products, etc.). Conversely, over-irrigation increases the cost of water pumping and can lead to yield losses by asphyxiation, leaching of nutrients, and may even lead to contamination of groundwater.

It is worthy to say that switching from surface to pressurized networks results in additional costs of investment, pumping and maintenance. Regarding the implication of sprinkler irrigation uniformity on water productivity, economic analysis results of Berman (2008) indicates that there are clear incentives for adopting more water-efficient systems despite the higher capital cost, because of the depressing effect of overwatering on crop yield. Under irrigation modernization process in Spain, Corominas (2010) reported that for the period 1970–2007, water consumption per hectare was reduced by 21%, while energy demand increased by 657%. Because of scarcity of water resources, Tunisian authorities have adopted a national program for water

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conservation and improvement of irrigation efficiency (Al Atiri, 2007). Furthermore, subsidies and incentives were granted to farmers willing to exchange their inefficient irrigation systems with modern ones. In Tunisia, sprinkler irrigation covers about 114,000 ha, representing 28.3% of the total irrigated area (DG/GREE, 2017). Notwithstanding the changing from surface to pressurized systems, a saving of 20% on the energy consumption can be achieved (ANME, 2011). This work is devoted (i) to evaluate the energy requirements for solid set sprinkler systems and (ii) to investigate the effect of irrigation performance on energy consumption of the on-farm sprinkler irrigation systems.

2. Materials and methods

2.1. Energy evaluation

The energy E (kWh) required to operate solid set sprinkler systems was evaluated based on the methodology developed by Amir et al. (1986) for linear-move irrigation machines. Fig. 1 illustrates the functional components of the irrigation infrastructure used to characterize the energy requirements for solid set sprinkler systems.

According to Fig. 1, the energy required for operating the solid set system can be split into two components: (i) the energy required to supply water from the source to the farm hydrant E_1 (kWh) and (ii) the energy required to distribute water to the irrigated area E_2 (kWh).

E_1 and E_2 may be written as following:

$$E_1 = \frac{\rho_w g V_d H_m}{36 \eta E_t} \tag{1}$$

$$E_2 = \frac{\rho_w g V_c H_d}{36 E_a} \tag{2}$$

where ρ_w is the specific weight of water (kg/dm^3), g is the acceleration of gravity (m/s^2), V_d is the volume of water to be applied to the irrigated area (m^3), V_c is the volume of water available to the crop (m^3), E_t is the water supply efficiency (%), E_a is the application efficiency (%), η is the pumping efficiency (dimensionless), H_m is the pressure head (m) required to deliver water from the source to the hydrant and H_d is the pressure head (m) required to distribute water on the soil surface.

Considering that application efficiency is:

$$E_a = 100 \left(\frac{V_c}{V_d} \right) \tag{3}$$

The total required energy is, therefore, calculated as the sum of E_1 and E_2 ($E = E_1 + E_2$):

$$E = \frac{\rho_w g V_c}{36} \left(\frac{100 H_m}{\eta E_a E_t} + \frac{H_d}{E_a} \right) \tag{4}$$

2.2. Application case studies

The above-mentioned energy calculation approach was applied to analyze the effect of irrigation performance on the energy E_2 (Eq. (2) required to distribute water at the soil surface. The first component E_1 is rather dependent on the water transport infrastructure.

For this purpose, experimental data on sprinkler irrigation performances (Yacoubi et al., 2010a, Yacoubi et al., 2010b) were used to analyze the impact of the on-farm application efficiency on the water distribution energy. Experimental associated field trials (Fig. 1) were performed in the irrigation perimeter of the lower valley of the Medjerda in northeast Tunisia.

Tables 1 and 2 summarize the values of the different parameters used to assess the energy required to distribute water on potato and tomato irrigated field, respectively.

T_0 is a control irrigation treatment corresponding to a management allowable deficit of 50% of the soil available water-holding capacity. In the second treatment T_1, the applied water depth is 30% greater than that applied with T_0 in order to minimize the under irrigated in the case of T_0.

3. Results and discussion

3.1. Case of the potato crop

3.1.1. Effect of the application efficiency on the water distributed energy

Table 3 shows that reduction in the application efficiency from 81% to 69% induces a substantial increase (34.4 %) in the energy required to distribute water on the soil surface.

3.1.2. Distribution energy cost

Table 4 summarizes the values of distribution energy costs expressed in Tunisian dinar per hectare and in kWh per ton of potato (one Tunisian dinar ≈ 0.36 USD). It should be highlighted that energy costs used in this work are those applied by the National Company of Electricity and Gas for day and night irrigation times.

Table 4 shows that the cost of energy distribution depends on the volume of water distributed on the field. Results

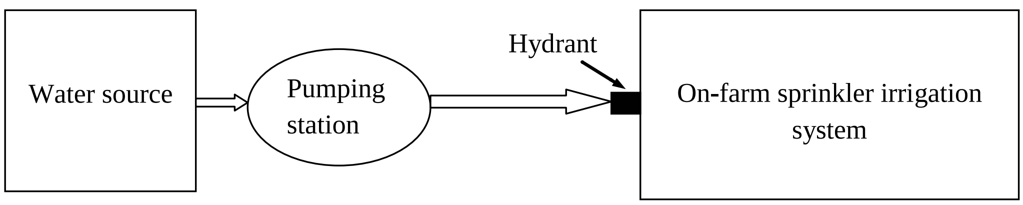

Fig. 1. Schematic representation of the irrigation infrastructures for energy requirement evaluation.

Table 1
Experimental data of sprinkler irrigated potato crop

	Treatment T_0	Treatment T_1
V_d (m³/ha)	3,200	4,300
E_a (%)	81	69
H_d (m)	36	36

Table 2
Experimental data of sprinkler irrigated tomato crop

	Day time	Night time
V_c (m³/ha)	5,490	6,417
E_a (%)	74.1	86.6
WDEL (%)	24	7
H_d (m)	35	35

Table 3
Effect of the application efficiency on the energy distribution

Treatment	V_d (m³/ha)	E_a (%)	E_2 (kWh/ha)
T_0	3,200	81	314
T_1	4,300	69	422

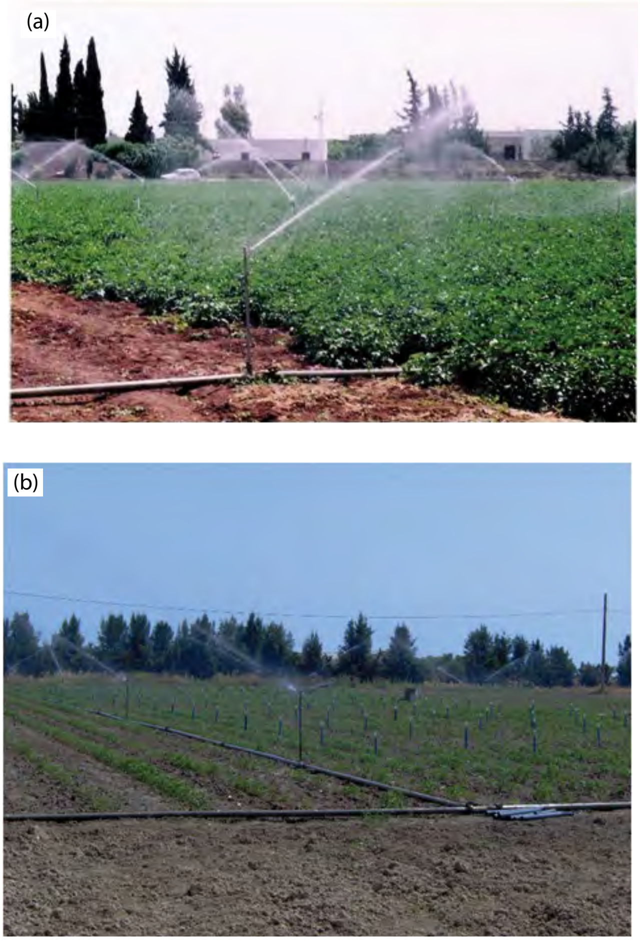

Fig. 2. Experimental sprinkler solid set systems: (a) potato crop, (b) tomato crop.

indicate also that reduction in application efficiency generates a relative increase of 22.4% in the energy cost expressed in kWh per ton as well as a relative decrease of 18% in the water use efficiency.

3.2. Case of the tomato crop

3.2.1. Distribution energy cost

For the tomato crop case, values of distribution energy costs are presented in Table 5.

Results show that irrigation time has a significant impact on distribution energy costs. Indeed, for night time, the energy cost (TND per hectare) was reduced by 22.8% although the net seasonal applied water was larger than that for day time. This reduction is due to the decrease in energy cost by night time. Also, results indicate that adoption of night irrigation reduces the energy cost expressed in kWh/T by 16.4% compared with day irrigation time.

Table 4
Energetic costs of the water distribution (case of the potato crop)

Treatment	Yield (T/ha)	Distribution energy cost (TND/ha)	Energetic cost (kWh/T)	Water use efficiency (Kg/m³)
T_0	46.2	40.1	6.8	14.4
T_1	50.7	53.9	8.3	11.8

Table 5
Energetic costs of the water distribution (case of the tomato)

Irrigation time	Relative yield loss (%)	Distribution energy cost (TND/ha)	Energetic cost (kWh/T)
Day	11	90.2	14.4
Night	3	69.6	12.0

4. Conclusion

A methodology to characterize and evaluate irrigation energy requirement for solid set sprinkler systems was presented in this work. Experimental data were used to analyze the impact of sprinkler irrigation performances on water distribution energy at the farm scale. Results obtained in this work indicated that energy and water saving can be achieved by improving irrigation efficiency and adopting proper irrigation management strategies. Under the arid and semi-arid local conditions, further investigations on the technical and socio-economic implications of irrigation modernization need to be assessed at a larger scale (irrigation district) in order to improve water and energy efficiency.

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Consideration of seasonal variations on water radiometric indices estimation of soil moisture content in arid environment in Saudi Arabia

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ABSTRACT

Remote sensing applications in agricultural practices are comprehensively reliable and cover a multidisciplinary fundamental interest both in local and regional level. Significantly, vegetation indices are the foremost essential in remote sensing applied for agricultural activities related to vegetation and/or water, particularly in an arid environment. Adequate water resources management plans are based on better fulfilling the water demand and supply equation. In arid environments, this equation is barely achieved due to water resources limitations. Remote sensing techniques improve the water resources management schemes by using five different water radiometric indices of Sentinel-2. Each of them plays a specific role in the quantification of soil/plant water content based on the interpretation of map surface water features and monitors the dynamics of surface water. The study area is located within the main agricultural region of Wadi As-Sirhan. The area is characterized by flourishing agricultural activities. Remote sensing data acquired by Sentinal-2 proved to be statistically sufficient to estimate soil water content in two different climatic conditions. Statistically, estimated winter indices are with better fit than summer indices. Modified Normalized Difference Water Index and second Normalized Difference Water Index best fitted winter soil water content estimations. Meanwhile, RMSE showed no differences between Normalized Difference Water Index and Normalized Difference Turbidity Index for both climatic conditions.

Keywords: Integrated water resources management; Sentinel-2; Soil water content; Remote sensing; Water radiometric indices

1. Introduction

The Kingdom of Saudi Arabia (KSA) has very low annual precipitation, high temperature, no lakes or flowing rivers and is classified as an arid region. Water, therefore, is infrequent and extremely valuable. With the rapid country growth and increasing water demand, the effect becomes cumulative. The scarcity of fresh water resources presents the most severe problem for the existence of biotic life in Saudi Arabia (Elhag 2016). Generally, the average annual rainfall is closely less than 80 mm, with a sporadic maximum annual rainfall that exceeds 500 mm, particularly in the south-western region (Bahrawi et al. 2016)

Saudi Arabia has experienced an elevated development in all divisions over the last four decades. As a result, a swift intensification in agricultural, industrial and domestic water demands has been perceived. Agriculture is the major water consumption sector as it consumes about 85% of the total national water use (Elhag et al. 2017). The government of Saudi Arabia subsidized the agricultural sector during the period 1974–2006 to improve the standard of living in rural areas and to attain self-sufficiency.

Soil water content depends on many parameters that are spatially and temporally variable such as soil type, vegetation cover, crop type, topography and precipitation. Considering all these variable factors, in collecting enough measurements for the account of the spatial variations of the vadose zone, soil water content is neither financially nor technically practical.

Soil water content is the amount of water available for plants uptake at the root zone; coarsely this zone is less than 50 cm of depth (Zhu et al. 2008). Within this thin layer, several

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essential biological and hydrological processes take place (Crippen 1990 and Walker 1999). It is very crucial to monitor this layer to ensure plants survival (Su et al. 1999). Traditional methods of soil water content estimation are usually valid for a small local level similar to a farm but it always costs time and effort and is not a sufficient method to estimate spatial and temporal variations of soil water content on a regional scale (Engman 1991 and Wood et al. 1992).

Remote sensing techniques are now widely used to forecast, monitor and estimate soil water content (Ochsner et al. 2013 & Psilovikos and Elhag 2013). Estimation of soil water content using remote sensing practices is different and divided generally into two groups of methods: (1) passive remote sensing method of estimation and (2) active remote sensing method of estimation (Palecki and Bell 2013). Both techniques depend on the capability of a certain wavelength to penetrate the root zone and register its reflection (Myneni et al. 1995 and Dasgupta 2007). Short wave infra-red (SWIR) wavelength can penetrate in the shallow root zone as it is either registered passively from the sun or actively using ground penetration radar (GPR) systems (Gao 1996 and Moghadas et al. 2013).

Low crop productivity is highly related to the availability of water resources. To optimize the use of limited water resources in arid environments unconventional methods of planning are required (Elhag and Bahrawi 2017). Soil water monitoring is a crucial feature of managing water requirements of agricultural fields founded on advanced irrigation techniques (Muñoz-Carpena et al. 2002). The main goal and challenge for farmers and decision makers is to keep soil water content within optimized range for better and efficient crop production and unsaturated soil (Muñoz-Carpena et al. 2005 and Elhag and Bahrawi 2014).

Relevant research studies were conducted in similar arid environments. Modified Normalized Difference Water Index (MNDWI) was applied by Zhang and Huai-Liang 2016 to monitor drought condition. Mathieu et al. 1998 was the pioneer in studying the relationship between laboratory reflectance data and remote sensing data. Other significant scholarly work was conducted by Elhag and Bahrawi 2017 who assessed the hydrological drought indices in other parts of Saudi Arabia.

Several radiometric water indices have been developed within the past few decades. Principally, McFeeters 1996 projected the Normalized Difference Water Index (NDWI). The index uses the green and the near infrared bands of remote sensing data. The index was projected to improve the extracted information from the remote sensing data regarding the soil moisture content. Later, MNDWI was developed by Xu 2006 to improve the limitations of NDWI, where the shortwave infrared was used instead of NIR band. Several academic research works were conducted by Xu 2006, Li et al. 2013, Du et al. 2014 and Singh et al. 2015 where MNDWI was considered to be a better radiometric water index over NDWI.

Remote sensing techniques provide the tool to estimate soil water content on a large scale in time and effort cost-effective manner (Chauhan 2003). Irrigation network in the designated area relays on advanced sprinkling irrigation systems. The huge plant water requirement in the study region is supplied from the underlying groundwater aquifer. Spatial correlation between soil water content and vegetation stress may alter the strategy of water management in the study area. Image correction is a preliminary procedure in digital image analysis. Atmospheric and radiometric correction techniques are also essential steps. According to Chavez 1996, atmospheric correction depends on the calibrated radiance value of these offset consents to decide the κ value. The κ decision rule is based specifically on the flying height. The λ^{-K} determines the offset values for the green, red and near infra-red band calibration (Beisl et al. 2008). Moreover, radiometric correction is required to harmonize the conducted measurements made with a variety of different satellite sensors under different environmental conditions (Zhu et al. 2015).

The current research work is based on founding a regression correlation between values of remote sensing water radiometric indices conducted from satellite images and ground truth data. Therefore, accurate synchronization of ground truth data collection and satellite bypassing were exercised to maximize the use of the irrigational water in the study area.

2. Materials and methods

2.1. Study area

The Wadi As-Sirhan or Sirhan Valley is a quadrangle wadi which lies in the Northwestern part of Saudi Arabia at about 1,000 km north of Jeddah. It expands from Sakakah city up to Jordan and lies between Lat 30 45–29 30 N and Long 37 50–39 30 E on the border with the Kingdom of Jordan (Fig. 1). It is in the west-central part of the Sirhan turayf basin and is underlain by Silurian to Miocene-Pliocene sedimentary rocks that are partly covered by volcanic flows. The map area also contains large areas of surface sand and gravel. Wadi As-Sirhan is characterized by 5 Million Cubic Meter (MCM) annual flow and 18 MCM annual discharge and safe yield of 7–10 MCM/y (Bahrawi and Elhag 2016). Hydrogeological investigations in Saudi Arabia demonstrate that groundwater is stored in more than 20 primary and secondary aquifers (Hoetzl 1995). It has been estimated that the groundwater reserves are about 1,919 × 109 m^3 of which 160 × 109 m^3 stored in deeper secondary reserves (Al-Rashed and Sherif 2000). The total volume of groundwater abstracted for irrigation in the designated study area has increased from 23 MCM in 1973 to 2,051 MCM in 2006, while the annual recharge does not exceed 10% (Elhag and Bahrawi 2014). The climate in the study area is confined to the semi-arid climate. About 80% of the study area receives precipitation less than 100 mm/y, mostly during the spring months. The area of Wadi As-Sirhan, situated at an altitude of around 650 m.a.s.l., is characterized by very hot summers with average monthly maximum/minimum in July: 33.9°C/17.7°C, and mild winters with average monthly maximum/minimum in January: 14.7°C/3.8°C. The calculated annual potential evapotranspiration (ETo), Penman-Monteith approach (FAO) for Wadi As-Sirhan is 2,643 mm/y. The soil of the study area is generally sandy with pH from 6.65 up to 7.4 and with electric conductivity (EC) from 0.031 up to 1.634 ms/cm. There were no significant differences in soil colors either in dry summer soils or wet winter soils. Organic matter content is low around (2.11%). The study

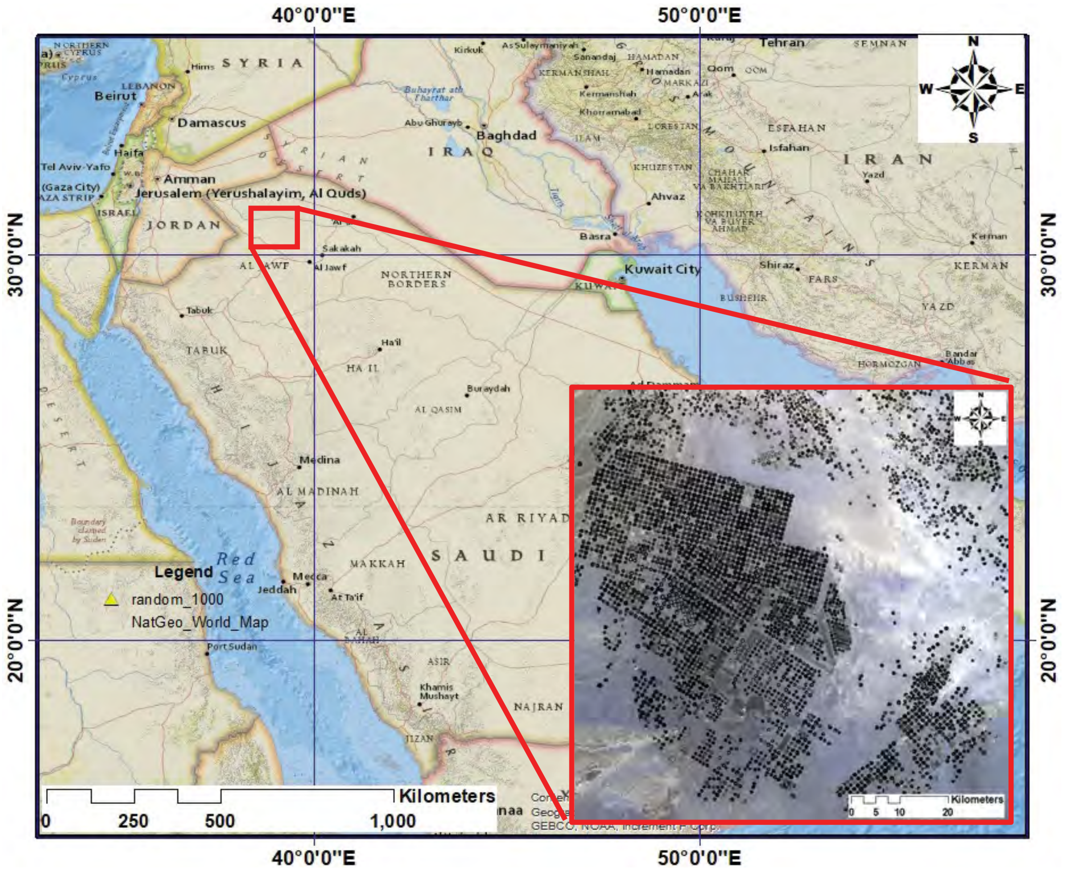

Fig. 1. Study area location in false-color composite over a natural color base map.

area is not covered by natural vegetation. It is reclaimed land for crop production mainly. Water radiometric indices interpretation is exercised on the ratio between red, near infra-red and infra-red bands of Sentinel-2 over the study acquired in 2016.

2.2. Methodological framework

2.2.1. Dataset and soil sampling

A total number of 150 random soil samples were collected from the cultivated land in Wadi As-Sirhan area with a minimum distance of 1,000 m between the location of the sample to avoid data clumping and only bare soil locations without crop cover were considered. Soil samples were taken from 0 to 10 cm depth then mixed well for soil moisture estimation in triplicates to obtain the average sample. The standard procedure of determining soil extract salinity in terms of electrical conductivity (EC) was followed according to Rhoades and Chanduvi 1999 under laboratory condition and validated against soil salinity values estimated from remote sensing data according to Elhag 2016. Location of winter samples was marked with wooden sticks for summer data collection (Fig. 2). Sentinel-2 images acquired in January and July 2016 were downloaded and processed to represent the winter and the summer seasons correspondingly. Sentinel-2 is made of 12 spectral bands with a 10-m resolution of visible bands (VI), 20 m resolution of vegetation red edge (VRE) bands and SWIR bands in addition to three bands related to coastal aerosols and water vapor of 60-m resolution. The remotely sensed water radiometric indices are conducted from several algorithms' exercises, basically VI, VRE and SWIR bands.

2.2.2. Estimation of soil water content

This study adopted the common gravimetric method of soil water content estimation. The soil water content is expressed either in terms of weight or volume. In the current research study, the soil water content is expressed in terms of weight as a ratio of the mass between dry and wet soil. Determination of the soil water weight ratio is carried out by drying the soil to a constant weight and calculating the soil sample mass after and before drying. The criterion for drying the soil samples to a constant weight is considered after heat treatment in an oven at a temperature between 100°C and 110°C. Within this range of temperature, it is assured that the water content in the examined samples will be evaporated without any alteration that may occur to the physical or the chemical characteristics of the soil samples. The soil water content in dry weight approach is calculated according to the formula (Klute 1986).

$$\theta_d = \frac{\text{wt of wet soil-wt of dry soil}}{\text{wt of dry soil}} \qquad (1)$$

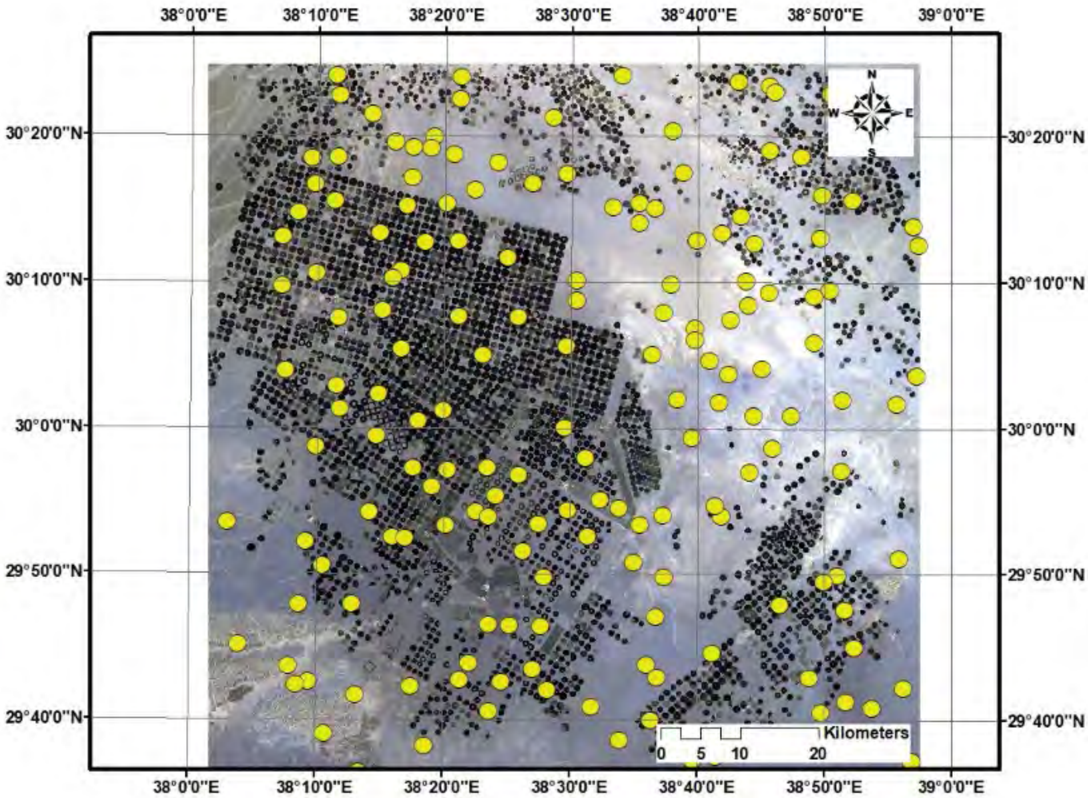

Fig. 2. Soil sample location in a false color composition of Sentinel-2.

Soil water content is calculated as the ratio between water mass and the mass of wet soil (θ_w). The alteration from θ_d to θ_w can be calculated as follows:

$$\theta_d = \frac{\text{wt of water}}{\text{wt of dry soil}} \tag{2}$$

After manipulation, the water content in wet and dry basis can be expressed as follows:

$$\theta_d = \frac{\theta_w}{1-\theta_w} \tag{3}$$

and

$$\theta_w = \frac{\theta_d}{\theta_d + 1} \tag{4}$$

2.2.3. *Remote sensing analysis*

The amount of water present in leaf internal structure mainly affects the spectral reflectance in the SWIR interval (ca. 1.2–1.7 μm). The SWIR reflectance is also sensitive to the canopy internal structure. Because the NIR is exaggerated by leaf internal structure and leaf dry matter, but not by the water content, the combination of SWIR and NIR into NDWI calculation removes the leaf dry matter and internal structure and retains the water content. NDWI is less susceptible to atmospheric scattering than NDVI, but it cannot eliminate totally the effects of the background soil reflectance's comparable with NDVI.

The MNDWI algorithm was developed by Xu 2006 to improve the open water features through an efficient elimination of land noise as well as vegetation and soil noise. MNDWI is calculated by the following equation:

$$\text{MNDWI} = \frac{\text{Green} - \text{SWIR}}{\text{Green} + \text{SWIR}} \tag{5}$$

The Normalized Difference Pond Index (NDPI) was developed by Lacaux et al. 2007 to distinguish the vegetation cover apart for its aquatic surroundings. NDPI is calculated by the following equation:

$$\text{NDPI} = \frac{\text{SWIR} - \text{Green}}{\text{SWIR} + \text{Green}} \tag{6}$$

The Normalized Difference Turbidity Index (NDTI) was developed by Lacaux et al. 2007 to estimate water turbidity. NDTI is calculated by the following equation:

$$\text{NDTI} = \frac{\text{Red} - \text{Green}}{\text{Red} + \text{Green}} \tag{7}$$

The NDWI was found by Gao 1996 and after that improved by Ganaie et al. 2013 to measure the liquid water molecules at the top of canopy level. NDWI is calculated by the following equation:

$$\text{NDWI} = \frac{\text{NIR} - \text{SWIR}}{\text{NIR} + \text{SWIR}} \tag{8}$$

The second Normalized Difference Water Index (NDWI-2) was developed by McFeeters 1996 to detect and measure the surface water extent in addition to the surface water of wetland environments. NDWI-2 is calculated by the following equation:

$$\text{NDWI} - 2 = \frac{\text{Green} - \text{NIR}}{\text{Green} + \text{NIR}} \tag{9}$$

where

B3 "G" is the green band of Sentinel-2.
B4 "R" is the red band of Sentinel-2.
B8 "NIR" is the near infra-red band of Sentinel-2.
B11 "SWIR" is the short-wave infra-red band of Sentinel-2.

The final step in image data analysis in the current study is data normalization. The above-mentioned Water Radiometric Indices are calculated within a range of –1 to +1. Therefore, Water Radiometric Indices were transformed into the same range of soil water content weights for comparability reasons using Hawkins and Pole 1989 transformation:

$$Z = \frac{1}{2}\ln\left(\frac{1+r}{1-r}\right) = \text{arctanh}(r) \tag{10}$$

where

ln is the natural logarithm function.
arctanh is the inverse hyperbolic tangent function.
r is the Fisher's z-transformation.

2.3. Regression analyses

The purpose of the regression analyzes is to envisage the regression potentials between soil salinity index from one side and the rest of the hydrological drought indices from the other side. Principle component analysis (PCA) is performed to transform a set of likely correlated with unlikely correlated variables. Principal components number is less/equal to the variables original number. Following Monahan 2000, PCA fundamental equations are:

First vector $w_{(1)}$ should be answered as follows:

$$w_{(1)} = \arg\max_{\|w\|=1}\left\{\sum_t (t_1)_{(i)}^2\right\} = \arg\max_{\|w\|=1}\left\{\sum_t (x_1 \times w)^2\right\} \tag{11}$$

The matrix form of the above equation gives the following:

$$w_{(1)} = \arg\max_{\|w\|=1}\left\{\|Xw\|^2\right\} = \arg\max_{\|w\|=1}\left\{w^T X^T Xw\right\} \tag{12}$$

$w_{(1)}$ should be answered as follows:

$$w_{(1)} = \arg\max\left\{\frac{w^T X^T Xw}{w^T w}\right\} \tag{13}$$

Originated $w_{(1)}$ suggests that first component of a data vector $x_{(i)}$ can then be expressed as a score of $t1_{(i)} = x_{(i)} \times w_{(1)}$ in the transformed coordinates, or as the corresponding vector in the original variables, $(x_{(i)} \times w_{(1)})\, w_{(1)}$.

2.4. Validation

Validation of Water Radiometric Indices values was carried out using the ground truth data collection. 150 soil samples were analyzed for gravimetric soil water content and plotted against the remotely sensed values. The average accuracy is estimated by a horizontal function of the tested dataset. The average reliability is estimated by a vertical function of the tested dataset. The overall efficiency estimated the diagonal function of the tested dataset. Following Congalton et al. 1983, a correspondence analysis was constructed as follows:

$$\text{CA} = \frac{N\sum_{i=1}^{r} xii - \sum_{i=1}^{r}(xij \times xji)}{N^2 - \sum_{i=1}^{r}(xij \times xji)} \tag{14}$$

where

r, the number of rows in the error matrix
x_{ii}, the number of observations in row *i* and column *i* (the diagonal cells)
x_{i+}, total observations of row *i*
x_{+1}, total observations of column *i*
N, total of observations in the matrix

3. Results and discussion

Realization of different water radiometric indices was computed succeeding to adequate atmospheric and radiometric corrections. Spatial distribution of the implemented water radiometric indices and their corresponded temporal acquisitions are illustrated in Figs. 3a–e. The first dataset was comprehended for winter Water Radiometric Indices (January 2016) then six months later (July 2016) the analysis procedures were repeated for the summer dataset (Figs. 3f–j).

Field data collection and remote sensing techniques were applied with precise synchronization to optimize the results. Soil water content collected from summer and winter seasons shows a significant correlation RMSE 0.01. Therefore, the agricultural practice in the designated study area suggests an equivalent amount of the irrigation water utilized in both seasons (Elhag and Bahrawi 2017).

Water radiometric indices conducted from remote sensing data showed inconsistent responses between winter and summer seasons (Table 1 and Figs. 4a and b).

The estimated radiometric indices tend to respond preferably to winter rather than to summer climatic condition (Fig. 5a). MNDWI shows a coherent pattern of estimation in different seasons. Such behavior could be considered as a lack of the index sensitivity in summer season rather than winter season (Wang et al. 2013 and Gautam et al. 2015).

NDPI shows an idealistic correlation between the two seasons (Fig. 5b). Henceforward, the only foreseen explanation is that there is no ponds formation in the study area and

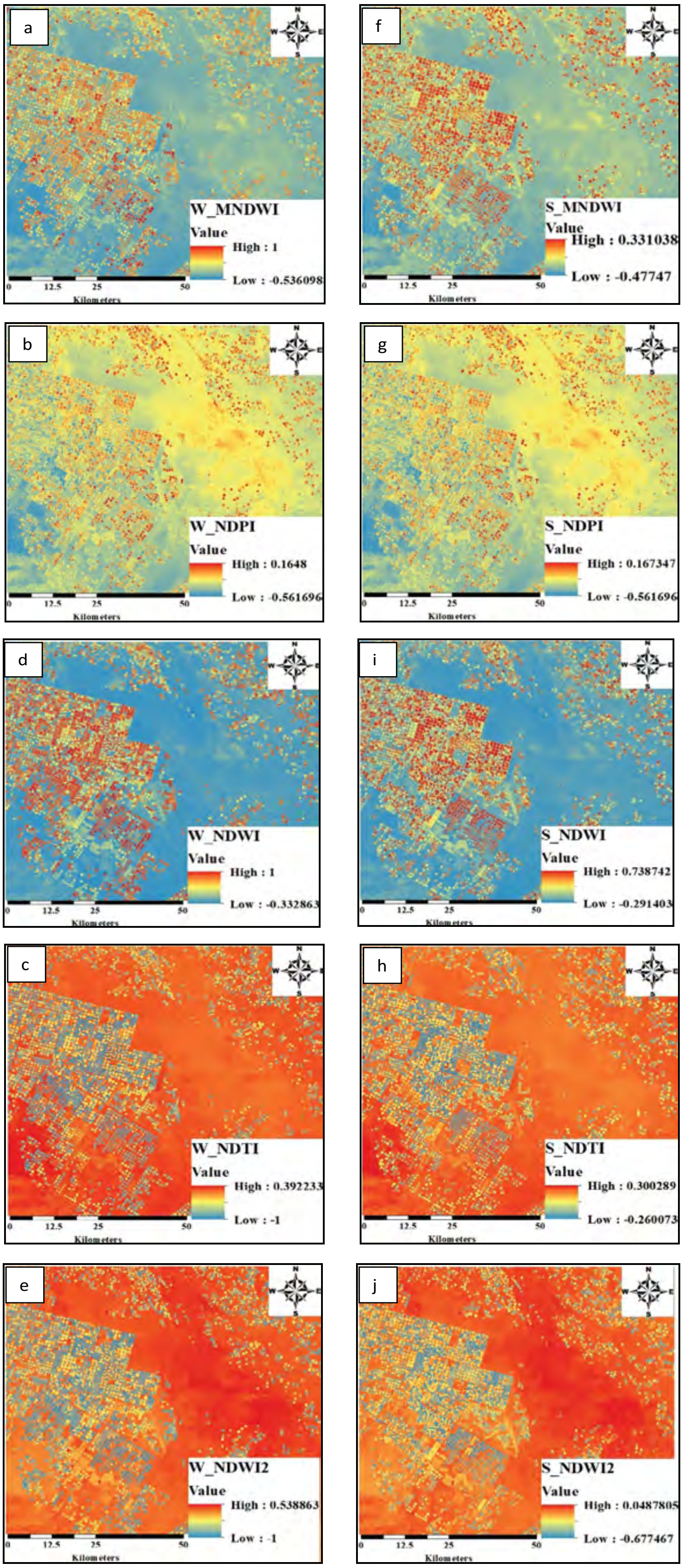

Fig. 3. Spatial distribution of five different water radiometric indices in two different seasons (January/July-2016).

Table 1
Statistical analysis of the estimated radiometric water indices

	Summer indices			Winter indices		
	R^2	RMSE	Equation	R^2	RMSE	Equation
MNDWI	0.6117	0.08	$0.3232x - 0.4061$	0.7146	0.06	$0.3813x - 0.4643$
NDPI	0.9046	0.01	$0.1432x - 0.4365$	0.9476	0.01	$0.1642x - 0.4439$
NDTI	0.5397	0.07	$0.258x + 0.0287$	0.5859	0.08	$0.3574x - 0.0029$
NDWI	0.4916	0.15	$0.5033x - 0.1983$	0.5501	0.15	$0.6539x - 0.2522$
NDWI-2	0.5718	0.07	$0.2702x - 0.4212$	0.6455	0.07	$0.3747x - 0.5051$

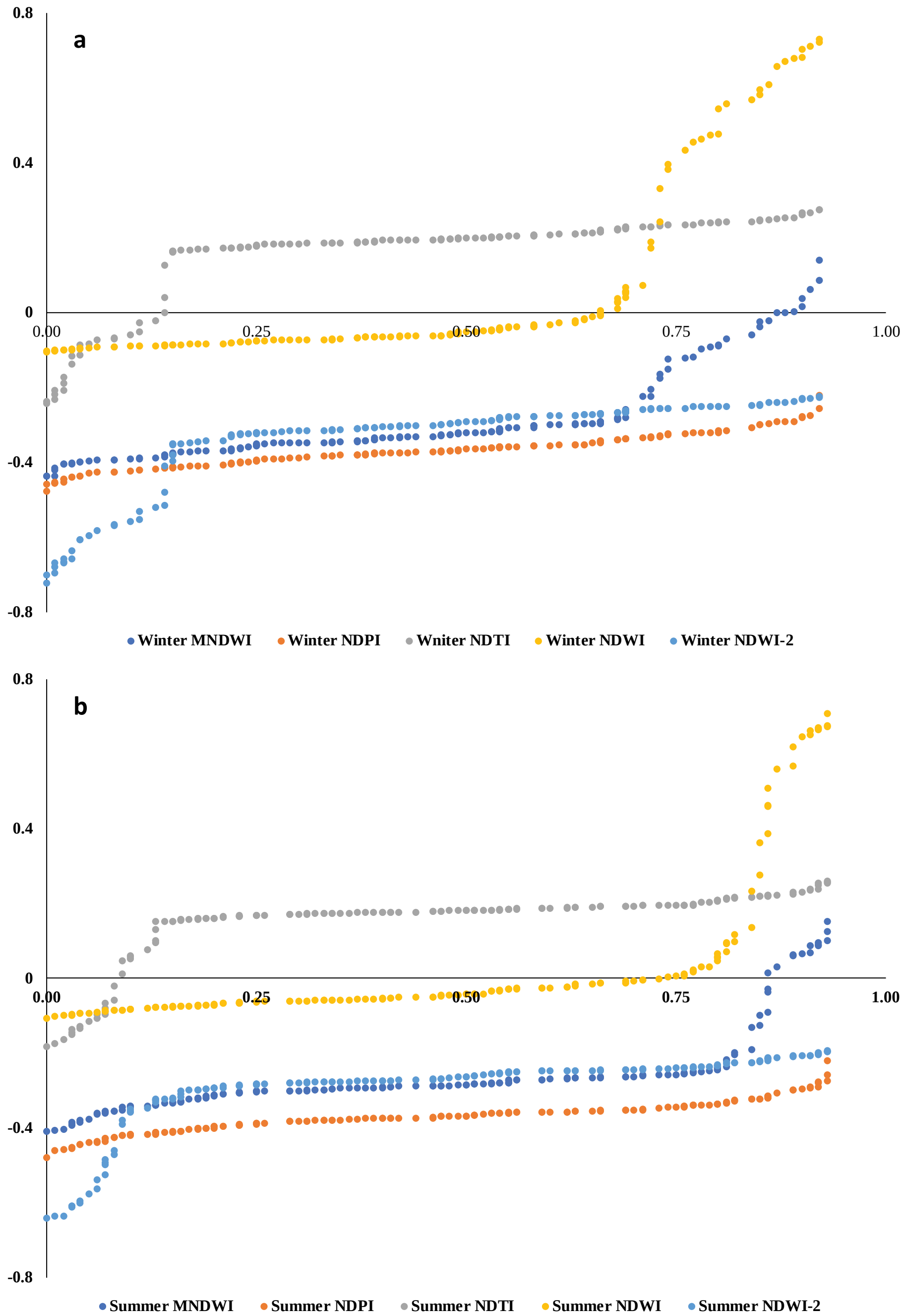

Fig. 4. Seasonal variation of the estimated radiometric water indices (a for winter and b for summer).

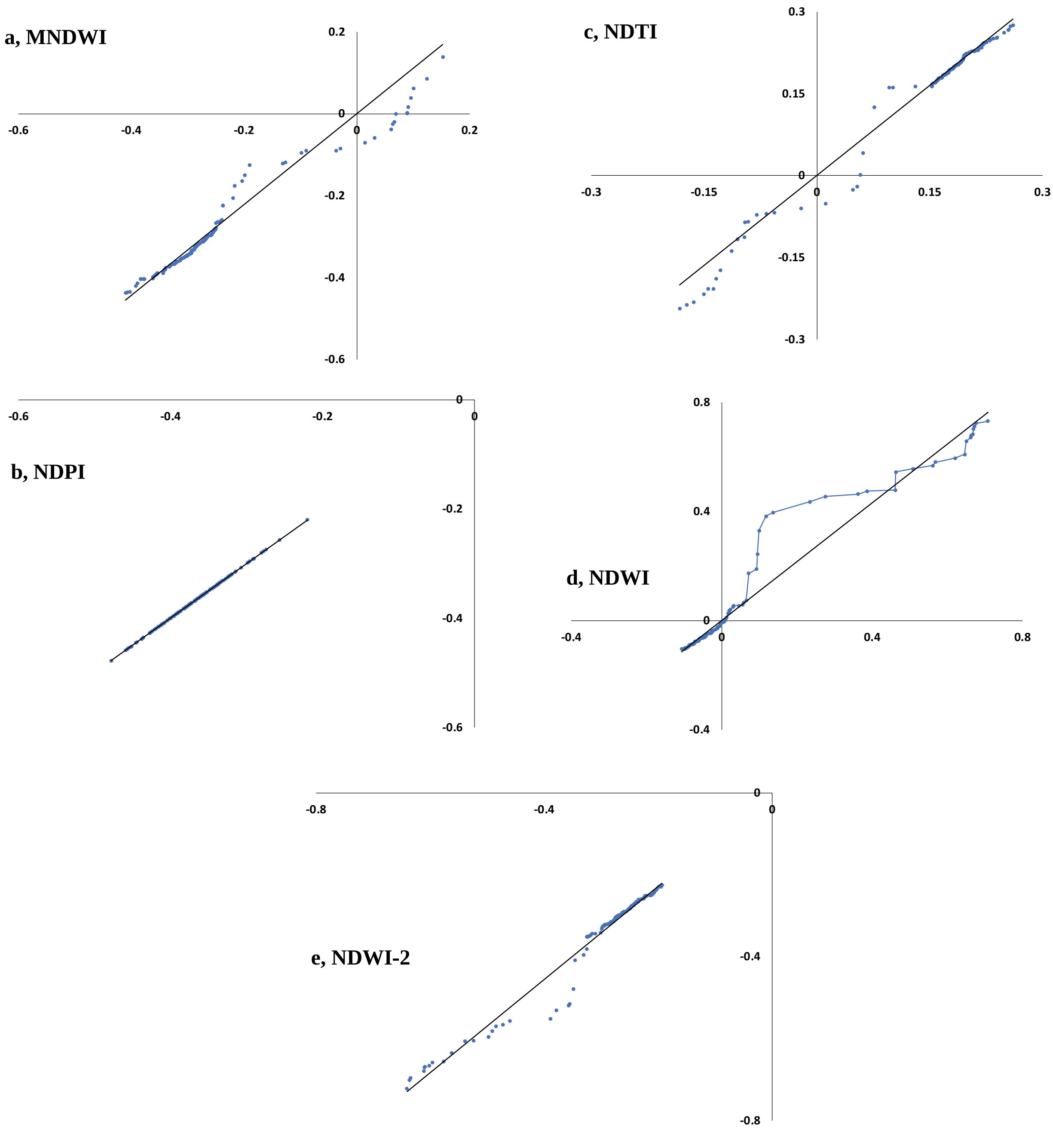

Fig. 5. Seasonal radiometric water indices intercorrelation (x axis is the winter measurements; y axis is the summer measurements).

hence the index cannot differentiate the seasonality dissimilarities. Consequently, NDPI can be exercised all year long with no season preferences (Ji et al. 2009 and Dambach et al. 2012).

On the other side, NDTI shows steady correlation along with the seasonal variations (Fig. 5c). NDTI is the only index that showed optimum correlation stability among the other radiometric water indices. Accordingly, NDTI behavior is explained by the lack of pure water surfaces and the irrigational water is considered as turbid water as it is mixed with soil particles at the surface level (Daughtry et al. 2005 and Serbin et al. 2009).

Similar behavior to NDTI but with less accuracy is expressed by NDWI. NDWI shows a robust correlation between lower NDWI values rather than the higher values (Fig. 5d). Such results may promote NDWI to be used in winter rather than in summer conditions (Chen 2006 and Gu et al. 2007).

In contrary, the improved index of NDWI was exercised to contradict the sensitivity of the index to the seasonal conditions. NDWI-2 shows significant correlations in summer conditions with no winter condition preferences (Fig. 5e). Therefore, NDWI-2 could be considered as a summer index (Soti et al. 2009 and Sánchez-Ruiz et al. 2014).

Principally, the Water Radiometric Indices used in the current research varied based on the utilized bands in each rationing. Therefore, categorization of different indices using principal component analysis will help to examine the indices discrepancies. Fig. 5 presents the grouping of different indices according to the PCA on covariances in both seasons.

Generally, different water radiometric indices fell into two groups in both seasons. The first group contained NDPI and it showed no seasonal variation and kept a neutral behavior. Meanwhile, NDTI from one side and NDWI and MNDWI from the other side showed an alternative behavior across the two seasons (Fig. 6). Additionally, NDWI-2 significantly correlated and grouped together (Table 2). Consequently, NDWI-2 is a superposed group (Dehni and Lounis 2012). Lack of correlation is the main reason of NDTI and NDWI insignificance (Table 2). The implemented band length is the driving force of the correlation inconsequentiality between the previously mentioned indices (Lillesand et al. 2014).

The dynamics of the soil water content dissimilarities proved by the seasonal variations added further complications to designate soil water content in a systematic uniform perspective. The use of different algorithms based on implementing different combinations and/or ratios of Sentinel-2 bands in the form of water radiometric indices evidenced to be more efficient to overcome water dynamicity problems (Lei et al. 2014 and Zhang et al. 2015).

Moreover, higher soil water content was related to the improper and intense irrigation systems which are based on the lack of an operative water resource management plan in the designated study area (Koshal et al. 2012).

The selection of the profound satellite bands adequate for accurate water radiometric mapping is not systematically comprehensive (Lei et al. 2014 and Zhang et al. 2013). Spatial inconsistency and land cover dissimilarities are the main controlling factors of the band sensor selection (Zhang et al. 2015 & Allbed and Kumar 2013). Consequently, the

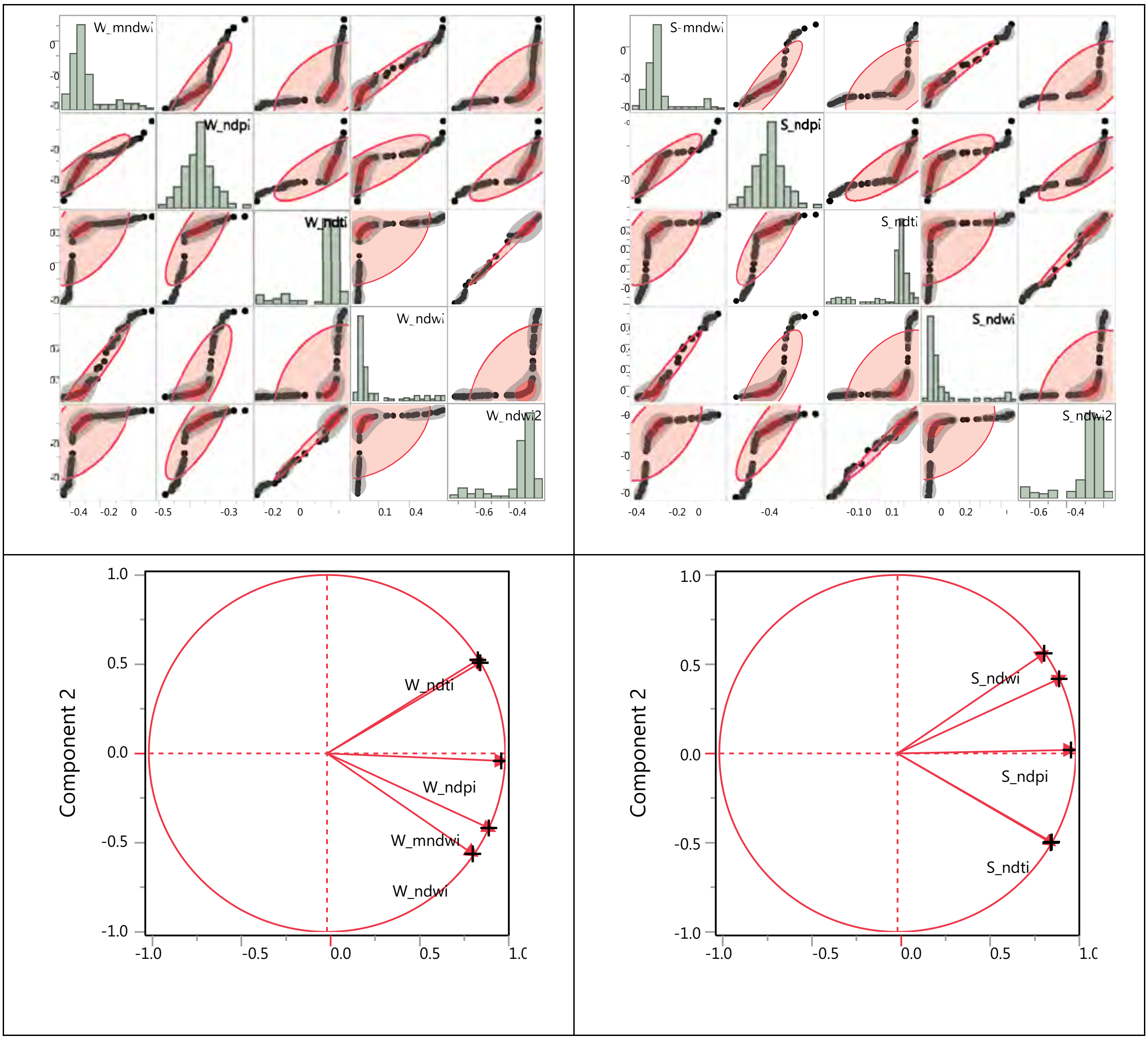

Fig. 6. Principal Component Analysis and its correlation matrix of the different water radiometric indices.

Table 2
Descriptive statistical analysis and covariant matrix

	W_mndwi	W_ndpi	W_ndti	W_ndwi	W_ndwi2		S–mndwi	S_ndpi	S_ndti	S_ndwi	S_ndwi2
W_mndwi	1.0000	0.9025	0.5499	0.9766	0.5677	S–mndwi	1.0000	0.8796	0.5742	0.9832	0.5787
W_ndpi	0.9025	1.0000	0.7874	0.7985	0.8125	S_ndpi	0.8796	1.0000	0.8085	0.7919	0.8214
W_ndti	0.5499	0.7874	1.0000	0.4068	0.9943	S_ndti	0.5742	0.8085	1.0000	0.4338	0.9917
W_ndwi	0.9766	0.7985	0.4068	1.0000	0.4208	S_ndwi	0.9832	0.7919	0.4338	1.0000	0.4370
W_ndwi2	0.5677	0.8125	0.9943	0.4208	1.0000	S_ndwi2	0.5787	0.8214	0.9917	0.4370	1.0000

Column	N	DF	Mean	Std Dev	Sum	Minimum	Column	N	DF	Mean	Std Dev	Sum	Minimum	Maximum	Maximum
W_mndwi	150	149	−0.293	0.116	−44.003	−0.437	S–mndwi	150	149	−0.256	0.120	−38.480	−0.410	0.152	0.139
W_ndpi	150	149	−0.370	0.043	−55.538	−0.478	S_ndpi	150	149	−0.370	0.043	−55.538	−0.478	−0.219	−0.219
W_ndti	150	149	0.157	0.121	23.6101	−0.243	S_ndti	150	149	0.148	0.102	22.2081	−0.182	0.260	0.275
W_ndwi	150	149	0.041	0.228	6.1484	−0.104	S_ndwi	150	149	0.034	0.208	5.1805	−0.106	0.708	0.731
W_ndwi2	150	149	−0.337	0.120	−50.563	−0.722	S_ndwi2	150	149	−0.296	0.103	−44.436	−0.640	−0.193	−0.224

utilized water radiometric indices may have different results in specific areas using different band ratios other than the use of Sentinel-2 as a source of remote sensing data (Zhu et al. 2015 and Drusch et al. 2012).

4. Conclusions

The groundwater resources in the Wadi As-Sirhan are the only water source for the agricultural practices that take place. Therefore, to sustain such agricultural activities in the designated study area, an adequate technique of monitoring soil water content is crucial. Remote sensing data acquired by Sentinal-2 proved to be statistically sufficient to estimate soil water content in two different climatic conditions. The implemented water radiometric indices in the current study can be primarily divided into two groups, climatic condition non-sensitive/ sensitive group. The non-sensitive group contains only the NDPI, while the sensitive group contains the rest of the Water Radiometric Indices. Within the second group, there are indices which are less accurate in summer rather than in winter. MNDWI and NDWI-2 best fitted winter soil water content estimations. Meanwhile, NDWI and NDTI least fitted winter estimations. However, NDTI was statistically proved to be the most defined water radiometric index for estimating soil water content. The current irrigational schemes in Wadi As-Sirhan are not taking into consideration the temporal changes in the climatic conditions, where both summer and winter irrigational schemes are almost the same. Thus, the existing agricultural strategy in Wadi As-Sirhan needs to be revised precisely by the decision makers. Moreover, coherent groundwater resources consumption and soil water content monitoring need to be implemented.

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Efficient use of water for food production through sustainable crop management: Kingdom of Bahrain

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ABSTRACT

Food production under unfavorable climatic conditions and limited water resources cannot be sustainably practiced unless crop water management techniques are designed to meet the present growing demands of water for increased food production. Bahrain, severely constrained by limited agricultural resources such as limited water resources, poor and declining quality of the soil, and unfavorable climate therefore water scarcity will reduce agricultural production and threaten country's food security. The aim of this paper is to analyze the efficient use of water for food production through better crop management. It focuses on the water use efficiency and water productivity of agricultural sector in Bahrain. The study provided a comprehensive analysis of the vegetable production activities in Bahrain and assessed their efficiency in terms of financial and economic profitability, especially their utilization of the scarce natural resources, water. The analysis conducted for three methods of certain vegetable production in different farms of vegetable production (traditional, green house and hydroponic methods). The irrigation method adopted under open agriculture is traditional, drip, sprinkler and bubbler irrigation while the protected house adopted drip irrigation. Policy analysis matrix (PAM) has been used in the study to analyze the comparative advantage of 12 crops production systems under traditional farming and protected and hydroponic farming systems in Bahrain using the 2016/2017 production data.

Keywords: Bahrain food production system; Water use efficiency; Sustainable crop management

1. Introduction

Due to arid climatic conditions natural sources of food production are limited in Bahrain. High temperatures limit yields for many stable food crops; soils are fragile and groundwater which can be renewed inherently scarce and are among the lowest in the world. Thus, due to shortage of fresh water, poor soil resources, low rainfall and high evapotranspiration in GCC countries constrain local agriculture production in meeting the food demand of the current and growing population (Salma Bani 2015). Also, climate change is likely to tighten these constraints.

Food production under unfavorable climatic conditions and limited water resources cannot be sustainably practiced unless crop water management techniques are designed to meet the present growing demands of water for increased food production. The deficit between available water and water demand is growing and expected to increase in the near future. Water scarcity will reduce agricultural production and threaten country's food security; therefore, the best

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use of water must be made for efficient crop production and higher yields. The aim of this paper is to analyze the efficient use of water for food production through better crop management. It focuses on the water use efficiency and water productivity of agricultural sector in Bahrain. The present status of agricultural water use will be outlined to point out the main factors of inefficiency in the use of irrigation water such as losses in the conveyance of irrigation water; low efficient on-farm irrigation methods, inefficiency related to the irrigation systems setup and losses due to inadequate irrigation practices.

Policy analysis matrix (PAM) has been used in the study to analyze the comparative advantage of 12 crops production systems under traditional farming and protected and hydroponic farming systems in Bahrain using the 2016/2017 production data. The actual measurement of competitiveness in this study focuses mainly on private resource cost which indicates competitiveness under real market conditions and domestic resource cost (DRC) which gives an assessment on the social or economic efficiency of an activity, that is, whether domestic resources are really used efficiently in current production.

Water productivity will be analyzed from an economic point of view through a study on economic considerations. Two scenarios will be elaborated by means of crop water requirements, costs and income of agricultural production. Finally, the paper will recommend the cultivation of crops which have low crop water requirements but have a high economic return together with an extensive use of treated sewage water for agriculture.

2. Food production system in Bahrain

Bahrain was one of the richest countries in the Arabian Gulf even prior to the discovery of oil resources in 1932. Its' pearl was the famous and best in the region, an important agriculture and trading center. However due to urbanization and expansion of new towns and communities as well as industrial sector land consumption which all resulted in pressure on agriculture in Bahrain. The biggest challenges Bahrain agriculture facing are limited agricultural lands and shortage of water resources. The total arable land in Bahrain is estimated to be 64,000 donum (Agricultural Statistics Year book 2017), in other words it is about 10% of the total area which amounts to 622 km^2. Two thirds of this arable land is cultivated.

The agriculture products produced locally covers only 12% of total consumption needs. The major crops grown are dates and fruit trees with a yield of 7.5 tons ha^{-1}, vegetables, mainly tomatoes, with a yield of 11.7 tons ha^{-1}, and fodder crops, mainly alfalfa, with a relatively high yield of 74.5 tons ha^{-1}. The alfalfa tolerates high salinity and is a cash crop grown all year round with high local demand. However, because of the very high irrigation water requirements of alfalfa, it is expected that this trend will have negative implications for the country's groundwater resources.

Tolner (2013) comprehensively described various aspects of Bahrain. According to him, the limited arable lands, sandy texture and associated high infiltration rate, low organic matter (0.05%–1.5%), low inherent soil fertility, low water and nutrient holding capacity, limited good quality water has resulted into focused low agricultural activities in Bahrain. Agriculture is mainly focused along the north-western coast of Bahrain Island. Irrigated agricultural farms present soil salinity within a range of 4–12 dS m^{-1}, while in the areas of recently abandoned agriculture (1,065 ha) it could reach 60 dS m^{-1}. Tolner (2013) also expressed declining of agricultural lands between 1956 and 1977 from about 6,460 ha (with 3,230 ha cultivated) to about 4,100 ha (with 1,750 ha cultivated). This decrease was attributed mainly to urban expansion, waterlogging and soil salinization due to deterioration of the quality of the groundwater used in irrigation. In an attempt to reverse the situation, the government initiated a major agricultural development program in the early 1980s represented by (1) the replacement of surface irrigation methods with micro-irrigation (more water efficient) by subsidizing more than 50% of the cost of their implementation, (2) the construction of major drainage systems to alleviate waterlogging and salt accumulation, (3) the provision of agricultural extension services in terms of educating and advising farmers on types of crops suitable for agriculture under prevailing conditions, (4) the introduction of TSE water in irrigation and, (5) the reclamation of new agricultural lands (Tolner 2013). This resulted in a gradual increase and restoration of agricultural lands to about 4,230 ha, with 3,165 ha irrigated at present, all power irrigated. These 4,230 ha can also be considered as the irrigation potential, should there be an increasing future use of nonconventional water sources, in addition to groundwater. The quantity of groundwater available in the future for agriculture is difficult to estimate since groundwater quality, and hence its availability for irrigation, changes with time. The small size of agricultural landholdings, ranging between 0.5 and 10 ha with an average of 2.5 ha and the fragmentation of the agricultural land.

2.1. Soil, water and land resources

2.1.1. Soil resource

The soils of Bahrain are mostly moderate to shallow in depth. The topsoil texture ranges from sand to loamy sand whereas it subsoils texture varies from loamy sand to sandy loam. The water holding capacity is very low and the available moisture is about 2%–6%. Infiltration rates are very high, above 120 mm/h. Most of the cultivated land became saline, mainly due to heavy applications of saline water during irrigation.

2.1.2. Water resource

The demand for water in Bahrain comes from domestic, agricultural and industrial sectors. The water demands in Bahrain are met through groundwater desalinated water and treated sewage effluent. About 70% of the total water demand is met by the island's groundwater resources. Bahrain being an arid to extremely arid climate, due to which recharge of aquifer is very slow or not at all. Groundwater has become less accessible and less acceptable environmentally; therefore, sufficient availability and adequate water quality are of crucial importance for sustainable development and protection of the environment. The question, however, is pertinent that can we increase water productivity and ensure enough water for sustaining the resource base for food production?

2.1.3. Agricultural land

Bahrain, severely constrained by limited agricultural resources such as limited water resources, poor and declining quality of the soil, and unfavorable climate. Also, due to urbanization and expansion of new towns and communities as well as industrial sector land consumption which all resulted in pressure on agriculture in Bahrain as result of which agriculture contributes only 0.4% to Bahrain's real GDP.

Agriculture development is concentrated on the north and northwest coast, as prescribed by soil, and water quality and availability. In the past, springs located at the contact of the limestone uplands (Dammam black slope) and the coastal fringe deposits were used for irrigation on the coastal lowland soils. These large continuous areas of flat, easily filled, permeable soils are served by groundwater of moderate quality, and this zone has been intensively cultivated.

2.2. Farming systems for efficient use of natural resources

Bahrain's agricultural policy reflects overall economic policy, which emphasizes diversification of the production base. Bahrain implemented a 2004–2015 plan for sustainable agricultural development to improve production and raise productivity. Development efforts in agriculture have included the promotion of intensified farming, Government assists agricultural producers mainly by offering subsidies for a number of inputs, such as 84% of the cost of machinery services; 40% of the price of modern irrigation equipments; and 50% of the price of pesticides; 40 percent of the price of plastic sheet; 50% of the price of veterinary drugs and animal vaccines; and 5% of the price of local poultry meat. Loans are also provided to farmers intending to launch programmes to protect date palms, and other farming activities.

Water is given high priority among other national priority issues in Bahrain due to the limited freshwater resources and escalating water demand. The highest consumption of abstract ground water is by agriculture sector at estimated rate of 66% as a whole. Committee for the protection of freshwater resources was formed with four main tasks: defining and evaluating freshwater resources; protecting freshwater quality, ecosystems and preventing groundwater pollution; integrating development and management of water resources; and, studying climate change effects on water resources. Bahrain has ratified the Convention on Wetlands of International Importance as Waterfowl Habitats (Ramsar Convention). To sustain water, two guiding principles have been followed to manage water more effectively in agriculture. The first approach dealt with the issue of reducing groundwater abstraction, while the second concentrated on finding alternative irrigation water for agriculture and ever-growing landscape projects. A number of actions have been worked on to reach these two objectives, including: enacting and strictly enforcing laws to reduce groundwater abstraction; increasing water use efficiency in agriculture; improving irrigation methods (modern irrigation techniques 75% of agricultural area is under flood irrigation); replacing high-irrigation requirement crops with others of less water demand; introducing tariffs for using groundwater; and using treated sewage effluent. Management of water used, agriculture under greenhouse was introduced in 1976 with the aim of increasing production and achieving a higher level of self-sufficiency in various agricultural products, particularly high-quality fresh vegetables crops. The main greenhouse crops produced are tomato, cucumber, pepper, squash, eggplant, lettuce, strawberry, bean and cauliflowers. However, new policies and institutions are needed for implementing a sound water use development program under these conditions.

Field crop production in Bahrain is diverse. There are three systems of producing a wide variety of fresh vegetables. The three systems of vegetable production are traditional agriculture, protected agriculture, and hydroponic system. Protected agriculture was introduced in Bahrain in 1976, and significant changes in the total area of greenhouse vegetable production have occurred. The total area under cultivation was 59.46 ha in 1996. An increasing number of farmers are now attracted to this new system of intensified cropping. Other investors with capital and land are also becoming interested.

Water scarcity in the region has been an issue for a long time, given the current trends of unsustainable water withdrawals, population increase and degradation of land resources. Bahrain being an arid to extremely arid climate as a result of which natural sources of water in Bahrain is limited to groundwater which can be renewed either very slowly or not at all. Groundwater has become less accessible and less acceptable environmentally; therefore, sufficient availability and adequate water quality are of crucial importance for sustainable development and protection of the environment. The question, however, is can we increase

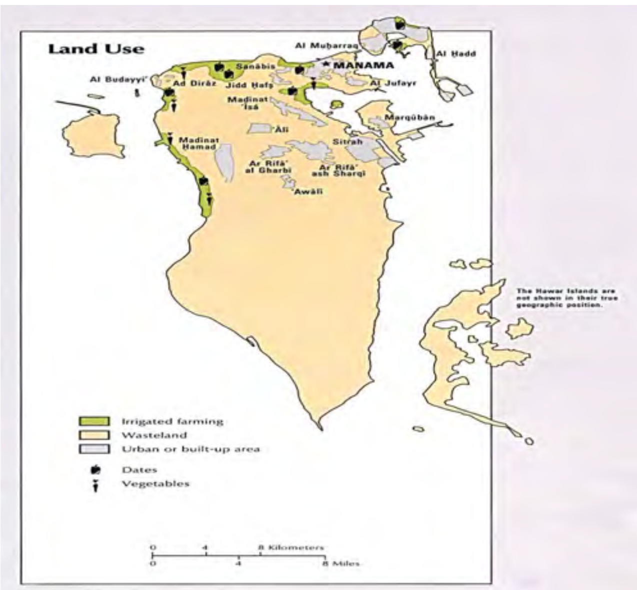


Diagram 2:1 Bahrain Agricultural Land Use
Source: Agricultural Engineering & Water Resources Directorate. Ministry of Municipal Affairs & Urban Planning Agriculture Affairs, Kingdom of Bahrain.

Traditional agriculture

Protected agriculture

Hydroponics system

Traditional irrigation systems

Drip irrigation systems

Modern irrigation hydroponic

water productivity and ensure enough water for sustaining the resource base for food production?

Unfortunately, due to lack of rain, agriculture is irrigated and mainly depends on ground water, therefore, the agriculture sector is the main groundwater consumer and consumes about 80% of the groundwater abstracted. The irrigation method adopted under open agriculture is traditional, drip, sprinkler and bubbler irrigation while the protected house adopted drip irrigation. Water scarcity will reduce agricultural production and threaten country's food security. Therefore, strategies to optimize water use in agriculture under conditions of scarcity need be developed to maximize return per unit of water instead of per unit of land and to improve local livelihoods.

The need to reduce groundwater abstractions has prompted the Government to consider the use of treated sewage effluent as an additional source of water for agricultural purposes. However, it is not utilized to its full capacity, and only 20% of the treated effluent is used, mainly on experimental farms, landscaping and certain industrial uses. Bahrain being an arid to extremely arid climate, due to which recharge of aquifer is very slow or not at all. Groundwater has become less accessible and less acceptable environmentally; therefore, sufficient availability and adequate water quality are of crucial importance for sustainable development and protection of the environment. The question, however, is pertinent that can we increase water productivity and ensure enough water for sustaining the resource base for food production?

The water withdrawal and use and their percentages for the year 2017 (the latest figures) are as follows:

Items	Quantity (Mm^3)	Percentage (%)
Gross total water withdrawal/ production and use	437.1	
Minus losses during transport	5.1	
Net total water withdrawal/ production and use	432.0	100
Of which from:		
• Renewable groundwater	103.8	24
• Non-renewable groundwater	54.6	12.6
• Desalinated water	234.1	54.2
• Treated wastewater	39.5	9.2
Of which used by:		
• Agriculture	143.0	33.1
• Municipal	258.4	59.8
• Industrial	30.6	7.1

Note: Wastewater from urban wastewater is excluded.
Source: Agricultural Engineering & Water Resources Directorate. Ministry of Municipal Affairs & Urban Planning Agriculture Affairs, Kingdom of Bahrain.

I asked a question in my previous email but you did not answer it. We were using the term exploitable before for certain reasons. The best is to use water withdrawal/ production and use format to make things comparable with our database and international requirements. The water withdrawal and use and their percentages for the year 2017 (the latest figures) are as follows:

3. Problem identification

Due to arid climatic conditions natural sources of water in Bahrain are limited to groundwater. Water scarcity will reduce agricultural production and threaten country's food security. Agriculture in the Kingdom of Bahrain witnessed in recent years many obstacles that affected its role in the development process and achieving food security in the country. Agricultural products produced locally cover only 12% of total consumption needs. The value of agricultural output is 16.2 million dinars at a contribution rate of 23% of the GDP, and the value of food imports amounted to more than 202 million Bahraini dinars, and the deficit of the balance of commodity trade in the Kingdom of Bahrain up to the borders of almost 173 million dinars. Therefore, with the world facing perfect storm of food scarcity, Bahrain needs to focus on lowering its food imports and increasing agricultural production to boost the contribution of agricultural sector to its gross domestic product. However, food production under unfavorable climatic conditions and limited water resources cannot be sustainably practiced unless crop water management techniques are designed to meet the present growing demands of water for increased food production. The deficit between available water and water demand is growing and expected to increase in the near future. The best use of water must be made for efficient crop production and higher yields.

4. Methodology

The aim of this paper is to analyze the efficient use of water for food production through better crop management. It focuses on the water use efficiency and water productivity of agricultural sector in Bahrain. The study provided a comprehensive analysis of the vegetable production activities in Bahrain and assessed their efficiency in terms of financial and economic profitability. Especially their utilization of the scarce natural resources, which is water in particular. The analysis conducted for three methods of certain vegetable production in different farms of vegetable production (traditional, green house and hydroponic methods). The irrigation method adopted under open agriculture is traditional, drip, sprinkler and bubbler irrigation while the protected house adopted drip irrigation. This paper employs the concept of comparative advantage of international trade theory to analyse the competitiveness of Bahrain vegetable production. In order to do this analyses, we will construct a modified PAM for the selected vegetable major competitive crops (cucumber, tomato, lettuce) in three production systems. The PAM framework and its modifications are discussed and applied in Monke and Pearson (1989), Monke et al., Yao and Tinprapha, and Yao. The framework will be adapted to the specific conditions of Bahrain and changed to incorporate aspects that are different from PAM approach.

4.1. Policy analysis matrix structure

The policy analysis matrix is a product of two accounting identities, one; defining profitability as the difference between revenues and costs and the other measuring the effects of divergences (distorting policies and market failures) as the difference between observed parameters and parameters that would exist if the divergences were removed. By filling in the elements of the PAM for an agricultural system, an analyst could measure both the extent of transfers occasioned by the set of policies acting on the system and the inherent economic efficiency of the system. Profits are defined as the difference between total (or per unit) sales revenues and costs of production. This definition generates the first identity of the accounting matrix. In the PAM, profitability is measured horizontally, across the columns of the matrix, as demonstrated in Table (4.1), Profits, shown in the right hand column, are found by the subtraction of costs, given in the two middle columns, from revenues, indicated in the left-hand column. Each of the column entries is thus a component of the profits identity-revenues less costs equals' profits. Each PAM contains two cost columns, one for tradable inputs and the other for domestic factors. Intermediate inputs-including fertilizer, pesticides, purchased seeds, compound feeds, transportation and fuel are divided into their tradable-input and domestic factor components. This process of disaggregation of intermediate goods or services separates intermediate costs into four categories – tradable inputs, domestic factors, transfers (taxes or subsidies that are set aside in social evaluations) and non-tradable inputs (which themselves have to be further disaggregated so that ultimately all component costs are classified as tradable inputs, domestic factors or transfers).

As shown in the Table (4.1), Monke and Pearson arranged the data in three rows; the first row for the private prices, the second row for social prices and the third row for the transfers, which are the difference between profits measured at private prices and those measured at social prices. This difference is also referred to as the effects of government intervention or divergences.

whereas: -

A = total revenue in private price (market prevailing price)
B = cost of tradable inputs in private price
C = cost of domestic factors in private price
D = private profit
E = total revenues in social price (price which are adjusted for government intervention)
F = cost of tradable inputs in social prices
G = cost of domestic factors in social prices
H = social profits

Table (4.1): the policy analysis matrix

	Revenues	Costs		Profit
		Tradable inputs	Domestic factors	
Private prices	A	B	C	D
Social prices	E	F	G	H
Divergences	I	J	K	L

Source: Erik and Pearson (1989).

The matrix is thus made up by the following identities: -

Private or financial profit	(D)	D = A-B-C
Social profit	(H)	H = E-F-G
International value added	(IVA)	E-F = H + G
Output transfers	(I),	I = A-E
Input transfers	(J),	J = B-F
Factors transfers	(K),	K = C-G
Net transfers	(L),	L = D-H = I-J-K

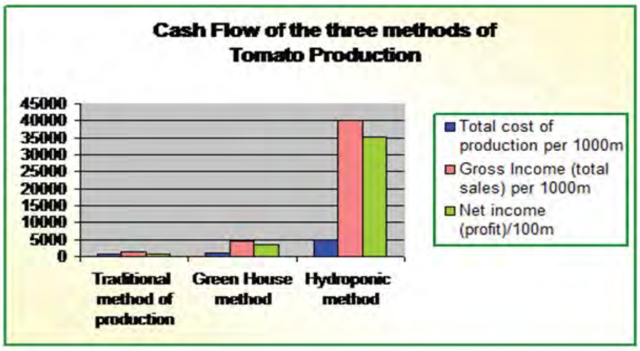
5. Findings/results

The study provided a comprehensive analysis of the vegetable production activities in Bahrain and assessed their efficiency in terms of financial and economic profitability. Especially their utilization of the scarce natural resources, which is water. The analysis conducted for three methods of certain vegetable production in different farms of vegetable production (traditional, green house and hydroponic methods). The irrigation method adopted under open agriculture is traditional, drip, sprinkler and bubbler irrigation while the protected house adopted drip irrigation. The activities that appear to have the best comparative advantage (i.e., lowest DRC values) are the greenhouse production of cucumbers and tomatoes (0.45 and 0.48, respectively). However, the production of vegetables under traditional irrigation systems did not show a very clear comparative advantage, with possible exception of green onions (DRC = 0.53). Therefore, result of the study shows that the green house and hydroponic methods outperformed the traditional method.

Figs. 1–3 show that the green house and hydroponic methods outperformed the traditional method. There is huge potential for increase in vegetable production by using non-traditional method of production. The expansion of vegetable production by non-traditional methods of production may lead to reduction of the import of fresh vegetables to zero. Accordingly, yes, for increasing the vegetable production by non-traditional method.

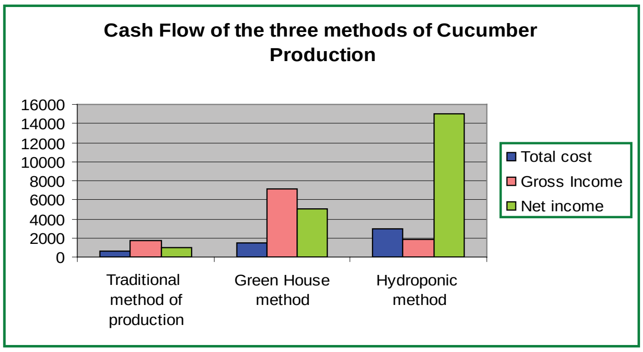
The best use of water must be made for efficient crop production and higher yields. Bahrain's local vegetable production can be increased by promoting vertical intensifying faming. Accordingly, in order to reduce ground water over pumping, total agricultural water use should be reduced by 50% and applying water tariff of 15fils/CM. The application of water tariff has very slight effect on the net profit and it increases significantly the returns to water which gives a good signal of financial and economic viability of such policy option.

Table 5.1
Cash flow statement (costs and revenue) of the three methods of tomato production.



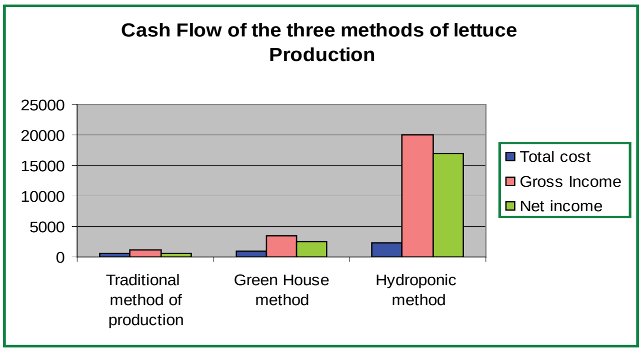
Source: different farms detailed cash flow statement (costs and revenue) of the three methods of lettuces production.

Table 5.2
Cash flow statement (costs and revenue) of the three methods of cucumber production.



Source: different farms detailed cash flow statement (costs and revenue) of the three methods of cucumber production.

Table 5.3
Cash flow statement (costs and revenue) of the three methods of lettuce production:



Source: different farms detailed cash flow statement (costs and revenue) of the three methods of lettuces production.

6. Conclusions and recommendations

The agricultural sector of Bahrain is facing many challenges including the inadequacy of water resources necessary for production process and the dependability of the cultivated space. Also, the effect of climate change worsens the challenges of dry areas which are characterized by acute water scarcity and land degradation. Since, climatic challenges impose constraints on sustainable agricultural development, greater emphasis is needed to safeguard natural resources and agro-ecological practices. Also, for food security purpose, there is an urgent need for adapting sustainable and economically viable crop production system to enhance production efficiency, productivity and quality.

In spite of these challenges, advances in science and technology, and closer cooperation and partnerships with between various organizations provide numerous opportunities. Increased agricultural production through vertical expansion by supporting infrastructure needed for developing and facilitating utilization of modern techniques that will contribute to raising productivity and increased self-reliance in some food commodities.

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Improving irrigation efficiency and conservation using modern irrigation programs in Saudi Arabia

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The continued expansion of agriculture and urban development in the GCC countries, which is located within the arid regions, accompanied with growing demand for water supply in different sectors calls for agricultural sector to look for practices that increase the irrigation efficiency and water conservation thereby increasing water productivity of crops.

In this presentation, we will explore some of the efforts in the determination of the actual water requirements as an introduction to water conservation with deficit irrigation (DI) programs and partial root drying (PRD) system using different soil conditioners such as polymers, compost and biochar. The crop water requirement is the core to establish water conservation program. The crop evapotranspiration (ETc) was assessed through pan evaporation (PE) method and estimation based upon Penman–Monteith (PM) equation. The results revealed good agreement between PE and PM ETc. The irrigation treatments consisted of four levels of ETc (40%, 60%, 80%, and 100% of ETc) in addition to the traditional one as practiced by local farmers. At the 60% and 80% ETc treatments, the DI was tested at different growth stages (initial, developmental, middle, and late stages of crop growth). Each of the treatments was carried out in three replicates. The results showed that soil salinity in general increased with decreasing level of applied water. The crop cucumber could tolerate shortage of water during the middle season growth stage, when the Ky values ranged between 0.57 and 0.76. The level of water used up in 100% ETc treatment was much lower than that in the traditional drip irrigation as practiced by farmers. In other words, the CWP values increased with water consumption being decreased. The results also indicated that the highest values for CWP were found for the most stressed treatment of 40% ETc, while on the other hand the overall crop productivity had decreased.

On studies of water conservation using DI and PRD of various crops, including tomatoes, cucumbers, potatoes. All of these studies have shown that reducing water use by 20% did not significantly affect productivity, and water productivity rose much with deficit when compared with traditional irrigation on farms as well as the provision of water, there was also significant savings in fertilizers and pesticides used.

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Research priorities and actions for sustainable agriculture water management in MENA region

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Keywords: MENA Region; Research; Water management; Agriculture; Sustainability

The MENA region is naturally exposed to chronic shortage of water and almost all available water resources have been already exhaustively used. Agriculture is the most important sector with respect to consumptive water use, equals about 80% of the total water resources. Global climate change and pollution coupled with increasing population pressure and rapid economic growth have a major impact on water resources and their availability. The complexity of these global issues and the need for developing and implementing appropriate ways to manage agriculture water resources present a multitude of challenges to the scientific community and research to advance the current thinking on the technical, economic, environmental, social, and political dimensions of sustainably managing agriculture water demand and supply at local, regional, and basin levels. This paper provides valuable insights into the current research landscape, in the enormous diversity of situations across the MENA region, as well as drawing attention to the existing trends and research gaps in terms of irrigation water security and multiple challenges in this field.

In light of the considerable expertise already present in the region, potential for research in three main categories are highlighted: (1) policy issues composed of research topics in relation with water law/governance/policy and water economics in the context of transition and dynamic change of the region's countries, (2) water resources management that integrate water quality and quantity, and (3) water management technologies providing innovative solutions that meet the challenge of agriculture sector in producing more food with less resources (water and energy) and less environment impact.

Research topics are explored from three point perspectives: "Relevance", "Gaps", and "Priorities". The paper presents some considerations about the relevance of the knowledge and skills in the domain of agriculture water management in the different context of the region. Basic research gaps, that receive little attention but are potentially important in the region such as crop productivity linked to water use efficiency, and unconventional water use, as key priorities for future research in the field have been addressed. More importantly, this work emphasizes the opportunities for potential research growth and knowledge transfer for a production and sustainable agriculture water management in MENA region.

To be competitive at the international level, research in the field of water management needs to be focused on local MENA problems and to take cognizance of a country's political context, local knowledge, skills, and culture. Particular efforts should be placed on generating collaborative research projects that is of relevance for the region rather than following a specific research agenda dictated by funding opportunities. It is through such approach that MENA region will be able to make its own valuable contributions to the global scientific community.

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Leveraging research for sustainable development in the Arab region

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The Arab region is the driest in the world, and it is home to 14 of the 33 most water-stressed countries on the planet. Additionally, low level of natural water abundance is intensified by wasteful approaches to water management and pollution from untreated wastewater. Several Arab countries have nearly exhausted their resources of renewable water, and some of them are facing frequent and prolonged water shortages that force them to make hard choices, regarding the management and allocation of these limited resources, in order to ensure the achievement of the sustainable development goals on national level. Prioritization of various demands for water resources, in such countries, is a complicated multi-dimensional process that entails not only national policies but also science-based solutions.

The International Center for Agricultural Research in Dry Areas (ICARDA) has conducted research, for more than 40 years, in the Arab region with an overall objective of enhancing food security and sustaining livelihoods of local rural communities through integrated agricultural production systems. Since its establishment in 1977, ICARDA has worked on the development of scientific approaches for the optimization of water and energy use for food production. Such approaches are instrumental for halting the alarming process of natural resources degradation, and ultimately breaking the vicious cycle connecting such degradation to poverty, in the Arab region.

ICARDA research findings have been used throughout the Arab region within national and regional interventions aimed at enhancing agricultural productivity while ensuring the long-term sustainability of the natural resources base in the region. Some of these interventions have led to significant improvements both in terms of efficiency gains in natural resources use and in terms of national policies. This presentation aims at showing these findings, how they are being used in various ICARDA interventions, how they contribute to improved national policies, and ultimately how they contribute to sustainable development in the region.

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Development of mobile stand-alone solar-driven reverse osmosis groundwater/seawater desalination plants for sustainable development in Egypt

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ABSTRACT

Egypt is experiencing a fresh water crisis. Many large and small communities in Egypt are suffering an acute shortage of fresh water that complies with minimum health requirements. Water desalination projects based on reverse osmosis (RO) technology are being introduced in Egypt to combat drinking water shortage in remote areas. RO desalination is a pressure-driven process. This work focuses on the design of an integrated brackish water and seawater RO desalination and solar photovoltaic (PV) technology. Two small mobile PV-driven RO desalination plants prototypes were designed, deployed and applied into two areas in Egypt. Solar-driven RO desalination can potentially break the dependence of conventional desalination on fossil fuels, reduce operational costs, and improve environmental sustainability. Moreover, the innovative features incorporated in the newly designed PV-RO plant prototype are focusing on improving the cost effectiveness of producing drinkable water in remote areas. This is achieved by maximizing energy yield through an integrated automatic single axis PV tracking system with programmed tilting angle adjustment. Mobility of the systems provides potable water to isolated villages and population as well as ability to provide good drinking water to different number of people from any source that is not drinkable. In the first project, a mobile battery-less photovoltaic powered groundwater reverse-osmosis (MSRO) desalinating unit was designed, manufactured and deployed in the Northwest coast of Egypt. This unit is capable of desalinating the brackish and saline groundwater as well as it was considered to produce 11 m^3/d of drinkable water for the Bedouins community. The second project focuses on designing, building and field-tested of an integrated mobile saline groundwater and seawater RO desalination and solar photovoltaic (PV) technology. The system was designed to produce 21 m^3/d of fresh water in Shalateen area, Southeast coast of Egypt.

Keywords: Design; Mobile; Reverse osmosis; Photovoltaic; Desalination; Northwest Coast; Shalateen; Egypt

1. Introduction

Desert regions in Egypt constitute more than 94% of the total area of the country. The other 6% of the area include mainly the cultivated lands in Nile valley and Delta. On the other hand, the majority of Egyptian population is concentrated within the area of the Nile valley and Delta whereas less than 5% of the population are scattered in all desert areas. Such situation resulted in serious economic, social and environmental problems. The current total water supply in Egypt is about 57.5 billion m^3/year, from which

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there is a fixed 55.5 billion m^3/year from the River Nile. The per capita water share was 771 m^3/year in 2005, which is below the international standards of water poverty line of 1,000 m^3/year. By the year 2025, this shortage will be severer, the total water demand will exceed 125 billion m^3/year that causes a shortage of more than 30%.

Desalination is a separation process that produces two streams, fresh water and saline solution (brine). Saline water is classified as brackish water when the salt concentration, mostly sodium chloride, is between 1,000 and 10,000 ppm, hard brackish water when the salinity is 10,000 to 35,000 ppm, and seawater when the salinity exceeds 35,000 ppm (Rizzuti et al. 2007). Seawater and brackish water desalination are attracting more and more interest and attention, as they are most important methods to solve the problem of water shortage (Matsuura 2001). The reverse osmosis (RO) process, which relies on the semi-permeable character of a polymeric membrane to achieve molecular separation under the driving force of hydraulic pressure, is one of the most popular technologies currently being used for brackish water and seawater desalination for the advantages such as saving energy, modularity, flexibility, ability to construct small size plants, high permeate quality and minimal chemical addition (Said et al. 2013, Shawky et al. 2011 and Shawky 2009).

Remote communities are often located in areas with access to seawater or brackish groundwater. For such communities, small-scale RO desalination can provide fresh water. Desalination is an energy-intensive process. Diesel generators or grid power are commonly used to power RO systems; however, diesel generators pollute the environment and their fuel is expensive. Grid power may not be available or may be expensive. Using photovoltaics to power RO desalination systems is a promising solution for such communities (Bilton et al. 2011). Solar energy coupled to desalination offers a promising prospect for covering the fundamental needs of power and water in remote regions, where connection to the public electrical grid is neither cost-effective nor feasible, and where water scarcity is severe. Moreover, the coupling of RO desalination with solar energy is a promising field of development in the desalination sector, with the potential to (i) improve its sustainability by minimizing or completely eliminating the dependence on fossil fuels, (ii) significantly reduce the operational costs of desalination plants (Ghermandi and Messalem 2009). Despite a steady reduction in the energy consumption of pressure-driven membrane processes in recent decades, energy consumption is still a major cost component of RO desalination plants, accounting for 40%–45% of total costs (Betts 2004).

The solar-powered RO systems principally can be classified into three groups: (1) solar thermal driven or Rankine cycle driven RO systems; (2) PV-driven RO systems; (3) hybrid (particularly wind-PV) powered RO systems (Aybar et al. 2010). The Middle East and North African region has outstanding solar resources which can be captured for use either by (PV) devices or by direct absorption as thermal energy. The distribution of this resource is more evenly spread over the entire region than other renewable energy resources, which tend to be site specific. Huge areas are available for this resource to be utilized. Long-term development of this on a large scale will hinge on technical developments that will reduce the cost of electricity generated by PV or by solar thermal power plants.

The main goal of this paper is reducing the total cost (capital + operating) of desalinated water, designing and testing of two small mobile PV-driven batteries-less powered groundwater reverse-osmosis (PV-RO) desalinating units for sustainable development in different localities in Egypt. The first unit is capable of desalinating brackish and saline groundwater and produces 11 m^3/d of potable water per day that complies with international standards to be deployed in the northwest coast of Egypt, where, the second unit is producing 21 m^3/d of fresh water and deployed in Shalateen area, Southeastern Egypt.

2. Methodology

Development of hybrids of solar and conventional desalination requires careful analysis and innovative engineering solutions. Hybrids of RO and solar energy are relatively less complicated than hybrids of thermal desalination (Childs et al. 1999). A stand-alone RO desalination unit powered by solar is proposed. To predict the water production, 131 different water points are selected based on the available solar radiation data, sunshine hours and salinity of the feed water. The proposed system includes two main subunits—the energy production and the desalination subunits. The energy production subunit includes PV array without batteries, and DC/AC inverter. Because of the high humidity for the area under application, battery-less system was our favorable choice. The membrane separation section of the desalination subunit is fed via a high-pressure reciprocating pump, which is connected to energy production subunit for the recovery of energy by the brine stream leaving the process. The RO desalination unit consists of three 4 × 40 inch spiral wound seawater Filmtec membrane modules. The DC power is produced from a PV array that consists of six TOPSUN TS-S415 solar PV panels of total peak power of 2,490 W that is connected to the DC motor. Taking account of this fact, a preliminary design of small-scale PV-powered RO battery-less desalination system is proposed in this study. The system is battery-less as the low annual water storage cost in a tank (1%) compared with the electrical energy storage cost in batteries (12%) proves that it is more cost-effective to store fresh water rather than to store electrical energy (Mohamed and Papadakis 2004). The proposed system is supposed to be a promising option by its compactness, its transportability, and its technical and economic feasibility. More than 150 articles were collected by the research team covers the following topics; geology, hydrology and hydrogeochemistry of the study area, water desalination plants, PV/wind-driven RO desalination plants and design of PV/wind RO desalination plants. Field work for Matrouh project took place within 2012–2013, during which water samples were collected from the study area. The present research is based on the results of 131 water samples (5 fresh samples, 9 saline samples and 117 brackish water samples) corresponding to all available water sources in the area.

A complete technical report for the groundwater evaluation for the area between Shalateen and Haliab was prepared by the research team as a side activity from the project.

The unit contains three Filmtec spiral wound membranes (SW30-4040) in one pressure vessel, dosing pumps of 1.2 kW for the feed water pretreatment and a 0.25 kW washing pump. To operate the RO desalination plant, these items should be considered as following.

2.1. Pre-treatment

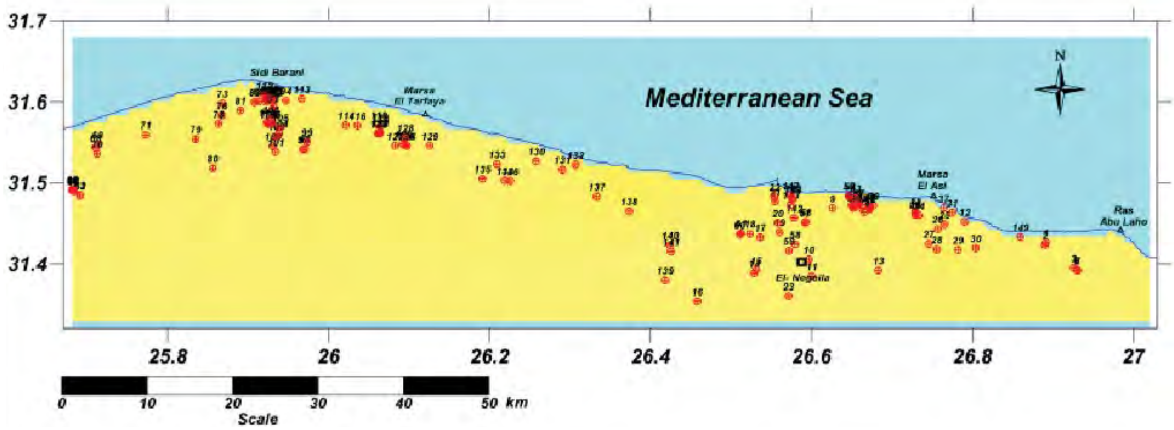
The incoming feed-water is pretreated to be compatible with the membranes by removing suspended solids, adjusting the pH, and adding a threshold inhibitor to control scaling caused by constituents such as calcium sulphate.

2.2. Pressurization

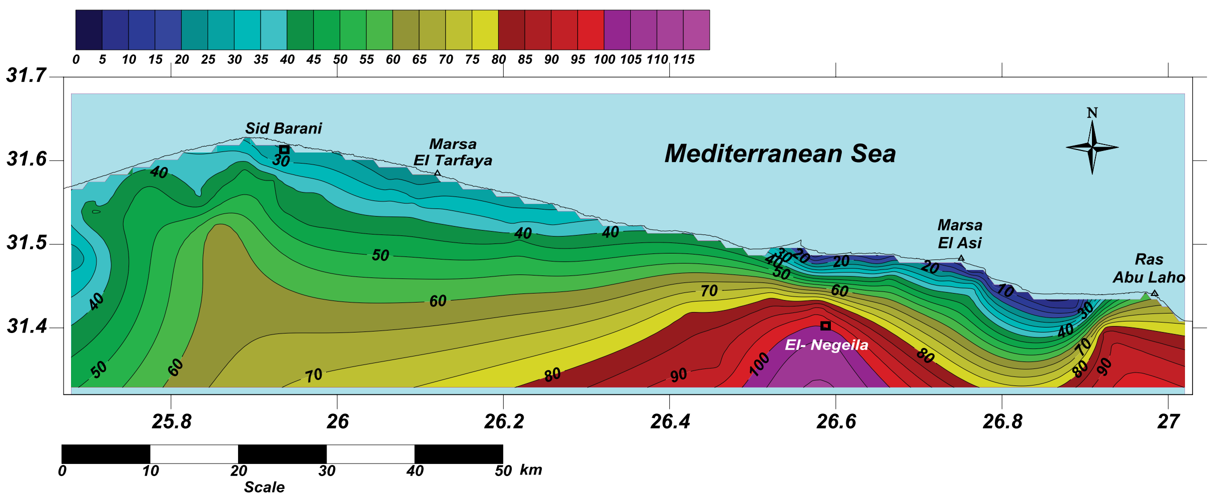
The pump raises the pressure of the pretreated feed water to an operating pressure appropriate for the membrane and the salinity of the feed water.

2.3. Energy recovery

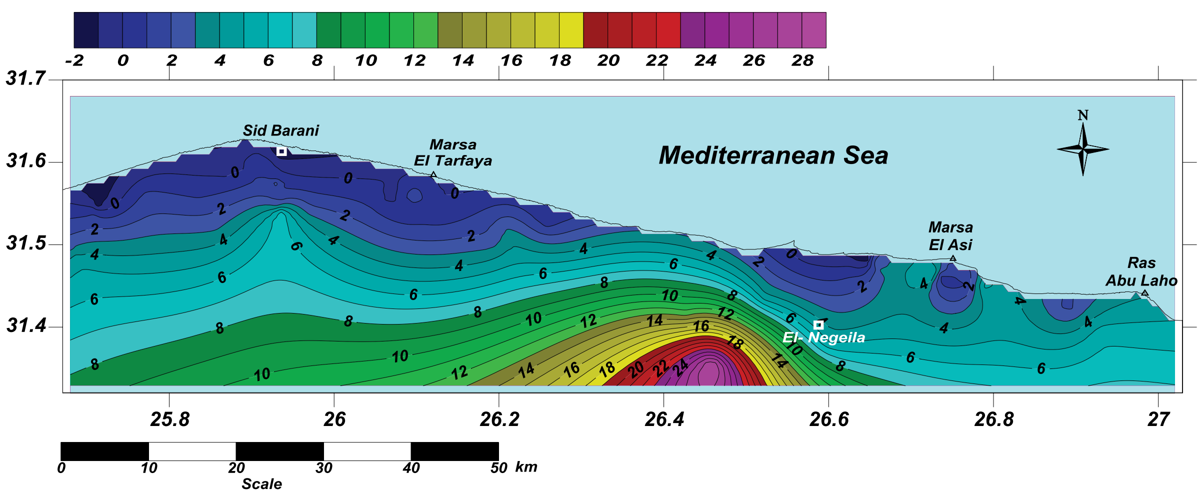
Seawater RO uses a very fine membrane that allows pure water to pass through, while mostly rejecting the relatively large salt molecules. The seawater feed must be pressurized (may be up to 69 bar/1,000 psi), first, to force the water through the mechanical constriction presented by the membrane and, second, against the natural osmotic pressure. Not all of the feed water can be forced through the membrane; some, typically more than half, must be allowed to pass over the membrane (cross-flow) in order to remove the salt. This water, known as the concentrate or brine, comes out of the RO module at a pressure only slightly below that of the feed pressure. In large RO plants, it is economically viable to recover the rejected brine energy with a suitable brine turbine. Such systems are called energy recovery RO systems.



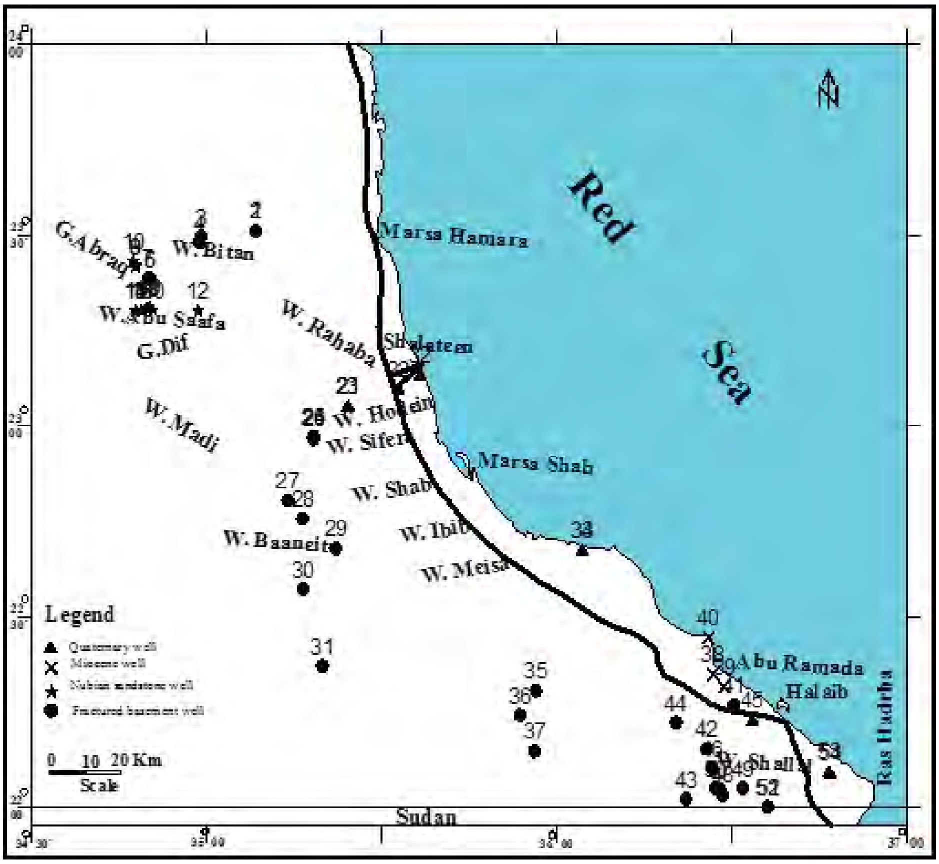
Well location map of the ground water in Matrouh area, Northwest coast of Egypt, May (2004 and repeated in May 2015).



Depth to water contour map in Matrouh area, Northwest coast of Egypt, May (2004 and repeated in May 2015).



Water level contour map of Matrouh area, Northwest coast of Egypt, May (2004 and repeated in May 2015).



Well location map of the ground water in Haliab and Shalateen area, May (2004 and repeated in May 2015).

3. Prediction of power consumption in the presence of energy recovery device

The use of a pressure exchanger to recover the hydraulic energy in the brine line plays a dominant role in the reduction of the size of the high-pressure pump and resulted in the reduction of the energy consumption power for the seawater which finally reduced the size of the hybrid energy system and the water production cost.

4. Survey on PV panels to choose the suitable type of panels

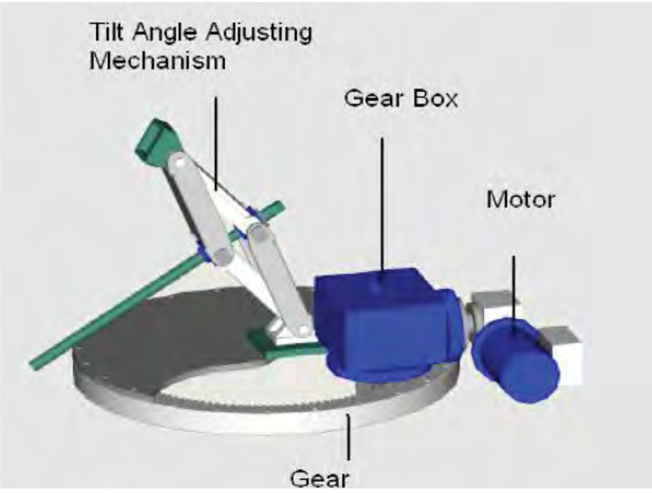
Selecting PV modules to satisfy total peak power requirements of the system. The PV generator will comprise efficient mono crystalline PV modules, a relatively high output power module will be selected to minimize the number of modules for better mobility considerations. The interconnection of the selected PV modules will be configured so that

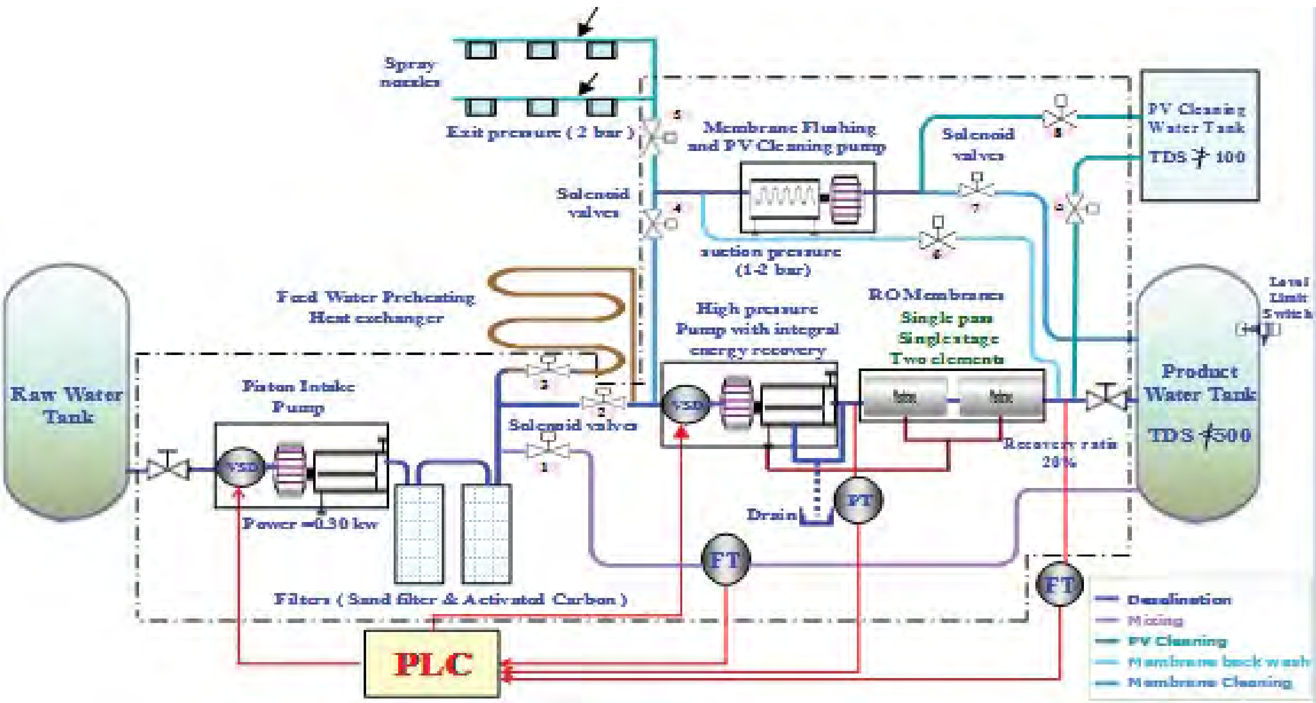
Mono-crystalline PV panels

the output voltage of the PV generator will fit with the input voltage of the inverter. Fourteen PV mono crystalline Si modules (each of 420 Wp with total peak power 5,880 Wp) were delivered by AOI.

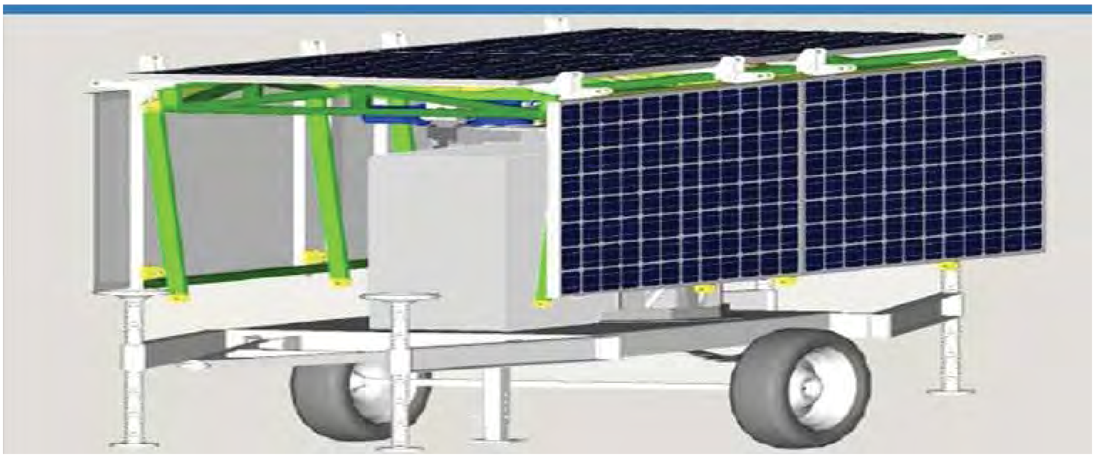
4.1. Assigning the structure, tracker system

To maximize the total solar radiation collected, PV tracking system is realized. For a simple tracking system, the daily solar tracking is achieved by rotating the PV array about the solar tracking axis staring at the azimuth angle at sun rise and ending at the azimuth angle at sun set. This rotation is achieved by incremental azimuth angular movements based upon the location of the system. The azimuth angle range is determined for each month and set in the PLC.

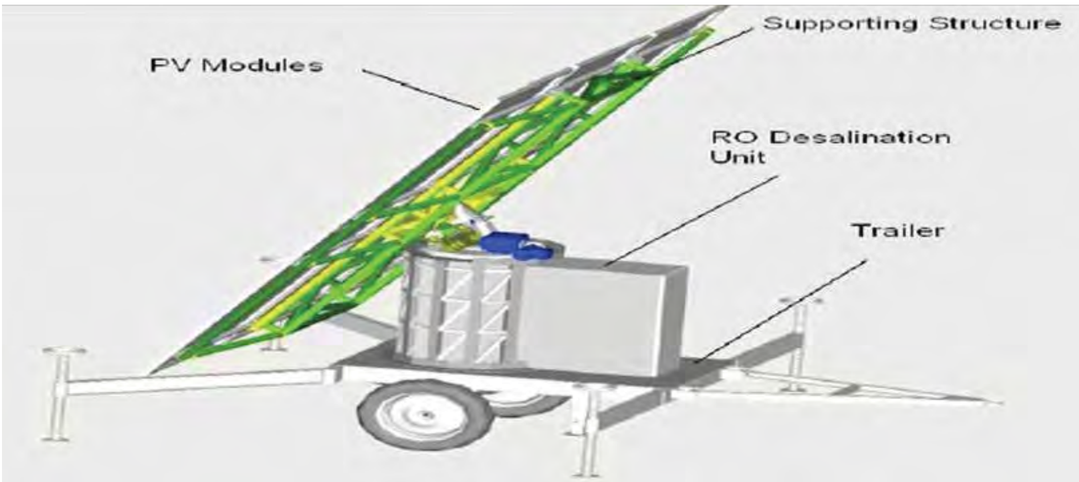




Schematic diagram for the integrated PV/RO system



Transportation mode



Operating mode

Structure of North coast unit

Structure of Shalateen unit

Structure of North coast unit

Structure of Shalateen unit

Transportation of North coast unit

Transportation of Shalateen unit

Factory testing of North coast unit

Factory testing of Shalateen unit

Matrouh unit in the final destination

Shalateen unit in the final destination

5. Conclusion

This work focuses on the improvement of mobile stand-alone solar driven RO groundwater desalination plants for maintainable expansion in different areas in Egypt. The aim of this study was working with the design of an integrated brackish water and seawater RO desalination and solar photovoltaic (PV) technology. Two small mobile PV-driven RO desalination plants prototype were designed, organized and applied into two areas in Egypt. Solar-driven RO desalination can potentially break the dependence of conventional desalination on fossil fuels, reduce operational costs, and improve environmental sustainability. Moreover, the innovative features incorporated in the newly designed PV-RO plant prototype are focusing on improving the cost efficiency of generating drinkable water in remote areas. A small mobile PV-driven RO desalination plant prototype without batteries was designed. Solar-driven RO desalination can potentially break the dependence of conventional desalination on fossil fuels, reduce operational costs, and improve environmental sustainability. This was achieved by maximizing energy yield through an integrated automatic single axis PV tracking system with programmed tilting angle adjustment.

Mobility of the systems delivers drinkable water to remote villages and population as well as aptitude to provide good drinking water to diverse number of people from any source that is not drinkable. First, a mobile battery-less photovoltaic powered groundwater reverse-osmosis (MSRO) desalinating unit was intended, contrived and organized in the Northwest coast of Egypt. This unit is able to desalinate the brackish and saline groundwater as well as it was deliberated to produce 11 m^3/d of drinkable water for the Bedouins community. Second, the designing, building and field-testing of an integrated mobile saline groundwater and seawater RO desalination and solar photovoltaic (PV) technology was achieved. The system was designed to produce 21 m^3/d of fresh water in Shalateen area, Southeast coast of Egypt.

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Modeling of temperature governed saturation states and metal speciation in the marine waters of Kuwait Bay – concern to the desalination process

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ABSTRACT

There is a change in temperature in the marine waters of Kuwait bay with respect to season and daily temperature. This variation in temperature affects the saturation and the speciation states of ions in the marine waters, which serve as the main source of desalination. The change in the saturation states of compounds constituted by major ions and the speciated metal ligands cause a differential impact on the RO membranes. This variation in temperature was considered and modeled using the average bay water composition to determine the saturation state of minerals concerning temperature. This composition was studied for variation from 10°C to 50°C using geochemical model PHREEQC. The metals such as B, Li, Sr, Ba, Fe, Mn, Be, Co, Cr, Ni, Se, Al, Mo and As were analysed in these water and the predominant species of these metals along with their variation with respect to temperatures considered were studied. The saturation states of calcium carbonates and calcium sulfates were considered as they form the significant major ions of marine waters. The order of state of saturation index (SI) is observed to be as, $SI_{Dol} > SI_{Cal} > SI_{Ara} > SI_{Gyp} > SI_{Anhy}$. There is a sharp decrease of pH with respect to increase in temperature was observed. The observation indicates the fact that beyond 25°C there is a decrease in the SI_{Cal}, SI_{Ara}, SI_{Dol} and there is an increase in the SI Anhy. Hence, it is inferred that the SI of carbonate minerals beyond 25°C is slightly reduced and that of sulfate minerals with respect to Ca are increased. This is mainly due to the preferential attraction of Ca to SO_4^{2-} than to CO_3^{2-} above this temperature, which is a reflex of common ions effect. Further it should be noted that pH of the water decreases with temperature and this indirectly affects the HCO_3 concentration in water. So, it is inferred that the carbonate salts are more prominent during winter and the sulfates during summer, and the pre-treatment should also be planned considering the saturation states of water with respect to season.

Keywords: pH; Saturation; Carbonate; Sulfate; Season

1. Introduction

The process of desalination has been studied by various authors for the salt deposits in the membranes (Rawajfeh et al. 2012). The formation of salts is dependent on several factors such as feed water composition (Hamdona et al. 1993), temperature (Amjad and Hooley 1986), pH (Klepetsanis and Koutsoukos 1989), operating pressure (Lee and Lee, 2000), flow velocity (Lee and Lee 2005), permeation rate (Wang et al. 2002). The studies have also proved high salt levels near the membrane, surface, where the particles are expected to be deposited. This has resulted mainly due to the concentration polarization which plays an essential role in the formation of scales in high pressure membrane system (Lee et al. 1999; Chong and Sheikholeslami 2001; Dydo et al. 2003). The rejects are observed to be accumulated in the surface of membrane (Hoef et al. 2008). It was very significant to note that the saturation state is higher at the surface of the membrane surface though the solution may be under saturated or near saturated (Antony et al. 2011). Apart from the surface precipitation, the deposition of salts along the membrane pores was also subsequently studied by various researchers (Oh et al. 2009; Darton et al. 2001). The studies Sheokholeslami and Ng (2001), and Sheikholeslami

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(2003a, 2003b) inferred that involvement of minor quantities of a different precipitating salt will affect the salt structure, its precipitation and thermodynamic properties. As the salts may act as a seed or absorbent or may dissolve or may contribute to the growth of salts (Nancollas and Zieba 1995; Klepetsanis 1995; Sheikholeslami 2003). Hence the study of co-precipitation of several salts simultaneously forms a feed solution which is complex. In this scenario, the feed water composition for the RO process (Kuwait Bay water) was studied by varying temperature to understand the co-precipitation behavior of predominant salts. An attempt was also made to understand the saturation state of oxides and hydroxide minerals in the membrane, thereby inferring the expectable salts to be precipitated in the membrane with respect to season.

2. Methodology

The average composition of 20 Kuwait Bay water samples was considered for the study (Table 1). Disequilibrium indices Log (IAP/KT) was calculated by PHREEQC (Parkhust and Appelo, 1999) for those minerals and other solids stored in the model data book for which the dissolved constituents are reported in the groundwater analysis.

Solubility equilibrium hypothesis was tested by computing ion activity product (IAP) from the activities of uncomplexed ions based on the stoichiometries of minerals and other solids in the WATEQ4F data base. The activity product is then compared with the solubility product (KT) for the same solid phases to the assumption that certain dissolved constituents in groundwater are in equilibrium with particular minerals and amorphous solids. Disequilibrium indices log (IAP/KT) were calculated to determine, if the water is in thermodynamic equilibrium log (IAP/KT = 0), oversaturated log (IAP/KT > 0) or undersaturated log (IAP/KT < 0) with respect to certain solid phases (Trusdell and Jones 1973). The variation of temperature to determine the influence of season was carried out in PHREEQC modeling by considering a variation of temperature from 10°C to 50°C. The model was considered for saturation index of the minerals as presented in Table 2.

3. Results and discussion

Scaling in industrial processes is plagued by the subsequent factors: (i) flow field, that is, speed of flow and solid/liquid interface conditions; (ii) substrate properties, that is, materials properties and surface conditions; (iii) bulk variables and composition, pH scale buffering capability, chloride and sulfate concentrations, and concentration of dissolved oxygen and (iv) thermal, that is, bulk temperature, surface temperature and heat flux. Surface crystallization happens because of the lateral growth of the size deposit on the membrane surface, leading to flux decline and surface blockage. Bulk crystallization arises once crystal particles square measure shaped within the bulk part through homogeneous crystallization and will deposit on membrane surfaces as sediments/particles, to create a cake layer that ends up influx decline. Additionally, concentrated scale forming conditions ends up in scale growth and agglomeration. This can be because of the random collision of ions with particles and secondary crystallization happens (Chidambaram et al. 2011) on the surface of those foreign bodies gift within the bulk part (Pervov 1991, Okazaki and Kimura 1984), coincidental bulk and surface crystallization can also occur for prime recovery in operation conditions. There are several elements/parameters considered in the study to understand the coprecipitation nature of the salts by calculating the saturation index calculations. Though there are several mineral saturation states and their saturation indexes can be classified into carbonates, sulfate, hydroxides, oxides, aluminosilicates, metal silicates, silicates, fluoride and phosphates. The present study will be concentrating more about, the most predominant form of saturation index carbonates and sulfates.

The chief minerals saturated in carbonates are in the following order, dolomite > huntite > magnesite > calcite > aragonite (Fig. 1). Other carbonate minerals are undersaturated indicating the fact that the saturated minerals tend to form scales or salt deposits in the membrane. The temperature variation studies indicate that saturated carbonates do not show much variation with increase in temperature of the feed solution except for that of huntitie and magnesite saturation, which increases with temperature. The morphological changes of $CaCO_3$ by crystallization and transformation were projected to be controlled by the particle activity product (IAP) (Pena et al. 2010, Ogino et al. 1987). Sawada (1997) deduced a time sequence through the amendment within the exponent of IAP at 25°C, numerous studies (Tzotzi et al. 2007, Chakraborthy et al. 1994, Greenlee et al. 2010, Rodriguez-Blanco et al. 2011) recommend that temperature- and pH-dependent scale are vital factors dominant in the formation of the ultimate crystalline section. Amorphous calcium carbonate can rework to calcite at low temperatures (<30°C) and to aragonite at higher temperatures (≥40°C; Rodriguez-Blanco et al. 2011). Though calcite presents the best physical stability beneath close conditions, the thermodynamically less stable mineral state of aragonite could also be stable beneath such temperature conditions or within the presence of alternative ions or inhibitors. Mg ions in

Table 1
All values in mg/L except for temperature in °C

Al	HCO_3	As	B	Ba	Br	Ca	Cl	Cu	F	Fe	K	Li	Mg	Mn	NO_3	Na	Ni	P	pH	SO_4	Si	Sr	Temp
0.070319	137.75	0.002999	4.87375	0.011735	85.48188	588.1163	26449.43	0.009735	3.273688	0.004207	524.79	0.286313	1711.325	0.000274	0.66121	14554.5	0.00056	0.052593	8.123	3694.4	0.288184	7.2475	24

Table 2
Saturation indexes considered for study with their chemical formulae

Carbonates and its composition		Oxides and its composition	
Aragonite	$CaCO_3$	Birnessite	MnO_2
Artinite	$MgCO_3 \cdot Mg(OH)_2 \cdot 3H_{2O}$	Bixbyite	Mn_2O_3
Calcite	$CaCO_3$	Bunsenite	NiO
	$CuCO_3$	Hausmannite	Mn_3O_4
Dolomite	$Ca\ Mg(CO_3)_2$	Halmatite	Fe_2O_3
Huntite	$Ca\ Mg_3(CO_3)_4$	Magnetite	Fe_3O_4
Magnesite	$MgCO_3$	Nsutite	MnO_2
Malachite	$Cu_2(OH)_2(CO_3)_2$	Pyrolusite	MnO_2
Natron	$Na_2CO_3 \cdot 10H_2O$	**Aluminosilicates and silicates and its composition**	
Nesquehonite	$Mg\ CO_3 \cdot 10H_2O$	Adularia	$KAl\ Si_3O_8$
	$NiCO_3$	Albite	$NaAl\ Si_3O_8$
Rhodochrosite	$MnCO_3$	Analcime	$NaAl\ Si_2O_6 \cdot H_2O$
Siderite	$FeCO_3$	Chlorite	$Mg_5Al_2\ Si_3O_{10} \cdot (OH)_8$
Strontianite	$SrCO_3$	Chrysolite	$Mg_3\ Si_2O_5(OH)_4$
Witherite	$BaCO_3$	Clinoenstatite	$MgSiO_3$
Hydromagnesite	$Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O$	Halloysite	$Al_2Si_2\ O_5(OH)_4$
Sulfates and its composition		Illite	$K\ Mg\ Al\ Si\ O_{10}(OH)_2$
Anhydrite	$CaSO_4$	Kaolinite	$Al_2Si_2\ O_5(OH)_4$
Antlerite	$Cu\ _3(OH)_4SO_4$	K. Mica	$KAl_3Si_3\ O_{10}(OH)_2$
	$Ba_3(ASO_4)$	Laumontite	$Ca\ Al_2Si_4\ O_{12} \cdot 4H_2O$
Barite	$BaSO_4$	Leonhardite	$Ca_2\ Al_4Si_8\ O_{24} \cdot 7H_2O$
Basaluminite	$Al_4(OH)_{10}SO_4$	Montmorillonite	
Celestite	$SrSO_4$	Phyllipsite	$Na_{0.5}\ K_{0.3}\ Al\ Si_3\ O_8 \cdot H_2O$
Chalcanthite	$CuSO_4.5H_2O$	Phlogopite	$K\ Mg_3\ AlSi_3\ O_{10}(OH)_2$
Epsomite	$MgSO_4.7H_2O$	Prehnite	$Ca_2\ Al\ _2\ Si_3\ O_{10}(OH)_2$
Gypsum	$CaSO_4.2H_2O$	Pyrophyllite	$Al_2Si_4\ O_{10}(OH)_2$
Turbanite	$Al\ OH\ SO_4$	Chalcedony	SiO_2
Mirabilite	$Na_2\ SO_4.10H_2O$	Quartz	SiO_2
	$MnSO_4$	Sepiolite	$Mg_2\ Si_3O_{7.5}$ OH. 3H
Thenardite	$Na_2\ SO_4$	Talc	$Mg_3\ Si_4O_{10}(OH)_2$
Alunite	$KAl_3(SO_4)_2(OH)_6$	Tremolite	$Ca_2\ Mg_5\ Si_8\ O_{22}(OH)_2$
Jarosite	K - $KFe_3(SO_4)_2(OH)_6$	Cristobalite	SiO_2
	Na - $NaFe_3(SO_4)_2(OH)_6$		
Hydroxides and its composition		Diopside	$CaMgSi_2O_6$
$Al(OH)_3$		**Phosphates and fluorides and its composition**	
Boehmite	AlOOH	FCO_3 apatite	Ca_{10} Na
			$Mg(PO_4)_5(CO_3)\ F$
$Cu(OH)_2$		Fluorapatite	$Ca_5(PO_4)_3\ F$
Brucite	$Mg(OH)_2$	Fluorite	CaF_2
Diaspore	AlOOH	Hydroxyapatite	$Ca_5(PO_4)_3$ OH
	$Fe(OH)_3$		$Mn\ HPO_4$
Gibbsite	$Al(OH)_3$		$Sr\ F_2$
Goethite	FeOOH	Strengite	$Fe\ PO_4 \cdot 2H_2O$
Manganite	MnOOH		
	$Ni(OH)_2$	Halite	NaCl
Portlandite	$Ca(OH)_2$		
Pyrochrosite	$Mn(OH)_2$		

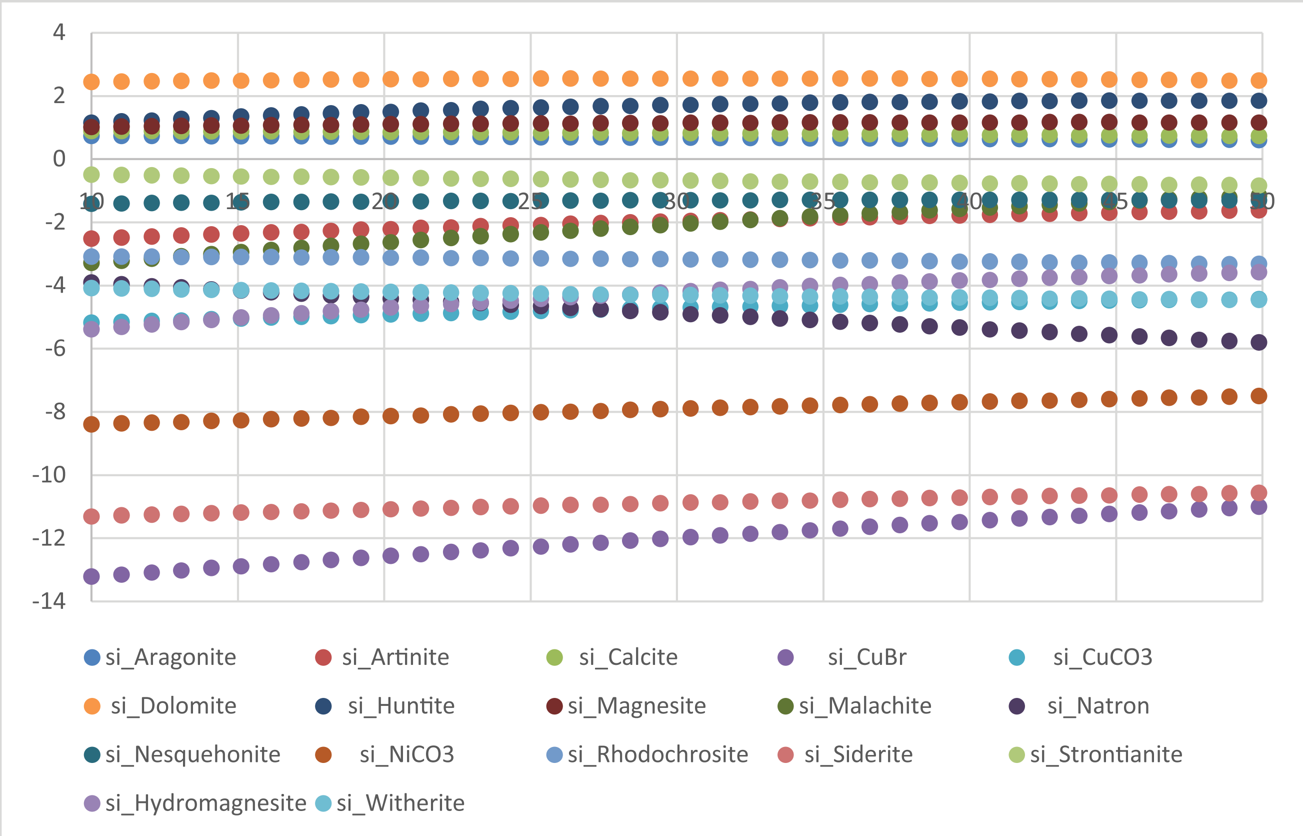

Fig. 1. Variation of the saturation states of carbonate minerals with respect to temperature in °C.

solutions saturated with $CaCO_3$ hinder the formation of vaterite and should favor the precipitation of aragonite mineral (Reddy and Nancollas 1976). Mg in water beside atomic number exerts a profound restrictive result on $CaCO_3$ precipitation evident from literature (Astilleros et al. 2010, Chen et al. 2006, Mucci and Morse 1983).

The variation of temperature with respect to pH and ionic strength of the solution shows that the there is an inverse relationship of these parameters. This variation in pH thus governs the precipitation of carbonate minerals. However, there is a direct relation to temperature and pCO_2 values in the solution (Fig. 2). The earlier studies infer that the carbonate precipitations are chiefly governed by pH and pCO_2 variations but that of sulfates by solubility (Zarga et al. 2013).

Scaling, a frequent development in water is characterised by the looks of the packaging of associate degree adhering crystalline deposit recognized basically by $CaCO_3$ and $CaSO_4{\cdot}2H_2O$ on the surfaces in step with the subsequent reactions.

$$CO_2 + H_2O + CaCO_3 = Ca\ (HCO_3)_2 \quad (1)$$

$$HCO_3 + H_2O = CO_3 + H_3O^+ \quad (2)$$

$$SO_4 + Ca + 2H_2O = CaSO_4{\cdot}2H_2O \quad (3)$$

All scaling processes by $CaCO_3$ result directly or indirectly from the primary reaction (Eq. (1)). The CO_2 exchange between the liquid and gaseous phases is the main explanation for any scaling. CO_2, in presence of a gasified section, can dissolve within the water. After association and ionization, CO_2 provides rise to associate degree acid product that permits the attack of the current $CaCO_3$ altogether the matter rocks. Then it dissolves and passes within the resolution within the style of carbonate that is way a lot of soluble than the carbonate. This transformation (reaction from left to right in Eq. (1)) corresponds to the matter rocks solubilization method once the water is in contact with atmosphere made in CO_2. If later this water loses the CO_2 by degassing and/or heating, the reaction will move to the other direction (reaction from right to left in combining weight. (1) and offers rise to $CaCO_3$ scale. throughout $CaCO_3$ precipitation, Ca ions can react with carbonate (CO_3^{2-}) ions that accelerate the formation of H_3O^+ ions, as shown in combining weight. (2), resulting in a pH scale decrease throughout germination. Few of the undersaturated carbonate minerals also show definite trends with respect to temperature; atrinite, malachite, hydromagnesite, nesquehonite, $NiCO_3$ and bromides of copper increases with temperature. Natron and witherite show decreasing trend with temperature.

Further, the saturation index of sulfates shows that only barite is saturated; gypsum, anhydrite and celestite show near saturation states (Fig. 3). Other sulfate minerals represented are undersaturated. The variation in temperature shows that there is an increase in saturation sates of the minerals such as anhydrite, celestite, antlerite, chalcanthite,

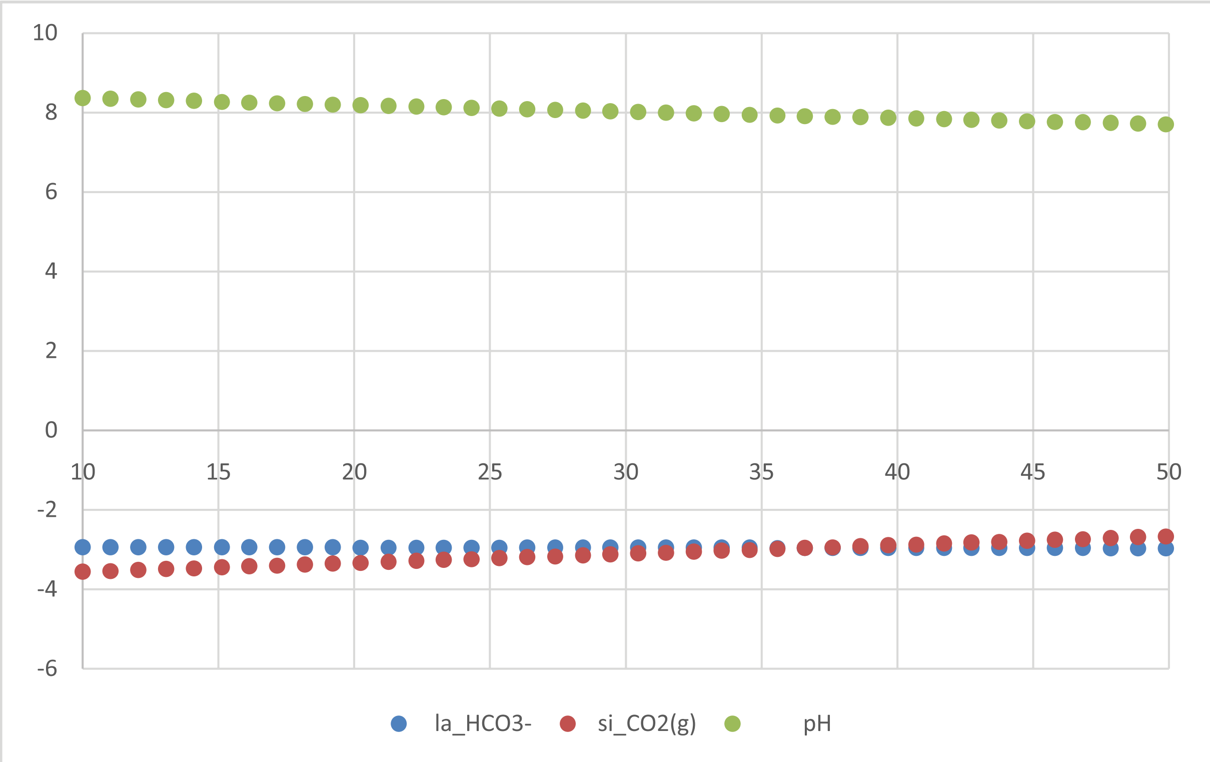

Fig. 2. Variation of pH, HCO_3 and pCO_2 with respect to temperature in °C.

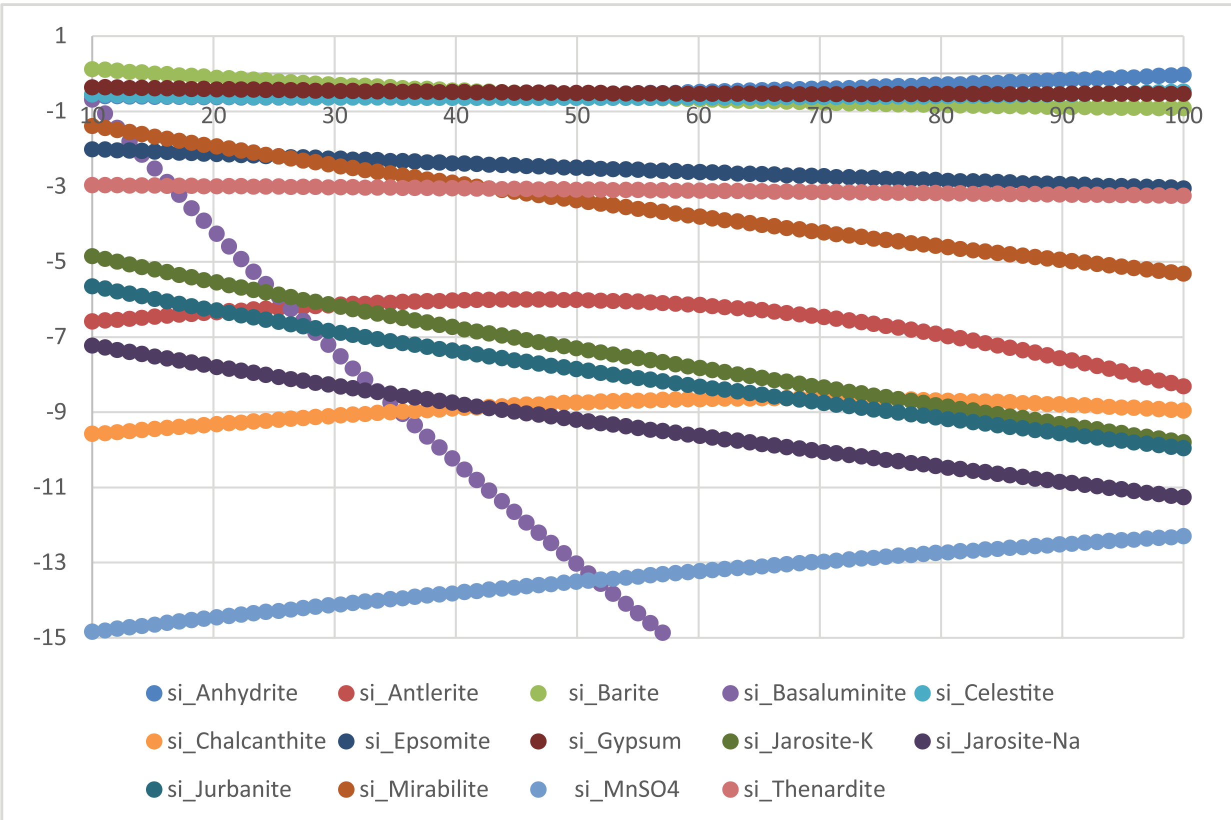

Fig. 3. Variation of the saturation states of sulfate minerals with respect to temperature in °C.

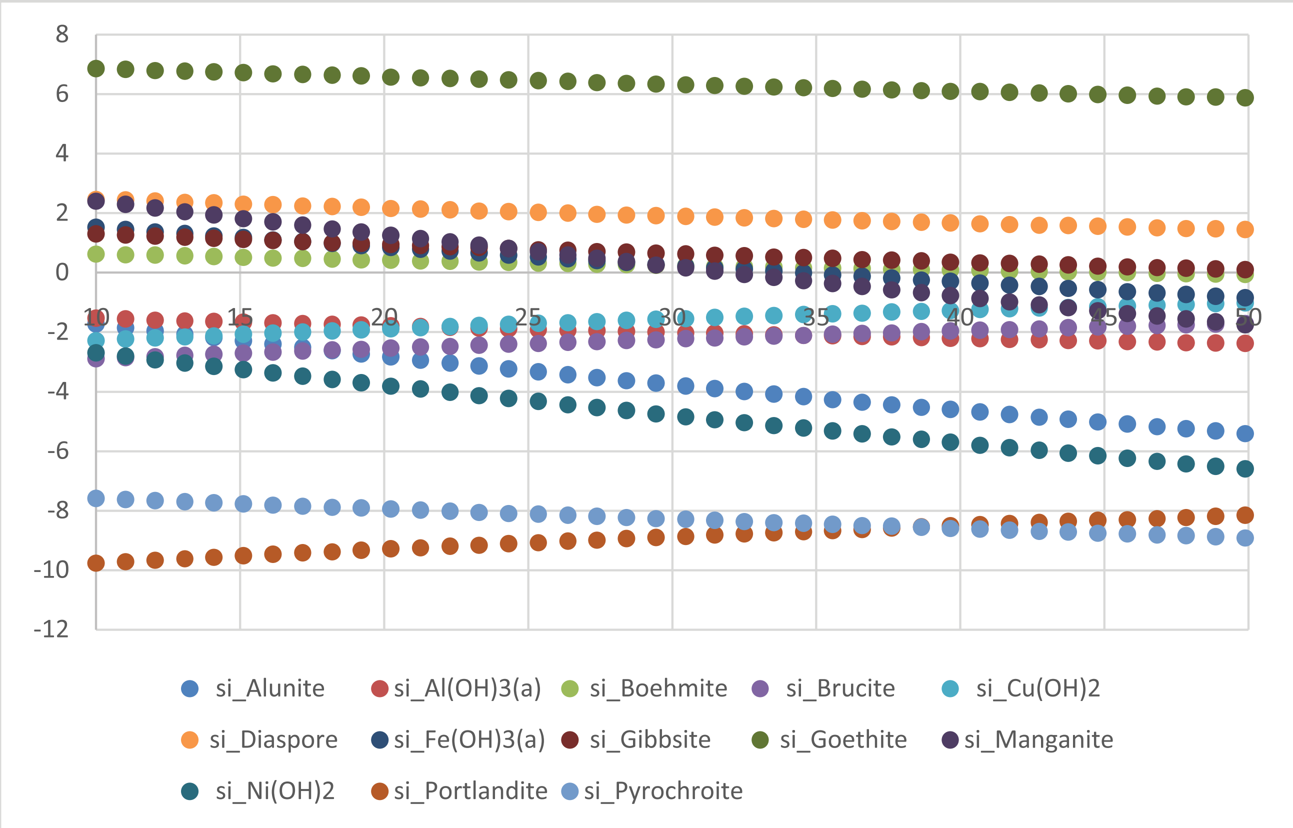

Fig. 4. Variation of the saturation states of hydroxide minerals with respect to temperature in °C.

thenardite and $MnSO_4$ with respect to temperature; whereas other minerals show a decrease, but it is, interesting to note that for this composition considered there is a decrease in saturation index of antlerite beyond 59°C and simultaneously beyond this temperature, there is an increase in saturation index of anhydrite.

Saturation index of hydroxides show that they are saturated with geothite, gibbsite, manganite, boehmite, diaspore, $Fe(OH)_3$ and other hydroxide minerals are undersaturated (Fig. 4). The variation in temperature shows that there is an increase in saturation states of brucite, $Cu(OH)_2$ and portlandite decrease in saturation states with respect to temperature. Oxide mineral saturation states show that they are saturated with composition of hematite, maghemite, magnetite, nsutite, pyrolusite and Bixbyite (Fig. 5). The variation with temperature shows that there is an increase in the saturation sates of the undersaturated minerals such as bunsenite, hausmannite and tenorite. However, all the saturated minerals show decrease in saturation with respect to increase in temperature.

The aluminosilicates show saturations of chlorite, kaolinite, K-mica, leonardite, montmorillonite and phlogopite. The increase in temperature elevates the saturation index of phillipsite, chlorite and pyrophyllite (Fig. 6). The feed water composition also shows saturation of tremolite, talc and chrysolite, which increases with temperature until 30°C and there is a drop in these values. Sepiolite, clinoenstatite and diopside are undersaturated, but the two later minerals increase their saturation beyond 20°C (Fig. 7). The composition of FCO_3 apatite, fluorapatite, hydroxyapatite and fluorite are saturated, but that of SrF_2 are undersaturated (Fig. 8). The temperature relationship to the saturation states of these minerals indicate that there is a decrease in saturation sates of fluorite and FCO_3 apatite.

4. Conclusion

The study on the temperature variation modeling on the average bay water composition shows that the carbonates such as aragonite, calcite, magnesite, huntite, malachite and dolomite; sulfates such as barite and gypsum; hydroxides such as geothite, gibbsite, manganite, boehmite, diaspore and $Fe(OH)_3$; oxides such as hematite, maghemite, magnetite, nsutite, pyrolusite and bixbyite; aluminosilicates such as chlorite, kaolinite, K-mica, leonardite, montmorillonite and phlogopite; silicates such as tremolite, talc and chrysolite along with FCO_3 apatite, fluorapatite, hydroxyapatite and fluorite are inferred to be predominant compositions to be precipitated in the membranes during winter. The increase in saturations are observed in huntite, dolomite, anhydrite, tenorite, pyrophyllite, chlorite, chrysolite and talc are also to be expected during summer as salts in membranes for the solution composition considered. The study reveals the fact that predominantly the dissolution capacities of the feed water have increased during summer resulting in reduced pH and lesser ionic strength under ideal conditions.

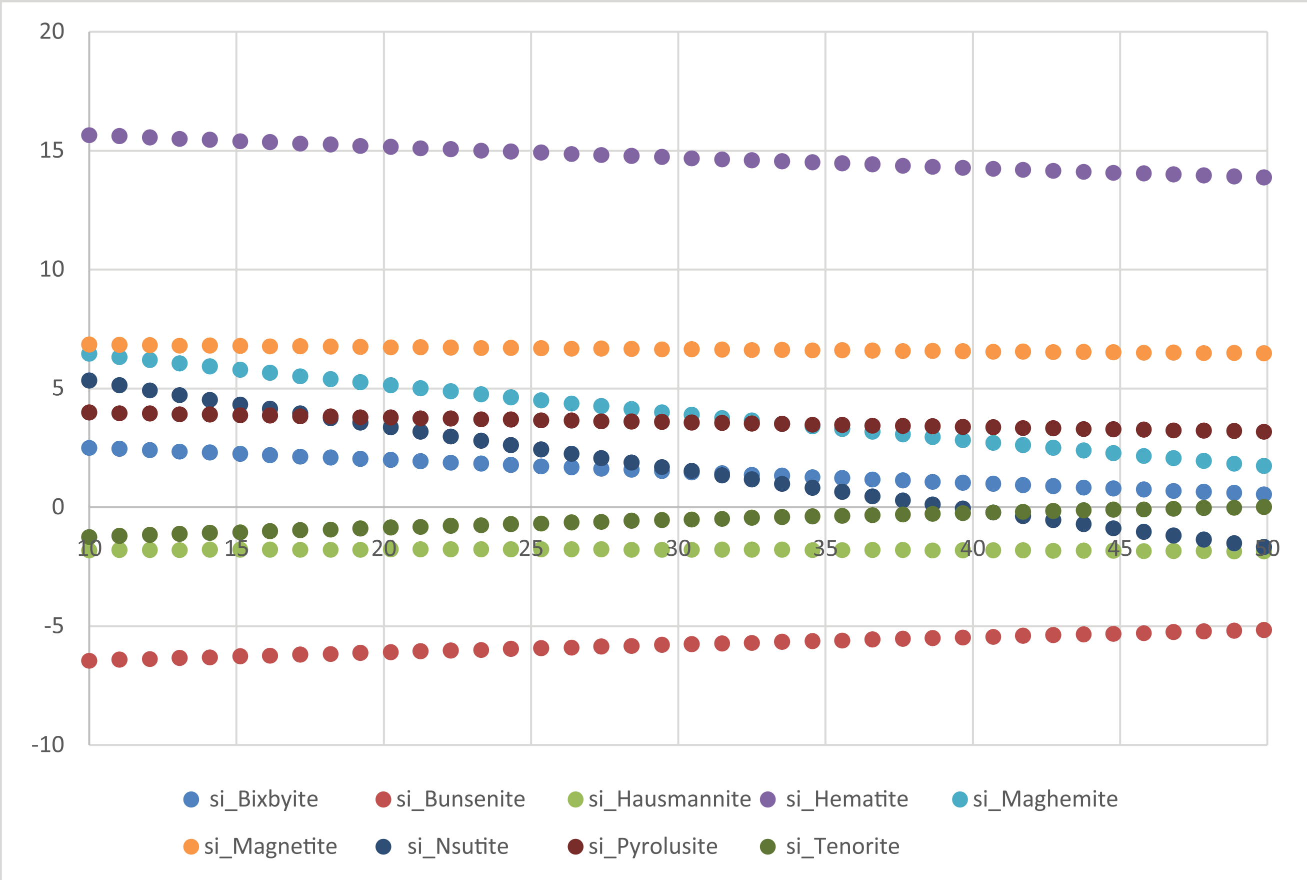

Fig. 5. Variation of the saturation states of oxide minerals with respect to temperature in °C.

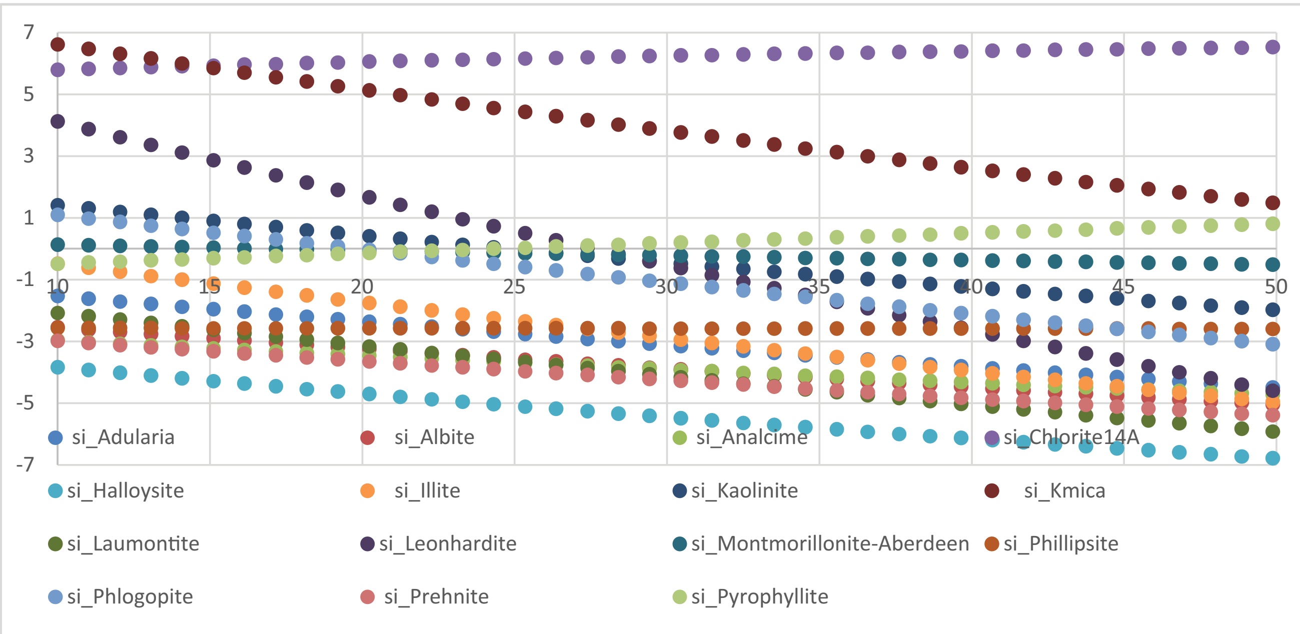

Fig. 6. Variation of the saturation states of aluminosilicate minerals with respect to temperature in °C.

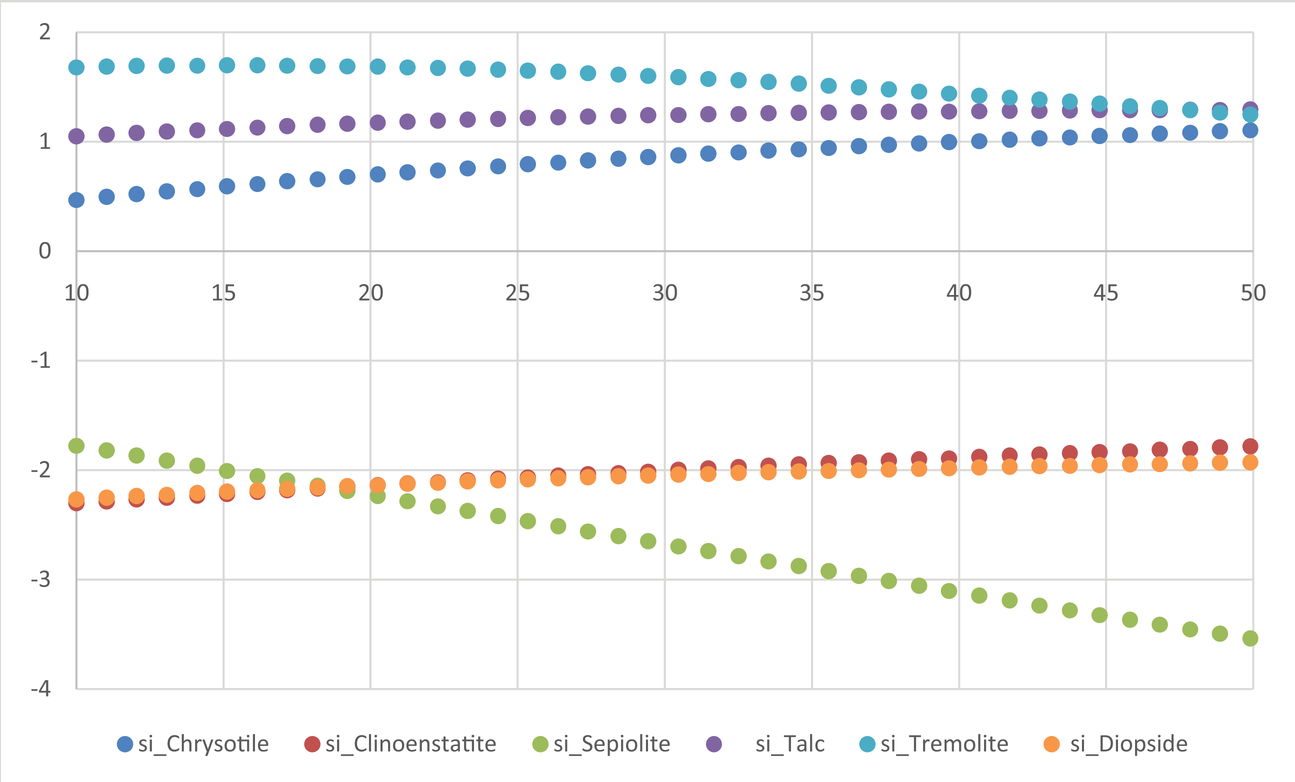

Fig. 7. Variation of the saturation states of silicate mineral minerals with respect to temperature in °C.

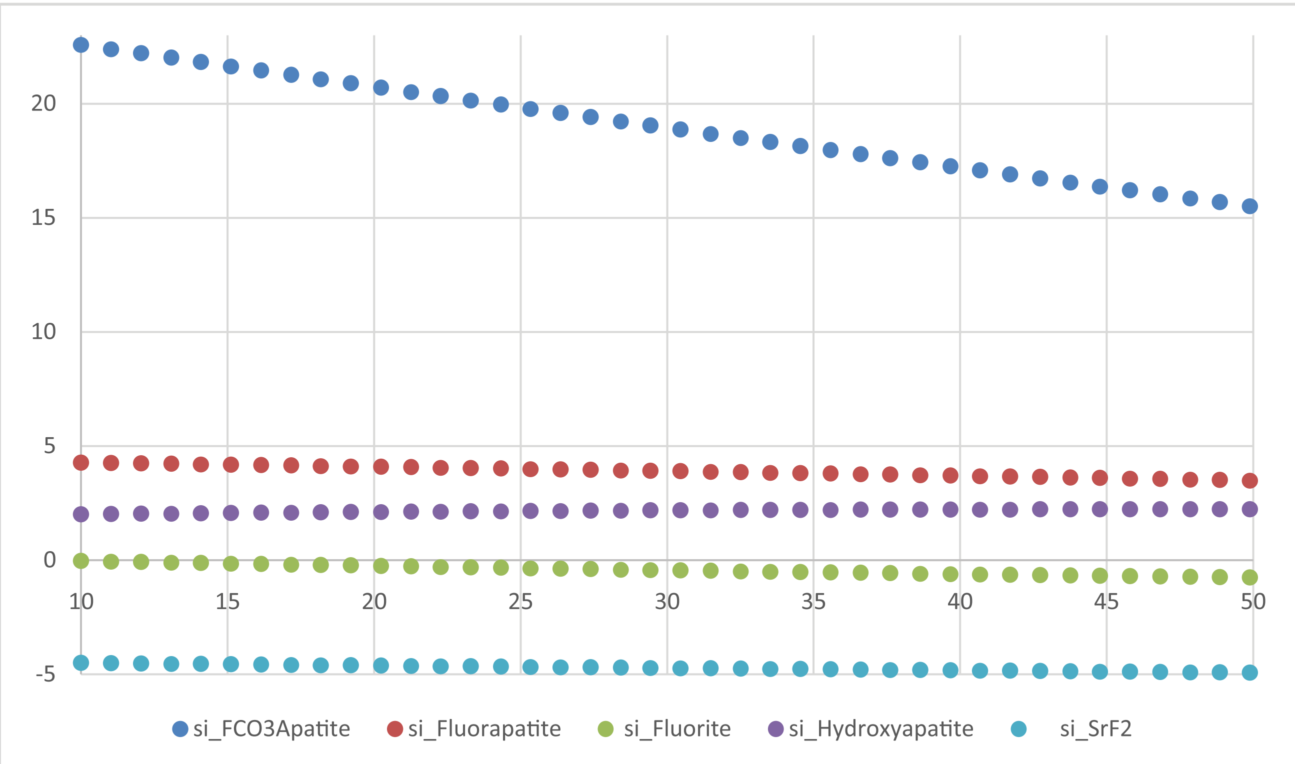

Fig. 8. Variation of the saturation states of fluoride minerals with respect to temperature in °C.

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Extraction of valuable minerals from reverse osmosis brine in Kuwait

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ABSTRACT

The availability of freshwater on earth is very less and a noticeable worry about the shortage of freshwater has emerged during the last decade especially in the Middle East and North Africa (MENA) countries. Most of the freshwater demands are provided by the desalination of seawater both thermal or membrane desalination technologies and desalination plants produce huge volumes of concentrated brine which are discharged back to the sea. This brine contains greater concentration of commercially valuable minerals than that in seawater. The literatures reported that the current disposal options have a number of severe limitations that are associated with technical challenges and environmental issues. As such, research studies have remarkably carried out into the development of mineral extraction processes with aim of producing valuable minerals from desalination brine. Therefore, this paper will review the appraisal of extraction of valuable minerals from Kuwait seawater desalination brine. To achieve this goal, bench-scale experiments were conducted by adopting suitable technologies present in the recent literature. Chemical precipitation method was experimentally implemented at Water Research Center (WRC) of Kuwait Institute for Scientific Research (KISR) with aim of extracting valuable minerals, including magnesium, calcium, boron, sulfate, and strontium, from the rejected brine of the main seawater reverse osmosis desalination units of Desalination Research Plant (DRP) and Shuwaikh Water Distillation Plant (SWDP). The mineral extraction experiments were performed by using sodium hydroxide as base at different processing temperature and pH. The results showed that the amount of extraction of minerals from Doha RO brine was 7.280 g/L. The major extracted mineral magnesium is about 98% and other minerals are lithium 78%, boron 51%, sulfate 18%, calcium 15%, and strontium 14%. For Shuwaikh brine, percentage of extracted minerals are boron 83%, magnesium 78%, lithium 34%, strontium 21%, calcium 18%, and sulfate 11% at 90°C at 10.0 pH. Based on the experimental data and mathematical calculations, the production of magnesium oxide from DRP and Shuwaikh RO plants is around 231 and 97,910 ton per year. The annual benefit from magnesium oxide production using Doha and Shuwaikh brine are 577,500 US$/Y and 244,775,000 US$/Y, respectively.

Keywords: Desalination brine; Chemical precipitation; Solubility; Brine management

1. Introduction

The State of Kuwait is fully dependent on conventional seawater desalination technologies due to the lack of fresh natural water resources. According to the Ministry of Electricity and Water (MEW), Kuwait has produced a total of 164,111 million gallons fresh water in 2017 (in which 146,922 million gallons are potable water and 17,189 million gallons are brackish water) (Statistical Review 2017). A recent study on global seawater desalination indicates that almost 80 × 10^6 m^3/d of desalinated water is produced every day, which leads to production of concentrated brine in the order of 100 × 10^6 m^3 every day (Tedesco et al. 2015). The reject from the desalination plants will be usually 10% to 15% more concentrated than usual seawater (Cipollina et al. 2012). The brine from seawater desalination plants that are installed in the coastal areas are commonly discharged back to the sea. The continuous release of rejected brines

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from desalination plants which is characterized by having a higher salinity and/or temperature than that of feed seawater will increase the seawater salinity level and harm the marine creatures (Latorre 2005; Peters & Pintó 2008). The presence of inorganic compounds and higher salt concentration of the rejected concentrate causes major environmental and regulatory problems for seawater desalination industry (Younos 2005). In addition, the cost of brine disposal varies from 5% to 33% of the total cost of desalination, depending on the amount of brine, the level of treatment before disposal, the nature of the surrounding environment and the disposal method (Glueckstern & Priel 1996). Thus, the reduction in brine volumes will reduce both potable water costs and, at the same time, the environmental impact of the desalination process.

The benefits of concentrate minimization and zero liquid discharge practices are often offset by their high operation and maintenance costs, and energy requirements (Koppol et al. 2004). As a result, the mineral extraction from seawater and brine rejected from the desalination plants attracted researchers all over the world due to the benefits in reducing the environmental effect and desalination cost as well as diversifying the land mining process (Bazedi et al. 2014). The concept of recovering valuable constituents from desalination concentrate was likely first proposed by Dr. John F. Mero in 1964, who claimed that rejected brines from desalination facilities would play a major role in future production of minerals from seawater (Mero 1965). The advantage of seawater mining of minerals is that seawater is homogeneous and there is no mineral grade difference as there is in the land (Loganathan et al. 2017). The developing nations can produce fertilisers containing plant nutrients (K, Mg, Ca, S, and B) from seawater at affordable prices compared with commercial fertilisers available on the market (Loganathan et al. 2017). The economic gains obtained by extracting minerals depend mainly on the concentration of minerals in brine and the market price of these minerals. It has been reported that Na, Ca, Mg, K, Li, Sr, Br, B, and U are potentially attractive for extraction (Loganathan et al. 2017). The minerals that can be recovered from the rejected brines of desalination plants vary depending on the desalination process and the feed water quality. Seawater reverse osmosis (SWRO) plants produce brine with concentration in the range of 65,000–85,000 ppm, whereas thermal desalination plants (MED, MSF) usually discharge a more diluted brine (Cipollina et al. 2012). The recovery of gypsum, sodium chloride, magnesium hydroxide, calcium chloride, calcium carbonate and sodium sulfate has been reported in literatures (Ahmed et al. 2003; Arakel et al. 2004). The main methods of recovery of minerals are solar evaporation, ED, MDC, and adsorption/desorption. Of these, the first three can recover only minerals such as Na, Mg, and Ca which are found at high concentrations (Loganathan et al. 2017).

The higher concentration of commercially valuable minerals in high saline brine discharged from Kuwait desalination plants has prompted us to conduct this research study of the mineral extraction. The study covered the simple chemical precipitation method. A preliminary literature study was conducted to shortlist the available best process for SWRO mining (Attia et al. 2015; Quist-Jensen et al. 2016) and accordingly extraction process is selected in the present article.

2. Materials and methods

All the chemicals and reagents required for the laboratory experiments, calibration and analysis were purchased from Sigma-Aldrich, Merck and used without any further purification. The quantitative and qualitative analysis was carried out using inductively coupled plasma optical emission spectrometry (ICP-OES: Thermo Scientific: iCAP 6000), conductivity meter (ORION STAR A222), spectrophotometer (LANGE DR 2800), and pH meter (ORION STAR A221) in standard analytical conditions. The laboratory scale mineral extraction experiments were conducted in a customized apparatus as shown in Fig. 1.

2.1. Sampling and physicochemical parameters determination

The rejected brine samples were collected from two SWRO desalination plants in Kuwait. The RO desalination units are at Desalination Research Plant (DRP) Doha and Shuwaikh with production capacity of 300 and 136,000 m^3/d, respectively. The total dissolved solids (TDSs) of rejected brine from DRP and Shuwaikh is ≈58,000 and ≈78,000 ppm, respectively. The total recovery of DRP RO plant is ≈40% whereas; of Shuwaikh SWRO plant is ≈50%–60%.

2.2. Mineral extraction method

Extraction of minerals from SWRO brines was conducted using laboratory scale assembly as shown in Fig. 1. Laboratory scale apparatus consists of a magnetic stirrer, pH

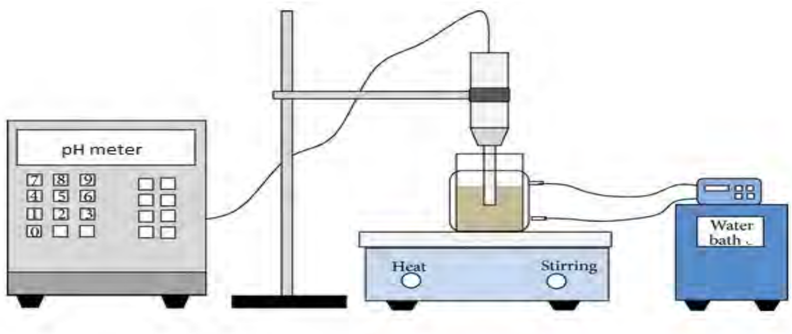

Fig. 1. Schematic diagram of the experimental apparatus assembly used for mineral extraction.

meter, and a glass beaker. One litre of RO brine was taken in a beaker with magnetic bead, and sodium hydroxide powder was added to achieve the required pH. After reaching constant pH, the curdy solution was kept in the oven for 1 h at a constant temperature in a closed vessel and the precipitate (crystal growth) was allowed to settle at room temperature. The precipitated mineral was separated using Buchner funnel under vacuum and dried at 90°C. The filtrate was analyzed to check the extracted minerals in the process. The flow diagram for the extraction method is shown in Fig. 2.

2.3. Standardization of precipitation methods

The mineral extraction capacity of different inorganic bases was studied. For these experiments, calcium hydroxide ($Ca(OH)_2$), sodium hydroxide (NaOH) and ammonium hydroxide (NH_4OH) were selected, and experiments were conducted as follows. A known quantity of (1 L) RO brine was taken in the beaker and powdered base was added to adjust the pH of the solution (pH: 9.0). The solution was stirred for 15 min and pH change was continuously monitored. The curdy solution was kept in the oven for 60 min at 90°C and, then allowed for crystallization at room temperature for 6 h. The precipitate was filtered and dried under vacuum for 10 h. The filtrate was analyzed using standard analytical protocols to verify the remaining minerals in mother liquid.

The amount of mineral extracted and % extraction of each mineral was calculated using the below equations:

$$\text{Amount of mineral extracted}\left(\text{mg/L}\right)=\left(C_i-C_f\right) \quad (1)$$

$$\%\text{ of mineral extracted}=\frac{\left(C_i-C_f\right)}{C_i}\times 100 \quad (2)$$

where

C_i = Initial mineral concentration (mg/L)

C_f = Final mineral concentration (mg/L)

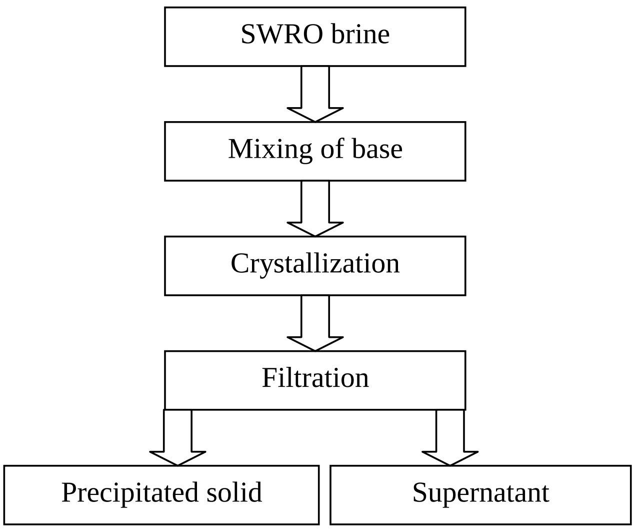

Fig. 2. Flow diagram of mineral extraction from SWRO brine.

The chemical reactions involved in the extraction process for different inorganic base are shown below:

$$\text{RO brine }\left(\text{MX}\right)+\text{Ca}\left(\text{OH}\right)_2\rightarrow\text{MOH, M}\left(\text{OH}\right)_2+\text{CaCl}_2 \quad (3)$$

$$\text{RO brine }\left(\text{MX}\right)+\text{NH}_4\text{OH}\rightarrow\text{MOH, M}\left(\text{OH}\right)_2+\text{NH}_3 \quad (4)$$

$$\text{RO brine }\left(\text{MX}\right)+\text{NaOH}\rightarrow\text{MOH, M}\left(\text{OH}\right)_2+\text{ NaCl} \quad (5)$$

where MX: mineral halide/sulfate.

2.4. Experimental procedure for mineral extraction at different temperature and pH

One litre of SWRO brine was treated with NaOH powder at different pH (8, 8.5, 9, 9.5, and 10). The solution was stirred for 15 min to stabilize the pH of the solution and continuously monitored the change in pH using pH meter. After observing the constant pH, the solution was kept for 1 h at different temperature (50°C, 60°C, 70°C, 80°C, and 90°C) to check the effect of temperature and pH on the mineral extraction. After 1 h, the curdy solution was kept at room temperature for crystallization and crystal growth. The precipitated minerals were filtered using Buchner funnel and solid particles were dried in an oven and filtrate was taken for analysis to check the remaining minerals in filtrate. The experiments were conducted in triplicate and mean values are considered.

3. Results and discussion

3.1. Effect of base on mineral extraction

The mineral extraction capability of $Ca(OH)_2$, NH_4OH, and NaOH were studied at pH 9.0. The result showed the extraction of calcium, magnesium, sulfate, boron, strontium, potassium, lithium, and sodium, and there was no change in halogen concentration.

3.1.1. $Ca(OH)_2$ as base

Fig. 3 shows the extraction percentage of each mineral using $Ca(OH)_2$ as base. The minerals that were extracted more are boron, strontium, magnesium, and sulfate with extraction percentage of 36, 25, 23, and 11, respectively. Other minerals are extracted at an extremely low percentage and a loss of 43% calcium hydroxide was observed in these experiments.

3.1.2. NH_4OH as base

Fig. 4 shows the percentage of extracted mineral using NH_4OH as base. The minerals that were extracted are boron, strontium, magnesium, and potassium with extracting percentages of 41, 12, 6, and 6, respectively. It is important to note that sulfate was not extracted while using NH_4OH as the base. In the case of magnesium, the extraction percentage reduced to 6% from 23% (using $Ca(OH)_2$ base). Compared

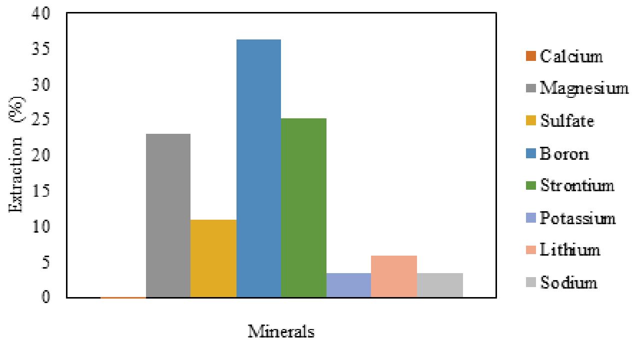

Fig. 3. Percentage of extracted minerals using $Ca(OH)_2$ as base.

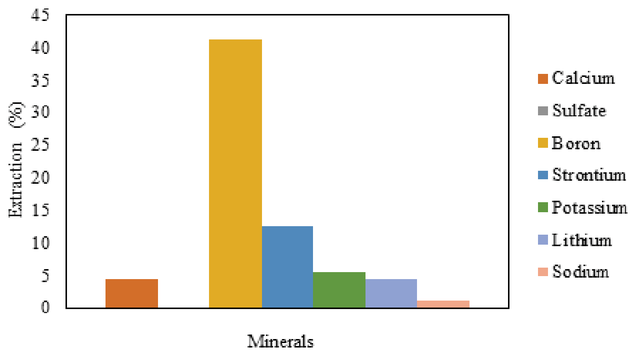

Fig. 4. Percentage of extracted minerals using NH_4OH as base.

with $Ca(OH)_2$ base, extraction percentage of minerals were less with NH_4OH base.

3.1.3. NaOH as base

The percentage mineral extracted using NaOH as base are presented in Fig. 5. The minerals that were extracted are boron, lithium, strontium, and magnesium with percentages of 40, 38, 23, and 20, respectively. The extraction process using NaOH as base was faster compared with $Ca(OH)_2$ and NH_4OH, and this is mainly due to faster reaction (conversion of chloride to hydroxide) and faster crystal growth of minerals in presence of NaOH. Based on the above experimental results, the amount and percentage of extracted minerals are more using NaOH as base compared with $Ca(OH)_2$ and NH_4OH. Therefore, all further experiments were conducted using sodium hydroxide as base with different pH and temperatures.

3.2. Effect of pH and temperature on mineral extraction (DRP SWRO brine)

3.2.1. Extraction of minerals at 90°C and at different pH

The effect of pH and temperature on mineral extraction was studied using NaOH as base. The experiment was carried out at 90°C and different pH ranging from 8.0 to 10. The precipitation of minerals started at pH 9.0 and no visible precipitation was observed at pH below 9.0. The filtrate analysis showed an increasing trend of mineral extraction percentage with an increase in pH as shown in Fig. 6. It is

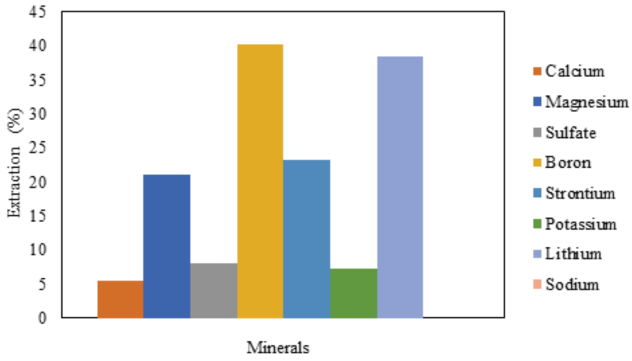

Fig. 5. Percentage of extracted minerals using NaOH as base.

observed from Fig. 6 that the major minerals extracted at 90°C and pH 10 are magnesium, sulfate, and calcium at concentration of 1,651; 700; and 168.8 mg/L, respectively. As shown in Fig. 7, approximately 98% of magnesium was extracted at 90°C and pH 10.

3.2.2. Extraction of minerals at 80°C and at different pH

The mineral extraction experiment was carried out at 80°C and different pH ranging from 8.0 to 10. At 80°C there was an increase in mineral extraction percentage with the increase in pH, but the rate of increase was less when compared with 90°C. At 80°C, there was a drastic change in the quantity of magnesium extracted when the pH was changed from 9.5 to 10 (41.5 to 750.8 mg/L) as shown in Fig. 8. The extracted minerals at 80°C and pH 10 are boron, lithium, magnesium, calcium, and sulfate with extraction percentage of 73, 66, 44, 13, and 8, respectively as shown in Fig. 9. It is observed that sulfate extraction percentage was almost the same and not affected much by the change in pH from 9 to 10.

3.2.3. Extraction of minerals at 70°C and at different pH

The extracted minerals at 70°C and pH 10 are boron, magnesium, strontium, and calcium with the percentage of 71, 70, 15, and 10, respectively (Fig. 10). A constant amount of calcium was extracted at pH 9.5 to 10 (116–120 mg/L) and a drastic increase in extraction ratio was observed for magnesium (from 34 to 1,193 g/L). Fig. 11 clearly shows that magnesium was the major extracted mineral at 70°C and pH 10.

3.2.4. Extraction of minerals at 60°C and at different pH

The mineral extraction at 60°C shows a high percentage of lithium extraction at pH 8.0. This may be due to the high reactivity and small size of the lithium ion. Other major extracted minerals at 60°C and pH 10 are boron and magnesium with extraction percentage of 77 and 48, respectively. Fig. 12 clearly shows the decrease in the amount of sulfate extracted with increasing pH from 8 to 10. But, the percentage of extraction of sulfate is extremely low compared with lithium, boron, and magnesium for all pH at 60°C as shown in Fig. 13.

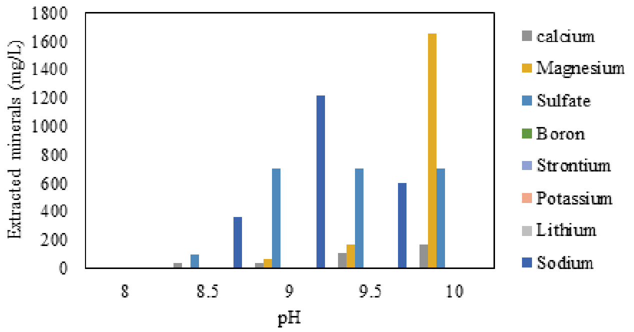

Fig. 6. Concentration of minerals extracted at different pH at 90°C.

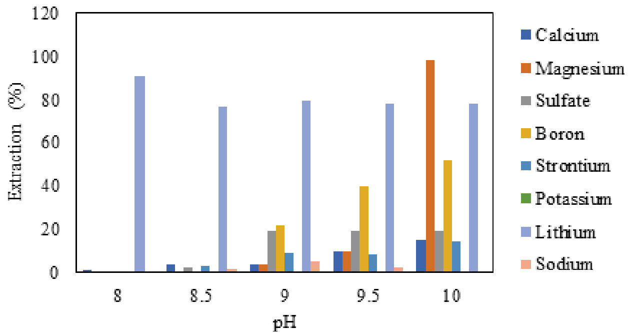

Fig. 7. Percentage of minerals extracted at 90°C.

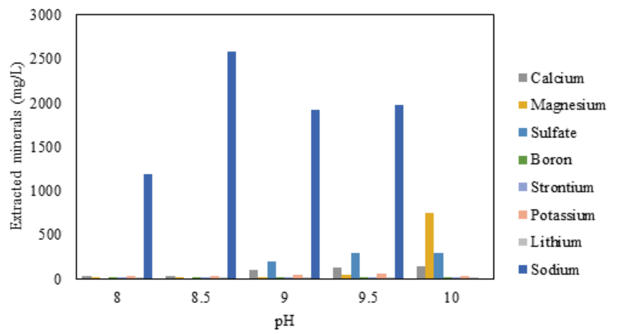

Fig. 8. Concentration of minerals extracted at different pH at 80°C.

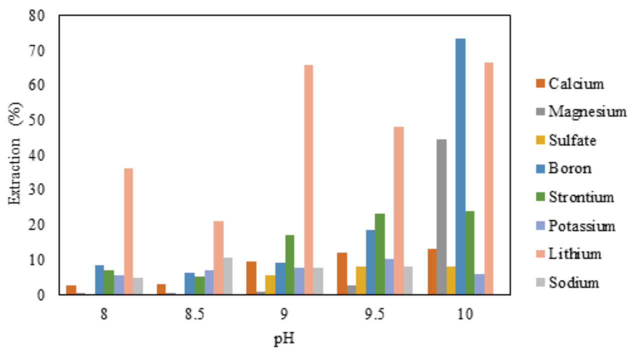

Fig. 9. Percentage of minerals extracted at 80°C.

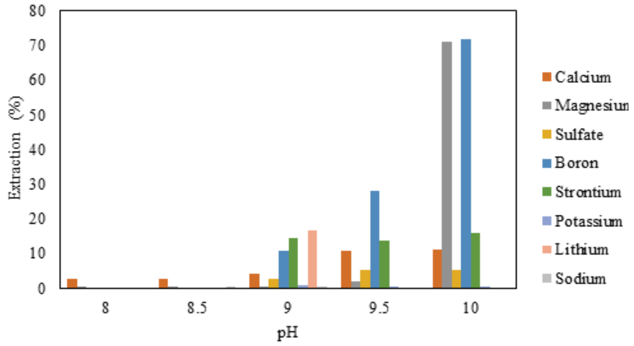

Fig. 10. Percentage of minerals extracted at 70°C.

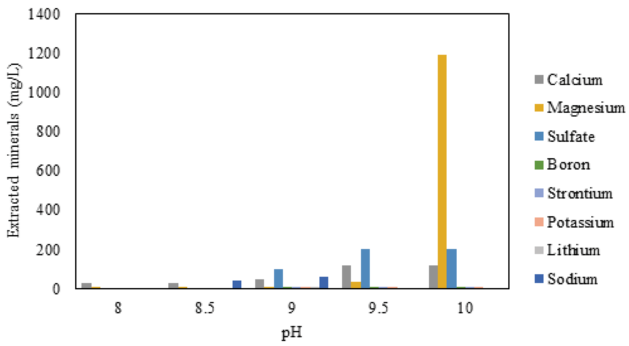

Fig. 11. Concentration of minerals extracted at different pH at 70°C.

3.2.5. Extraction of minerals at 50°C and at different pH

At 50°C there was an increase in mineral extraction percentage with increase in pH, but the rate of increase was very less when compared with 90°C. At 50°C, there was a drastic change in the amount of magnesium extracted when the pH was changed from 9.5 to 10 (38 to 1,095 mg/L). It was observed from Fig. 14 that at pH 10 the major extracted minerals are magnesium and boron with extraction percentage of 73 and 65, respectively. Fig. 15 clearly shows that the amount of magnesium extracted at pH 10 was very high compared with sulfate, boron, lithium, etc. It is important to note that magnesium extracted at pH 10 was the best condition to isolate pure magnesium from the DRP SWRO brine compared with higher temperature.

3.3. Effect of pH and temperature on mineral extraction (Shuwaikh SWRO brine)

3.3.1. Extraction of minerals at 90°C and at different pH

The effect of pH and temperature on mineral extraction for Shuwaikh SWRO brine was studied using NaOH as base. The experiment was carried out at 90°C and different pH ranging from 8.0 to 10. There was no visible precipitation was observed at pH below 9.0. The filtrate analysis showed that there is an increase in the percentage of minerals extraction with an increase in pH as shown in Fig. 16. The amount of sodium hydroxide consumed for extracting minerals from Shuwaikh SWRO brine was almost double

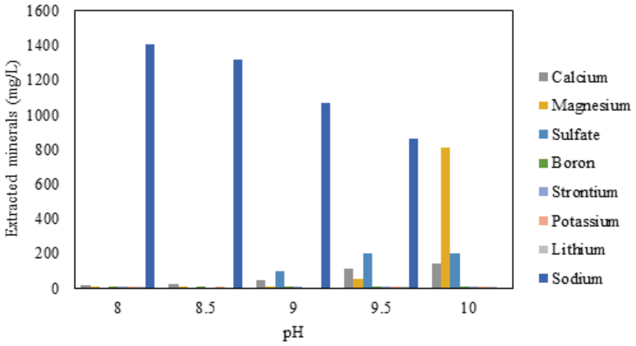

Fig. 12. Concentration of minerals extracted at different pH at 60°C.

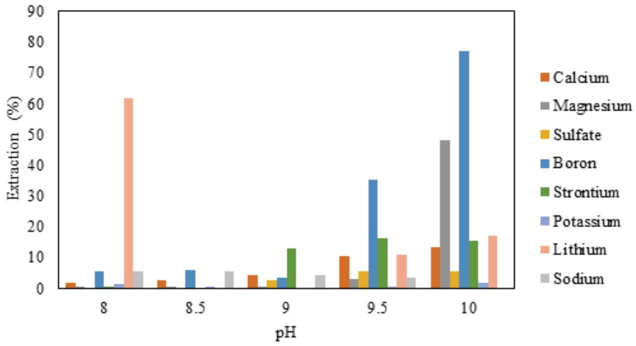

Fig. 13. Percentage of minerals extracted at 60°C.

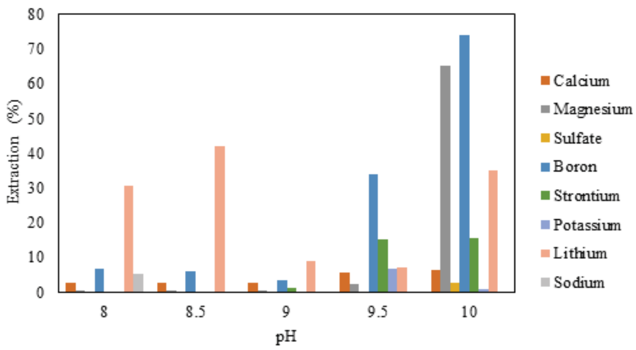

Fig. 14. Percentage of minerals extracted at 50°C.

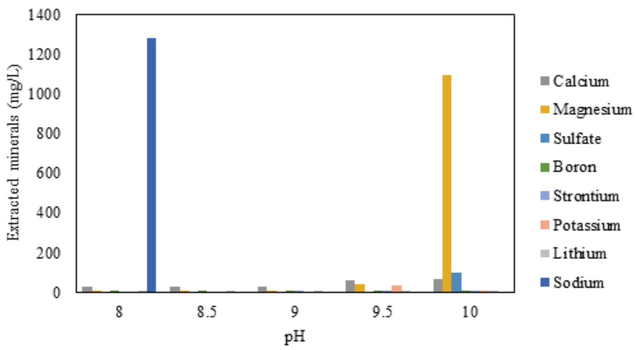

Fig. 15. Concentration of minerals extracted at different pH at 50°C.

than the amount used for extracting minerals from DRP SWRO brine. This consumption is mainly due to more concentration of convertible (mineral chlorides) minerals in Shuwaikh SWRO brine. The major extracted minerals are calcium (164 mg/L), magnesium (2,157 mg/L) and sulfate (600 mg/L). More than 80% of boron and 78% of magnesium was extracted by using sodium hydroxide as base at 10.0 pH. The extracted mineral concentrations and percentage of extractions are shown in Figs. 15 and 17.

3.3.2. Extraction of minerals at 80°C and at different pH

The amount of minerals extracted at 80°C is slightly less than the total mineral extracted at 90°C. At 80°C with pH 9.5 to 10.0, a drastic increase in magnesium and boron extraction was observed. The concentration of magnesium extracted was only 12 mg/L at pH 9, but at pH 10 it was 2,060 mg/L. The major minerals extracted from these experiments are calcium (165 mg/L), magnesium (2,060 mg/L), sulfate (500 mg/L), and boron (6 mg/L). The graphical representations are shown in Figs. 18 and 19.

3.3.3. Extraction of minerals at 70°C and at different pH

The extraction of mineral at 70°C shows that there is a reduction in the total amount of minerals extracted. The major extracted mineral was boron and is about 82%. The other extracted minerals are magnesium (67%), lithium (67%), calcium (13%), and sulfate (7%). Figs. 20 and 21

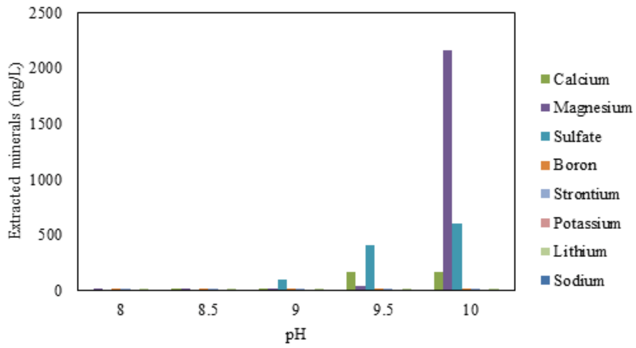

Fig. 16. Concentration of minerals extracted at different pH at 90°C.

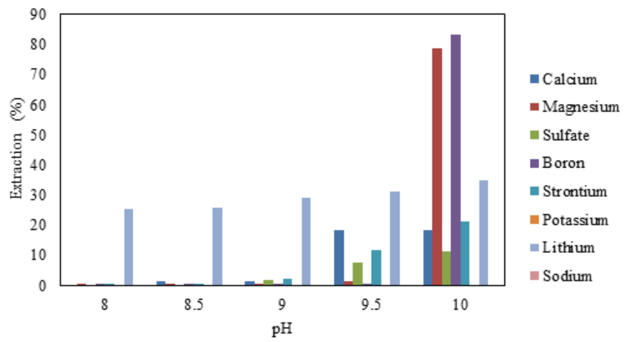

Fig. 17. Percentage of minerals extracted at 90°C.

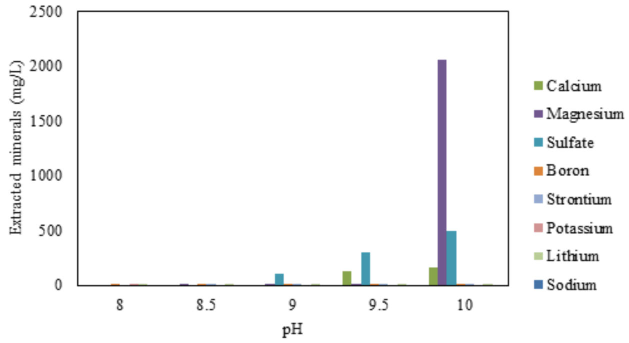

Fig. 18. Concentration of minerals extracted at different pH at 80°C.

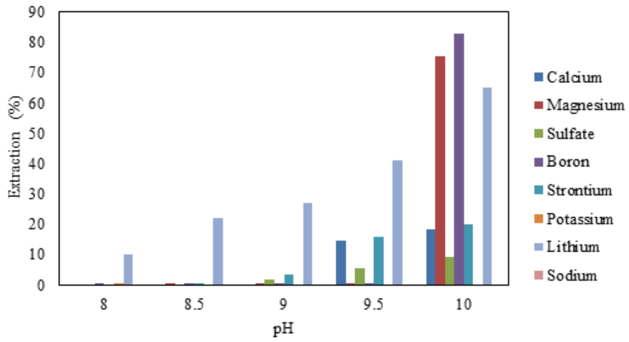

Fig. 19. Percentage of minerals extracted at 80°C.

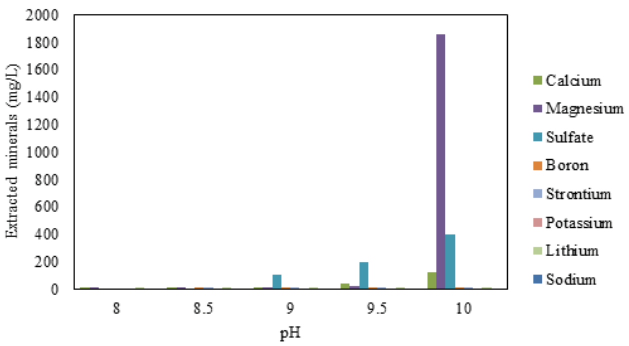

Fig. 20. Concentration of minerals extracted at different pH at 70°C.

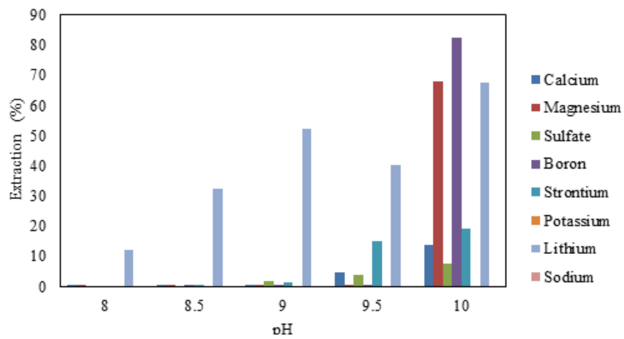

Fig. 21. Percentage of minerals extracted at 70°C.

clearly shows that the mineral extracted at 70°C was less than the mineral extracted at 90°C. The extracted minerals are magnesium (1,856 mg/L), sulfate (400 mg/L), calcium (124 mg/L), and boron (6.0 mg/L).

3.3.4. Extraction of minerals at 60°C and at different pH

The mineral extraction at 60°C shows that a high percentage of magnesium extraction at pH 10.0 the percentage of magnesium extracted was about 90%. Other major minerals extracted at 60°C are calcium, sulfate, boron, and strontium at concentrations of 112, 300, 5.89, and 1.7 mg/L, respectively. In these experiments, most of the divalent cations extracted faster than the monovalent ions. The amount and percentage of extracted minerals are shown in Figs. 22 and 23.

3.3.5. Extraction of minerals at 50°C and at different pH

At 50°C the amount of mineral extracted was considerably lesser than the amount of mineral extracted at higher temperatures. It was observed that very less concentration of minerals extracted below pH 10.0. The major extracted minerals at 50°C and pH 10.0 are magnesium and boron at 82% and 67%, respectively. From Figs. 24 and 25, it is evident that magnesium can be extracted in good percentages even at lower temperatures by increasing the pH to 10.

3.4. Preliminary economic evaluation of magnesium oxide production using SWRO brines

The laboratory scale mineral extraction experiments showed that magnesium was extracted in more quantity from SWRO brines. The SWRO brine of Kuwait contains higher concentration of magnesium compared with other minerals and the by-product of magnesium (MgO, $MgCl_2$, etc.) are widely used in constructions and chemical industries and have high commercial values. Therefore, the preliminary economic evaluation of magnesium oxide production using Kuwait SWRO brines was performed.

DRP SWRO plant capacity is about 300 m³/d and TDS in brine is approximately 54,900 ppm. The amount of magnesium present in DRP SWRO brine is 1,673 mg/L. The recovery ratio is about 25%–30% and quantity of the rejected brine is approximately 210 m³/d. From the above data, it was calculated that 351.33 kg of magnesium is present in DRP SWRO brine per day.

Accordingly, the amount of magnesium present in the rejected brine from DRP SWRO plant calculated is approximately 141 ton/year. Based on the results obtained in this study and assuming that 98% of magnesium can be extracted using NaOH as base at 90°C and pH 10, then the amount of magnesium that can be produced per year is ≈ 138 ton/year.

The molar mass of Mg is 24.3050 g/mol, whereas, molar mass of MgO is 40.3044 g/mol. So, theoretically, 1 g of magnesium can produce 1.658 g of magnesium oxide. Accordingly, the total amount of magnesium oxide (MgO) that can be produced per year from DRP SWRO brine is 228 ton/year. Considering the market price of MgO at 2,500 USD per ton, the annual benefit that can be achieved by extracting MgO from DRP SWRO brine is 572,010 USD per year.

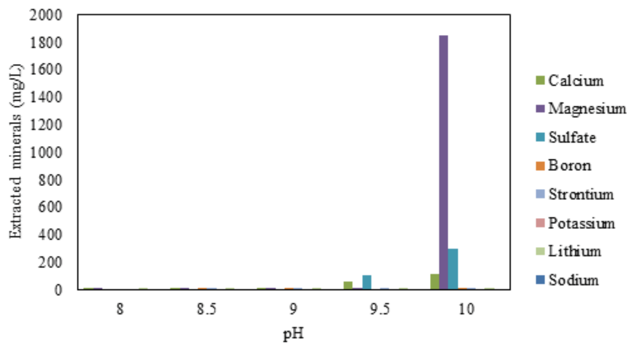

Fig. 22. Concentration of minerals extracted at different pH at 60°C.

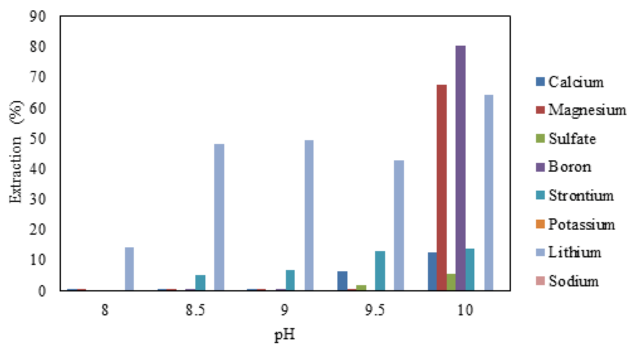

Fig. 23. Percentage of minerals extracted at 60°C.

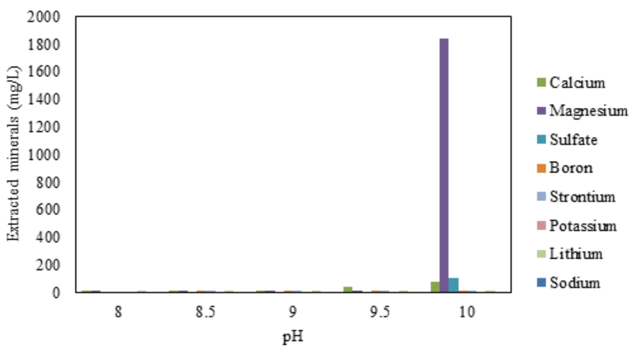

Fig. 24. Concentration of minerals extracted at different pH at 50°C.

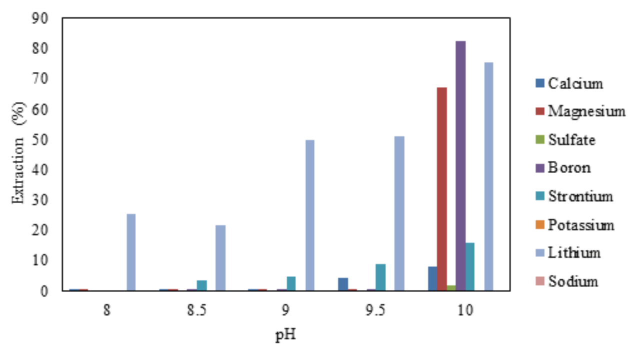

Fig. 25. Percentage of minerals extracted at 50°C.

Shuwaikh SWRO plant capacity is about 136,000 m^3/d (30 MIGD) and TDS in brine is approximately 78,000 ppm. The amount of magnesium present in Shuwaikh SWRO brine is 2,703 mg/L. The recovery ratio is about 50%–60% and quantity of the rejected brine is approximately 68,000 m^3/d. From the above data, it was calculated that 183,804 kg of magnesium is present in Shuwaikh SWRO brine per day.

Accordingly, the amount of magnesium present in the rejected brine from Shuwaikh SWRO plant calculated is approximately 73,967 ton/year. Based on the results obtained in this study and assuming that 78% of magnesium can be extracted using NaOH as base at 90°C and pH 10, then the amount of magnesium that can be produced per year is ≈59,053 ton/year.

Accordingly, the total amount of magnesium oxide (MgO) that can be produced per year from Shuwaikh SWRO brine is 97,909 ton/year. Considering the market price of MgO at 2,500 USD per ton, the annual benefit that can be achieved by extracting MgO from Shuwaikh SWRO brine is 244,772, 500 USD per year.

4. Conclusion

The mineral extraction from actual SWRO brines was conducted using chemical precipitation process. In the process, mineral extraction capability of three different inorganic bases was studied. The study proved that NaOH is the best suitable base for extracting minerals from Kuwait SWRO brine. In addition, the effect of basicity and temperature was conducted for DRP and Shuwaikh SWRO brine at standardized conditions for maximum mineral extraction. The mineral extraction results showed that there is a change in total concentration of extracted mineral with an increase in temperature from 50°C to 90°C as well as with the increase of pH from 8.0 to 10.0. The extracted minerals are magnesium, lithium, boron, sulfate, calcium, and strontium. The experimental results showed that the precipitation or extraction of minerals started only at pH above 9.0 and decrease of temperature reduced the total extracted mineral concentration. The preliminary calculation showed that approximately 228 and 97,909 ton/year of magnesium oxide can be produced from DRP and Shuwaikh SWRO brine, respectively. Accordingly, the annual benefit from the produced magnesium oxide is 572,010 and 244,772,500 USD per year from DRP and Shuwaikh SWRO brine, respectively. Therefore, the integration of mineral extraction plants to seawater desalination plants reduces brine disposal problem, and the economic return from mineral extraction will benefit in reduction of overall water production cost.

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A comparative study of two different forward osmosis membranes tested using pilot-plant system for Arabian gulf seawater desalination

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ABSTRACT

A pilot-scale forward osmosis (FO) desalination system of capacity 10 m^3/d was successfully established at Doha desalination research plant (DRP) of Kuwait Institute for Scientific Research (KISR), during October, 2016. The pilot-plant system has access to evaluate the performance of different FO membranes developed by world leading manufacturers and also the efficiency of different draw solutions (DS). The current study was aimed at evaluating the performance of two different hollow fiber FO membranes with different bore diameters of 135 and 230 μm, respectively. The DS consisted of high osmotic polyelectrolyte thermoresponsive polymer; whereas the feed solution (FS) was Arabian Gulf seawater supplied from the beach well of DRP, to demonstrate the direct application of pilot-plant FO system for desalination application. The FS was passed through the bore side and polymer DS was passed through the shell side of the membrane. The DS which was diluted due to the water permeated through the membrane as a result osmotic pressure difference was sent to the coalescer at 85°C, where the diluted polymer DS was separated into supernatant water and concentrated polymer DS. The membrane performance was evaluated in terms of FO flux, salt rejection and water recovery. The membrane with 230 μm has observed highest performance during FO operation with water recovery of around 30% and by reducing the total dissolved solids from 40,000 to 130 ppm. The high performance associated with 230 μm membrane is attributed to the more diffusion of the highly concentrated DS towards membrane lumen side. Such diffusion resulted in high osmotic pressure difference which is considered as the driving force across the membrane. Additionally, less pressure-drop experienced by the 230 μm membrane between its bore side and outer shell side could be the reason for its high-water recovery. The results of this study demonstrated the potential of using FO membrane with larger bore diameter with controlled flow rate to attain high performance in the thermal-based FO seawater desalination.

Keywords: Forward osmosis; Polymer draw solution; Hollow fiber membrane; Bore diameter; Arabian Gulf seawater desalination

1. Introduction

The State of Kuwait depends on the Arabian Gulf seawater (AGS) as a main source to produce freshwater through conventional desalination processes. Multi-stage flash distillation (MSF) and reverse osmosis (RO) desalination technologies are currently being utilized in the existing desalination plants of the Ministry of Electricity and Water (MEW) of Kuwait. MSF desalination plants continue to dominate due to their proven high operational reliability and the convenience of their integration with existing power plants (Ettouney and Wilf 2009). The proportion of desalination capacity supplied by RO is increasing due to its better economics when compared with MSF process. However, in general, these processes are prohibitively expensive and energy intensive. Additionally, these technologies provide low water recovery and discharge high levels of brine to the environment (Ahmad 2012). Furthermore, these systems are sensitive to the corrosion and scaling problems as well as fouling (Ge et al. 2013, Stone et al. 2013 and Mulder 1996). Therefore, focus on commercializing non-conventional desalination technologies developed by recent researches and developments in seawater desalination technologies is substantially needed to eliminate the limitations of MSF and RO technologies.

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The research studies shows that the forward osmosis (FO) membrane process has high potential for seawater desalination applications and can be one of the sustainable solutions for seawater desalination in near future (Wang et al. 2015 and Cath 2010). The absence of high pressure pumps in FO can lower energy consumption in seawater desalination process compared with RO (Hartanto et al. 2016). FO is driven by the osmotic pressure gradient between two solutions and eliminates the requirement for high hydraulic pressure. In FO process, water naturally infuses through a semipermeable membrane from the feed solution at a lower osmotic pressure to the draw solution at a higher osmotic pressure. A regeneration process removes water from the diluted draw solution and re-concentrates the draw solution for reuse.

The advantages of FO over conventional RO such as 20% and 30% less energy requirement, less brine discharge to the surrounding environment, low fouling potential and high physical cleaning efficiency, and higher boron rejection has been reported in literatures (Hartanto et al. 2016, Cath et al. 2006, McGinnis and Elimelech 2007, Mi and Elimelech 2010, Husnain et al. 2015 and Nicoll 2013). In spite of these advantages of FO process in seawater desalination applications, the FO process has not yet reached commercial level applications. The key fact that limits the extensive use of the FO desalination process is the development of a viable draw solution (DS) and DS recovery system that is possibly capable of continuously and constantly producing high osmotic pressure vital for keeping the water flux at desired levels in the FO process, and at the same time to produce high-quality water with total rejection of DS residue in the final product water (Coday et al. 2014). Thus, the establishment of effective DS and DS regeneration system with energy-saving still remains as a major challenge for FO seawater desalination applications (Linares et al. 2014, Lutchmiah et al. 2014 and Lou et al. 2014). Hence, a breakthrough in FO technology is necessary to solve the aforementioned limitations by focusing on areas, such as FO membrane development, exploration of an innovative DS and DS recovery system, in order to compete with the existing technologies.

The researchers worldwide are still conducting researches in developing ideal DS and DS recovery system for desalinating high saline water with low water production cost. The three main requirements that are considered to be ideal for DS are, namely, higher osmotic pressure for high water flux, simple and low-cost regeneration, and least possible reverse solute flux (Ge et al. 2013 and Chekli et al. 2012). Conventional inorganic DS that generates high water flux has higher reverse solute flux due to its small molecular size (McCutcheon et al. 2005 and Achilli et al. 2010). As a result, polymers with relatively high molecular weight have been examined as FO draw solutes and observed that it reduces reverse flux and can be regenerated using ultrafiltration and membrane distillation (Ge et al. 2012). Draw solutes based on thermoresponsive compounds have attracted FO developers due to their unique response to temperature (Ling et al. 2011, Noh et al. 2012 and Han et al. 2013). Trevi Systems Inc. (TSI) have developed thermoresponsive polymer DS and subsequent thermal DS recovery system for seawater desalination application. Thermally responsive draw solutes are attracting researchers due to its simplicity, the absence of using extra chemicals and, most of all, the possibility of using less expensive and clean energy sources such as solar thermal energy and low-grade industrial waste heat (Cai et al. 2015). The thermo-responsive draw solutes are generally lower critical solution temperature (LCST) materials. The LCST materials are miscible with water at higher concentrations at temperatures below the phase transition temperature and can withdraw water from feed solutions (Nakayama et al. 2014). The diluted LCST materials exhibits liquid–liquid (L–L) phase separation from water at a temperature higher than the phase transition temperature. The phase transition temperature of LCST materials can be reduced by altering the chemical structure. Thus, the energy requirement for the separation of draw solutes can be greatly reduced by using a LCST material with a low-phase transition temperature (Kim et al. 2011).

TSI has developed a FO pilot-plant hybridised with thermal separation system (FO-TS) for seawater desalination using the thermos-responsive polymer. The energy requirement of the FO-TS system is 87.5% less than the conventional RO by using solar energy or waste heat (Carmignani et al. 2012). Compared with FO-RO hybrid system, FO-TS technology is insensitive to the osmotic pressure as it can be operated with higher DS concentrations. However, a post-treatment system using conventional membrane processes, such as nano-filtration (NF) or brackish water (BW) RO membrane may still be required to polish the final product water. Pilot-level studies on thermally responsive organic compounds are greatly required as there is no significant information and data on the viability and efficiency of the aforementioned FO technology for seawater desalination (Cai and Hu 2016). Furthermore, testing and analysis of a full-scale FO module on a pilot scale is essential to design a commercial-scale FO pilot plant (Kim and Park 2011). The performance of large-scale commercialized spiral-wound FO membranes has been reported (Lutchmiah et al. 2014 and Kim and Park 2011),whereas limited studies have been reported for FO HF (Shibuya et al. 2016).

The FO technology has not been investigated in the State of Kuwait for seawater desalination applications. Accordingly, Kuwait Institute for Scientific Research (KISR) in collaboration with international FO developers are conducting studies on FO technology at laboratory and pilot-scale levels to take lead in the development and innovation in this area of research. These studies are vital to investigate the FO system for desalinating the AGS under the prevailing conditions of Kuwait for a better understanding and filling the existing gaps of know-how in recovering DS and product water from the diluted DS of the FO system at a reasonable cost and reliability with less harm to the environment. Therefore, this paper will provide the initial findings of ongoing pilot-scale study conducted by KISR on FO technology for seawater desalination application using commercially available hollow fiber (HF) FO membranes and thermoresponsive polymer DS developed by TOYOBO Co., Ltd. and TSI, respectively. The study is on-going and shows the primary results.

2. Materials and methods

2.1. Pilot-scale test unit

The FO pilot-plant test unit with a capacity of 10 m^3/d was constructed by Trevi Systems Inc., USA, for desalinating

AGS as shown in Plate 1. This pilot plant utilizes the integration of thermal and membrane separation system comprising of coalescer and NF membrane processes for DS regeneration.

2.2. Materials used in pilot-scale investigations

The Trevi System's FO pilot plant is designed for continuous operation. The FO pilot-plant is a hybrid unit of four processes: (1) pre-treatment system and anti-scalant dosing, (2) FO process, (3) polymer draw solution regeneration process, and (4) the post treatment system. The pre-treatment side consists of feed pump, cartridge filters, anti-scalant dosing, pH sensors, temperature sensors and conductivity recorders. The FO part consists of DS pump, various valves and sensors and the FO membrane module. The draw solution regeneration part consists of three heat exchangers, stainless steel coalescer, heater loop, and various sensors and automated valves. The post-treatment system comprises of supernatant pump, nano filters, product water polishing tanks, and assorted automated valves and sensors. The membrane used was recently developed commercial 10-inch HF FO membrane from TOYOBO, Japan. The HF membranes are made of cellulose triacetate and are available at bore diameter of 230 and 135 micron. The HF FO membranes had an outer active layer surface. The HF FO module configuration is similar to HF RO and has four ports; FS inlet, FS outlet, DS inlet and DS outlet. The cross-wound HF FO membranes have high packing density and preferable flow pattern compared with other module configurations (Shibuya et al. 2016). The schematic illustration of the tested HF FO module with cross-wound configuration is shown in Fig. 1 (Shibuya et al. 2016). The FO HF membranes tested are 135 and 230 micron membranes. The thickness of 135 micron HF membrane is 100 µm, whereas, for 230 micron HF membrane is 140 µm. The number of HF in the 135 membrane module is around 500,000 whereas in 230 micron membrane is around 220,000. The large number of HF membranes results in a higher total effective membrane area. The packing density was approximately 50% around a central core tube from which the polymer DS was supplied. The polymer draw solution used was ethylene oxide-propylene oxide copolymer (TL-1150-1) patented by Trevi systems Inc. and the coalescer temperature was set at 85°C. The cloud point temperature of the DS is between 40°C and 90°C. The feed used was AGS obtained from beach well located at DRP in Doha, Kuwait.

2.3. Experimental procedure used in pilot-scale investigations

The AGS obtained from beach well is passed to the bore side of the FO membrane at pressure less than 2 bars. The direction of the feed flow was in axial direction. The DS which is heated to 85°C is passed to the DS heat exchanger and cooled to temperatures lower than 40°C. The DS is then passed to the shell side of the FO membrane through the centre core. The direction of the DS flow was in radial direction between HF tubes. As the FS and concentrated DS flows through the bore side and shell side of the semi-permeable membrane, respectively, due to the osmotic pressure gradient, pure water is drawn through the membrane from the FS into the DS. Thus the DS is infused with and diluted by the pure water that has left the FS. The diluted DS is then fed to the DS recovery systems consisting of coalescer and heat exchangers which are set at temperatures higher than the phase separation temperature of the DS. As a result, the diluted DS is separated into supernatant water and concentrated DS. The concentrated DS is again circulated back to the FO membrane system for further water production and the process continues. The supernatant water is then passed through the post treatment system and heat exchangers and final product water is produced. The flow rates, conductivity, pressure, and temperature of all streams were recorded using a data logging system. In order to assess the efficiency of the innovative HF FO membrane and thermos-responsive polymer for AGS desalination at pilot-scale level, and to check the

Plate. 1. FO Pilot Plant at Desalination Research Plant (DRP).

stability of FO pilot plant for commercial applications under the prevailing conditions of Kuwait, an operating envelope was prepared.

2.4. Osmotic pressure measurement

The osmotic pressures of the concentrated and diluted DS were measured using a Wescor 5600 vapor pressure osmometer. The osmolality (m in mol/kg) of DS was measured for DS and then, the osmotic pressure was theoretically calculated using the following equation (Money 1989 and Cheng et al. 2013):

$$\pi = m\ \rho RT$$

where π is the osmotic pressure, ρ is the density of water, and R and T are the ideal gas constant and absolute temperature, respectively. The theoretically calculated value is then compared with the osmotic pressure value obtained from the refractive index measurements using Atago PAL-RI meter.

3. Results and discussions

This section will give a brief overview on the data obtained so far on the performance of the FO pilot plant.

The DS flow rate was varied from 8 to 18 liter per minute while maintaining the FS flow rate constant. The DS is dispersed to the shell side of the membrane through a central core tube in the membrane module as shown in Fig. 1. The DS then runs radially through the membrane module and the concentration of the DS will be the maximum at the area near to the centre tube. As it flows radially through the membrane between the HF tubes, it gets dilute due to infusion of water molecules from the feed, and will be of less concentration as it reaches the area far to the centre tube. So, with increasing flow rate of DS it is possible to have less DS concentration gradient radially across the membrane. The lower concentration gradient across the membrane at higher DS flow rates resulted in overall high water flux and product flow rate as shown in Tables 1 and 2.

In addition, the higher DS flow rate might lessen the polymer layer thickness on the membrane surface and thus reduces the concentration polarization effect (Kim and Park 2011, Chakrabortty et al. 2015 and Kim et al. 2014). The effect of DS flow rates upon production capacity and water recovery is not linear and this could be due to the restricted capacity of the DS heat exchanger as well as, the limited split-up capacity of coalescer used in the present system. As the DS flow increases, the lasting time of the polymer in the coalescer is reduced and this will

Table 1
Effect of DS flow rate upon production capacity and water recovery ratio using 230 micron membrane

FS flow rate, LPM	DS flow rate, LPM	Capacity, m^3/d	Recovery ratio %
16.0	8.1	5.5	23.7
	10.1	6.3	28.8
	12.1	7.0	31.2
	14.1	7.2	31.1
	16.1	7.1	29.9
	18.1	6.5	28.9

Table 2
Effect of DS flow rate upon production capacity and water recovery ratio using 135 micron membrane

FS flow rate, LPM	DS flow rate, LPM	Capacity, m^3/d	Recovery ratio %
16.0	8.1	4.6	22.6
	10.1	4.8	27.6
	12.1	4.9	28.5
	14.1	5.2	27.9
	16.1	4.7	26.6
	18.1	4.2	25.8

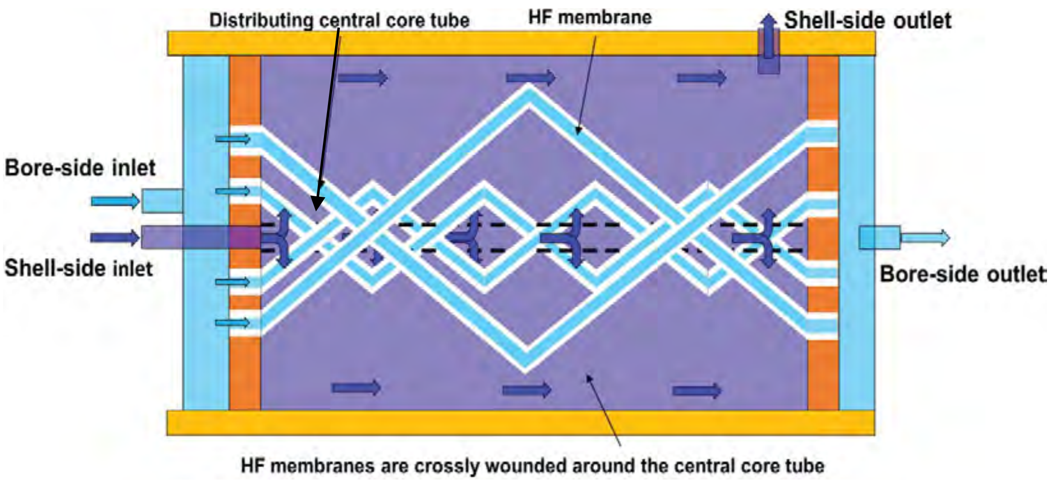

Fig. 1. Schematic of FO HF module with a cross-wound HF configuration.

reduce the rate of separation of polymer into concentrated DS and supernatant water. The non-linear performance in production capacity and water recovery was observed with both 135 and 230 micron membranes. The water recovery was less with 135 micron membranes as compared with 230 micron membrane. The number of HF in the 135 membrane module is higher than in 230 micron membrane. This may slightly reduce the flow of DS into the outermost layers of the module and results in less recovery.

The pilot plant was tested at two FS flow rates, 16 and 14 LPM. Tables 3 and 4 show that higher FS flow rates are suggested to increase the product flow rate. The FS is distributed to the bore side of the membrane and it runs in axial direction as shown in Fig. 1.

As the FS flows through the HF from the inlet to the exit side, the polymer DS pulls water and the FS will get concentrated as it reaches the exit. The DS will be at high concentration nearby the central core tube. Thus, at the FS exit, the FS in the HF tubes near the central core tube will be highly concentrated. There will be a high concentration gradient among the FS inlet and exit in the HF tubes near the central core tube. It is anticipated that as the FS flow rate is increased, the concentration gradient of FS between the inlet and outlet will be less than at lower FS flow rates. The effect of FS flow rate upon production capacity and water recovery is not as evident with the tested 16 and 14 LPM FS flow rates as seen in Tables 3 and 4. The FS flow rate of 12 and 18 LPM will also be tested in forthcoming tests to have more valid data and the results will be reported in a later stage of the project.

Tables 5 and 6 show the preliminary physiochemical analysis of all the three streams of water from the pilot plant, namely, AGS feed, product and brine. The pH, conductivity and total dissolved solids (TDS) were measured by pH, conductivity and TDS meters, respectively. The other parameters

Table 5
Physiochemical analysis of AGS feed, FO product and FO brine using 230 micron membrane

Parameter	Unit	AGS feed	FO product	FO brine
pH		7.5	7.2	7.3
Conductivity	mS/cm	54.8	0.29	75.6
TDS	ppm	39,841	133	62,387
Calcium	mg/L	784	2.16	1,176
Magnesium	mg/L	1,314	5.83	1,846
Sulfate	mg/L	1,980	0	2,100
Chloride	mg/L	25,457	69	38,780
Sodium	mg/L	13,853	44	21,515
Alkalinity	mg/L	142	5.5	232
Boron	mg/L	3.3	0.21	3.2
Nitrate	mg/L	4.6	0.7	4.9
Copper	mg/L	<0.05	<0.05	<0.05
Chromium	mg/L	<0.05	<0.05	<0.05
Iron	mg/L	<0.05	<0.05	<0.05
Silica	mg/L	103	0.49	101.5
Phosphate	mg/L	0.52	0.02	0.40
Fluoride	mg/L	5.8	0.02	5.7

Table 3
Effect of FS flow rate upon product water flow rate and water recovery using 230 micron membrane

DS flow rate, LPM	Product capacity, m^3/d		Recovery ratio %	
	FS flow rate 14 LPM	FS flow rate 16 LPM	FS flow rate 14 LPM	FS flow rate 16 LPM
8.1	5.3	5.5	26.1	23.7
10.1	6.0	6.3	30.2	28.8
12.1	6.2	7.0	31.2	30.1
14.1	6.4	7.2	31.3	31.1
16.1	5.7	7.1	27.9	29.9
18.1	5.4	6.5	28.1	28.9

Table 4
Effect of FS flow rate upon product water flow rate and water recovery using 135 micron membrane

DS flow rate, LPM	Product capacity, m^3/d		Recovery ratio %	
	FS flow rate 14 LPM	FS flow rate 16 LPM	FS flow rate 14 LPM	FS flow rate 16 LPM
8.1	4.1	4.6	23.9	24.6
10.1	4.2	4.8	24.8	27.6
12.1	4.4	4.9	26.1	28.5
14.1	4.7	5.2	28.1	27.9
16.1	4.3	4.7	25.9	26.6
18.1	3.9	4.2	24.1	25.8

Table 6
Physiochemical analysis of AGS feed, FO product and FO brine using 135 micron membrane

Parameter	Unit	AGS feed	FO product	FO brine
pH		7.5	6.7	7.4
Conductivity	mS/cm	57.2	0.19	78.6
TDS	ppm	43,797	78	61,266
Calcium	mg/L	776	2.64	1,144
Magnesium	mg/L	1,144	1.17	1,720
Sulfate	mg/L	4,300	0	4,600
Chloride	mg/L	27,200	63	40,940
Sodium	mg/L	14,835	51	20,100
Alkalinity	mg/L	108	4.3	155.6
Boron	mg/L	2.59	0.24	2.9
Nitrate	mg/L	3.5	0.7	4.3
Copper	mg/L	<0.05	<0.05	<0.05
Chromium	mg/L	<0.05	<0.05	<0.05
Iron	mg/L	<0.05	<0.05	<0.05
Silica	mg/L	20	0.574	20.1
Phosphate	mg/L	0.15	0.11	0.3
Fluoride	mg/L	4.3	0.13	4.8

such as calcium, magnesium, chloride and sulfate were assessed by ion chromatography system, whereas, boron and sodium are estimated by inductively coupled plasma optical emission spectrometry (ICP-OES). The parameters such as nitrate, copper, chromium, iron, silica, phosphate and fluoride are estimated by spectrophotometer (DR-6000). All analysis was done in triplicate and average values are taken for reporting.

The FO pilot plant in a single-stage process using single HF FO 230 µm membrane reduced the TDS from 39,841 to 133 ppm, whereas, 135 µm membrane reduced the TDS from 43,797 to 78 ppm. The TDS of RO first-stage produce at DRP is about 390 ppm. This shows that the TDS of FO product is lower than RO first-stage product. The 135 micron membrane showed improved TDS than 230 micron membrane and this would be due to the more number of HF and increased membrane area. The rejection of boron by the HF FO membrane is highly noticeable as it was reduced from 3.3 to 0.21 mg/L, which is practically not achievable from a single-stage RO. The reverse salt flux is tested by measuring the refractive index values of the product water and observed no traces of polymer in product water. This indicates that the post treatment system used in the pilot plant is highly efficient to treat the supernatant water and convert it to product water.

The performance stability of the HF FO membranes was tested by operating the pilot plant 24 h per day for 30 d at FS and DS flow rates of 14 and 16 LPM, respectively. The FO membrane as well as the pilot plant showed a steady operation in terms of TDS for the final product water and % water recovery values as shown in Figs. 2 and 3. There was no major change in TDS and water recovery percentage values during the observation period.

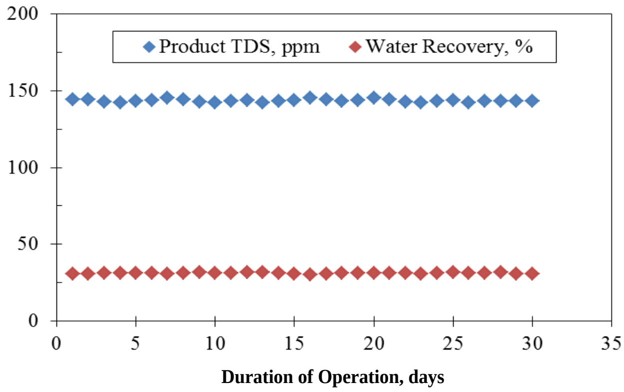

Fig. 2. Product TDs and FO pilot-plant water recovery distribution over a period of 30 d continuous operation using 230 micron membrane.

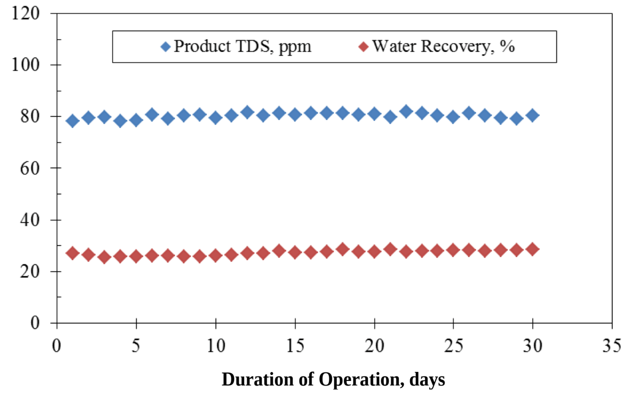

Fig. 3. Product TDs and FO pilot-plant water recovery distribution over a period of 30 d continuous operation using 135 micron membrane.

The primary calculation of energy required by the conventional electrical heater for DS recovery in the FO pilot plant is approximately 35–40 kWh/m^3, which is much lower than that the conventional MSF and MED desalination processes. The thermal energy consumption of an MSF plant is around 70–78 kWh/m^3 (Karaghouli and Kazmerski 2013 and Banat 2007) and the MED plant is around 62 kWh/m^3 (Karaghouli and Kazmerski 2013). It is worthy to note that the total energy consumption by the FO pilot plant without the conventional electrical heater of the DS recovery system was around 2.4 kWh/m^3. However, the energy consumed by PLC and control panel used in the pilot-plant test unit was measured and is around 1.4 kWh/m^3. This figure is quite high because of the low production capacity of the tested pilot plant. This figure can be drastically reduced by increasing the permeate capacity of the FO pilot plant. The results so far shows that the tested FO pilot plant can produce freshwater with an energy requirement less than the conventional desalination processes, provided the energy needed for DS recovery is supplied in the form of low-grade industrial waste heat or solar thermal energy. In order to proceed to the semi-commercialization of FO pilot plant, a detailed monitoring and analysis of water quality, FO performance stability and actual total energy consumption should be carried out for a longer period of time. The on-going operation of the FO pilot plant at DRP for a period of 1 year will provide a series of data or trends to confirm the performance reliability of FO technology for AGS desalination.

4. Conclusion

This study evaluated the feasibility of using innovative FO technology toward the desalination of AGS at a pilot-scale level using two different hollow fiber FO membranes with different bore diameters of 135 and 230 μm, and data produced from this study provided a platform to implement FO technology in Kuwait at a commercial scale. This study is also innovative considering the use of thermo-responsive polyelectrolyte DS in a FO desalination system with single-stage FO desalination process. The product water quality parameters obtained from the FO pilot plant using hollow fiber FO membranes are promising and proved that FO technology can produce water that meets the international standards. The FO pilot plant over a continuous stable operation of 30 d was capable to produce product water of TDS ≈ 70 to 150 ppm at water recovery ratio of ≈30%. The results of the pilot-scale study also established the potential of using thermally separable polyelectrolyte DS in FO system and its economic benefits over NaCl based DS used in FO-RO integrated system. This study also reveals that the FO desalination system is economically beneficial in commercial scale by integration of DS regeneration system with the low energy sources such as waste heat. However, detailed techno-economic analysis is also recommended to estimate the actual energy consumption of the investigated FO process and compare the results with the conventional desalination technologies such as MSF and RO.

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Direct solar desalination using nano/micro-porous polymeric membrane via thin film evaporation

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ABSTRACT

Thin film evaporation from nanoporous membranes is a promising thermal desalination approach because it utilizes the passive capillary pumping of liquid to the evaporating interface and allows for high heat transfer rates due to the large evaporating area in addition to the capillary pumping driving force. In this study, solar energy was used as a heat source to evaporate seawater through in-house fabricated polyvinylidene fluoride (PVDF) nano/micro-porous membranes incorporated with nanoparticles. Compromising between the available area for evaporation via changing pore size and the available material for conductive transfer of heat to the liquid thin film is complicated and require a deep study experimentally and theoretically. The objectives of this study are to investigate the pore size effect and thermal conductivity on the vapor flux by fabricating fumed silica and carbon nanotube membranes. The fabricated membranes were characterized by scanning electron microscopy, contact angle analyzer (CA), capillary flow porometry and porosity to further understand the observed thin film evaporation effects. The preliminary results showed that CNT is an effective nanoparticle to obtain higher vapor flux (18.48903 g/min m^{-2}) in thin film evaporation that incorporated with solar simulator this is due to good ability of CNT to absorb light and converted to thermal energy. It is recommended to investigate more membranes with deep analysis to achieve the paper objective.

Keywords: Thin film evaporation; Nanoparticles; Carbon nanotube; Fumed silica; Pore size; Thermal conductivity

1. Introduction

Water is a very valuable element for nature, human life and global economy. It provides a sustainable high-quality for agriculture, industry, recreation, energy production, and domestic consumption (Gewin 2005). About 97% from the total mass of water on the world is salty and 3% is freshwater. However, most of the 3% of freshwater is trapped in glaciers and ice caps making it difficult to reach (Gleick 1996). So, in this world we are suffering from freshwater scarcity which is a critical problem worrying people. Especially with the increase in population number, demand for water is increased in addition to the rise in water pollution. Because of that the need of alternative resources of freshwater is a must, therefore many technologies have existed to solve this problem.

One of the newest technology is using thin film evaporation combined with solar simulation to generate steam (Peng et al. 2018). As solar energy is renewable and environment friendly, it will be utilized as source of heat to evaporate water. Beside the solar energy many studies have been made to enhance the evaporation rate by incorporation of nanoparticles in thin film evaporation membrane (Plawsky et al. 2014). Seeding membranes with nanoparticles will increase the surface area and will enhance the thermal properties of the membrane (Ni 2014). Recently, Neumann et al. 2012 was able to generate steam in bulk water with Au nanoparticles (NPs) with the power of 10^3 kWm^{-2}. Carbon nanotubes [7] and fumed silica nanoparticles (Suzuki et al. 2014) were used in this study.

Compromising between the available area for evaporation via changing pore size and the available material for conductive transfer of heat to the liquid thin film is complicated. Since more porous membrane increases the evaporation surface area and at the same time this leads to having less conductive material for heat transfer which at the end will reduce the evaporation rate. The aim of this study is to develop an efficient nonporous membrane based water desalination system that can eventually be incorporated into a solar radiation. This paper will focus on, investigating the pore size and meniscus shape effect on the vapor flux by fabricating flat sheet CNT membranes mixed with PVDF. In addition, examining the thermal conductivity effect on

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the vapor flux by changing the concentration of fumed silica in the PVDF polymeric solution. Therefore, it is best to choose the favorable nanoparticle for solar absorption in thin film evaporation with higher efficiency.

2. Methodology

2.1. Materials

PVDF (Kynar 741) is the polymer used in fabrication and it was obtained from Arkema. PVDF has favorable properties as a material for fabricating porous membranes via the phase inversion technique. Ethanol and dimethylacetamide (DMAc) supplied by Alfa Aesar (>99.5% purity) were used as the solvent for PVDF. The functionalized carbon nanotube with PEG and modified fumed silica with a surface area of 125 m^2/g was used as the additive to the membrane sheet.

2.2. Membrane preparation

2.2.1. CNT membrane

PVDF and CNT were ground in ethanol and then added to 50% solution of ethanol and DI water, the solution was sonicated at 40 W of power for 15 min. The prepared solution was casted on copper sheet using doctor blade with thickness of 5 mm. Two different drying methods used in CNT fabrication (oven and freezer) in order to manipulate the pore size of the membrane.

2.2.2. FS membrane

Phase inversion technique was followed to fabricate FS membrane, in which PVDF, FS, DMAc were blended for 8 h using a magnetic stirrer and sonicated for 10 min to have homogeneous solution and later it is kept for 24 h for degassing. The prepared solution was casted using doctor blade with thickness of 500 μm on a non-woven support (Novatexx 2471, donated by Freudenberg-Filter, Germany) at 60% relative humidity. The casted membrane was immersed in a coagulation bath containing deionized water (Mavukkandy et al. 2017).

2.3. Membrane characterization

The microstructure of the membrane surface was observed using scanning electron microscopy (SEM, Quanta-250, FEI, Hillsboro, OR, USA). Samples were coated with gold and palladium at 50 Å thickness in order to create conductive surfaces. The mean pore size and pore size distribution were measured using a capillary flow porometer (CFP, Porous Materials Inc., Ithaca, NY, USA) using Galwick as the wetting liquid. A gravimetric method was used in order to calculate volume porosity using Galwick®. To test the hydrophobicity of the membrane, the contact angle on the membrane surface of DI water was measured using the sessile drop method with a contact angle goniometer (KrüssDSA 10 Mk2, Hamburg, Germany). To enhance the data accuracy, at least six drops at different location of the sample were taken and their readings were averaged. Other studies such as thermal analysis and UV absorption are in the progress.

2.4. Thin film evaporation experiment

Thin film evaporation experiments were carried out under controlled conditions using a lab-scale setup. The experimental device was designed (Fig. 1) for nonporous membrane to achieve high evaporation flux over a large area using solar simulator as a source of heat.

The feed liquid was 35 g/L NaCl solution and DI water which passes to the supported membrane structure at room temperature through the connected pipe and circulated at a constant flow rate of 15 mL/min. Due to capillary effect of nonporous membrane, the water flowing through the membrane pores and evaporating from the membrane surface by absorbing heat from the solar simulator. The water passes throughout the structure and circulated back to the system. The mass of the water was measured at steady-state condition for 6 h in order to measure the evaporation flux due to the mass change over the period. The electrical conductivity was measured at the beginning and at the end of the running experiment for each sample.

3. Result and discussion

3.1. Effect of mass change of FS on evaporation flux

Fig. 2 shows how the mass changed of the vapor with source of heat and without it for each membrane. Starting with FS membranes, the result shows that at time = 4 h the change of mass are about 2.5 g for FS-3 and FS-4, while it is slightly increased in FS-5 reaching 3 g at t = 4 h as shown in Figs. 2b, d and f, respectively. The calculated evaporation flux shows the same trend as well, since FS-3 and FS-4 have almost the same evaporation flux 7.89525 and 7.929286 g/min m^{-2}, respectively, while FS-5 membrane provides better evaporation flux 9.334505 g/min m^{-2} (Fig. 3).

3.1.1. Morphology

The physical characteristics were examined to understand the membrane mechanism. Fig. 4 shows the morphologies of FS-3, FS-4 and FS-5, which all have the same structure at different magnification. This is because of only a slight change of added fumed silica in each membrane while other parameters are constant.

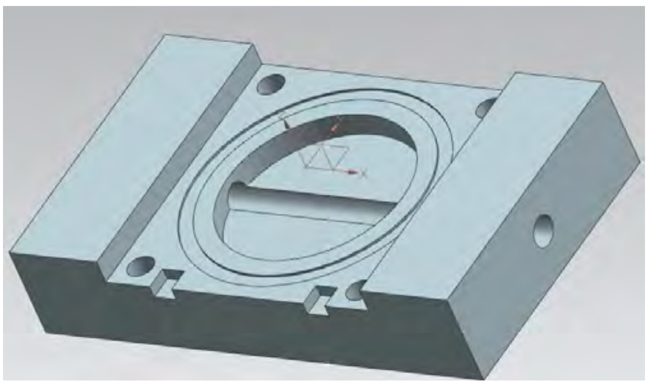

Fig. 1. 3D schematic of supported membrane structure.

3.1.2. Porosity and wettability

The listed result in Table 3 shows the different porosity % and mean pore size among FS-3, FS-4 and FS-5, but FS-3 and FS-4 have close result. However all FS membrane have CA in range of 75°, see Fig. 5.

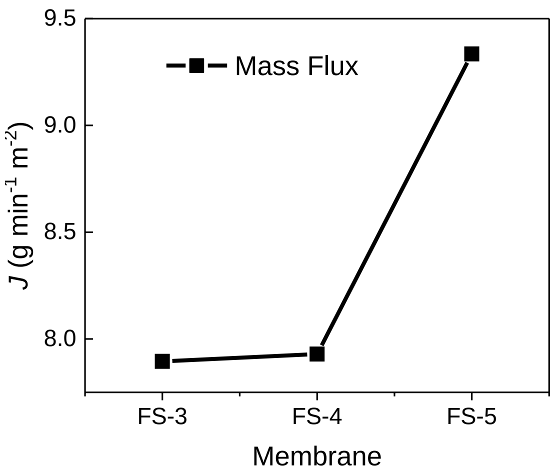

Fig. 2. Evaporation flux of FS membranes

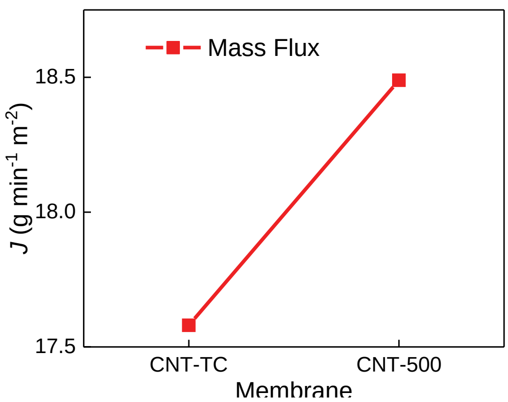

Fig. 3. Evaporation flux of FS membranes.

Table 1
CNT membrane preparation parameters and membrane thickness

Membrane Code	PVDF mg	CNT mg	Drying method	Thickness μm
CNT-TC	400 mg	400 mg	Oven at 120°C	200
CNT-500	400 mg	400 mg	Freezer	203
CNT-1000	400 mg	400 mg	Freezer	190

Table 2
FS Membrane preparation parameters and membrane thickness

Membrane code	PVDF wt%	Fumed silica wt%	DMAc wt%	Thickness μm
FS-3	15	3	82	410
FS-4	15	4	81	400
FS-5	15	5	80	530

3.1.3. Thermal analysis

The study of thermal conductivity was one main objectives of this paper. It's expected that, the evaporation flux will increase as the thermal conductivity increase. This study is still in progress and more samples with various mass of FS will be fabricated to achieve the objective.

3.2. Effect of CNT membrane on evaporation flux

Comparing the CNT result with FS membranes, the mass changed during the thin film evaporation experiment was higher in CNT membrane, at t = 4 hr the evaporated mass exceed 4 g in both CNT-TC and CNT-500 membranes. This is because of the better light absorbance in black membrane as shown in Fig. 2, since the temperature change in CNT membrane were higher than FS membranes. The evaporation flux was 17.58021 and 18.48903 g/min m^{-2} for CNT-TC and CNT-500 respectively, and it's almost doubled in comparing with FS evaporation flux.

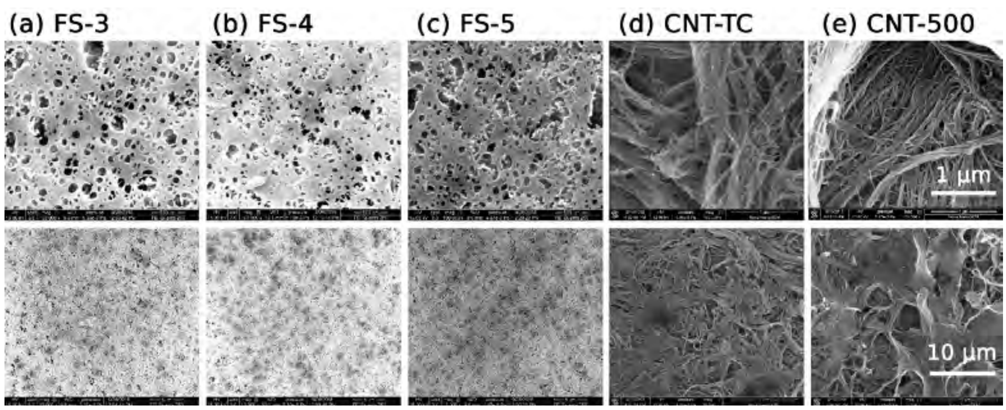

Fig. 4. SEM images of membrane samples prepared with nanoparticles.

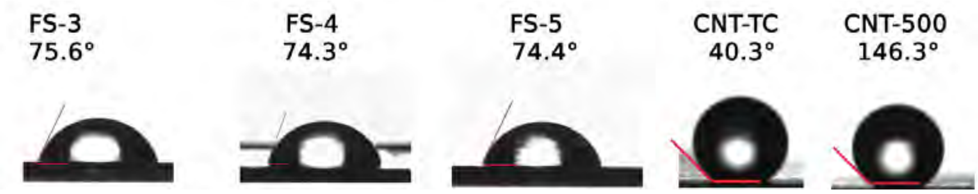

Fig. 5. Membranes' contact angle.

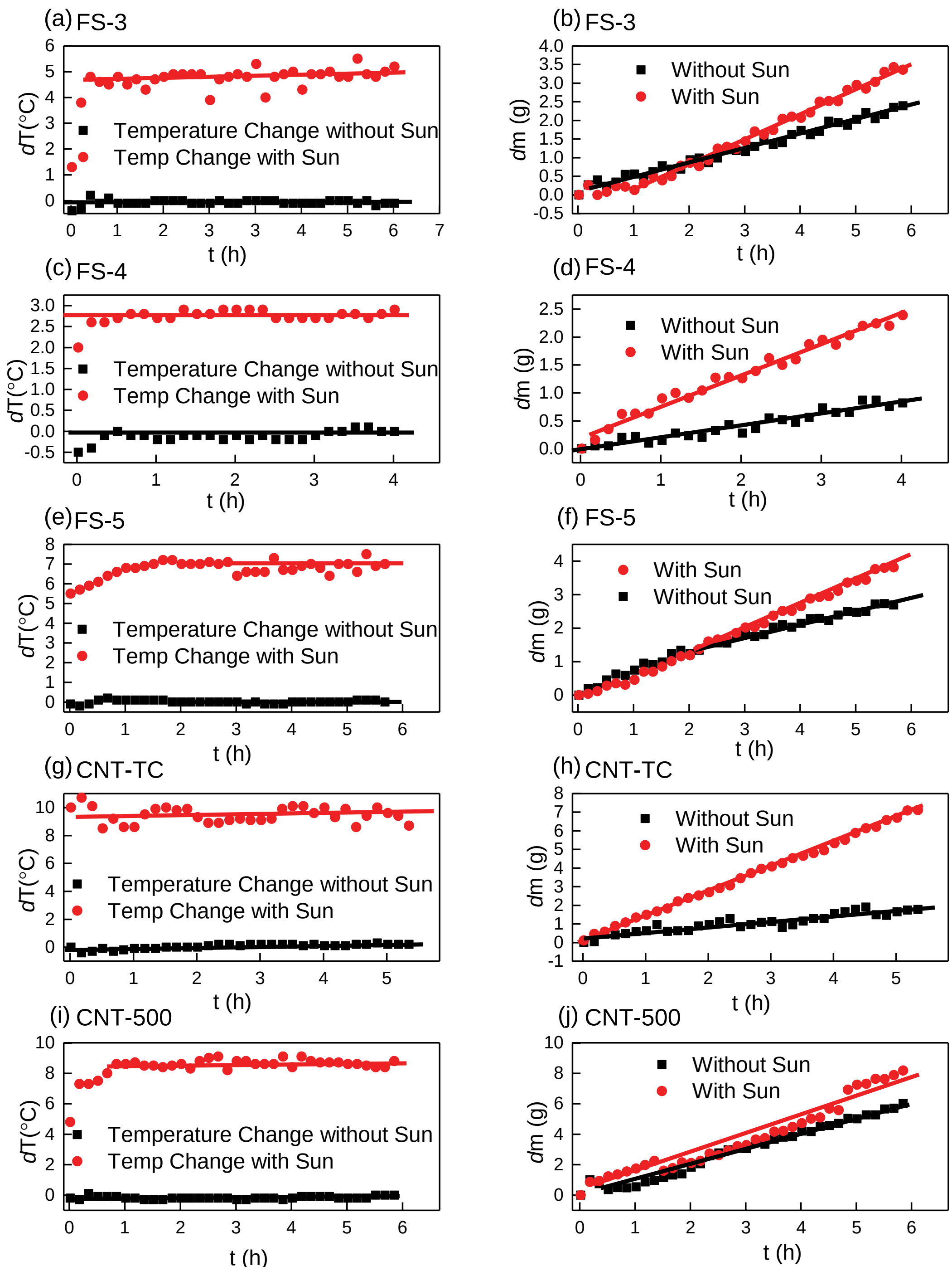

Fig. 6. Mass and temperature change of the membranes in this film evaporation test

Table 3
Porosity and MPS of Fabricated membrane

Membrane code	Mean pore size (MPS) μm	Porosity %
CNT-TC	0.1781	64.9
CNT-500	0.2234	71.6
FS-3	0.1279	81.1
FS-4	0.1186	83.1
FS-5	0.2267	74.6

3.2.1. Morphology

Fig. 4 shows the morphologies of CNT membrane, and its structure different than FS membranes. From the SEM picture, we can conclude that CNT-TC has smaller pores than CNT-500. This is because of using a different drying method. CNT-TC was dried using oven while CNT-500 dried using freezer.

3.2.2. Porosity and wettability

CNT-500 is more porous membrane than CNT-TC with MPS 0.2234 μm and 0.1781 μm, respectively. And both are super hydrophobic membranes which are favorable for thin film evaporation as shown in Fig. 5.

Even the evaporation flux was better in the bigger pore size membrane for CNT membranes we cannot give a conclusion in effect of pore size in evaporation flux. Since, more membranes with different pore sizes need to be investigated and tested.

4. Conclusion

Through a study of FS and CNT nanoparticles in thin film evaporation, it has been shown that CNT is an effective nanoparticle to obtain higher vapor flux in thin film evaporation that incorporated with solar simulator. One of the reasons is CNT has high ability to absorb light and converted it to thermal energy. The results show that there is an effect of pore size in steam generation via nanoporous membrane and it is still in progress and under investigation to end up with clear conclusion. And the same for thermal conductivity analysis, adding more semi conductive nanoparticle will increase the ability of converting light to thermal energy and thermal conductivity as well. The tradeoff between porosity and thermal conductivity of the membrane requires a deep study experimentally and theoretically.

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Assessment of performance recently developed acriflavine thin film composite nanofiltration membrane for seawater treatment and RO brine concentration

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ABSTRACT

To enhance the permeation and salt rejection properties of polysulfone membrane, novel TiO_2 nanoparticle incorporated acriflavine thin film composite (TFC) was fabricated. Fabricated TFC membranes were characterized thoroughly using Fourier transform infra red (FT-IR), atomic force microscope, field emission scanning electron microscope and contact angle (CA). The signature peaks in FT-IR spectra were identified to confirm the interfacial polymerization (IP) of acriflavine and TMC. TiO_2 nanoparticle incorporation in the TFC layer was analysed using elemental mapping analysis and EDX. The addition of TiO_2 nanoparticle in acriflavine TFC layer resulted change in morphology of membrane and contact angle. The highest pure water flux was reached up to 67.1 $Lm^{-2}\ h^{-1}$ with 0.1 weight percentage of TiO_2 nanoparticle dosage (TFC 4). The water flux of 53.0, and 44.5 $Lm^{-2}\ h^{-1}$ were achieved for TFC 4 membrane using Arabian Gulf Seawater, and reverse osmosis (RO) brine, respectively. Most importantly, TFC 4 membrane showed less fouling with more than 99% of ionic rejection for magnesium, calcium, and sulfate ions. From the studies, it was concluded that, novel TiO_2 nanoparticle incorporated acriflavine TFC membranes are having high capability of rejecting divalent ions and suitable for seawater treatment and RO brine concentration applications.

Keywords: Desalination; TiO_2 nanoparticle; Salt flux; Water flux

1. Introduction

The freshwater resources in the state of Kuwait are very limited and more than 90% of freshwater is produced from thermal and membrane desalination process. The major share of seawater desalination in the state of Kuwait is taken by thermal processes which are multistage flash (MSF) and multieffect distillation. In the state of Kuwait, thermal desalination process is coupled with power generation plants to reduce the capital and operating cost. However, thermal desalination processes are suffering from scaling, corrosion, and low efficiency (low water recovery) compared with reverse osmosis (RO). In the recent decades, RO technology becoming popular as an alternative seawater desalination technology due to high water recovery and low energy consumption compared with thermal seawater desalination. However, RO still has a number of challenges such as significant concentration polarization, scaling, and fouling (Ge et al. 2013; Stone et al. 2013; Ahmad 2012). Additionally, RO is considered as an energy-intensive system because it requires operating pressure greater than 50 atm, and the requirement of a high hydraulic pressure to overcome the osmotic pressure generated by seawater (Ge et al. 2013; Stone et al. 2013). In the recent years, thin film composite (TFC) membranes showed a promising way of producing fresh water at low-energy consumption and high purity. The selectivity, low resistance, and high flux attracted researchers to search new effective thin film coating for the

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TFC membrane fabrication process (Zh et al. 2018; Zhang et al. 2018). In membrane technology, microfiltration and ultrafiltration membranes are sources as a base polymer membrane for producing TFC membrane. The selectivity of ions in desalination process depends on the pore size, charge on the surface of membrane and hydrophilicity (Werber et al. 2016). The hydrophilicity of the membrane can be altered by incorporating nanoparticle and modification of selective layer in the thin film. Among the TFC membrane, the polyamide type cross-linking coating has attracted due to its excellent pH stability, ion selectivity, and thin film forming capability (Maruf et al. 2012). The disadvantage of polyamide-based TFC membrane is its low chlorine tolerance, less chemical stability, and low antifouling behaviour. The aforementioned drawbacks can be overcome by developing new polyamide cross-link polymer with chemically stable functional groups. Further, the modification of TFC membrane by incorporating nanoparticle showed a promising approach to overcome the chemical stability, chlorine tolerance, and antifouling characteristics (Lau et al. 2012; Son & Jegal 2010).

Acriflavine is one of the 3,6-diamine with a quaternary amine at tenth position of the anthracene ring. The diamine at the end of the anthracene ring is more basic and highly reactive. The planar structure of the acriflavine is one of the advantages for cross-link polymerization and to develop a continuous defect-free thin film (Sikorski & ski 2014; Eldaroti et al. 2013; Can et al. 2014). In the pharmaceutical field, acriflavine is generally used as an antiseptic and antibacterial agent in the drug development. In the aquarium hobby, it is used as an antifungal agent to treat various fungal infections in fish and preventing fish egg loss to fungus. The acriflavine family drugs induce cellular strain to fungus and reduce the further growth and on the other hand, acriflavine derivatives are good antibacterial and antimalarial agents (Kawai & Yamagishi 2009).

In the present study, a novel approach for the fabrication of polyamide layer is demonstrated using acriflavine as amine monomer and TMC as acid monomer via IP technique. Further, acriflavine in aqueous solution was incorporated with TiO_2 nanoparticles to study the effect of nanoparticle on permeation and selectivity of the novel TFC layer. The membranes were characterized in detail using instrumentation techniques such as atomic force microscope (AFM), field emission scanning electron microscope (FESEM) and contact angle goniometer. The practical application of TFC membranes was evaluated by performing a rejection and permeation studies for seawater sample and brine discharge obtained from the desalination plant.

2. Experimental

2.1. Preparation of acriflavine TFC membranes

Acriflavine TFC membranes were fabricated on the surface of pre-cast PSf substrate by IP method. The 0.01, 0.05, and 0.1 weight percent (wt.%) of TiO_2 nanoparticles were dispersed in two weight percentage of acriflavine aqueous solution with 1.1 equivalent of triethylamine (TEA). Clearly dispersed nanoparticle acriflavine solution was filtered to remove undissolved and agglomerated nanoparticles from the solution. The substrate membrane was clamped horizontally on the glass plate and aqueous solution of nanoparticle-dispersed acriflavine solution was poured and kept for two min to penetrate solution to pores of the substrate. The excess solution was drained off and residual drops were removed by soft rubber roller. After 1 min, 0.1% (w/v) TMC solution in hexane was added and kept for 1 min to IP, then TMC solution was drained off. The unreacted TMC was removed by hexane washing and kept inside the oven at 60°C for 10 min to complete polymerization. The newly fabricated TFC membrane was washed with deionized (DI) water and stored in DI water (Xie et al. 2012). Based on the concentration of TiO_2 used for fabricating TFC membranes, the prepared TFC membranes are labelled as TFC 1 (control: 0% TiO_2), TFC 2 (0.01% TiO_2), TFC 3 (0.05% TiO_2), TFC 4 (0.1% TiO_2). The compositions of newly fabricated TFC membranes are tabulated in Table 1. The chemical reaction involved in the formation of PA layer is shown below.

2.2. Characterization of TFC membranes

ALPHA-FTIR spectrophotometer (Bruker Company) was used to characterize the chemical structure and confirm the incorporation of TiO_2 nanoparticle in the acriflavine TFC membranes. The measurement was taken with 64 scans in the range of 4,000 to 400 cm^{-1}. The contact angles were measured using optical contact angle and interface tension meter from USA KINO (model-SL200KB). Keysight 8500 FESEM was used to study the surface and cross-sectional morphology of the membranes. The membrane surface topological features were analyzed using Concept Scientific Instrument (Nano-Observer), France, by scanning the membrane surface over 10 μm × 10 μm dimensions.

2.3. Evaluation of membrane performance

The performance of TFC membranes was studied on self-stirred membrane permeation cell (Sterlitech HP4750 STIRRED CELL) having effective membrane diameter of

Table 1
Composition of costing solution and contact angle

SL No	Code	% Composition			Contact angle (°)
		Acriflavine wt.%	TMC wt.%	TiO_2 wt.%	
1	TFC 1	2	0.1	0	66.89
2	TFC 2	2	0.1	0.01	53.97
3	TFC 3	2	0.1	0.05	51.89
4	TFC 4	2	0.1	0.1	51.12

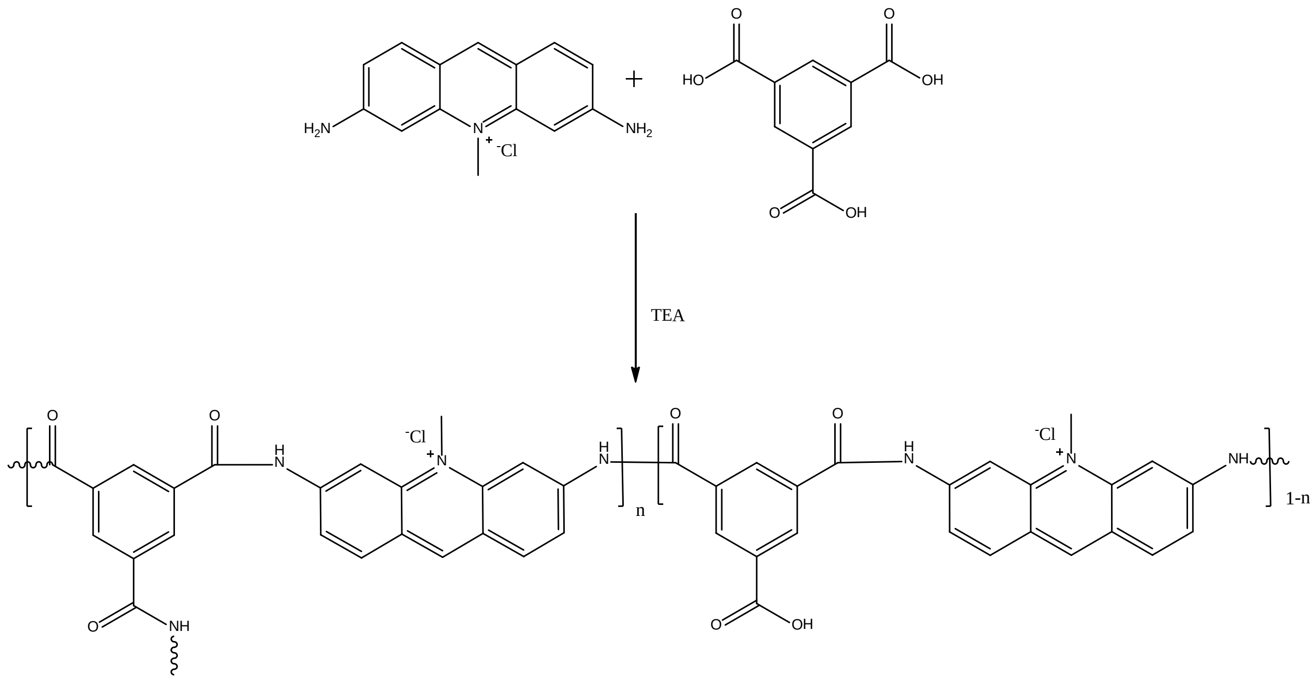

Fig. 1. Chemical reaction of acriflavine and trimesic acid (TEA: Triethylamine).

5 cm at pressure 9 bar. The feed solution used for the experiments are DI water, seawater, and RO brine. The water flux (J_w) and salt rejection (R) of the TFC membranes were calculated using Eq. (1).

$$J_w = \frac{Q}{A \times \Delta t} \tag{1}$$

where J_w (L/m^2 h) is the pure water flux (PWF), Q is the volume of water (L) permeated through the membrane of effective area A (m^2) over a time Δt (h).

$$\% \text{ Rejection} = \left(1 - \frac{C_p}{C_f}\right) \times 100 \tag{2}$$

where C_p and C_f are the concentrations of the feed and permeate. Each membrane was tested three times and average values were reported.

3. Results and discussion

3.1. FTIR analysis

The FTIR spectra of acriflavine, PSf, TFC, and TiO_2 TFC are presented in Fig. 2. The sharp peaks at 1,457; 1,601 cm^{-1} corresponds to C=N and C=C of the acriflavine aromatic ring, respectively. Aromatic C–H and N-methyl (N-CH_3) stretching peaks have appeared at 2,913; 2,919; 2,954; 3,030 cm^{-1} and free amine (NH_2) as a doublet at 3,315 and 3,431 cm^{-1}. In PSf spectrum, two peaks at 1,294–1,324 cm^{-1} correspond to O=S=O of the polysulfone and high intense peak at 1,586 cm^{-1} is due to C=C of the aromatic rings present in the PSf polymer. The aromatic C–H and CH_3 stretching peaks have appeared at 2,873; 2,969; and 3,038 cm^{-1} (Moradihamedani et al. 2015). In neat TFC polyamide (PA), the peak 1,445 cm^{-1} corresponds to C=O attached to amide link (C–N) and 1,602 cm^{-1} corresponds to the C=O of the carboxylic acid which is formed due to end of the polymer chain or end of polymer branching. The aromatic C-H and N-methyl (N–CH_3) stretching peaks have appeared at 2,987; 3,008; and 3,032 cm^{-1}. The N–H of the amide appeared as a singlet at 3,343 cm^{-1} and disappearance of NH_2 peaks at 3,315; 3,431 cm^{-1} and absence of 1,770 cm^{-1} C–Cl peaks conforms the formation of PA layer (Shawky et al. 2011). The spectrum TiO_2TFC shows all the corresponding peaks of PSf, PA, and a broad peak of NH and –OH (TiO_2) at 3,389 cm^{-1} confirms theTiO_2 incorporated acriflavine TFC.

3.2. Membrane morphology

The permeation and rejection properties of the membrane are strongly depending on the morphology of the membrane. The FESEM is the prominent technique to study the morphological variation of newly developed acriflavine TFC membrane (Hebbar et al. 2018, Khorshidi et al. 2018). Fig. 3 shows the surface, cross-sectional FESEM of TFC 4 membrane. All the membranes exhibited rigid-valley structure, which is due to the IP of acriflavine amine and TMC (Wei et al. 2011). The cross-sectional image clearly shows the formation of thin (~100–300 nm) PA layer on the PSf substrate membrane. In the cross-section of the substrate membrane, the figure-type interconnected structure which will provide little resistance to permeate transportation and mechanical strength. On the top of the figure-type projection, a distinctive very thin sublayer of PA confirms the formation of active TFC layer which is responsible for the selectivity of ions as well as flux (Lau et al. 2015; Lalia et al. 2013).

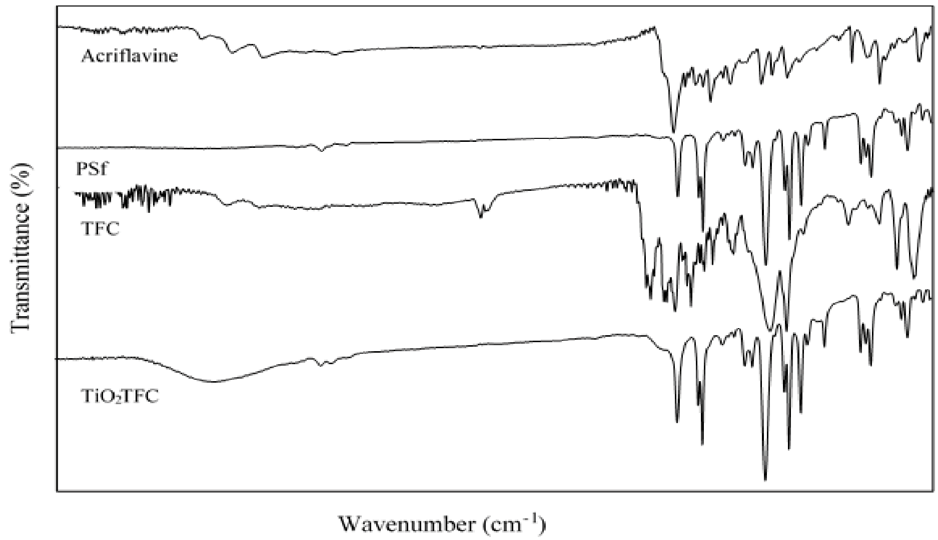

Fig. 2. FT-IR spectra of acriflavine, PSf, TFC, and TiO_2TFC.

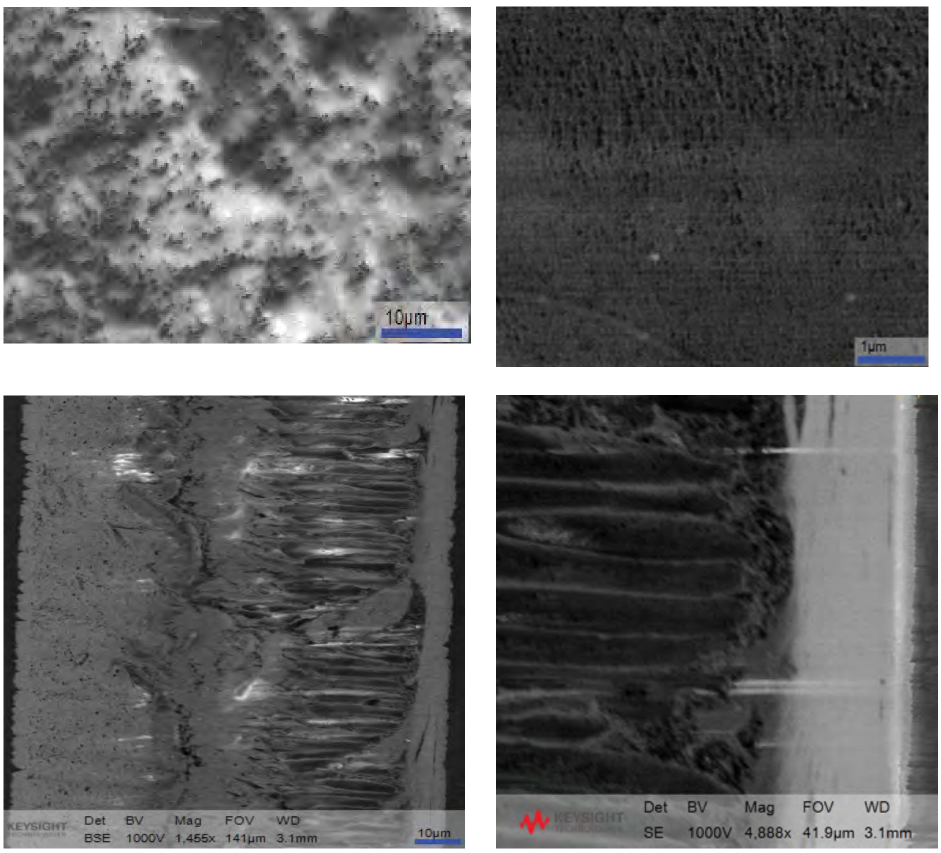

Fig. 3. Magnified surface, cross-sectional FESEM images of TFC 4.

The surface analysis was carried out to study the topological feature and surface roughness of acriflavine TFC membranes using nano-observer AFM instrument by scanning the membrane surface over 10 µm × 10 µm dimensions. The three-dimensional AFM images are shown in Fig. 4 and surface roughness parameters are presented in Table 2 as maximum mean roughness (R_a), route mean square roughness (R_q) and maximum feature height (R_{max}). From the results, increasing trend of roughness values by increasing the TiO_2 concentration in the acriflavine TFC membrane was observed. The lowest maximum mean roughness (R_a) observed was 19.2 nm for acriflavine TFC

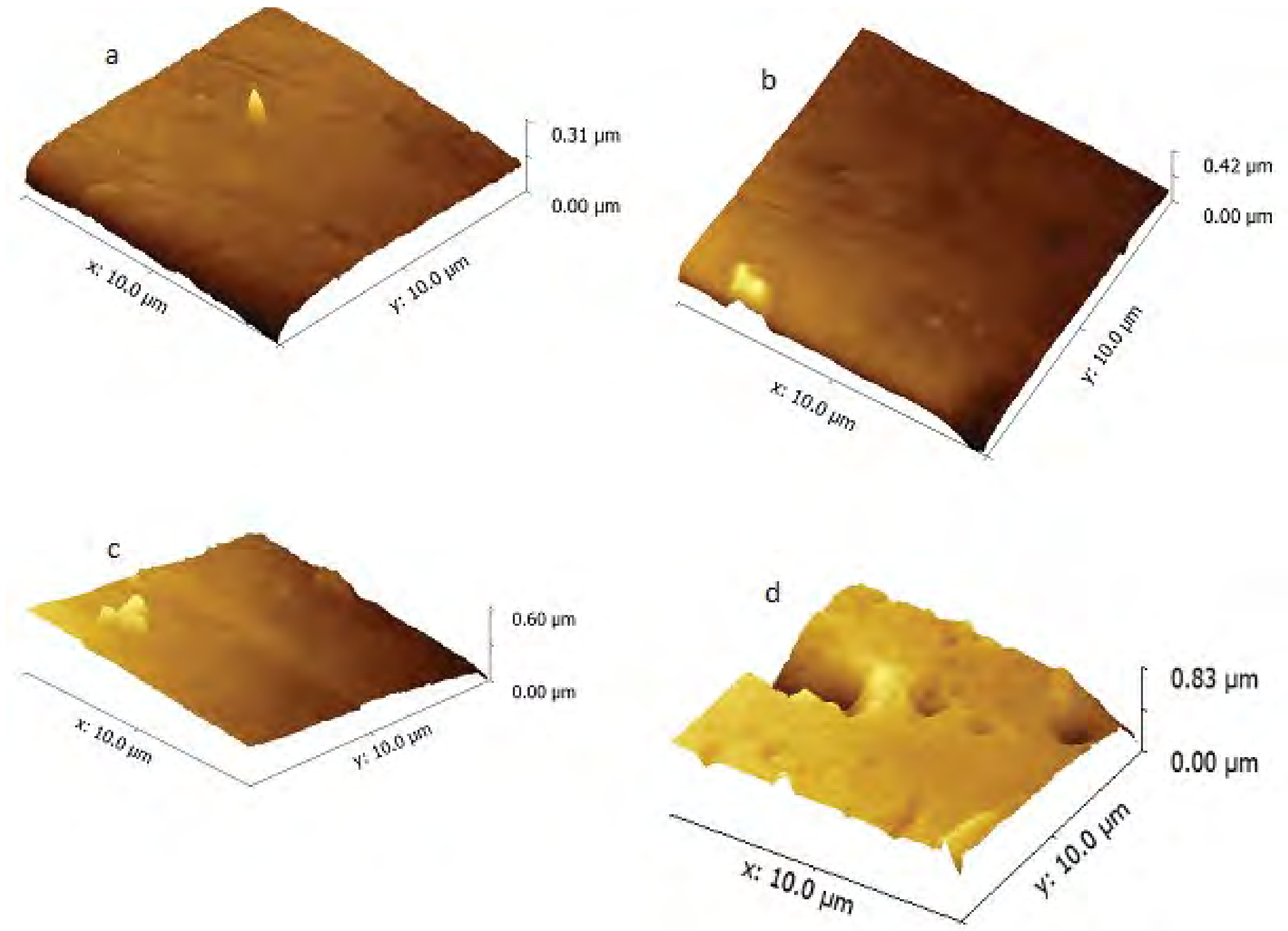

Fig. 4. Three-dimensional AFM images of (a) TFC 1, (b) TFC 2, TFC 3 and (c) TFC 4.

membrane without any nanoparticle addition and highest was observed for TFC 4 (71.7 nm). It is interesting to note that the roughness of the membrane increases as the concentration of TiO_2 increases in acriflavine TFC. This may be due to participation/interaction of TiO_2 nanoparticles in the process of the IP reaction and also fast reaction rate between acriflavine, TMC in the presence of TiO_2 nanoparticles (Ghanbari et al. 2015).

3.3. Contact angle study

The membrane hydrophilicity is a very important parameter for high water flux and antifouling property. The change in hydrophilicity (CA) with the addition of TiO_2 nanoparticle was investigated by measuring contact angle. In general, lower is the CA of the membrane indicates the more hydrophilic nature (Hebbar et al. 2015). From Table 1, highest CA (66.89°) was observed for acriflavine neat TFC membrane compared with TiO_2 nanoparticle incorporated membranes. The TFC 1 (neat TFC) having N–CH_3 group in the acriflavine aromatic ring may be the reason for the highest CA. The CA of the acriflavine TFC membrane was decreased with the loading of 0.01 to 0.05, 0.1 percentage of TiO_2, this is due to the additional porous structure on PA and both chemical and structural properties of the membrane surface (Peyravi et al. 2014).

Table 2
Surface roughness parameters of membranes

Membrane	Roughness		
	R_a (nm)	R_q (nm)	R_{max} (nm)
TFC 1	19.2	24.5	163.3
TFC 2	37.1	47.4	170.1
TFC 3	69.9	86.2	324.5
TFC 4	71.7	104.9	593.6

3.4. Membrane performance study

The desalination performance of the TFC membrane mainly depends on the structural properties of thin film and its chemical nature. However, nature of feed solution also plays a major role. Preliminary permeation test was conducted for all the membrane using DI water as feed. From the results (Fig. 5), it is clearly shown that the acriflavine TFC membrane with 0.1% TiO_2 showed high pure water

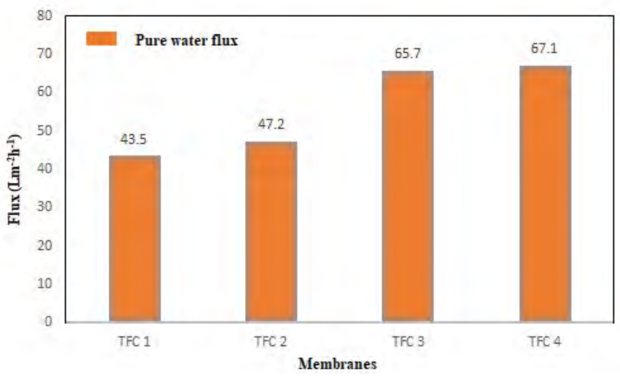

Fig. 5. Pure water flux of the membranes at 0.9 MPa pressure.

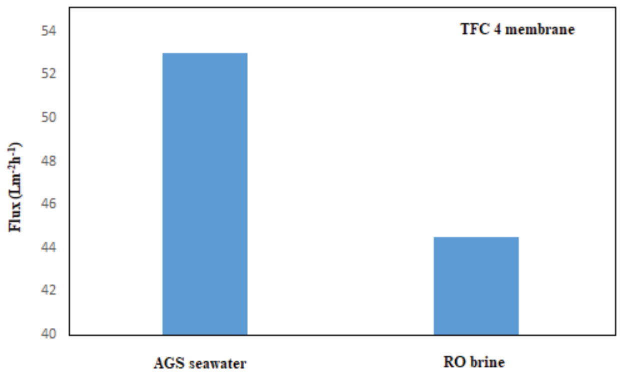

Fig. 6. Water flux of the TFC 4 membrane at 0.9 MPa pressure for AGS and RO brine feed.

flux compared with other membranes. The order of pure water flux is TFC 4 > TFC 3 > TFC 2 > TFC 1. This increasing trend of pure water flux with increasing concentration of TiO_2 in acriflavine TFC is due to the additional porous structure of PA and both chemical and structural properties of the membrane surface. On the other hand, the charge on the PA layer due to the quaternary amine (positive charge in the acriflavine aromatic ring: $^{+}N–CH_3$) will attract the water molecules on the surface of the membrane will lead to enhanced permeation.

The actual seawater desalination study was conducted for TFC 4 membrane using Arabian Gulf seawater (AGS) and RO brine as a feed. Table 3 shows the physicochemical analysis of AGS and RO brine. The desalination performance of the TFC 4 membrane for AGS and RO brine was shown in Fig. 6 and flux obtained was 53.0 and 44.5 $Lm^{-2}h^{-1}$ for AGS and RO brine, respectively. The physicochemical parameters of permeate water from the desalination of AGS and RO brine was shown in Table 4 and percentage of salt rejection are presented in Fig. 7. The permeate flux for RO brine feed is less compared with AGS, this may be due to the high salinity of RO brine. TFC 4 membrane showed significant high rejections for divalent ions compared with monovalent ions for AGS and RO brine feed. The reason for highest rejection for divalent ions is due to the larger size, higher charge of ions (Krieg et al. 2004). The rejected ions are 88.2 (Mg^{2+}), 62.6 (Ca^{2+}), 99.8 (SO_4^{2-}), 39.8 (Cl^-), 31.8 (Na^+), and 30.9 (K^+) percentage for AGS as a feed and 99.5 (Mg^{2+}), 99.1 (Ca^{2+}), 99.8 (SO_4^{2-}), 68.3 (K^+), 18.6 (Cl^-), and 16.8 (Na^+) percentage for RO brine as a feed. TFC 4 membrane rejected 99% of Mg^{2+}, Ca^{2+}, and SO_4^{2-}. The permeate obtained from

Table 3
Physiochemical analysis of AGS and RO brine

Parameters/unit	AGS at Doha desalination plant Kuwait	RO brine
Total dissolved solids, mg/L	45,377	54,900
Conductivity	58.3	69.4
Magnesium, mg/L	1,325	1,673
Calcium, mg/L	730	1,090
Boron, mg/L	3.7	9.8
Lithium, mg/L	1.21	1.7
Strontium, mg/L	14.6	121
Sodium, mg/L	14,488	17,905
Potassium, mg/L	316.4	997
Chloride, mg/L	24,876	68,593
Sulfate, mg/L	3,430.5	4,159

Table 4
Physicochemical parameters of permeate water from the desalination of AGS and RO brine

Parameters/unit	Permeate		Reject	
	AGS	RO brine	AGS	RO brine
Conductivity	27.05	71.09	62.856	85.11
Magnesium, mg/L	5.8	197	2,039	3,013
Calcium, mg/L	6.0	407.2	1,006	1,507
Sodium, mg/L	12,051	12,051	13,316	30,520
Potassium, mg/L	100	688	340	1,223
Chloride, mg/L	20,230	41,176	26,086	68,603
Sulfate, mg/L	3.9	6.84	6,433	21,704

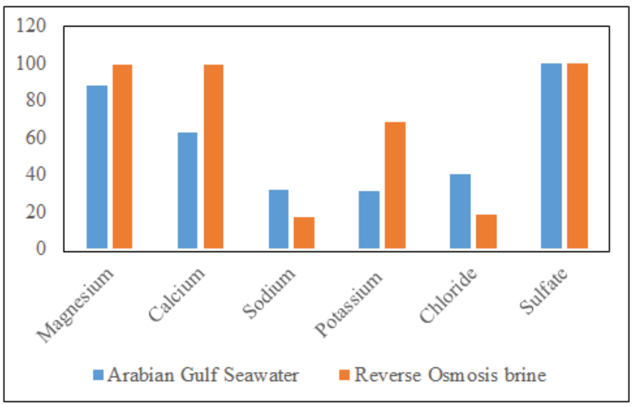

Fig. 7. Percentage salt rejection.

the desalination experiments shows very low concentrations of divalent salts. But the monovalent salts rejection is low as compared with divalent ions. Based on the salt rejection study, acriflavine TFC membrane is a highly promising membrane for seawater desalination pretreatment application and RO brine concentration. The long-term experimental (24 h test) test shows less fouling for TFC 4 membrane compared with TFC 1 membrane for RO brine as a feed. The antifouling character of TFC 4 membrane may be due to neutralized charge distribution on the acriflavine TFC with TiO_2 nanoparticle on the surface of membrane and change in surface morphology of membrane.

4. Conclusion

The TiO_2 nanoparticle incorporated acriflavine TFC membranes were fabricated on PSf support by an IP method. The fabricated novel TFC membranes were characterized using FT-IR, AFM, and SEM. The FT-IR spectra show the TiO_2 nanoparticle incorporation in acriflavine TFC and cross-sectional SEM and 3D AFM images exhibited the changes in morphology and surface roughness properties of resultant acriflavine TFC membrane. The inclusion of TiO_2 nanoparticle into acriflavine TFC membrane aided as performance modifier which increased water flux and high salt rejection. The TFC 4 membrane showed contact angle of 51.12° and pure water flux of 67.1 $Lm^{-2}\,h^{-1}$. The salt rejection experiments showed excellent rejection for divalent ions for AGS and RO brine feed solution. The study concluded that TiO_2 nanoparticle incorporated acriflavine TFC membranes are having the high capability of rejecting divalent ions and suitable in desalination pretreatment and RO brine concentration applications.

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Synthesis and evaluation of nanocomposite forward osmosis membranes for Kuwait seawater desalination

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ABSTRACT

Multistage flash (MSF) and reverse osmosis (RO) are the two major desalination technologies currently serving the needs of freshwater in Kuwait. MSF is energy intensive and suffer from low water recovery, while RO desire energy to fulfil its pressure requirement for the process. Thus, globally the scientists are focusing on the innovative desalination technologies which could be operated at low cost and environmentally friendly. In this regard, forward osmosis (FO) is one such emerging technology which can be operated under "Non-Pressure" requirement conditions to reduce the energy/cost of the desalination process. The principle of FO involves flow of the pure water across the semipermeable membrane by maintaining an osmotic pressure gradient between the feed solution (low concentration solution) and draw solution (high concentration solution). Related to this concept, a project was conducted at Kuwait Institute for Scientific Research to fabricate potential and fouling control membranes for the FO desalination. The aim of this paper is to present the important outcomes of the project in fabricating different types of membranes and results related to the high-performance thin film nanocomposite (TFN) membranes obtained in the project compared with commercial FO membranes. The TFN membrane with 0.05 wt.% nanoparticle composition resulted in high flux of vs. the commercial CTA membrane. Therefore, this work concluded that a suitable selection of nanoparticles and their proper modification is essential to fabricate potential membranes for FO application. Further, a nano-based FO membrane showed a potential application in FO desalination compared with commercial FO membranes.

Keywords: Membrane fabrication; Flux; Reverse salt flux; Nanoparticles; Chemical modification

1. Introduction

At present world is facing the problem of water scarcity that is expected to grow worse soon. To meet this issue scientists are focusing on the innovative membrane technologies for the development of alternative water sources such as seawater desalination, and wastewater recovery (Shannon et al. 2008). Reverse osmosis (RO) desalination is the technical process designed to remove salts from the seawater to produce fresh water. The major factor influencing the selection of RO desalination technology is its high energy requirements. The total cost of desalination depends on energy (50%–70%), maintenance (20%–35%) and labor (10%–15%) costs. For Kuwait, a nonconventional water resource such as seawater is an absolute necessity to bridge the gap between supplies and demands. In Kuwait, the need of fresh water production by desalination is increased drastically. It means that the energy requirements for the process are also expected to increase by the same ratio. Forward osmosis is a novel, low-energy, and thus low-cost method for the desalination of seawater (Nicoll 2013). Unlike RO, it utilizes osmotic pressure gradient ($\Delta\pi$) as the driving force for the filtration of solute (salts) from the feed (seawater) (Fig. 1). Thus, no external pressure requirements made this process a less energy-consuming and low cost (Blandin et al. 2014). The fabrication of potential FO membranes is one of the major steps toward the optimization of FO desalination technology. Later, this technology itself can be integrated with RO or membrane distillation or nanofiltration to produce fresh water from seawater (Zaviska

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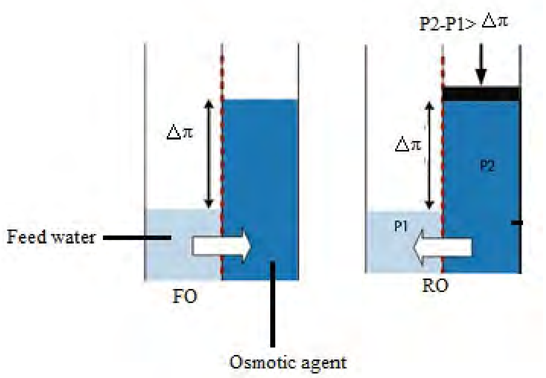

Fig. 1. Working principle of forward osmosis and reverse osmosis.

and Zou, 2014). The world's first FO desalination plant was developed by Modern Water technologies, in Oman during 2012. Currently, world-wide, the researchers are focusing on the mitigation of the major challenges in this field such as the development of low fouling and high flux membranes, and cost-effective draw solutions for the FO process.

Forward osmosis (FO) is one such emerging technology which gained more applications in water purification, seawater desalination, wastewater treatment, food processing, and pharmaceutical industry (Akther et al. 2015). It is an energy-efficient process that operates at low pressure or without additional pressure compared with RO. In FO, the water transport from dilute feed solution (FS) to the concentrated draw solution (DS) will take place through the semipermeable membrane (Huang et al. 2006). The driving force of FO comes from the osmotic pressure difference between the feed solution (FS) and draw solution (DS) separated by the membrane as presented in Fig. 1. The permeating water dilutes the DS, but only to a certain extent, that is, until an osmotic equilibrium is reached between the DS and the FS (Phuntsho et al. 2014). At the same time, there is a slow diffusion of solutes through the membrane from the DS to the FS due to the high concentration difference of ions between the two streams called as reverse solute flux (RSF). RSF not only reduces the effective osmotic driving force across the membrane but also increases the replenishment cost and scaling issue (Wang et al. 2015).

Advances in nanotechnology have led to the development of nano-structured materials, which may form the basis for novel FO membranes (Zaib and Fath 2013). From past one decade, the fabrication of different types of FO membranes especially in their thin film composite form was explored. Many studies have demonstrated that thin-film nanocomposite (TFN) membranes can be the solution to improve not only membrane water permeability but also antifouling resistance (Hamid et al. 2011). By incorporating a small quantity of hydrophilic nanomaterial into a polyamide (PA) layer is apparently able to improve characteristics of PA selective layer without compromising salt separation efficiency. Inorganic nano additives such as titanium dioxide (TiO_2), carbon nanotubes (CNTs), silica, silver, halloysites, and zeolite nanoparticles have contributed to improved flux and antifouling characteristics. A nano additive can improve PA film formation by offering the increased diffusion rate of monomers to the interface, increasing the hydrophilicity of the top PA surface and by reducing the roughness of the top PA surface formed (Ghosh et al. 2008). The entrapment of nanomaterial into the PA skin layer during interfacial polymerization is simpler and more effective when compared with the coating technique; since coating often results in pore plugging during fabrication process causing undesirable permeability characteristics.

Based on the above literature survey, this paper synthesizes nano-FO membranes and compares their performance with the commercial FO membranes. In the first stage, the fabrication of FO polymeric membranes by the chemical modification nanoparticles namely titanium dioxide (TiO_2), and halloysite nanotubes (HNT), was carried out while the carboxylic acid functionalized CNTs were directly purchased from Sigma-Aldrich Co. In the second stage, flat-sheet thin film nanocomposite FO membranes were fabricated, and their performance was evaluated in terms of flux. The study also includes the characterization of the membranes for surface hydrophilicity, morphology and roughness.

2. Experimental

2.1. Materials

The TiO_2 anatase powder, HNT and carboxylic acid functionalized CNT were procured from Sigma-Aldrich Co. The substrate polymer polysulfone (PSF) was procured from Sigma-Aldrich Co. All other solvents for the chemical modification and dope preparation were procured from Merck. For the membrane fabrication de-ionized water was used for phase inversion process.

2.2. Preparation of aminated titania nanotubes (ATNT) and dopamine modified HNT (PHNT)

The surface modification of TNTs was performed using silane coupling agent (3-aminopropyl) triethoxysilane (AAPTS) using literature reported procedure (Emadzadeh et al. 2015). Briefly, 2 g of TNTs was added to pure ethanol (25 mL) followed by 30 min sonication in bath. 0.5 g of APTES was added to the solution and stirred at 90°C for 4 h followed by filtration and subsequent washing using ethanol, ethanol/water (1:1 v/v), and water. The final products ATNTs were then dried at 100°C in a vacuum oven for 12 h. Fig. 14 presents the chemical structure of ATNTs.

The chemical modification of HNT was achieved using the procedure reported in the literature (Hebbar et al. 2016). HNT (10 mg/mL, 500 mL) was dispersed in DI water first by magnetic stirring for 15 min followed by ultra-sonication for 10 min. The base tris (hydroxymethyl) aminomethane was added to the HNT suspension until a pH of 8.8 was reached. Then, 0.2 mg/mL of dopamine powder was added to the HNT suspension and stirred at 30°C for 6 h. The product, polydopamine coated HNTs were collected by centrifugation and were washed with DI water for three more times (150 mL × 3). Finally, the brown coloured

DHNT was dried at 80°C for 10 h before using for characterization and membrane preparation.

2.3. General optimized procedure for the fabrication of thin film nanocomposite membranes

A thin film composite (TFC) membrane is composed of a thin selective layer of polyamide cast over the surface of substrate or support polymeric membrane layer. In the current work, the TFC membranes were fabricated via a two-step procedure.

2.4. General optimized procedure for the fabrication of substrate layer

Polymer (15.0 wt%) was taken in mixture of solvents DMF: NMP (62.25:20.75 wt%) at 26°C, and PEG (Mw = 600 Da, 2.0 wt%) was added at the same temperature. The mixture was stirred at 60°C for 4 h to obtain the homogeneous solution. The solution was degassed at 40°C for 2 h to remove the trapped air bubbles. The dope solution was poured onto a glass plate and casted by using a casting knife adjusted for the thickness of 150 μm. The glass plate was immediately immersed into a coagulation bath containing DI water at 25°C–26°C. After 20 min of coagulation process, the DI water was replaced with fresh water in the coagulation bath, and the membrane could stand for 24 h. Finally, the membrane was dried at 25°C–26°C.

2.5. General optimized procedure for the fabrication of polyamide layer by incorporating nanomaterial

The top active polyamide layer of TFN membrane was prepared by interfacial polymerization on the surface of a substrate layer. Nanomaterials in various concentrations (0.01, 0.05 and 0.1 w/v%, this concentration of nanomaterials was selected based on literature review) were dispersed in 2% (w/v) amine aqueous solution and sonicated for 2 h at 25°C–26°C followed by stirring for 30 min at the same temperature to avoid nanotubes agglomeration. The incorporation of nanomaterials into PA layer was carried out by taking the nanomaterials in aqueous amine solution due to their better dispersion. Amine aqueous solution was poured onto the top surface of the substrate, which was held horizontally for 2 min to ensure the penetration of amine solution into the pores of the substrate. The excess amine solution was then drained off from the substrate surface, and a rubber roller was employed to remove the residual droplets of amine solution. Now, 100 mL of 0.1% (w/v) acid solution in *n*-hexane was poured onto the substrate surface. The acid solution was drained off from the surface after 1 min contact time. After that, the TFN-FO membrane was cured at 80°C in an oven for 5 min. The unreacted amine and acid from the TFN membrane surface were removed by rinsing with pure *n*-hexane, and the membranes were dried at 25°C–26°C. All the prepared membranes were stored in a DI water container until they were tested.

2.6. Membrane characterization

The IR spectra of the modified nanoparticles were recorded using ATR-IR spectrometer from Bruker. The spectrum was recorded in the range of 600–4,000 cm^{-1} by directly placing the samples on the diamond prism followed by 32 scans. The TEM images of the modified TNTs were recorded using LVEM5 instrument (Delong America). The surface morphology of the membranes was recorded using Keysight 8500 field emission scanning electron microscope, and the imaging was conducted with back scattering electrons (BSE) mode to overcome charging effect. The surface contact angles of the membranes were recorded using optical contact angle and interface tension meter from USA KINO, model-SL200KB. The surface AFM images of the membranes were recorded using Concept Scientific Instrument (Nano-Observer), France, by scanning the membrane surface over 5 × 5 μm dimensions.

2.7. Determination of FO performance

FO experiments were conducted through a laboratory scale fabricated FO setup (Fig. 2). It consisted of PTFE cross-flow FO cell with outer dimensions of 12.7 × 10 × 8.3 cm (Sterlitech, USA), two pumps to maintain feed and DS flow (KNF, USA), and two flow meters (Blue-White Industries). The cross-flow velocity of both solutions was fixed at 8.0 cm/s, and the temperature was maintained at 25°C ± 0.5°C. The membrane coupons were inserted in the membrane cell in two different orientations: active layer facing the feed solution (AL-FS) mode and active layer facing the draw solution (AL-DS) mode. In this study, the aqueous solutions with concentrations of 2 M NaCl and 10 mM NaCl were used as draw and feed solutions, respectively. The high-performance membrane from each series was further subjected to flux and RSF study at two other concentrations of DS (0.5 M and 1.0 M). The FS concentration was maintained at same concentration of 10 mM NaCl to study the impact of DS concentrations on the flux as well as RSF values of the membranes. The water flux of the FO process, J (L/m^2h), was calculated from the volume changes of the draw solution and DI water using Eq. (1).

$$J = \frac{\Delta V}{A \Delta t} \quad (1)$$

where ΔV (L) is the volume change over a predetermined time Δt (h), and A is the effective membrane surface area (m^2).

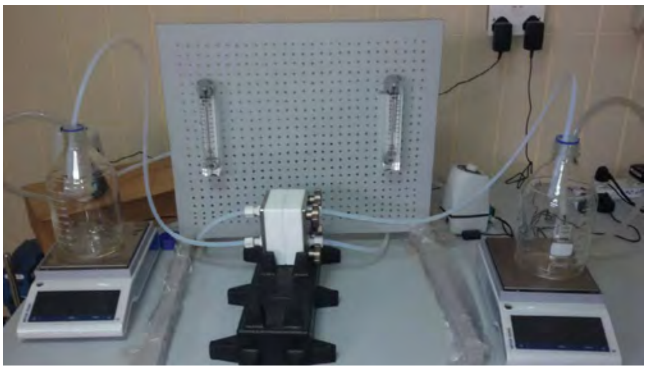

Fig. 2. Self-fabricated lab-scale FO performance test unit.

The RSF is a measure of the diffusion of draw solute to the feed solution during the FO process. To determine the RSF value, the concentration of back diffused DS was measured in terms of conductivity using a calibrated conductivity meter (ORION STAR A-221 model, Thermo Scientific). The RSF, J_s (gMH), was determined using Eq. (2).

$$J_s = \frac{\Delta C_t V_t}{A \Delta t} \tag{2}$$

where C_t (g/L) and V_t (L) are the reverse solute concentration and the volume of the feed solution, respectively, at an arbitrary time t.

3. Result and discussion

3.1. Characterization of ATNT and PHNT

3.1.1. FTIR analysis

For ATNT as shown in Fig. 3, a broad peak around 3,259 cm^{-1} is due to the $-NH_2$ of ATNT merged with the peak of partly unreacted –OH groups of TNT (Wang et al. 2013). The presence of two absorption peaks at 1,102 and 1,213 cm^{-1} correspond to stretching frequencies of Si–O and C–N, respectively. Meanwhile, the peak at 2,894 cm^{-1} is due to stretching vibration of Ti–O in modified TNTs (Niu and Cai, 2009).

Fig. 4 shows the ATR-IR spectra of the HNTs and PHNTs. The HNT spectrum showed absorption peaks at 3,694 and 3,625 cm^{-1} due to the stretching vibration of the –OH groups. The peak at 909 cm^{-1} attributed to the bending vibration of the Al–OH bonds and the spectral band at 1,020 cm^{-1} corresponds to the stretching vibration of Si–O bonds. Compared with HNT spectrum, the modified PHNT displayed additional bands at 1,496 and 1,615 cm^{-1} assigned to aromatic C-C stretching vibrations of symmetric and asymmetric modes, respectively (Gunasekaran et al. 2007). The PHNT spectrum displayed a broad peak in the range of 3,200–3,422 cm^{-1} corresponding to the –OH groups of the polydopamine. Also, additional peak appeared at 1,651 cm^{-1} corresponds to the carbonyl group of polydopamine confirmed the polydopamine surface modification of the HNTs.

The TEM images of the both ATNT and PHNTs are presented in Fig. 5. The image of ATNT and HNTs displayed

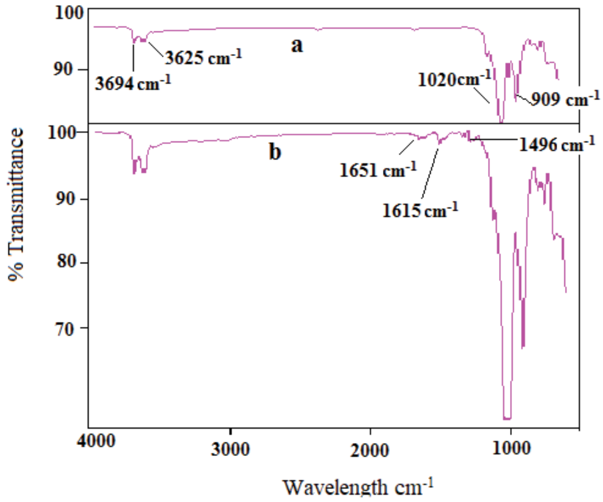

Fig. 4. FTIR spectra of HNT and PHNT.

tubular structures with varying length of 100 to 500 nm. The modification of HNTs resulted in thicker HNTs and increased the thickness of about 20–25 nm compared with neat HNTs. Overall, TEM results further supported the formation of polydopamine layer on the surface of the HNTs as observed by the previous researchers (Chao et al. 2013).

3.2. Characterization of membranes

3.2.1. Morphology of membranes

The surface images of TFN membranes clearly indicated the formation of porous ridge-valley structures by the loading of 0.05 wt% of CMWCNT, PHNT and ATNT into PA layers, respectively (Fig. 6). The chemical modification of nanoparticles enhanced the hydrophilicity of the nanoparticles which favoured the movement of nanoparticles to the surface of membranes during interfacial polymerization reaction to form polyamide layers. Hence, the loading of nanoparticles resulted in ridges and valley structures.

3.2.2. Roughness of the membranes

It is well known fact that the incorporation of nanoparticles into the PA layer will increase the surface roughness

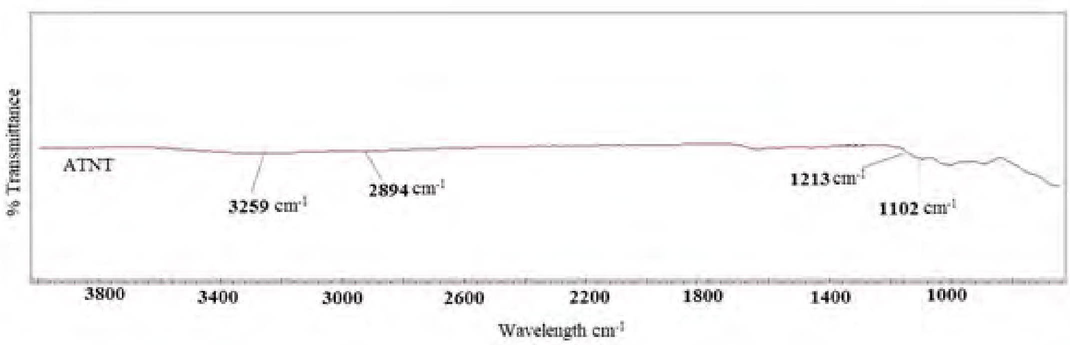

Fig. 3. FTIR spectra of ATNTs.

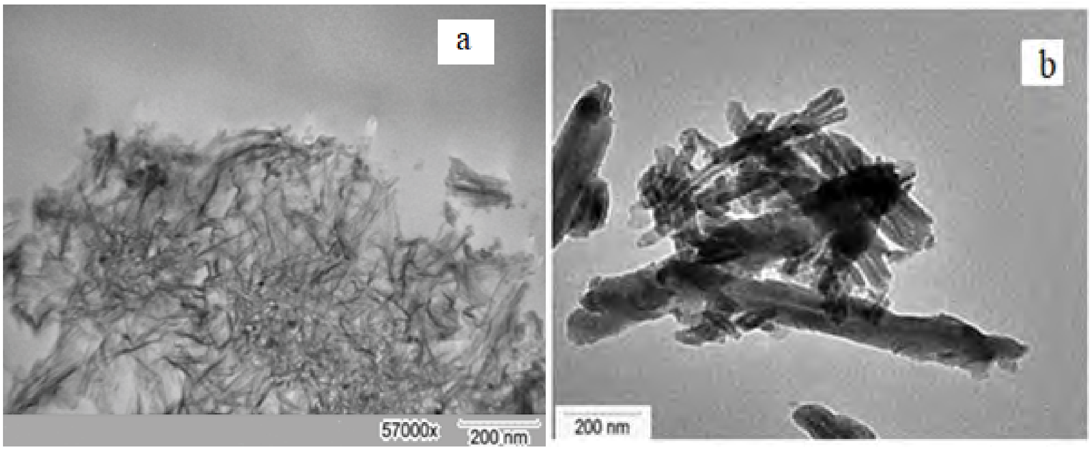

Fig. 5. TEM images of (a) ATNT and (b) PHNT.

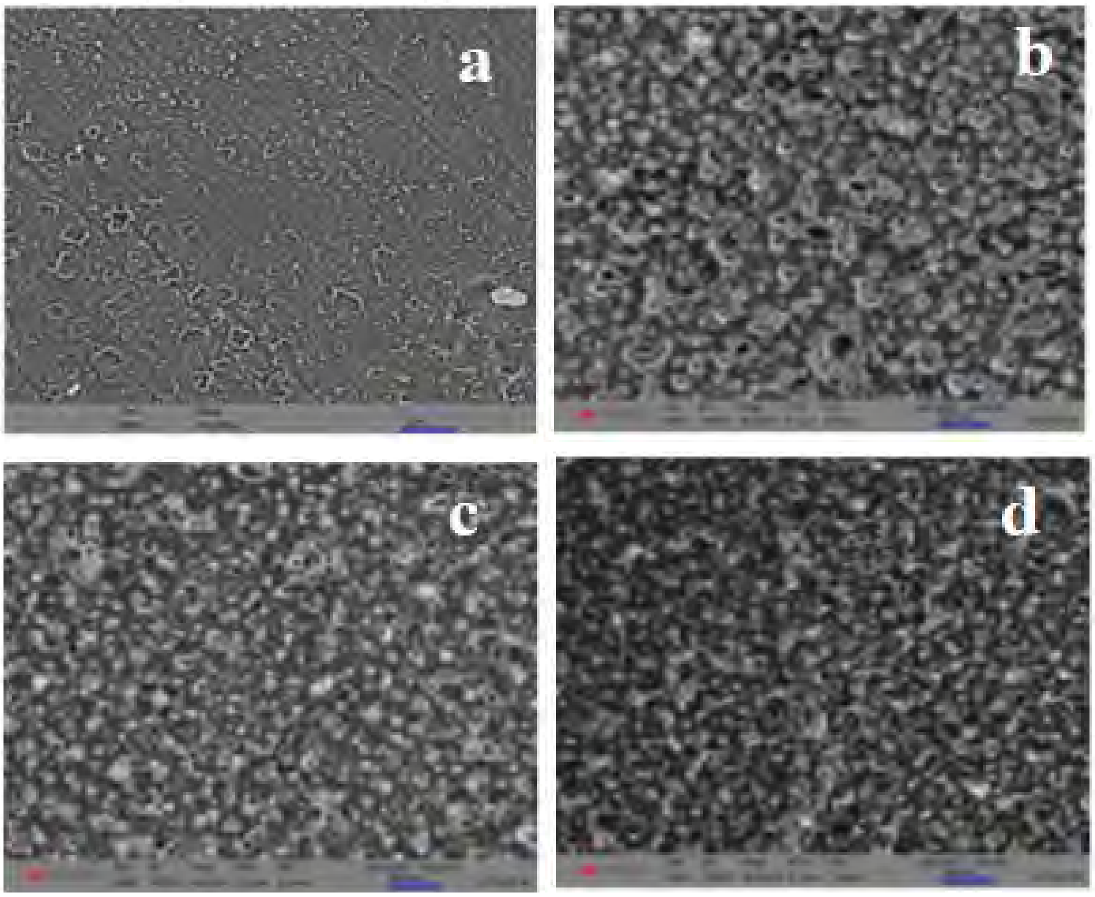

Fig. 6. Surface FESEM image of (a) control TFC membrane, (b) TFN-0.05 ATNT, (c) TFN-0.05 CCNT and (d) TFN-0.05 PHNT membranes.

values of the membranes. This could be explained by the fact that during the formation of PA layer via interfacial polymerization reaction the nanoparticles tend to partly agglomerate on the surfaces leading to more ridges and valleys as observed under SEM images. From Fig. 7, the increase in average roughness value is quite high for the loading of 0.05 wt% of CMWCNT might be due to quite higher hydrophobic characteristics of these nanoparticles compared with ATNT and PHNT.

3.2.3. Hydrophilicity of membranes

The lower value of contact angle signifies higher hydrophilicity of the membrane surface. The control TFC membrane

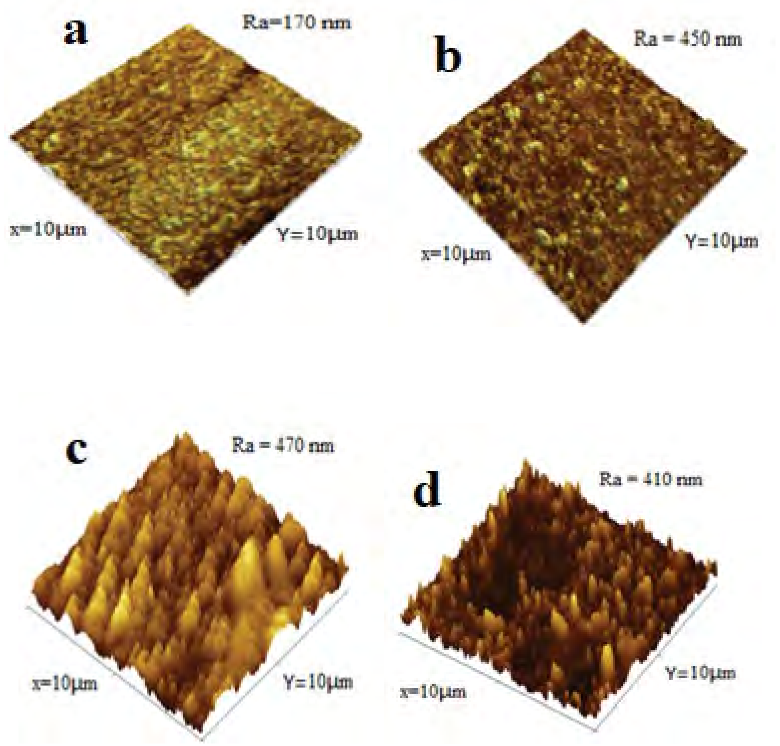

Fig. 7. Surface 3D AFM images of (a) control TFC membrane, (b) TFN-0.05 ATNT, (c) TFN-0.05 CMWCNT and (d) TFN-0.05 PHNT membranes.

Table 1
A detailed comparison of the FO performance between the different membranes prepared in this work and commercial FO membranes

Membrane	FO flux	PRO flux	RSF ($g/m^2 h$)/FO	RSF ($g/m^2 h$)/PRO	Remarks
HTI CTA flat sheet	13.5	25	5.0	10.4	Commercial cellulose acetate flat sheet FO membrane selected for comparative study
Sterlitech flat sheet	14	26.5	2	4.2	Commercial TFC FO membrane selected for comparative study
HTI TFC flat sheet	30	59	4	10	Commercial TFC FO membrane selected for comparative study
TFC control	12.2	20.4	2.8	4.3	Control TFC membrane
TFN-0.05ATNT	19.4	30.3	2.3	4.0	TFN membrane prepared by loading of 0.05 wt% ATNT into PA layer; produced high flux; relatively less RSF
TFN-0.05CMWCNT	18.2	28.6	2.8	3.7	TFN membrane prepared by the loading of 0.05 wt% CMWCNT into PA layer; produced high flux; relatively less RSF
TFN-0.05PHNT	17.6	28.4	3.2	4.8	TFN membrane prepared by the loading of 0.05wt% PHNT into PA layer; produced high flux; relatively less RSF

exhibited a contact angle of 59.02° and the loading of ATNT, PTNT and CMCNT has reduced the contact angle values to 53°, 52° and 56 °, respectively, representing least hydrophilicity of membrane with PHNT particles.

3.2.4. Membrane FO performance

The FO performance in terms of flux was improved by the loading of nanoparticles and 0.05 wt% loading was the optimized loading composition for any nanoparticles selected in the study. The FO performance of the TFC control membrane and TFN membranes are presented in Table 1. Extra pores formed on the STNTs surfaces by sintering effect might create additional channels for the transport of water molecules. Also, the PHNTs possess tubular morphology and their incorporation into membrane matrix provided inner nano channels that improved the water flux (Hummer et al. 2001). This increased flux is due to the formation of new nano pathways created by nanotubes for the extra passage of water molecules (Emadzadeh et al. 2015). The presence of the water channel through the hollow nanotubes and the void between the nanotubes and polyamide matrix contributed to the improved flux of TFN membranes. The maximum flux was observed when active layer facing DS mode (PRO mode). This is due to the higher resistance offered by the top dense layer for the penetration of draw solute molecules in PRO mode (Amini et al., 2016). Though the RSF of the TFN membranes is higher than the TFC membrane, this increased RSF is much lower compared with drastic improvement in flux of the TFN membranes at both FO and PRO modes.

4. Conclusions

The nano-based FO membranes fabricated in this work demonstrated a better performance than commercial HTI CTA flat sheet and Sterlitech flat sheet membranes. The general optimized protocols were developed for the fabrication of different nano-based FO membranes. The characterization data provided the morphological, and chemical characteristics of the newly fabricated FO membranes in favour of FO desalination applications. The correlation study between membrane characterization and its performance result demonstrated the potentiality of the high-performance FO membrane towards their large-scale fabrication. The incorporation of modified ATNT, CMWCNT and PHNT with hydrophilic chemical functional groups into polyamide layer of TFN FO membranes improved the performed better than commercial FO membranes. However, most recently HTI, USA, was successful in commercializing cellulose triacetate based TFC membrane with a maximum FO flux 30 L/m^2 h and considered as the highest performer in FO desalination research. Hence, FO membrane fabrication work is not limited to the polymers selected in this project and a further research is recommended to identify the other polymers for potential FO membrane fabrication.

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Development of solar absorbing nanoporous membranes for direct solar seawater desalination

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ABSTRACT

Because of the abundance of solar energy, solar-based desalination is an attractive technology to meet the ever-increasing water demand. In this study, we develop efficient, low cost, and optimized nanoporous membranes for direct solar desalination of seawater. Our objective is to develop a black-body like membrane that maximizes solar absorption via the structure design and coating. To fabricate our envisioned solar absorbing membranes, we developed two different and distinct approaches, the first being a flat-sheet membrane via phase inversion and the second via chemical vapor deposition. The absorbance for each membrane was measured using a UV(vis) spectrometer. The structures of the prepared membranes were characterized and observed by scanning electron microscopy and atomic force microscopy. The meanflow pore size, bubble point pore size and pore size distribution were measured using a capillary flow porometer. Also, the porosity was calculated experimentally using a gravimetric method using Salwick as a wetting liquid. Contact angle measurements were also performed to know the hydrophobic/hydrophilic nature of the membranes. In CNT, the absorption and the porosity increase as the PVDF concentration decreases while the contact angle increases as the PVDF concentration increases. The contact angle measurements for the AC and graphene membranes with different rates decrease with the increase of the activated carbon and graphene percentage in the membrane. The graphene has the highest absorption form all the membranes approximately 97%.

Keywords: Membrane distillation; Polyvinylidene fluoride; Hydrophobic; Coating

1. Introduction

In nature solar energy is the primary driving force for the formation of fresh water from oceans and seas. The energy demands and combined the need for freshwater is particularly challenging, due to the arid, humid, dry, hot and a desert environment with frequent dust storms in the Arabian Gulf region. Because of the abundance of solar energy, solar-based desalination is an attractive technology to meet the ever-increasing water demand.

The main purpose of this research proposal is looking up in developing the water desalination system, which at the end can be combined into the spectral splitting configuration. Other water desalination can be from these advancements too. In water desalination system proposal, the solar energy is absorbed into a nanoporous membrane with a spectrally eclectic surface. By this method, thermal energy can be possessed maximally with less radiative losses. The water will evaporate from top of the nanopores after the heat is delivered to the membrane. Using a condenser, the generated vapor is condensed to produce a clean water as shown in the below figure. The membrane design and development is the key novelty of the work. Specifically, the membrane has to have high rate of desalination (evaporation), spectral selectivity in order to maximize the solar radiation absorption, anti-fouling in order to lessen significant clogging and decreases efficiency over time.

Membranes can be fabricated using many types of materials, polyvinylidene fluoride (PVDF) is an attractive MD membrane material, which can be made into membranes via phase inversion. It has low surface energy, good thermal stability and low conductivity. Also, activated carbon was used as active materials for its high capacitance performance and the low-cost attribute. Carbon nanotube (CNT) which is large molecules of pure carbon that are long, thin, and it has a shape such as tubes with diameter in nanoscale.

2. Statement of the problem

Water scarcity is a major global challenge. While many large-scale technologies are being developed for clean water such as reverse osmosis and multi-stage flash, high energy

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demand can make it impractical, especially for point-of-use systems and remote infrastructure. Solar-based desalination is an attractive alternative with the abundance of solar energy.

In this study, we develop efficient, low cost and optimized nanoporous membranes for direct solar desalination of seawater. However, in order to do that, we will fabricate and experimentally characterize various polymeric membranes towards a low-cost approach. We will also explore various solar absorber coatings that can effectively maximize the heating of the membrane with minimal losses.

3. Objectives

In this study, we develop efficient, low cost and optimized nanoporous membranes for direct solar desalination of seawater. Our objective is to develop a black-body like membrane that maximizes solar absorption via the structure design and coating. The structural design involves hierarchal structures with increased roughness and hence forth increased surface area available for solar energy absorption. This is done via simple and low-cost phase inversion membrane fabrication techniques developed within our labs. The blackbody-like membranes we develop should poses high thermal conductivity, which is the other objective we focus on in this investigation.

4. Materials and methods

4.1. Materials

Polyvinylidene fluoride (PVDF) polymer (HSV900, Mw 92,840 kDa, Arkema, Colombes, France), dimethylacetamide (DMAC, Sigma-Aldrich, St. Louis, NA, USA) as a solvent, deionized (DI) water as the polymer and non-solvent, non-woven support (Novatexx 2471, donated by Freudenberg-filter, Weinheim, Germany), activated charcoal and graphene nanoplatelets.

4.2. Membrane preparation

4.2.1. AC and graphene nanoplatelets membranes

In a typical synthesis, PVDF (12 g) was first dissolved in dimethylacetamide (DMAC) under magnetic stirring to obtain a clear homogeneous solution. AC was added under magnetic stirring and ultrasonication to obtain a clear homogeneous solution. Then, the polymer solution was cast on a non-woven support at room temperature using a doctor blade with adjustable height to give a wet-casting thickness of 500 µm, which was immediately immersed in a coagulation bath of deionized water at 20°C. Finally, the membranes were dried in vacuum oven at 60°C for 24 h. The mass of AC used were 7, 9 and 12 g. A number of membrane samples were prepared via phase inversion which was similar to the AC membrane preparation but by replacing the AC by graphene nanoplatelets. The mass of graphene nanoplatelets used were 7, 9 and 12 g.

4.2.2. CNT membranes

Using the mass balance to measure the required amount of CNT and PVDF depend on the sample's concentration of PVDF, with a constant total mass of 800 mg for all the samples. Then, dissolve the CNT and PVDF in a mortar with 50 mL of the mixture of DI water and ethanol, then grind with a pestle for 2 min. Pour the 150 mL of DI water and ethanol in a beaker with grinded CNT and PVDF with magnetic stirrer. The solution was mixed under magnetic stirring and sonicated to obtain a clear homogeneous solution for 15 min. Then, the solution was cast on a copper sheet using a doctor blade with thickness of 5 mm. Finally, the membranes were dried in oven at 120°C for 1 h.

4.2.3. Chemical vapor deposition

To fabricate our envisioned solar absorbing membranes, we developed a flat-sheet membrane via chemical vapor deposition., we use anodised aluminium oxide membranes as the base material and grown high absorbance blackbody like multilayer three-dimensional graphene coating which grows on the top and bottom surface of the membrane and within the nanoporous structure.

4.3. Membrane characterization

The absorbance for each membrane was measured using a UV(vis) spectrometer. The structures of the prepared

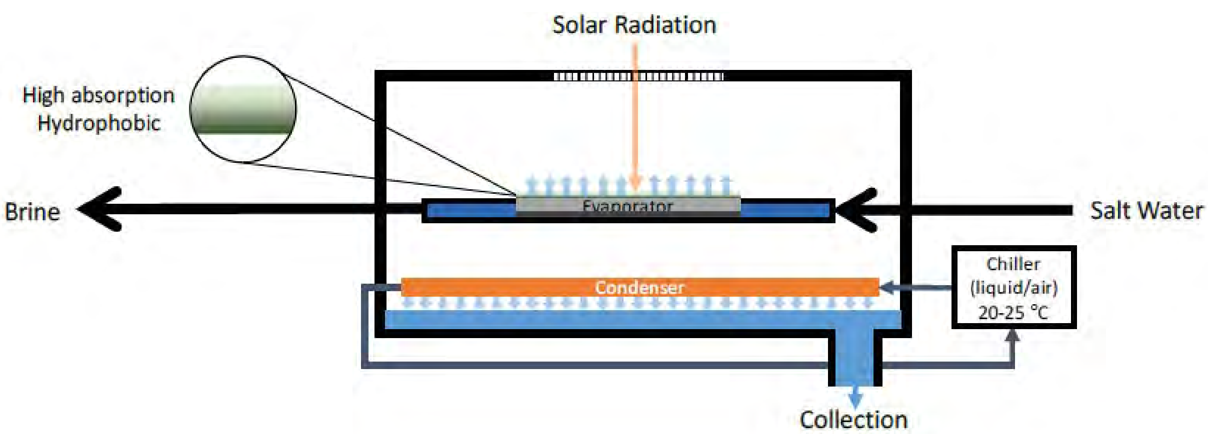


Fig. 1. Nanoporous evaporator based desalination device.

Fig. 2. CNT membrane fabrication.

membranes were characterized and observed by scanning electron microscopy (SEM) and atomic force microscopy. The mean flow pore size, bubble point pore size and pore size distribution were measured using a capillary flow porometer. Also, the porosity was calculated experimentally using a gravimetric method using Salwick as a wetting liquid. Contact angle measurements were also performed to know the hydrophobic/hydrophilic nature of the membranes.

4.4. Evaporation experiments

All membranes are tested in a device fabricated specifically for the purpose of this study (Fig. 3). The membranes are tested for their ability to evaporate seawater using direct sun light. Measurements of mass fluxes and temperatures are taken, and the overall efficiency of the device is calculated. This study aims at demonstrating these solar absorbing membranes as the core enablers for future direct solar desalination technologies.

5. Results and discussion

The contact angle (CA) measurement is a way to describe the hydrophobic or hydrophilic behavior of a material. In principle, it provides information about the wettability of an ideal surface. In most cases, the intrinsic value of

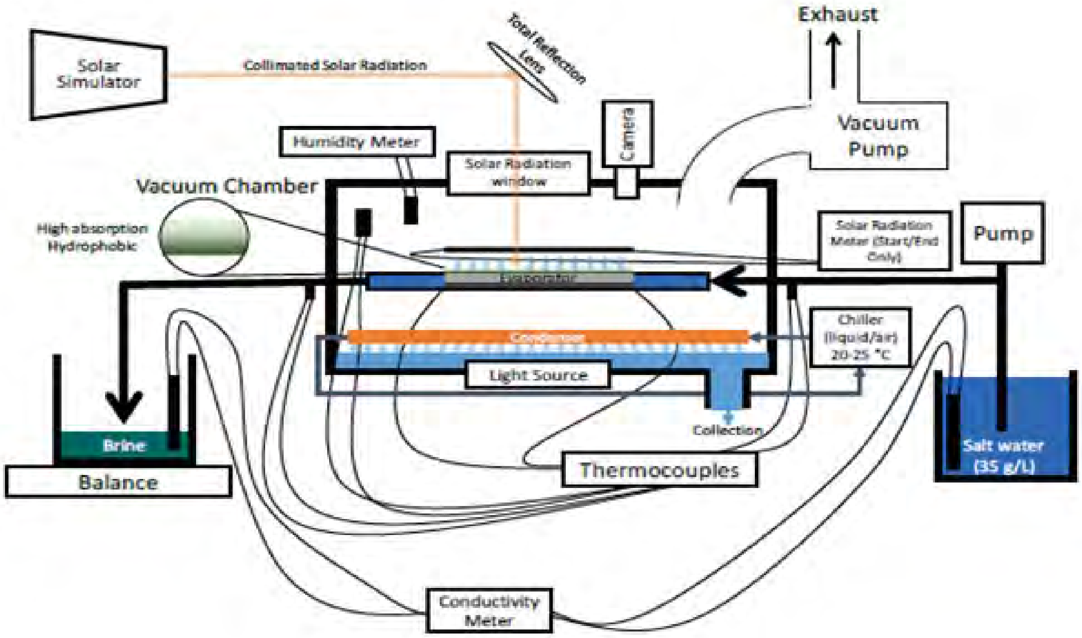


Fig. 3. Experimental setup for membrane characterization.

Table 1
Membranes properties with casting thickness of 500µm and PVDF concentration of 12% (w/w)

Chemicals	Mass (%)	CA (°)	Porosity (%)	Absorbance (%)
PVDF	12	95.5	28.6	9.1
Activated carbon	7	83.6	31.91	94.39
	8	81	34.91	94.40
	11	74	40.21	95.33
Graphene	7	74.6	29.02	96.29
	8	68.6	35.98	97.25
	11	66	45.41	97.99

contact angle is perturbed by surface porosity and roughness, heterogeneity, etc. (Drioli et al. 2006).

If the affinity between liquid (droplet) and solid is low on a smooth surface is greater than 90°m the material is considered hydrophobic (Drioli et al. 2006).

The contact angle measurements for the AC and graphene membranes with different rates of mass found that for each membrane, the contact angle decreases with the increase of the activated carbon and graphene percentage in the membrane. However, the contact angle of CNT increases as PVDF% increase and it seems all are hydrophobic.

The absorbance of AC, graphene and CNT membranes were measured using a UV(vis) spectrometer.

5.1. Scanning electron microscopy

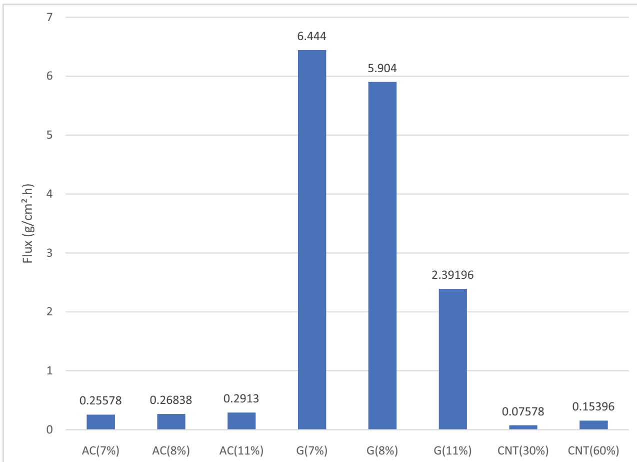
The microstructures and morphologies were characterized by field emission scanning electron microscope. The SEM observations of the membrane samples and the samples were mounted with conductive glue to metal stubs and then coated with gold by sputtering. These samples were then viewed in the SEM at different magnification.

SEM images of the PVDF membranes with different percentages of activated carbon and graphene nanoplates are shown in Figs. 4 and 5.

Table 2
Membranes properties of CNT

Chemicals	PVDF (%)	CA (°)	Porosity (%)	Absorbance (%)
CNT	30	103.9	32.23	95.5
	45	115.18	22.92	94.9
	60	104.25	20.94	94.4
	75	108.1	19.44	94.2

5.2. Flux result from evaporation experiment



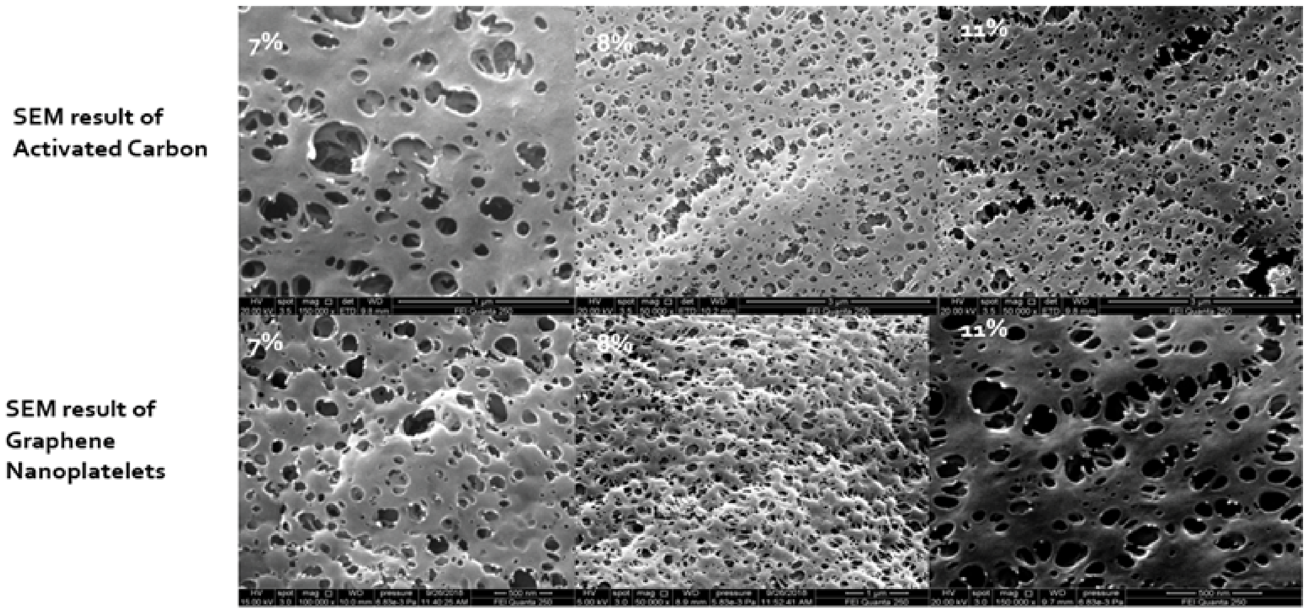


Fig. 4. SEM photo of AC and graphene nanoplates.

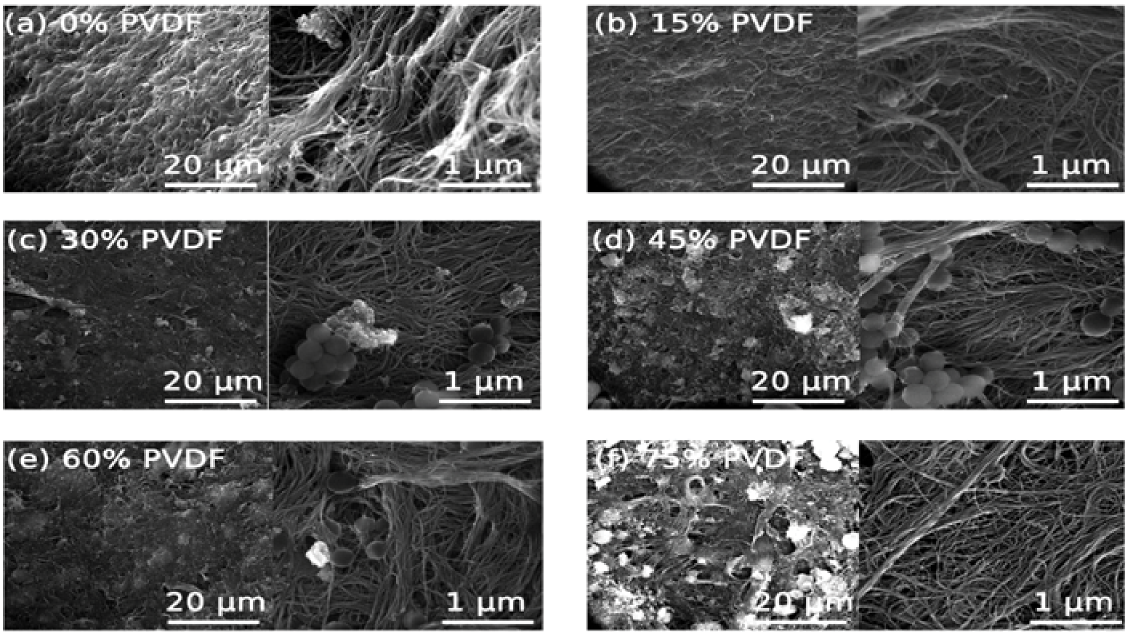


Fig. 5. SEM photos of CNT membranes.

6. Conclusion

As a results, from CNT membranes, the absorption and the porosity increase as the PVDF concentration decreases while the contact angle increases as the PVDF concentration increases. The contact angle measurements for the AC and graphene membranes with different rates decrease with the increase of the activated carbon and graphene percentage in the membrane. Also, it was found from SEM that activated carbon can enhance considerably the porosity of the membrane. The contact angle and the hydrophobic characteristic decrease with the increase of the activated carbon concentration in the membrane. Graphene membranes resulted in high evaporation flux. The complete set of results and the result of evaporation experiment will be analysis and be included in the full submission.

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Experimental study on effect of different mass flow rate in an inclined solar panel absorber solar still integrated with spiral tube water heater

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ABSTRACT

This paper aims to analyze the performance of the inclined solar panel basin (ISPB) still integrated with a spiral tube collector (STC) at diversified mass flow rate of water (m_f). The maximum freshwater obtained at the m_f at 1.8, 3.2 and 4.7 kg/h is 8.1, 6.9 and 6.1 kg, respectively. The daily average thermal and exergy efficiency of the ISPB still integrated with the STC at the m_f at 1.8, 3.2 and 4.7 kg/h is 47.9%, 39.3% and 31.02% and 9.8%, 7.9% and 5.6%, respectively. When the m_f increases, there are a decreases in the still distillate yield, thermal and exergy efficiency.

Keywords: Active inclined solar panel basin solar still; Effect of mass flow rates; Freshwater

1. Introduction

Sustainable power source plays an important role in the movement of worldwide advancement in various routes because of its feasible nature. The developing interest for utilization of limited energy sources has expanded extensively over a time of a very long while, to the detriment of nature. This has prompted the development of a few natural issues, for example, a dangerous atmospheric change in some countries and the increasing of the demand for potable water. Solar energy-based desalination is a potential solution for the shortage of freshwater, because of the plenitude and accessibility of both salt water and sun energies (Manokar et al. 2018).

Alaudeen et al. 2018 researched a stepped tray basin sequential solar still with the inclined flat plate collector (FPC) together with a conventional basin type solar still. The experiments were conducted by the wick, the wick with coconut coir and sponge, the wick with wooden chip and pebbles, the wick with sand and wick with coal, pebbles and sponge. Results of the proposed system were compared with the CSS. It was found that an integrating the FPC with wick and sponge, wick and rock, sponge produced the maximum distilled of about 1,305 and 1,745 kg/m^2, respectively. Sharon et al. 2017 fabricated the ISS with partitioned absorber and wick absorber and conducted the experiments on the ISS at two different conditions (i) the ISS with splitting the absorber for reducing the volume of the basin water. (ii) the ISS with a black blended woolen wick. It was reported that the ISS with partitioned absorber and wick basin produced the maximum yield of about 4.475 and 4.620 L, respectively. Hansen et al. 2015 studied the ISS with innovative wick materials and wire mesh in the absorber plate. In this experiment, three different absorber plates were used (i) flat absorber plate, (ii) rectangular stepped absorber plate, (iii) weir absorber. The freshwater production was increased about 71% in the case of weir mesh absorber plate with water coral fleece than the flat absorber plate. Naveen Kumar et al. 2017, Panchal et al. 2018 and Kabeel et al. 2019 theoretically studied the performance of triangular pyramid solar still (TPSS) integrated to the ISS with baffles. Theoretical analysis has been made by varying the water mass in the TPSS (20 to 100 kg). It was submitted that the TPSS and the TPSS integrated with the ISS produced the maximum hourly productivity of 0.6 and 1.3 kg/m^2, respectively, at 20 kg of water mass. The maximum daily productivity from the TPSS and the TPSS integrated with the ISS was 3.2 and 7.2 kg/m^2, respectively, at minimum water depth. It was submitted that as increasing the water mass from 20 to 100 kg, the

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yield from the still decreases about 6%–46% at morning and increases about 46%–86% at evening. The reason for higher productivity at evening was water storage effect. Higher the water mass in the basin can store the available heat energy and produced the yield at evening and night time. The effect of insulation on the performance of the inclined solar panel basin (ISPB) still and the comparative studies of the passive and active ISPB still was studied by Manokar et al. 2018. From the literatures, it is inferred that only research was carried out an active ISS. Hence the main objective of the present study is experimental investigation on ISPB still integrated with the spiral tube collector (STC) at different mass flow rate of water.

2. Design and construction of the ISPB still integrated with the STC

In an ISPB still integrated with the STC, the salt water from the cylindrical water storage tank is fed into a solar water heater at a constant m_f. The water flowing inside the absorber tube of solar water heater gets heated and heated water is again fed into the passive ISPB still. The schematic diagram of the ISPB still integrated with the STC is shown in Fig. 1. The photographic view of the ISPB still integrated with the STC is shown in Fig. 2. A STC solar water heater was fabricated comprising of a flat spiral tube solar collector, storage tank and control valve. The flat collector of 0.9 m (L) × 0.6 m (W) × 0.004 m (H) was fabricated with 20 mm thickness wooden box covered with 4 mm thick window glass. This water heater was mounted on supporting steel structure. 10 mm diameter and 1 mm thick copper tube in spiral shape with three winding (with 50 mm gap between successive windings) was used to circulate water in the collector. Cylindrical storage tank made up of plastic with 50 liters capacity was mounted on a steel stand.

3. Results and discussion

3.1. Hourly variations of solar irradiance, wind speed, atmospheric temperature and collector cover temperature

Variations of the solar intensity and atmosphere temperature during the study of an ISPB still integrated with the STC are shown in Figs. 3a and b. From the graph, it is clear that at the morning session solar intensity increases and reached its peak value at 1 P.M and at the evening session it is decreasing. The maximum solar intensity of 880, 870 and 900 W/m^2 and the daily average solar intensity of 699, 696 and 719 W/m^2 are noted on 1.8.2017, 4.8.2017 and 6.8.2017, respectively. The maximum atmosphere temperature of 33°C, 32°C and 35°C is noted on 1.8.2017, 4.8.2017 and 6.8.2017, respectively. During the experimental day, the daily average atmospheric temperature is between 30°C and 33°C.

Variations of wind speed and the collector cover temperature during the study of an ISPB still integrated with the STC are plotted in Figs. 4a and b. During the investigational day, the daily average wind speed is noted as 1.1, 1.8 and 2 m/s on 1.8.2017, 4.8.2017 and 6.8.2017, respectively. The maximum collector cover temperature of an ISPB still integrated with the STC is 53°C, 52°C and 47°C on 1.8.2017, 4.8.2017 and 6.8.2017, respectively. The daily average collector cover temperature of 47.1°C, 45°C and 43.2°C is measured for the wind speed of 1.1, 1.8 and 2 m/s, respectively.

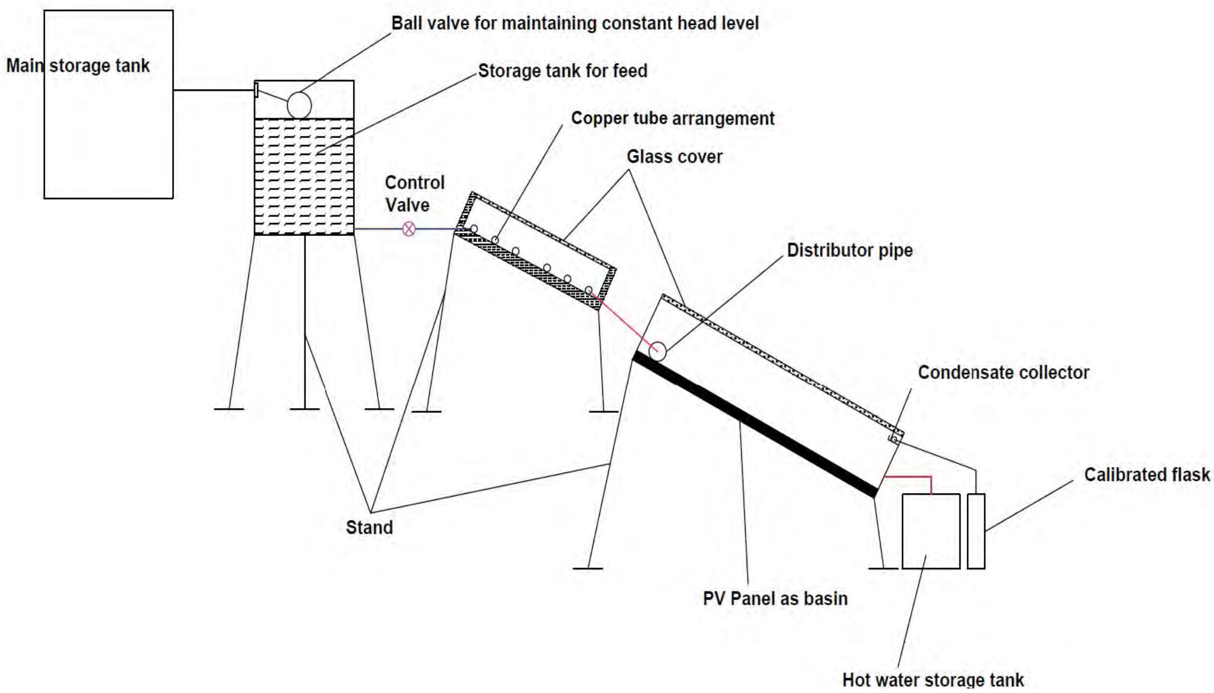

Fig. 1. Schematic diagram of the ISPB still integrated with the STC.

Fig. 2. Photographic view of the ISPB still integrated with the STC.

3.2. Effect of mass flow rate on basin and water temperature of an ISPB still integrated with the STC

Variations of the basin temperature for an ISPB still integrated with the STC under different m_f are plotted in Fig. 5a. Basin temperature increases with increasing of solar intensity and reached its peak value at 2 P.M and after that its value reduced. The maximum basin temperature of 72°C, 69°C and 65°C is obtained for the m_f at 1.8, 3.2 and 4.7 kg/h, respectively. The daily average basin temperature of an ISPB still integrated with the STC at the m_f at 1.8, 3.2 and 4.7 kg/h is 62.1°C, 59.1°C and 55.2°C, respectively. When the m_f increases from 1.8 to 3.2 kg/h and from 1.8 to 4.7 kg/h there are a decreasing of basin temperature of about 4.8% and 11.1%, respectively. An increasing m_f resulted in, higher volume of flowing saline water in an ISPB still basin which results in the lower basin temperature.

Variations of water temperature for an ISPB still integrated with the STC under the different m_f are plotted in Fig. 5b. Water temperature is directly proportional to the basin temperature and it reached the peak value at 2 P.M after that it gets reduced. The maximum water temperature of an ISPB still integrated with the STC at the m_f at 1.8, 3.2 and 4.7 kg/h is 76°C, 73°C and 70°C, respectively. The daily average water temperature of 65.7°C, 63°C and 60.7°C is obtained for the m_f at 1.8, 3.2 and 4.7 kg/h, respectively. The daily average water temperature is reduced up to 4.1% and 7.6% when the m_f increases from 1.8 to 3.2 kg/h and from 1.8 to 4.7 kg/h, respectively. An ISPB still integrated with the STC operates at minimum m_f increases the contact time between the saline water and spiral tube absorber which results in higher water temperature and hence higher productivity. When the m_f increased, the volume of flowing water in the absorber plate increased which reduces the contact time between the saline water and absorber plate and hence produced less productivity.

3.3. Effect of mass flow rate on accumulated yield, thermal and exergy efficiency of an ISPB still integrated with the STC

Variations of EHTC for an ISPB still integrated with the STC at different m_f are shown in Fig. 6a. The maximum EHTC of 94.03, 83.47 and 73.36 W/m^2 K is obtained for an ISPB still integrated with the STC operates under the m_f at 1.8, 3.2 and 4.7 kg/h, respectively. The daily average EHTC for an ISPB still integrated with the STC under the m_f at 1.8, 3.2 and 4.7 kg/h is 64.43, 57.37 and 50.98 W/m^2 K, respectively. There is a 10.97% and 20.88% decreases in daily average EHTC when the m_f increases from 1.8 to 3.2 kg/h and from 1.8 to 4.7 kg/h, respectively. An increasing m_f decreased the saline water temperature and also the EHTC.

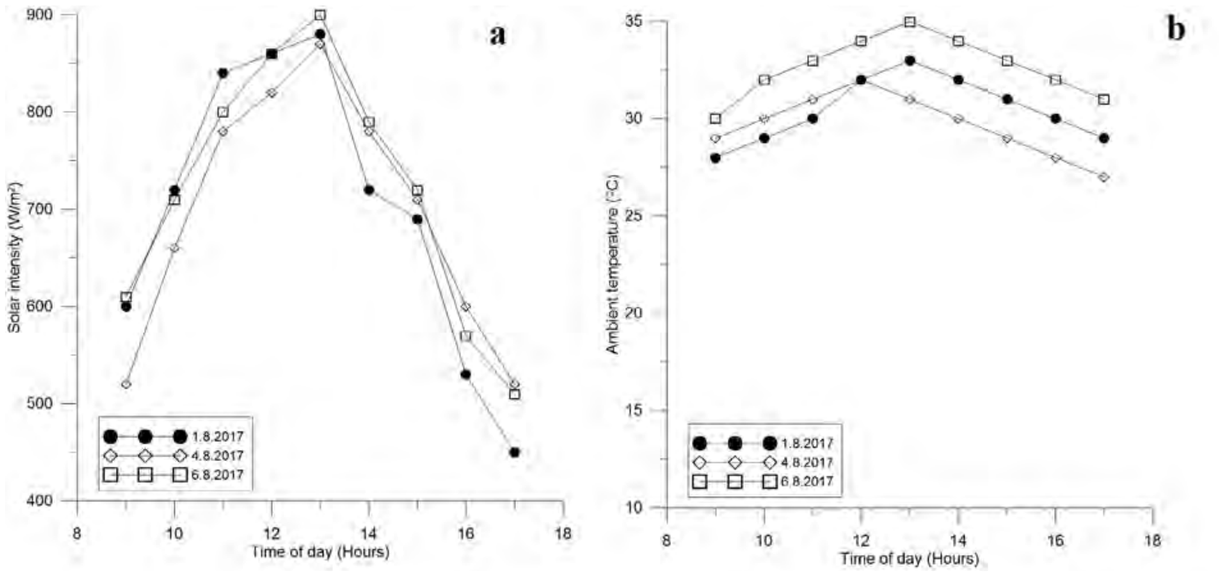

Fig. 3. (a) Diurnal variation of solar intensity, (b) atmospheric temperature.

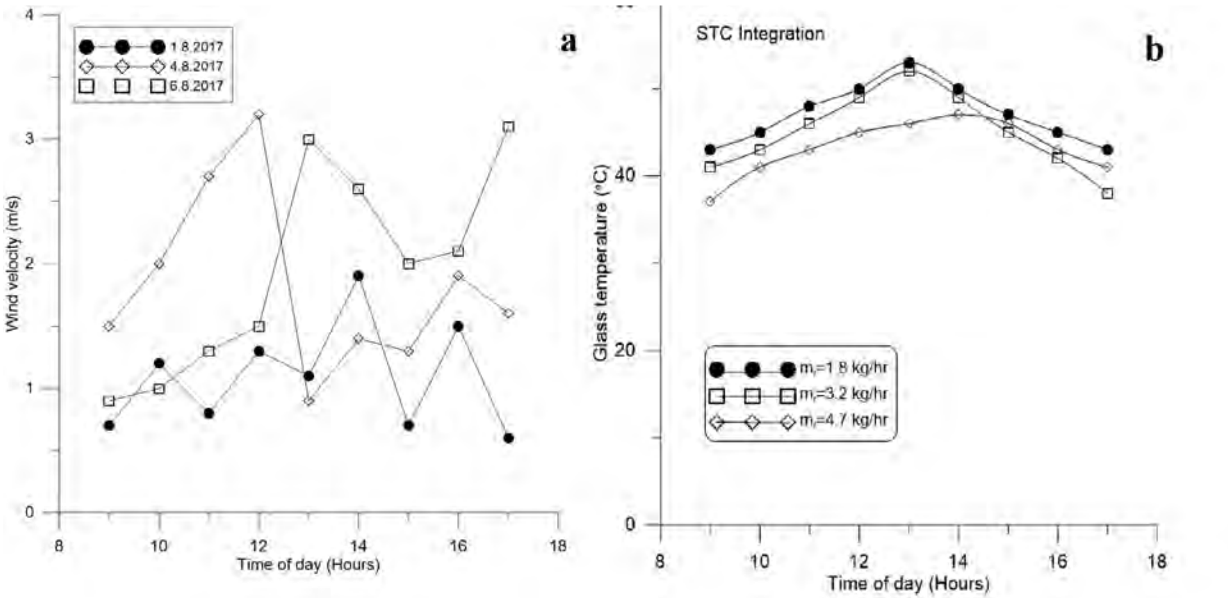

Fig. 4. (a) Diurnal variations of wind speed, (b) collector cover temperature.

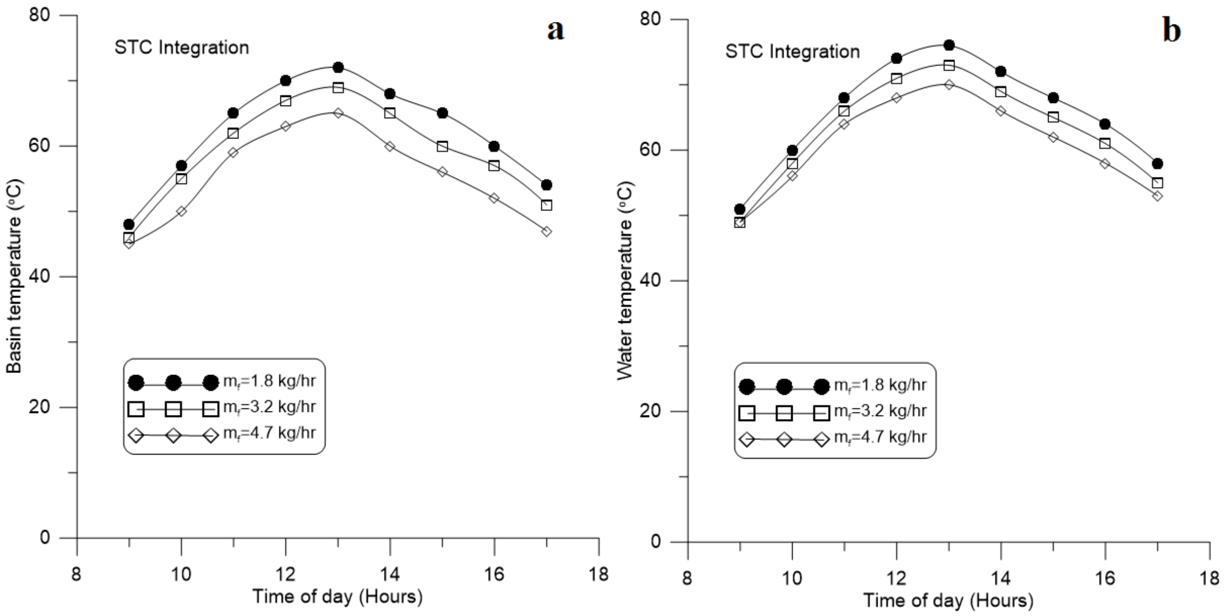

Fig. 5. Hourly variations of (a) basin temperature and (b) water temperature for an ISPB still integrated with the STC.

The EHTC from water to collector cover is given by Manokar et al. 2018:

$$h_{e,w-g} = 16.273 \times 10^{-3} \text{x} h_{c,w-g} \left[\frac{P_w - P_{gi}}{T_w - T_{gi}} \right] \quad (1)$$

The convective heat transfer coefficient from water to collector cover is given by Manokar et al. 2018:

$$h_{e,w-g} = 0.884 \left[\left(T_w - T_{gi} \right) + \frac{\left(P_w - P_{gi} \right)\left(T_w + 273 \right)}{\left(268.9 \times 10^{-3} - P_w \right)} \right] \quad (2)$$

Partial vapour pressure at water temperature is given by Manokar et al. 2018:

$$P_w = \exp\left(25.317 - \left(\frac{5,144}{273 + T_w} \right) \right) \quad (3)$$

Partial vapour pressure at inner surface of collector cover is given by Manokar et al. 2018:

$$P_{gi} = \exp\left(25.317 - \left(\frac{5,144}{273 + T_{gi}} \right) \right) \quad (4)$$

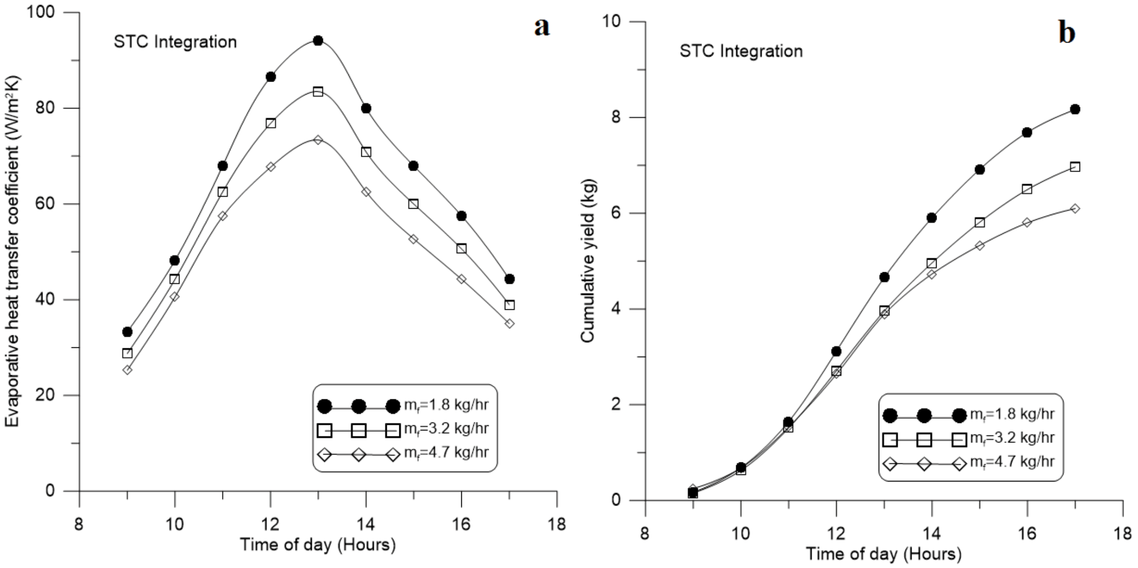

Fig. 6. Hourly variations of (a) EHTC and (b) accumulated yield from an ISPB still integrated with the STC.

Variations of cumulative yield from an ISPB still integrated with the STC at different m_f are shown in Fig. 6b. The maximum daily productivity from an ISPB still integrated with the STC is maximum at minimum m_f. The daily yield from an ISPB still integrated with the STC at m_f at 1.8, 3.2 and 4.7 kg/h is 8.1, 6.9 and 6.1 kg, respectively. The amount of fresh water production mainly depends on the water temperature. It can be seen that water temperature of an ISPB still integrated with the STC increased by maintaining the minimum m_f. It is found that the daily fresh water production rate decreases up to 14.68% and 25.3% when the m_f increases from 1.8 to 3.2 kg/h and from 1.8 to 4.7 kg/h, respectively.

Variations of thermal efficiency of the ISPB still integrated with the STC at different m_f are shown in Fig. 7a. The maximum thermal efficiency of the ISPB still integrated with the STC at m_f of 1.8, 3.2 and 4.7 kg/h is 68.3%, 61% and 54.3%, respectively. It is found that 47.9%, 39.3% and 31.02% daily average thermal efficiency for the ISPB still integrated with the STC at the m_f at 1.8, 3.2 and 4.7 kg/h, respectively. The thermal efficiency of an ISPB still integrated with the STC is decreased when the m_f is increased. There are a 17.9% and 35.2% decreases in daily average thermal efficiency of an ISPB still integrated with the STC when the m_f increases from 1.8 to 3.2 kg/h and from 1.8 to 4.7 kg/h, respectively.

Thermal effectiveness of the ISPB still integrated with STC is given by [13,14]:

$$\eta_{A.\mathrm{th}} = \frac{m_{\mathrm{ew}} h_{\mathrm{fg}}}{\left[A_c \times I_c(t) + A_s \times I_s(t)\right] \times 3{,}600} \times 100 \tag{5}$$

Variations of exergy efficiency of the ISPB still integrated with the STC under different m_f are shown in Fig. 7b. The maximum hourly exergy efficiency of an ISPB still integrated with the STC is 15.5%, 12.5% and 10.2% at m_f at 1.8, 3.2 and 4.7 kg/h, respectively. The daily average exergy efficiency of 9.8%, 7.9% and 51.6% is obtained for the m_f at 1.8, 3.2 and 4.7 kg/h, respectively. Increasing the m_f results in decreasing the exergy efficiency of an ISPB still integrated with the STC. When the m_f increases from 1.8 to 3.2 kg/h and from 1.8 to 4.7 kg/h, the exergy efficiency of an ISPB still integrated with the STC decreases up to 19.3% and 43.7%, respectively.

The exergy efficiency of an ISPB still integrated with the STC is given by Manokar et al. 2018:

$$\eta_{a.e} = \frac{e_{a.\mathrm{out}}}{e_{p.\mathrm{in}} + e_{\mathrm{fpc}.i}} \tag{6}$$

An active exergy output of an ISPB is given by Manokar et al. 2018:

$$e_{a.\mathrm{out}} = \left(m_d \mathrm{x} \mathrm{h}_{\mathrm{fg}}\right)\left(1 - \left[\frac{T_a + 273}{T_w + 273}\right]\right) \tag{7}$$

An active exergy input of an ISPB still is given by Manokar et al. 2018:

$$e_{a.\mathrm{in}} = e_{p.\mathrm{in}} + e_{\mathrm{fpc.in}} \tag{8}$$

An exergy input to the STC is given by Manokar et al. 2018:

$$e_{\mathrm{fpc.in}} = Q_u \left[1 - \frac{T_a + 273}{T_W + 273}\right] \tag{9}$$

Useful heat gained by the STC is given by Manokar et al. 2018:

$$Q_u = \left(1 \times A_p\right) - q \tag{10}$$

Heat lost from the STC is given by [14]:

$$q = \mathrm{UA}\left(T_b - T_a\right) \tag{11}$$

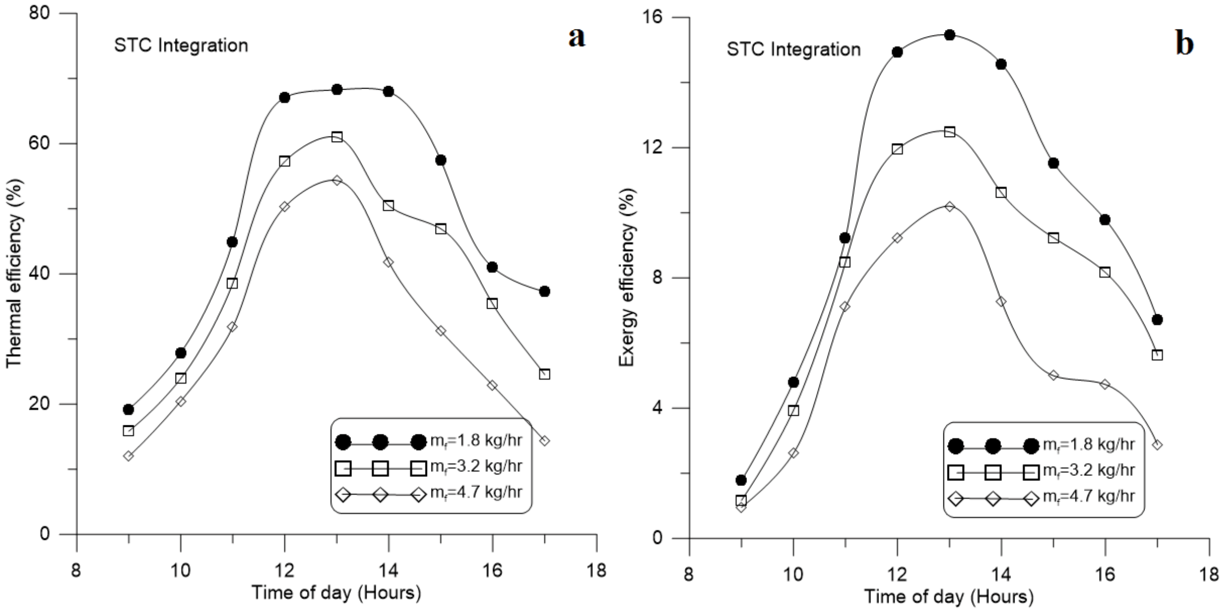

Fig. 7. Hourly variations of (a) thermal efficiency and (b) exergy efficiency of the ISPB still integrated with the STC.

4. Conclusions

The effect of varying different m_f in an ISPB still integrated with the STC was experimentally studied. The results inferred that an increasing m_f reduces the performance of an ISPB still. When the mass flow rate of ISPB still is varied from 1.8 to 3.2 kg/h, the daily productivity, thermal and exergy efficiency of the system decreases about 14.68%, 17.9% and 19.3 %, respectively. Further the mass flow rate of ISPB still is varied to 4.7 kg/h, the daily productivity, thermal and exergy efficiency of the system decrease to about 25.3%, 35.2% and 43.7%, respectively.

Abbreviations

CSS	—	Conventional solar still
EHTC	—	Evaporative heat transfer coefficient
ISPB	—	Inclined solar panel basin
m_f	—	Mass flow rate of water

Nomenclature

A	—	Area, m^2
h	—	Heat transfer coefficient, W/m^{2}K
$I(t)$	—	Solar intensity, W/m^2
L	—	Latent heat of vaporization, kJ/kg K
M	—	Hourly productivity from solar still, kg/m^2 h
P	—	Partial vapour pressure, N/m^2
T	—	Temperature, °C
H	—	Efficiency, %

Subscript

a	—	Ambient
c	—	Convective
d	—	Daily
e	—	Evaporative
g	—	Glass
gi	—	Inner glass
pv	—	Photovoltaic
s	—	Surface area of condensing cover
w	—	Water

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Future prospects for desalination in the GCC countries

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The total area of the Gulf Cooperation Council (GCC) countries is about 2.6 million km^2 with an approximate total population of 53.4 million in 2016. The per capita total renewable water resources (TARWR) in GCC countries in 2014 was just 86.6 cubic meters, compared with the global average of almost 17,575 cubic meters. It is predicted that water availability in the GCC countries will be reduced significantly by 2030.

Desalination is considered the major water supply in the GCC countries. About 63% of the water supply in GCC countries comes from desalination. The current GCC seawater desalination capacity is nearly 18.2 million m^3/d (4,000 MIGD). Conventional water resources such as fresh surface water and renewable groundwater are limited. Reuse of treated wastewater is about 900 million cubic meters, which is equivalent to 31.0% of the total treated wastewater. Treated wastewater is used mainly for irrigating green areas.

It is expected that the total annual GCC water demand will increase by 40% in 2030 and may reach more than 50 billion cubic meters (Bcm). This may lead to a large deficit in the GCC water resources of about 20 billion cubic meter. The GCC countries plan to install and expand more desalination plants to meet the growing domestic water demands.

In this work, the contribution of desalination plants in bridging the gap between supply and demand in the GCC countries will be examined. The future prospects for desalination in the GCC countries depend on integrating established and emerging desalination technologies. Several recently developed desalination technologies promote lower energy consumption based on renewable energies. Nuclear energy offers an attractive and economical alternative source for power generation and water desalination for sustainable development in the energy and water sector.

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Water Treatment Using Nanotechnology Enhanced Membranes

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Membrane filtration has seen an increased demand in recent years especially in water treatment and desalination due to population growth, stringent drinking water and wastewater disposal legislations, and emergence of non-conventional wastewater such as produced water from oil and gas fields. Membranes are used in pre- and post-water treatment as well as in water desalination. In addition, membranes are used in a wide range of industrial, medical and environmental applications. Polymeric membranes are still prevailing in such applications because of their high permeability, low cost, mechanical strength, ease of fabrication, and thermal and chemical stability. In addition, polymeric membranes are diverse in their fabrication processes, membranes' properties and applications making them the best choice for a wide range of natural or wastewater treatment. However, membrane fouling is a major obstacle reducing the efficiency of membrane water treatment. Fouling is the accumulation of matter at the surface of the membrane. It causes rapid increase in differential pressure, reduction in water production, lower water quality and shorter membrane lifetime.

There is an emerging interest towards the modification of membranes using semiconductor metal oxides nanomaterials such as zinc oxide, titanium dioxide, iron (III) oxide (α-Fe_2O_3) and zinc sulfide. These nanomaterials enhance the physical and chemical properties of the membranes to ensure high membrane performance. Specific chemical species in the nanomaterials functionalizes the membranes by interacting with the polymeric membrane chemical groups. Controlled synthesis of functionalized membranes is essential to fabricate membranes with high permeability and salt rejection as well as better resistance to fouling and scaling at reasonable costs.

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Reverse osmosis seawater desalination: Qatar experience and vision

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Keywords: Reverse osmosis; Thermal desalination; Seawater desalination; Water problems; Qatar National Vision 2030; New desalination plants

Water desalination and clean water has been identified as one of the grand challenges in Qatar National Vison 2030. As Qatar economy is based on seawater desalination to overcome the water shortages, reduce the carbon footprint, preparation for FIFA 2022 World cup while achieving the goal of vision 2030 Qatar is shifting from the energy-intensive convention thermal desalination process to a much cleaner membrane based reverse osmosis (RO) process for seawater desalination. Two major RO desalination projects are underway in Qatar. The Ras Abu Fontas project built at a cost of QR1.75 billion will have a capacity to provide 36 MIGD (164,000 m^3/d) of desalinated water daily to meet the needs of about 1 million people in the country. Umm Al Houl will produce 284,000 m^3/d and will reach 614,000 m^3 per day after the start-up of the new facility. This is the first time that reverse osmosis technology has been implemented on a large-scale production plant in Qatar. Previous implementation of RO in Qatar has been limited and on small scale, such as the trial in Dukhan, where 750 m^3/d of high salinity water was treated for boiler feed water. This presentation focusses on the RO desalination plants implementation in Qatar and its challenges such as turbidity issues, membrane fouling and pretreatment. Qatari waters are very complex with high salinity in the GCC region and high level of colloids and organic matter. Qatar University is also in the process of establishing a Water Center/Unit to support the water desalination industry in Qatar and provide futuristic benefits.

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Session 7

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Drinking water demand forecasting using artificial neural network in Tunisia

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1. Introduction

Managers of drinking water systems hardly work to supply consumers with appropriate quality, quantity and pressure with the least treatment and management costs. This task can be strongly enhanced if water demands are accurately known in advance as long as possible.

The stochastic nature of drinking water demand (DWD) at daily and hourly time step is an evidence and was largely studied for characterization. DWD patterns of large cities depend on socio-economic rhythms, sizes (population), supply network proprieties and climate. DWD long-term (annual) trend can be identified using statistical analyses seen the dominance of the population annual growth and/or socio-economic sectors. Short-term (daily and hourly) patterns of DWD are more influenced by climatic conditions and socio-economic rhythms, difficult to fit with statistical approaches.

A literature review confirmed the efficiency and the robustness of artificial neural network (ANN) to forecast DWD in a large specter of socio-economic contexts as California (Ghiassi et al., 2008), Bangkok (Babel et Shinde, 2010), Mecca en Arabie Saoudite (Ajbar et Ali, 2015) et Laminga Jos (Gwaivangmin, 2017).

Seen the huge increase of DWD in Tunisian cities, starting from 2010, without a parallel reinforcement of water resources and hydraulic infrastructures, drinking water shortage becomes a real risk that can affect citizen's welfare and the economic activities of many sectors (hotels, industries, restaurants, schools, universities, administration, etc.).

In order to contribute to reduce risk of water shortage associated to inadequacy between hydraulic systems and DWD, this research aim is to develop robust models to forecast short-term DWD using ANN. The challenge is to forecast daily DWD for the longest period, for different supply networks to optimize tanks and water treatment plant (WTP) management.

2. Methodology

The calibrated methodology to forecast daily DWD is composed of three steps: (i) building of a daily database of drinking water supply and the lowest and heighted temperatures (January 2008 to December 2017); (ii) pre-processing and statistical analysis to identify the explanatory variables of the DWD; (iii) building, training and validation of the designed ANN using MATLAB script. In this step, the elaborated database is divided in two sets: the first one (90%) for ANN training and the remaining (10%) for validation.

Statistical indicators used to evaluate the performances of the trained ANN as well as to evaluate the validation phase are: (i) correlation coefficient; (ii) average absolute error and (iii) maximal absolute error.

3. Case study

Tunis City is supplied by drinking water by the main WTP "Ghedir El Golla" (GEG) through 21 main tanks, by gravity (Fig. 1).

Tunis City consumes almost 150 million m^3 per year, supplied by GEG WTP, with an average of 5.0 m^3/s.

The proposed methodology is applied for two supply networks in Tunis city feed by two tanks: "Belvedere Haut" and "Manouba 72", each of them have a capacity of 10,000 m^3 and characterized by maximal water level equal to 72 m. Next figure shows the daily supply trend as well as daily maximal air temperatures observed at Carthage meteorological station (2008–2017).

Their respective maximal daily supplies are estimated to 50,000 and 25,000 m^3.

4. Results

4.1. Statistical analysis and selection of ANN inputs

Statistical analysis was used to evaluate the correlation between water supply (VDJ1) and minimal and maximal temperatures (exogenous variables) as well as the previous 7 d water supply (endogen variables): VDJ-1 to VDJ-7. Tables 1 and 2 shows the detailed correlation results:

For both tanks, it is proved the strong relationship between temperature (min and max) and the supply volume. Maximal temperature was more correlated to supply volume for both studied tanks. It is also shown that previous

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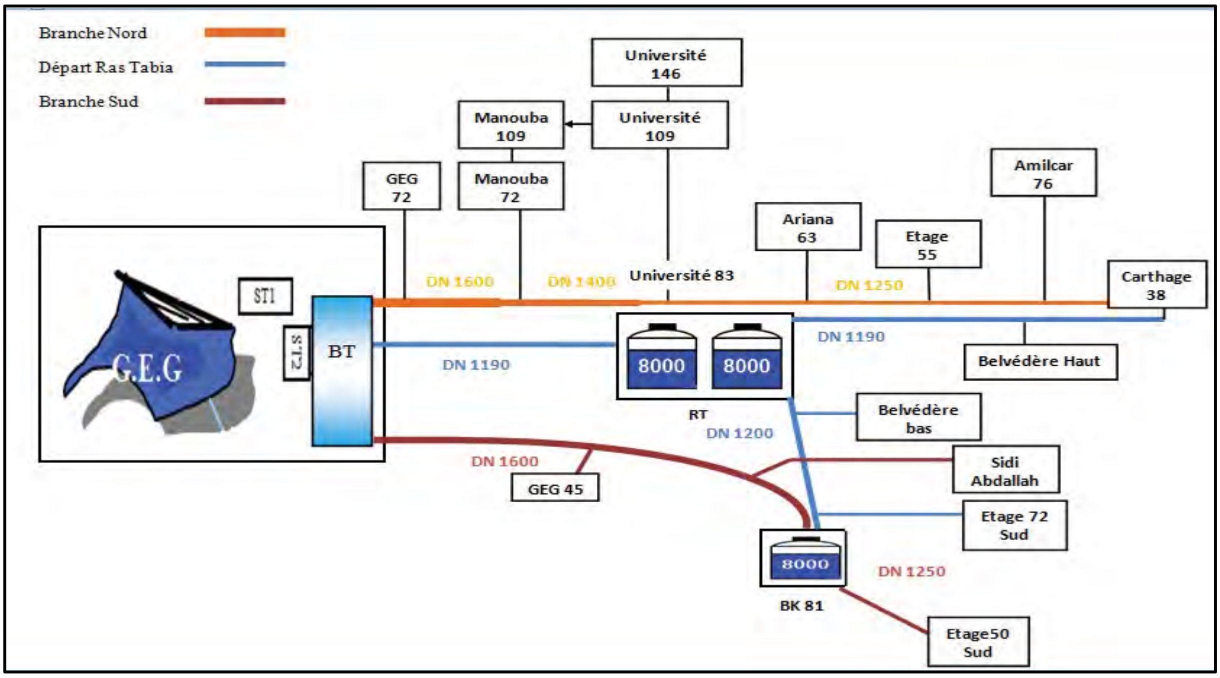

Fig. 1. Simplified schematic of the drinking water supply network for Tunis City.

Table 1
Matrix of correlation coefficients for Manouba 72 tank

Variables	Tmin	Tmax	VDJ1	VDJ-1	VDJ-2	VDJ-3	VDJ-4	VDJ-5	VDJ-6	VDJ-7
Tmin	1									
Tmax	0.882	1								
VDJ1	0.574	0.580	1							
VDJ-1	0.572	0.576	0.958	1						
VDJ-2	0.571	0.572	0.928	0.958	1					
VDJ-3	0.572	0.573	0.904	0.928	0.958	1				
VDJ-4	0.574	0.573	0.888	0.904	0.927	0.958	1			
VDJ-5	0.572	0.575	0.873	0.888	0.904	0.927	0.958	1		
VDJ-6	0.572	0.574	0.861	0.874	0.888	0.904	0.928	0.958	1	
VDJ-7	0.573	0.574	0.85	0.862	0.874	0.888	0.905	0.928	0.958	1

Table 2
Matrix of correlation coefficients for Belvedere haut tank

Variables	Tmin	Tmax	VDJ	VDJ-1	VDJ-2	VDJ-3	VDJ-4	VDJ-5	VDJ-6	VDJ-7
Tmin	1									
Tmax	0.879	1								
VDJ	0.370	0.374	1							
VDJ-1	0.369	0.376	0.890	1						
VDJ-2	0.373	0.374	0.801	0.89	1					
VDJ-3	0.372	0.375	0.744	0.801	0.89	1				
VDJ-4	0.373	0.373	0.710	0.744	0.801	0.89	1			
VDJ-5	0.376	0.377	0.693	0.71	0.744	0.801	0.89	1		
VDJ-6	0.376	0.378	0.680	0.693	0.71	0.744	0.801	0.89	1	
VDJ-7	0.375	0.377	0.673	0.68	0.693	0.71	0.744	0.801	0.89	1

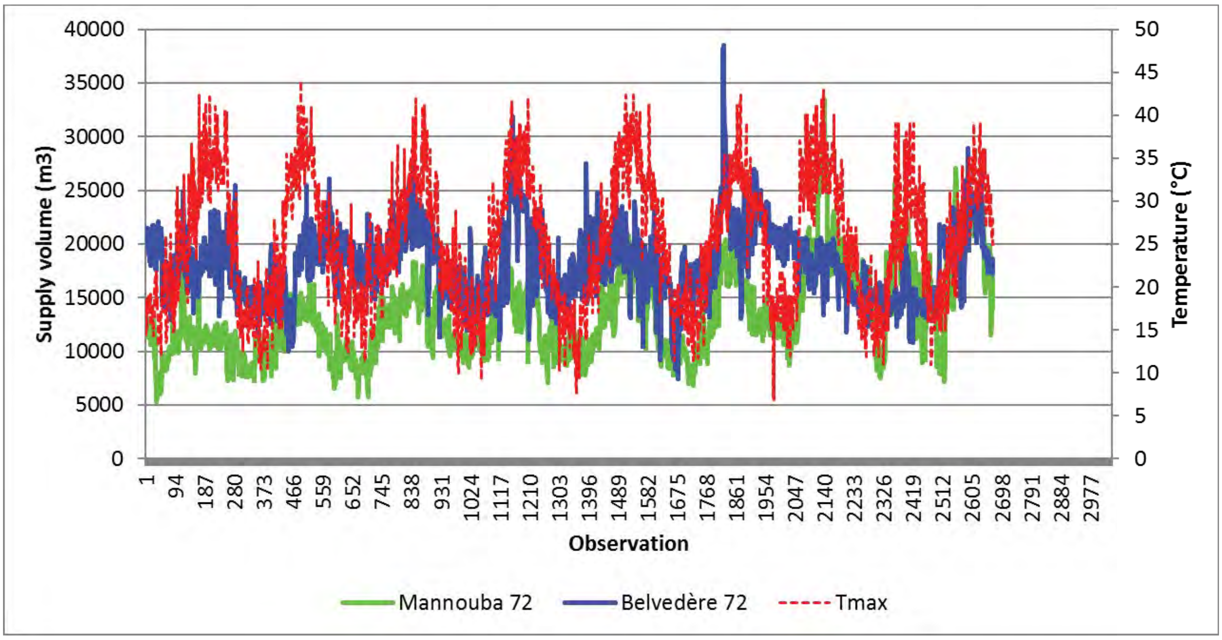

Fig. 2. Daily supply of “Manouba” and “Belvédère Haut” tanks.

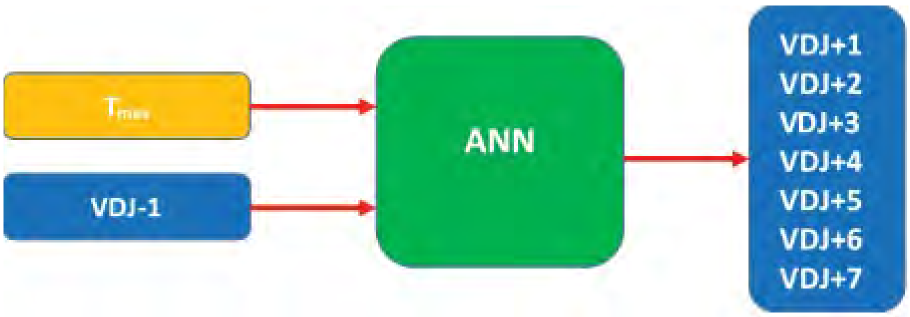

Fig. 3. ANN structure to forecast daily DWD for Manouba 72 and Belvedère Haut tanks.

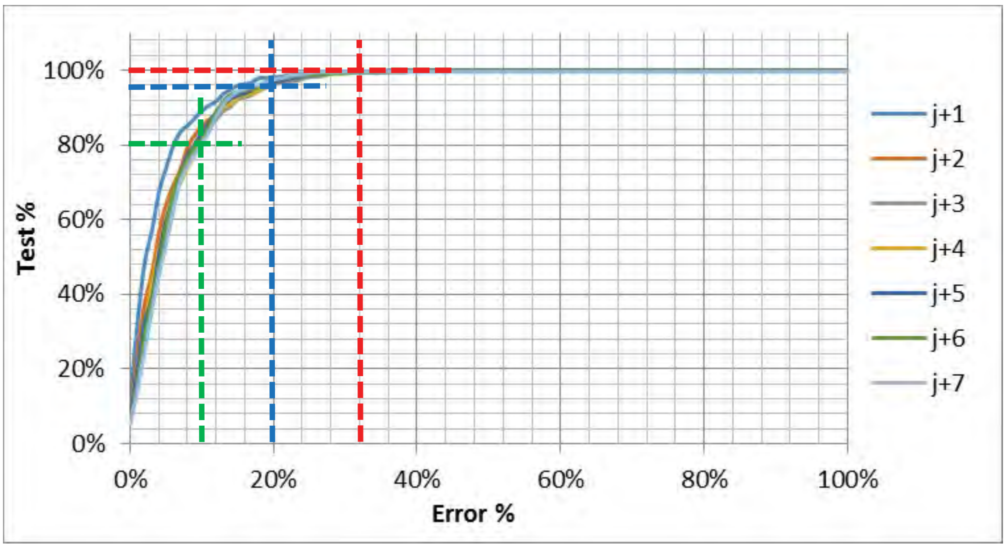

Fig. 4. Frequency curve of forecasting errors for “Belvédère Haut” tank.

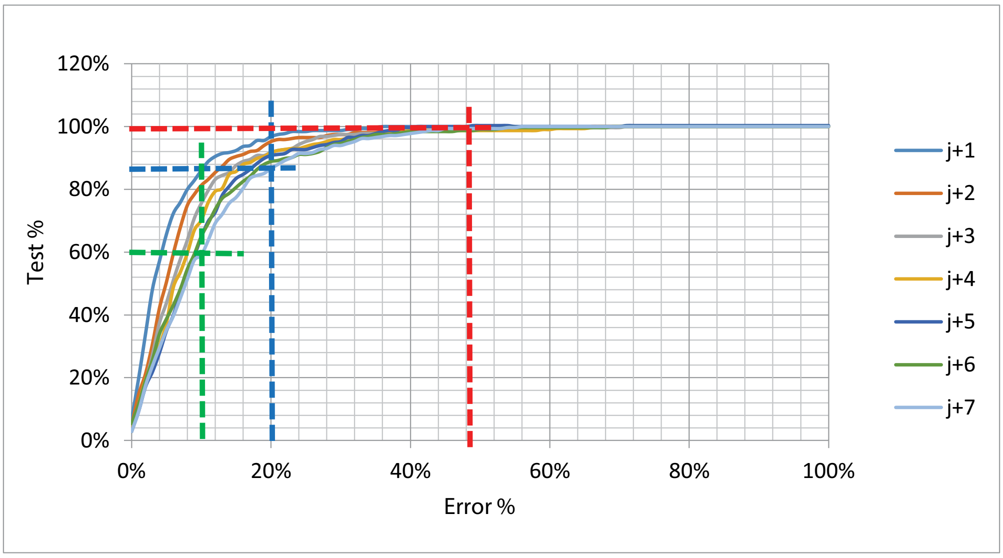

Fig. 5. Frequency curve of forecasting errors for "Manouba 72" tank.

supply volumes are strongly correlated to supplies of the following days. Indeed, historical supply represents indirectly importance of the supply network and the population as well as the socio-economic activity category. Supply of the previous day was the most correlated to supply volume.

Seen the previous results, it is decided to use the maximal temperature and the supply volume of the previous day as inputs for the ANN to forecast daily supply volumes for the following 7 d. Therefore, the ANN structure adopted in this research is given by Fig. 3.

4.2. Forecasting drinking water supply

After training phases using 90% of the database, the ANN of the two tanks were used to forecast supply volumes of the seven following days for the remaining 10% of the study period. The Fig. 4 summarize the relative estimation errors.

It is clear that for "Belvédère Haut" tank, the ANN was efficient to forecast drinking water supply up to 7 d with acceptable error. The error was the lowest for 1 d and the highest for 7 d. 100% of the forecasting tests are characterized by errors less than 36%. Among them, 96% are characterized by errors less than 20%. For 80% and 88% of the tests, respectively, for the forecast of 7 d and 1 d, the errors are less than 10%.

For "Manouba 72" tank, the ANN was efficient for the first day forecast. The error increases in parallel to the forecasting horizon. 100% of the forecasting tests are characterized by errors less than 48%. Among them, 84% to 96% are characterized by errors less than 20%, respectively, for the forecast of 7 d and 1 d. For 60% to 88% of the tests, respectively, for the forecast of 7 d and 1 d, the errors are less than 10%. More explorations, in terms of inputs and data processing, are required to improve the obtained forecasting performances for "Manouba 72" tank.

Forecasts of DWD showed acceptable results proving that ANNs are successful in predicting daily DWD supplied by the studied tanks. Only the maximum temperatures and the supply of the previous day are used as input to accurately forecast DWD for seven following days.

5. Conclusions

The main conclusion of the present research is the robustness of ANN to forecast daily DWD for one following week using one endogen (historical demand) and one exogenous (temperature) variables. Long time series and good quality of the input data are necessary to succeed the training and the validation of the ANN. As a perspective, this research can explore the forecasting efficiency for longer period (15 to 30 d).

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Reduction of the technical losses component of the NRW in water networks in Sultanate of Oman

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ABSTRACT

This paper discusses challenges and solutions to reduce non-revenue water (NRW) and unaccounted for water in water networks in sultanate of Oman by reducing the technical losses. Water supply system is one of the essential subjects for the governments and people in the main cities or rural villages, the water utilities must ensure continuous supply of clean and safe water in distribution with sufficient flow and adequate pressure with minimum failures. The world witnesses many instances of people lacking access to this essential commodity. (Water Partners Jp Co., 2017). This paper highlights the main issues, problems and solutions in water networks which are related to the water technical losses in NRW. Public Authority for Water (PAW/DIAM) is responsible for providing the potable water in all people in Oman as per the international standards. Reducing the water losses in the networks is one of the main challenges in Public Authority for Water. This paper is discussing the successful used methods and technologies in PAW to reduce the technical losses by 33,000,000 cubic meter in 2017 (DIAM, 2017). There are achievements in reducing the losses by controlling and managing the pressure in water networks. There are improvements in updating the specifications and standards of pipes rapiers and installations. Also the leak detection teams in PAW have used advanced technologies to find the invisible leaks in the water networks. The rehabilitation of old pipes is a major factor to reduce NRW. Finally, as a result of the done works in 2017, there are recommendations to ensure the reducing of water losses to reach to the acceptable level of non-revenue water in future.

Keywords: Pressure management; Leaks detection; Pipes rehabilitations; District metering area

1. Introduction

The Public Authority for Water (PAW/DIAM) is responsible for providing drinkable water to all people in Oman. In this paper, we will focus on the methods and tools which caused the reduction of non-revenue water (NRW)/ unaccounted for water (UFW) by getting and analyzing the collected data to detect the root causes of main problems with its solutions. This paper attempts to document the experience gained in reducing NRW using best international practices and methodologies. The total number of customers in PAW/DIAM is more than 500,000 in 12 zones with total length of about 18,000 km. The paper will cover and study the main used techniques (DIAM, 2018).

Potable water system has many complicated components such as desalination plant, pumping stations reservoirs, tanker filling stations, networks, and other water supply system components. It is very important to have good monitoring and controlling system to ensure the continuity of supply.

The water supply networks vary in age from old and new systems, and also in terms of water production sources: desalination plants or groundwater wells. In the network, there are many pumping stations and tanker filling stations depending on the needs of the area for the flow and pressure. The PAW supply network serves both domestic and non-domestic costumers.

Based on the IWA, the water supply system components can be divided into authorized consumption and water losses (Fig. 1). NRW consists of the water losses and the unbilled authorized consumption. The water losses are divided to two main categories which are the commercial losses and the real or technical losses. This paper is discussing the technical components to reducing NRW (Bill Kingdom, 2006).

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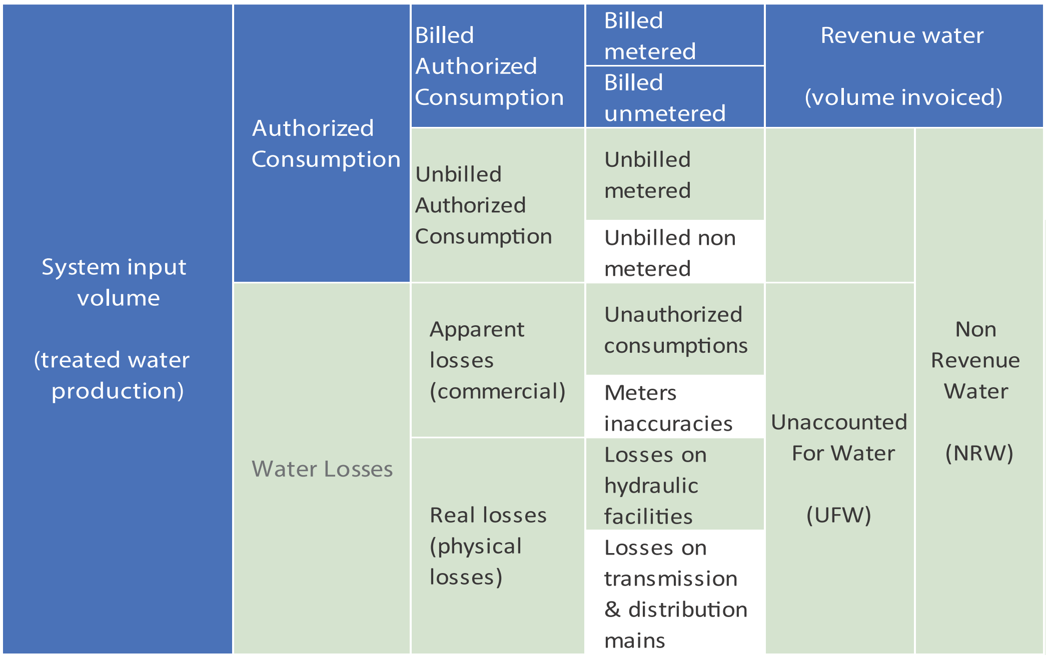


Fig. 1. Non-revenue water standard (International Water Association).

2. Discussion

Global water demand is largely influenced by population growth, urbanization, food and energy security policies, and macro-economic processes such as trade globalization, changing diets and increasing consumption. By 2050, global water demand is projected to increase by 55%, mainly due to growing demands from manufacturing, thermal electricity generation and domestic use (UN Water, 2015).

Water Utilities understands the urgency of NRW management. Reducing NRW is one of the critical steps to help cities and countries meet future demands. It is common now to witness big water shortage in cities around the world, sometimes even to cut supply to an entire city due to drought, demand, climate change, population growth, etc. Water Utilities now face tough challenges to ensure sustainable water supply. Maintaining a low NRW is top priority for water utilities. However, achieving low NRW is not an easy task.

According to the International Water Association (IWA), the main parameters for reducing NRW (Fig. 2) are active leakage control, pressure management, networks rehabilitations, and speed and quality of repair (LAMBERT, 2003), the typical losses in water supply system as technical and commercial are shown in Fig. 3 from the production to billing collection (Malcolm Farley, 2011). In this paper, we will show the detailed implementation of each one with more initiatives from the operation teams in public authority for water in Oman.

2.1. Reduction of NRW in Oman (PAW/DIAM)

In 2017 Public Authority for Water (DIAM) has achieved great results of reducing NRW. The water losses reduced from 118.2 to 84.6 million cubic meters with reduction of 33.6 Mm^3. the percentage reduction was from 35.86% to 24%.34 with reduction of 11.5% (Fig. 4). Also although the continuous increase in the number of customers each year, there is reduction in production percentage in 2017 comparing with the previous years which mean there is effective controlling of water losses (Fig. 5). These impressive results have been achieved by using very effective techniques, methods and technologies which will be discussed in this paper.

The water supply system in Oman as shown in Fig. 6 consists of production sites from desalination plants or wells, the pumping station, the transmission lines, tanker filling stations, reservoirs and networks. One of the great achievements in PAW is creating 250 district metering areas (DMA). The DMAs are monitored continuously by SCADA systems (Fig. 7), so in case of any abnormal consumption of water in any area, the system is alerting the operators to take the required actions for investigating the issues.

2.2. Leak detection team's tools and equipment in PAW/DIAM

There are 12 professional teams for leak detection in the public authority of water using advanced equipment, tools and systems for discovering the invisible leaks in the networks as following:

The ground microphones, correlators, listening sticks and the system for monitoring the flow and pressure in the networks are shown in Fig. 8. There is also in Fig. 9 an example of noise loggers' system for leak detection by analyzing the sound in the pipes and data analysis system in Fig. 10.

2.3. Installation standards and quality of repair

Updating the standards and specifications is essential to improve the performance, the following example Figs. 11 and

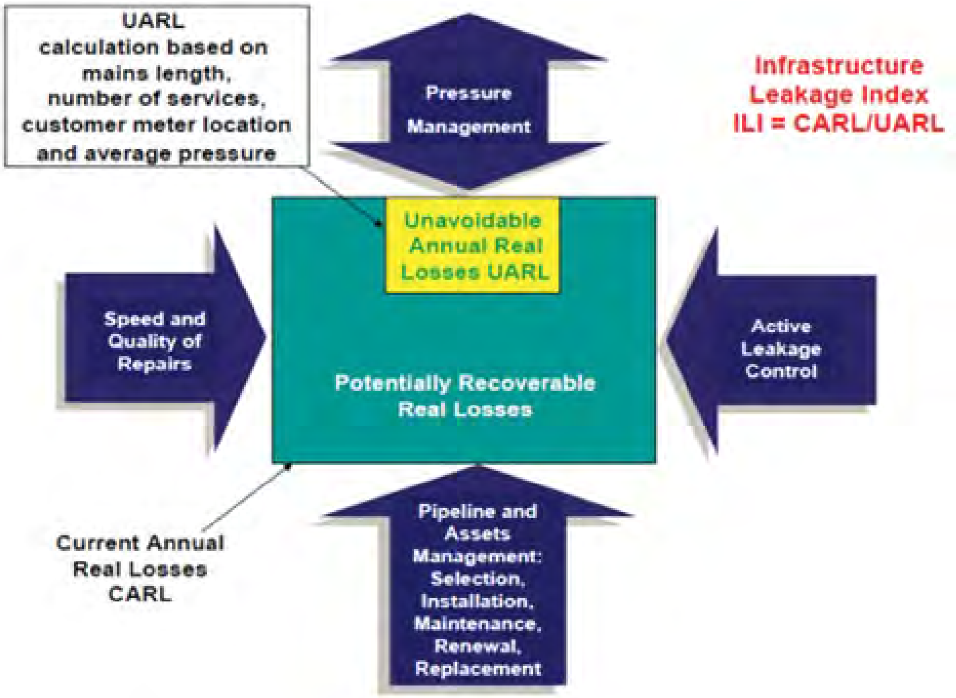


Fig. 2. IWA standard for reducing NRW/water technical losses.

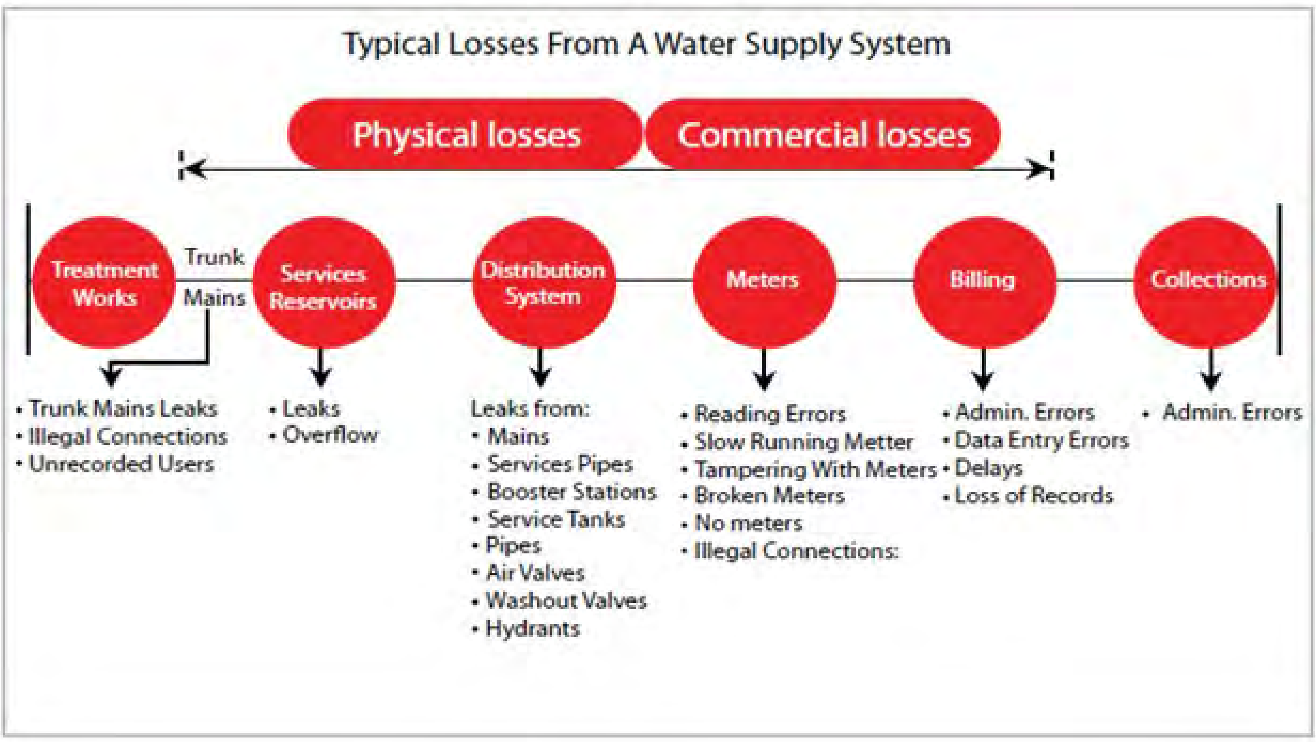
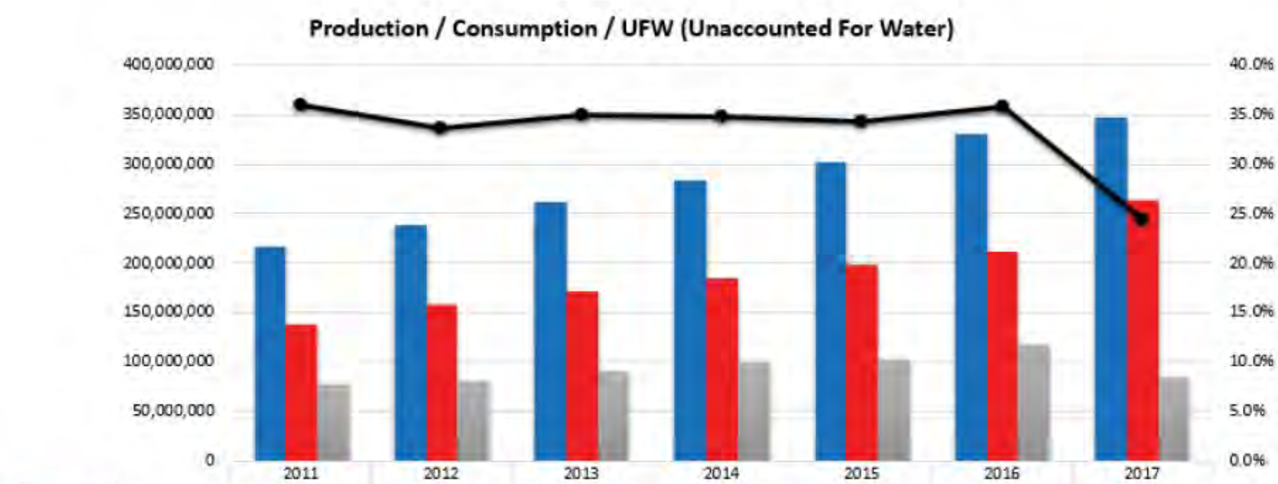


Fig. 3. Typical losses in water supply system.



	2011	2012	2013	2014	2015	2016	2017
Production	215,900,000	238,200,000	262,199,120	283,135,760	301,008,112	329,787,928	347,684,307
Accounted Consumption	138,290,000	158,010,000	170,609,120	184,625,760	197,668,112	211,522,119	263,051,772
UFW	77,610,000	80,190,000	91,590,000	98,510,000	103,340,000	118,265,809	84,632,536
UFW%	35.9%	33.7%	34.9%	34.8%	34.3%	35.86%	24.34%

Fig. 4. Production, consumption and UFW/NRW in Public Authority of water (DIAM) in Oman.

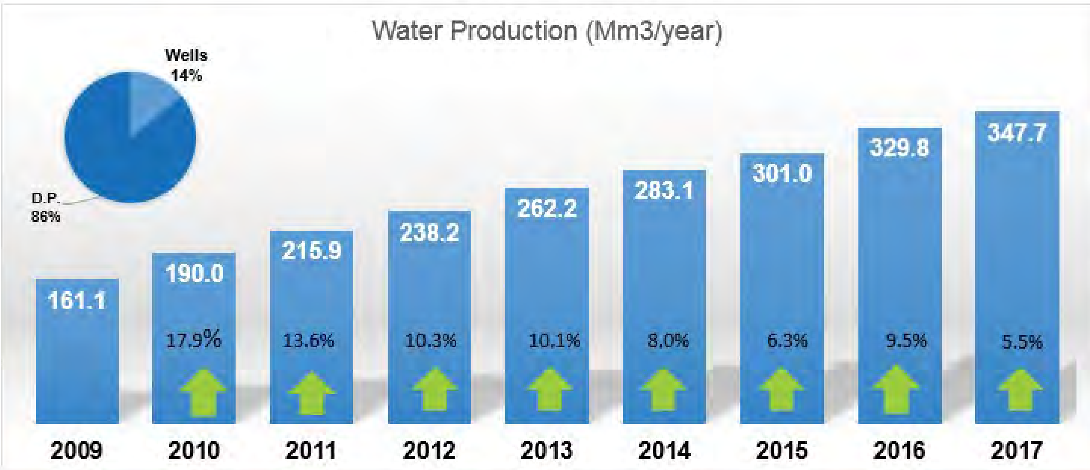


Fig. 5. Water production increasing in Oman.

12 is updating the standard of house connections to reduce the leaks.

2.4. Pressure management

The pressure is the first factor which causes leaks and breakdown in water networks, so it is very important to keep the pressure in the system within the best range, in PAEW many pressure reducing valves have been installed recently, the results were great and direct in the number of leaks and the losses of water (Figs. 13 and 14).

2.5. Pipes rehabilitation

In all water networks, the renewal and rehabilitation is continuous process, because the pipes have operating life, after the period pipes start deteriorating and break finally (Fig. 15).

The basis of pipes rehabilitations should be based on technical data analysis such as the number of leaks, age of the networks and the operation pressure (Fig. 16).

2.6. Leaks reasons

The major factors of technical losses are the leaks in the networks, the main identified reasons are as following:

- High pressure
- Age of the pipes
- Poor quality of materials
- Poor quality of installation
- Wrong storing of the materials

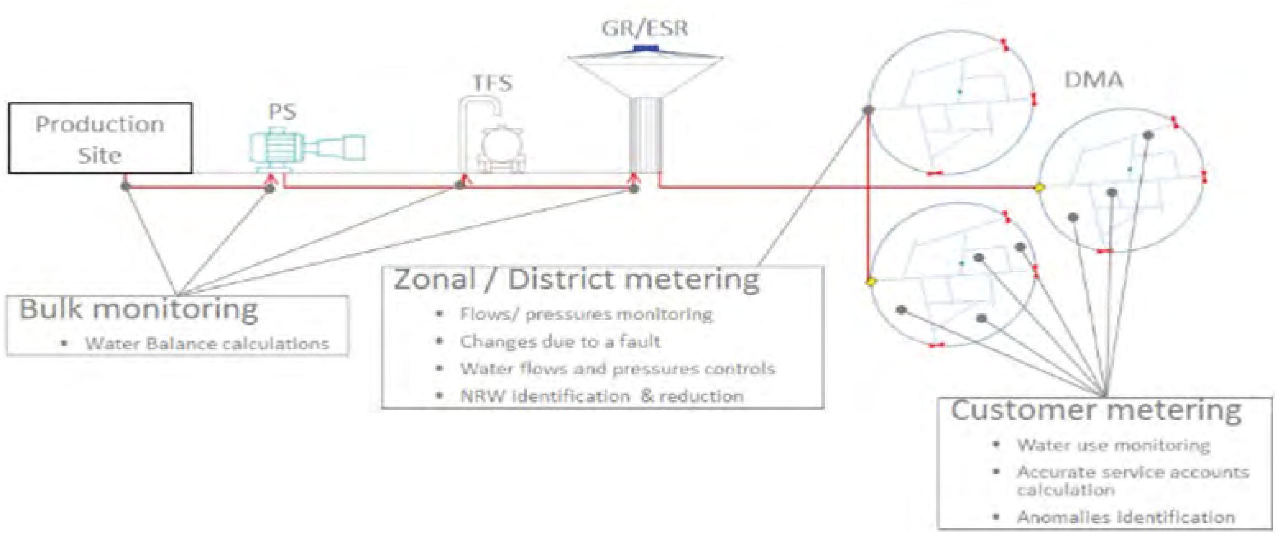


Fig. 6. Water supply system in Oman.

Fig. 7. PAW/DIAM SCADA system.

- Wrong selection of the materials
- Wrong design (no hydraulic modeling)
- Wrong operation
- Poor maintenance
- Water quality
- Corrosion
- Soil condition and load

2.7. Main factors of reducing technical losses

The main identified factors of reducing the leaks and increasing the operational performance are as following:

- Improve networks designs
- Improve installation standards and quality of repair

Sr.	Tool & Equipment Name
1	Correlators
2	Ground Microphone
3	Listening sticks
4	Metal Detector
5	Plastic pipe Detector
6	Pressure Transducer
7	Pressure Gauge
8	Insertion probe flow meter
9	Clamp on flow meter
10	Noise loggers
11	Pressure Data loggers
12	Flow Data loggers
13	Helium gas detector
14	Softwares

Fig. 8. Used leak detection tools and softwares.

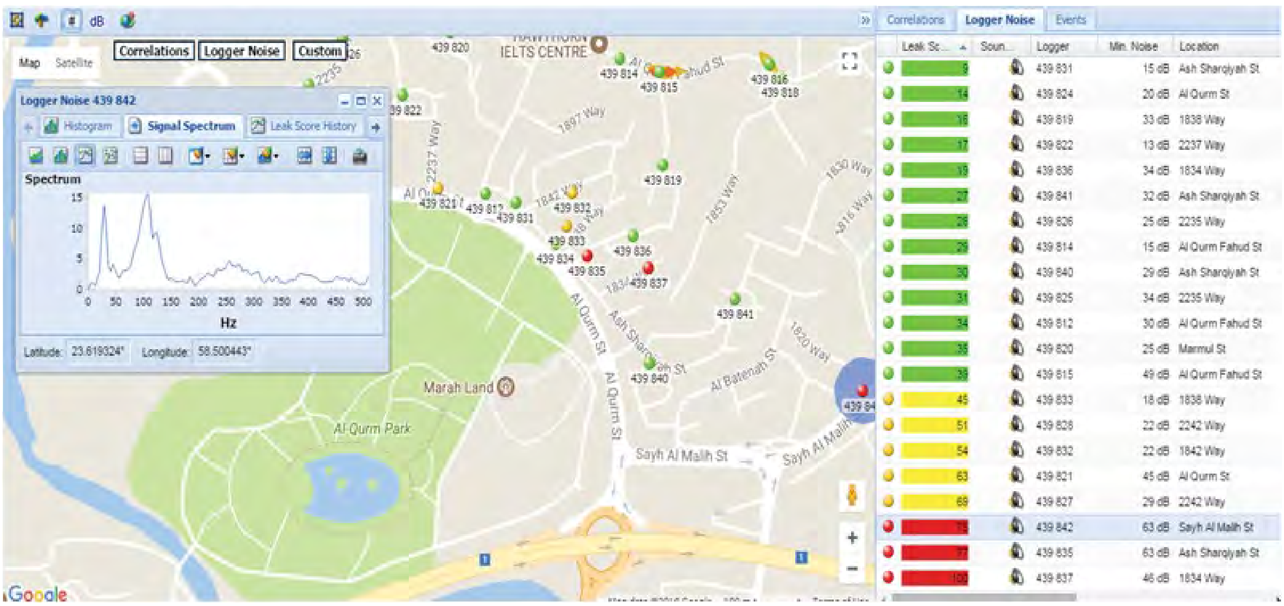
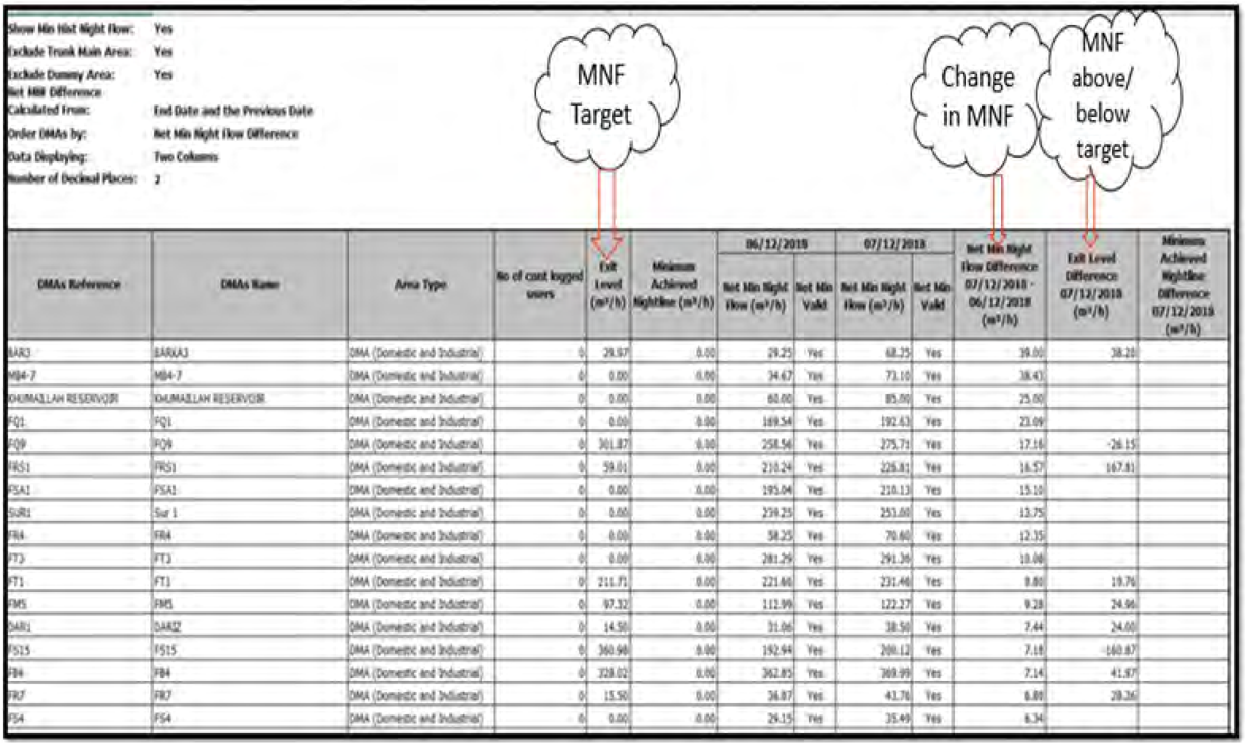


Fig. 9. Leak detection system for noise loggers.



Show Min Hist Night Flow: Yes
Exclude Trunk Main Area: Yes
Exclude Dummy Area: Yes
Net MNF Difference
Calculated From: End Date and the Previous Date
Order DMAs by: Net Min Night Flow Difference
Data Displaying: Two Columns
Number of Decimal Places: 2

DMAs Reference	DMAs Name	Area Type	No of cust logged users	Exit Level (m³/h)	Minimum Achieved Nightline (m³/h)	06/12/2018		07/12/2018		Net Min Night Flow Difference 07/12/2018 - 06/12/2018 (m³/h)	Exit Level Difference 07/12/2018 (m³/h)	Minimum Achieved Nightline Difference 07/12/2018 (m³/h)
						Net Min Night Flow (m³/h)	Net Min Valid	Net Min Night Flow (m³/h)	Net Min Valid			
BAR3	BARKA3	DMA (Domestic and Industrial)	0	29.97	0.00	29.25	Yes	68.25	Yes	39.00	38.28	
MB4-7	MB4-7	DMA (Domestic and Industrial)	0	0.00	0.00	34.67	Yes	73.10	Yes	38.43		
KHUMAILLAH RESERVOIR	KHUMAILLAH RESERVOIR	DMA (Domestic and Industrial)	0	0.00	0.00	60.00	Yes	85.00	Yes	25.00		
FQ1	FQ1	DMA (Domestic and Industrial)	0	0.00	0.00	169.54	Yes	192.63	Yes	23.09		
FQ9	FQ9	DMA (Domestic and Industrial)	0	301.87	0.00	258.56	Yes	275.71	Yes	17.16	-26.15	
FRS1	FRS1	DMA (Domestic and Industrial)	0	59.01	0.00	210.24	Yes	226.81	Yes	16.57	167.81	
FSA1	FSA1	DMA (Domestic and Industrial)	0	0.00	0.00	195.04	Yes	210.13	Yes	15.10		
SUR1	Sur 1	DMA (Domestic and Industrial)	0	0.00	0.00	239.25	Yes	253.00	Yes	13.75		
FR4	FR4	DMA (Domestic and Industrial)	0	0.00	0.00	58.25	Yes	70.60	Yes	12.35		
FT3	FT3	DMA (Domestic and Industrial)	0	0.00	0.00	281.29	Yes	291.36	Yes	10.08		
FT1	FT1	DMA (Domestic and Industrial)	0	211.71	0.00	221.66	Yes	231.46	Yes	9.80	19.76	
FM5	FM5	DMA (Domestic and Industrial)	0	97.32	0.00	112.99	Yes	122.27	Yes	9.28	24.96	
DAR1	DAR2	DMA (Domestic and Industrial)	0	14.50	0.00	31.06	Yes	38.50	Yes	7.44	24.00	
FS15	FS15	DMA (Domestic and Industrial)	0	360.98	0.00	192.94	Yes	200.12	Yes	7.18	-160.87	
FB4	FB4	DMA (Domestic and Industrial)	0	328.02	0.00	362.85	Yes	369.99	Yes	7.14	41.97	
FR7	FR7	DMA (Domestic and Industrial)	0	15.50	0.00	36.87	Yes	43.76	Yes	6.89	28.26	
FS4	FS4	DMA (Domestic and Industrial)	0	0.00	0.00	29.15	Yes	35.49	Yes	6.34		

Fig. 10. Netbase system for data analysis.

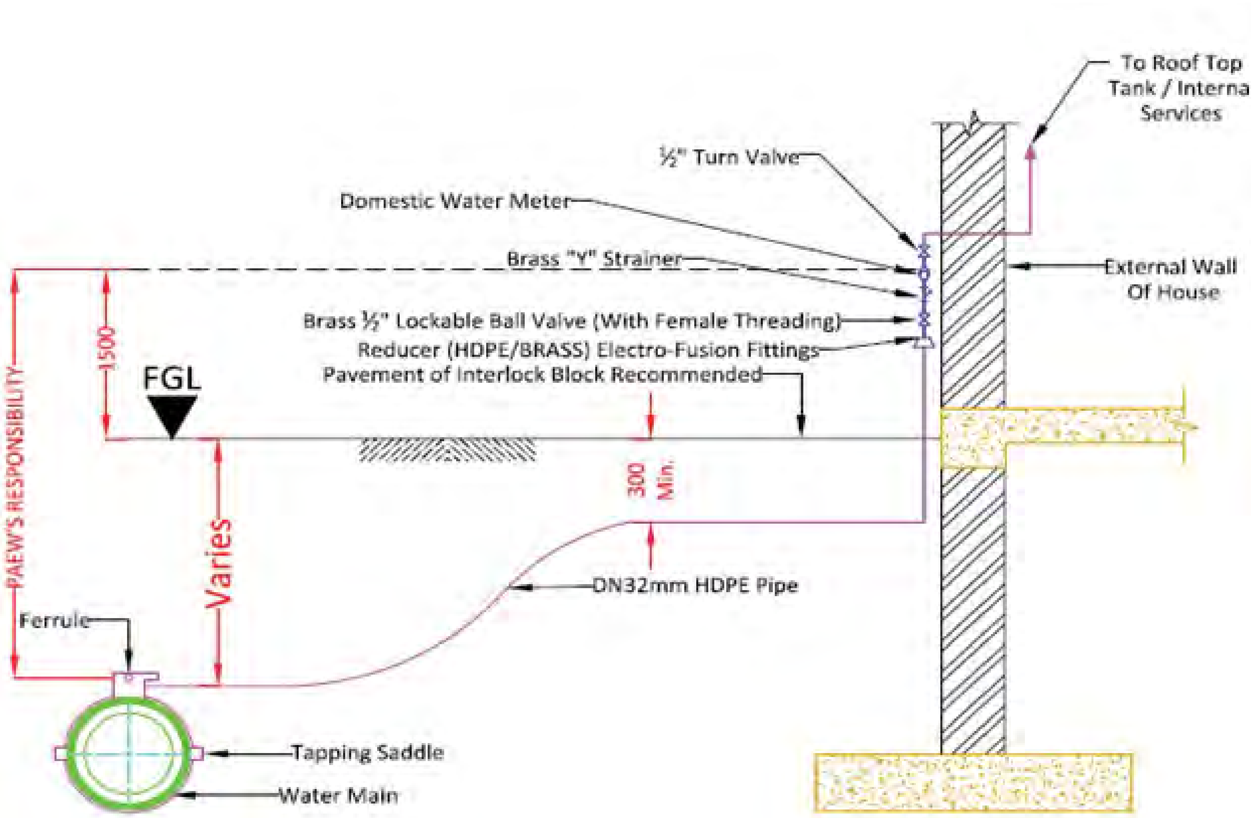


Fig. 11. Old house connection standard in PAW/DIAM in Oman.

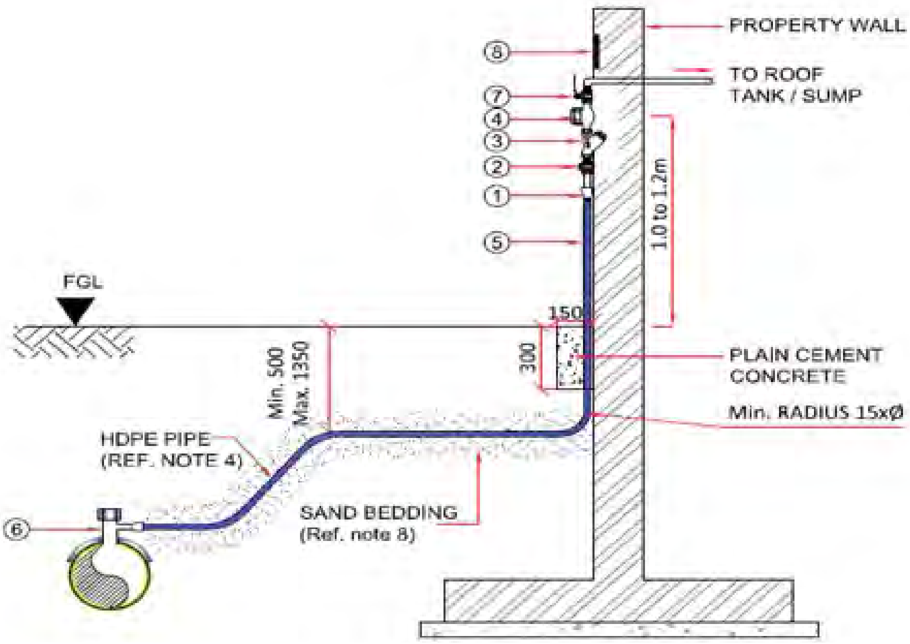


Fig. 12. New house connection standard in PAW/DIAM in Oman.

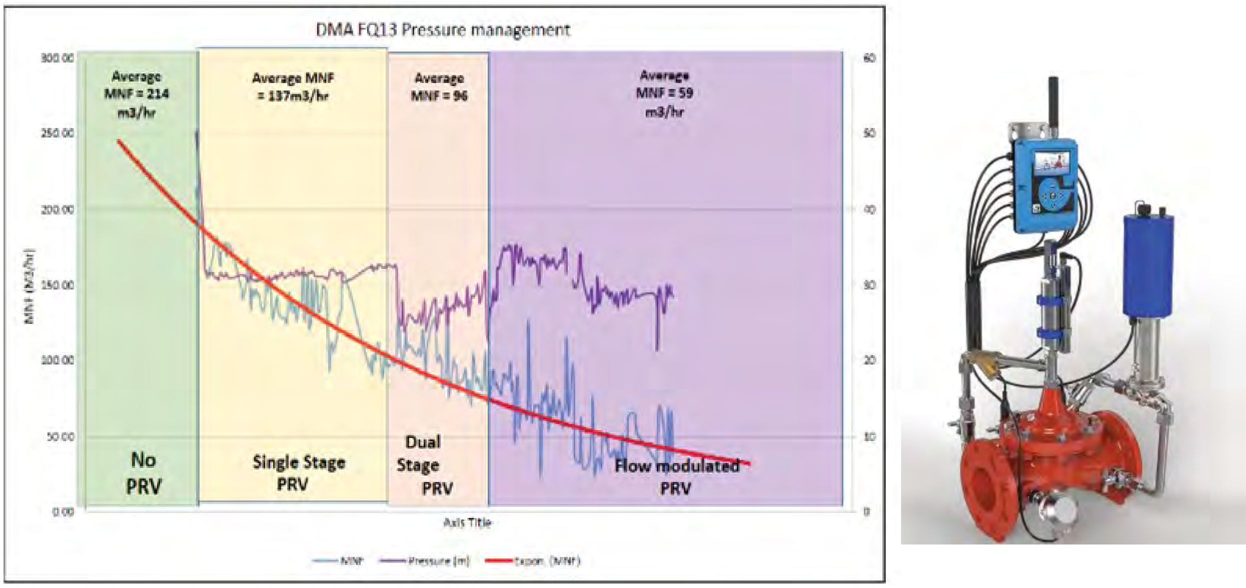


Fig. 13. Reduction in water losses by pressure management.

- Pressure management
- Pipes rehabilitation
- Improve PPM and CM
- Activate leak detections
- Improve QMS, reporting and documentations
- Improve monitoring and controlling
- Improve analyzing methods
- Introduce key performance indicators
- Using of new technologies
- Increasing the technical skills
- Improve water quality
- Create research department

3. Conclusion and recommendations

The saved amount of water in 2017 by using the shown methods and techniques to reduce the technical losses was 10,223,913 m^3/year, which caused a great achievement and reduction in NRW/UFW from 35.86% to 24.34%. PAW is continuing the initiatives and activities to reduce NRW and

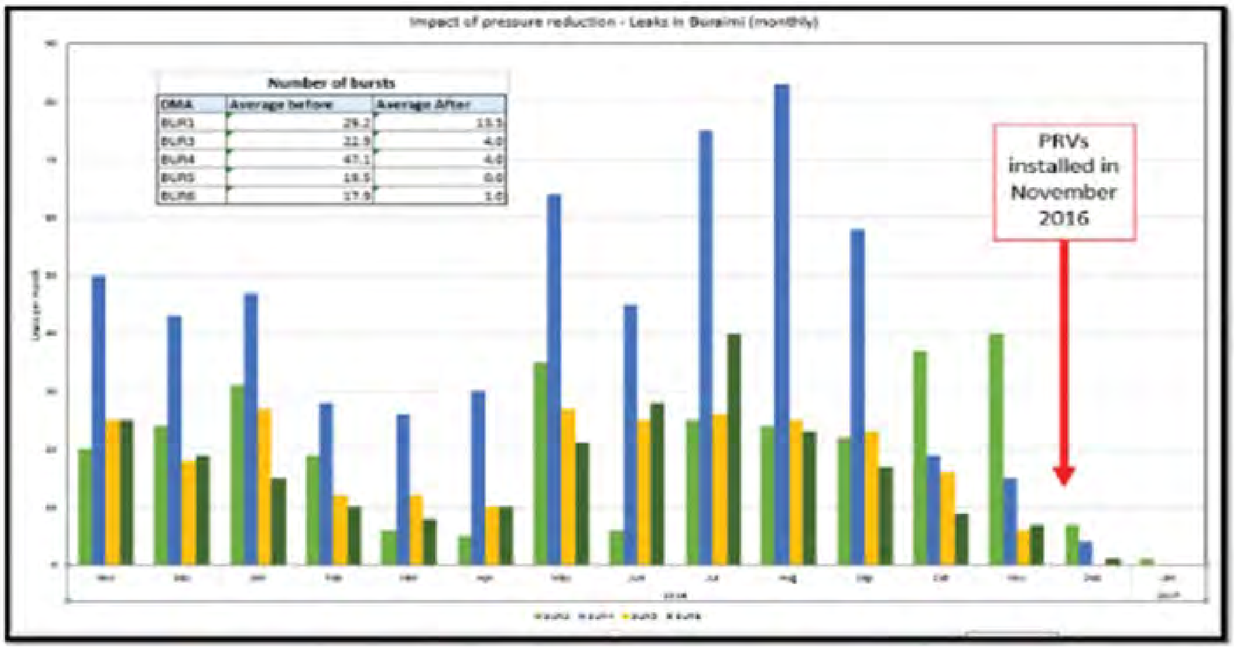


Fig. 14. Reduction in number of leaks by pressure management.

Fig. 15. Reduction in water losses by pipes rehabilitation.

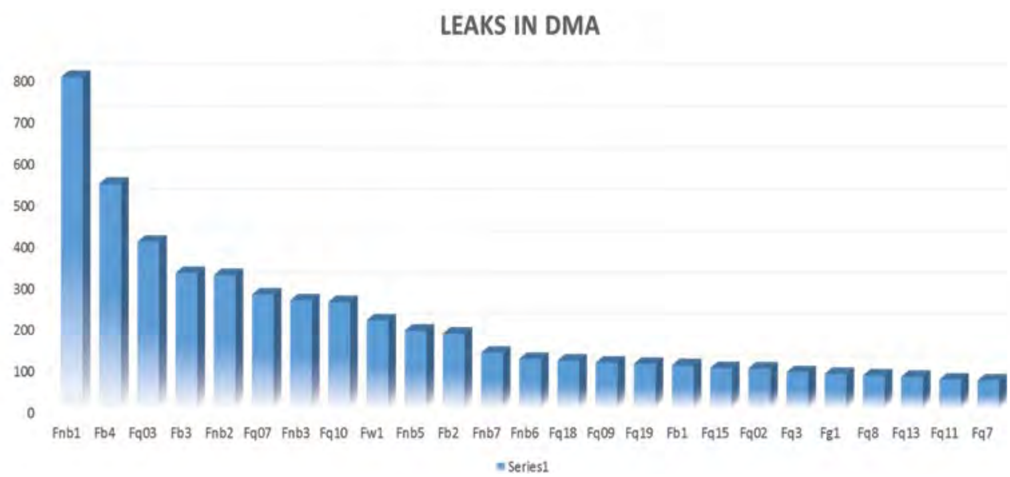


Fig. 16. Number of leaks per district metering area (DMA).

technical losses by utilizing the full capabilities of the existing tools. In parallel there are new technologies that have been implemented in 2018 such as satellite leak detection which can also enhance the work of the teams responsible about leak reduction. The most important part is to create clear action plans for reducing the water losses with detailed data analysis and following up for all areas to ensure the best results.

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Energy optimization in water supply system in the Sultanate of Oman

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ABSTRACT

In water supply systems, the power cost is one of the most important components in which large amounts of energy are required for production, pumping, transportation, and distribute the water in the networks. The water supply systems are the most important public utility for safe supply of potable water. Energy consumption in water supply system represents a major concern in the Sultanate of Oman. This paper discusses several studies and actions have been done in water operational assets to reduce and optimize the power consumption. The public authority for Water in Oman (Diam) has implemented many successful energy optimization methodologies and tools in desalination plants, pumping stations, wells and water distribution networks such as energy recovery devices, variable frequency drivers, pumps overhauling, rescheduling of pumping times, bypassing the pumping stations, maintenance of wells.

Keywords: Water network; Pumping stations; Energy recovery device; Variable frequency drivers; Maintenance

1. Introduction

Providing safe drinking water is a highly energy-intensive activity. Energy usage can vary based on water source, facility age, treatment type, storage capacity, topography, and system size. The growing demand for electricity has a direct impact on the environment. The intervention to increase the efficiency of water systems becomes one of the essential subjects in the Public Authority for Water in Oman (DIAM). This report highlights the main initiatives and activities in reducing the power consumption in the operational assets of water supply system in Oman such as desalination plants, pumping stations and reservoirs.

Electricity consumption by water utilities has typically accounted for about 3% of all electrical energy consumption in the United States and United Kingdom. Increasing the energy efficiency can reduce power consumption for pumping by as much as 5%–25% (Bunn 2009).

Providing safe drinking water is a highly energy-intensive activity. Drinking water and wastewater systems are typically the largest energy consumers accounting for 25%–40% of a municipality's total energy bill. Approximately 80% of municipal water processing and distribution costs are for electricity (Water, 2013).

2. Discussion

The consumption of electric energy, due to the water pumping, represents the biggest part of the energy expenses in the water industry sector. Among several practical solutions, which can enable the reduction of energy consumption, the change in the pumping operational procedures shows to be very effective, since it does not need any additional investment but it is able to induce a significant energy cost reduction in a short term (Ramos, 2013).

This increment in the energy prices has created the need for increased emphasis on efficient energy use. Therefore, energy efficiency in water distribution applications must be regarded as a priority when more efficient system operation is sought (Habibi, 2014).

The introduction of the cost reflective tariff for industrial electricity has stimulated PEW to increase its focus on energy efficiency in its installations. There project to stimulate electricity saving in all PEW facilities and to increase awareness of energy efficiency by changing consumption behavior, motivate staff to use electricity properly and to reduce losses. This campaign is planned to run to the end of 2018 (DIAM, 2017). An overview of water supply system in Oman is shown in Fig. 1.

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The main components of the system are desalination plants, wells, pumping stations, tanker filling stations, reservoirs and networks (transmission/distribution).

In 2016, the Public Authority of Water started an evaluation of energy consumption in many operational locations, Fig. 2 shows the power consumption in the assets (Diam & Seureca, 2016).

The consumption varies from site to site from less than 10,000 to 60,000 MWh/year, the types of selected locations are desalination plants, pumping stations, wells.

For desalination plants, key performance indicators are the recovery percentage and the specific consumption (Fig. 3).

For pumping stations, booster pumping stations and well fields, an average efficiency of 70% is an accepted value based on benchmark and international standard (Fig. 4; Diam & Seureca, 2016).

Efficiency of pumps (excl. Well Field)	70%
Efficiency of pumps in Well Field	65%
Pump energy indicator	4.5 kWh/1,000 m^3/m

Pumping stations are the water distribution system components that provide the greatest opportunity for cost savings due to improved operation. Optimal operation in these cases corresponds to minimizing pumping energy consumption while maintaining adequate service.

There is no single simple approach to minimizing pumping energy costs because there is no single reason that pumping systems are operated less than optimally. Some of these reasons include:

- Pumps which were incorrectly selected.
- Limited capacity in the transmission/distribution system.
- Limited storage capacity.
- Inefficient operation of pressure (hydro pneumatic) tanks.
- Inadequate or inaccurate telemetry equipment.
- Inability to automatically or remotely control pumps and valves,
- Cost reflected tariff constraints.
- Lack of understanding of demand or capacity power charges,
- Operator errors.
- Control strategies.

The efficiency percentage is lower for the wells, around 65% efficiency as shown in Fig. 5 (Diam & Seureca, 2016).

The main required actions for power optimization in the operational assets are as following:

Sr.	Required action
1	Bypassing the pumping stations to supply water directly to networks
2	Change of impeller and coating
3	Cleaning of suction line
4	Frequent maintenance/cleaning of strainer for well fields
5	Installation of new pump with motor and as a replacement of existing
6	Installation of VFD in pumping stations
7	Lighting optimization
8	Optimization of impeller diameter
9	Pump operation at valve throttled opening
10	Installation of ERD in desalination plants
11	Reduction/change in operating hours of pump and combinations
12	Refurbishment/ internal coating of pump
13	Replacement of existing belt to flat belt for high pressure pump driven
14	Voltage optimization
15	Suction lines modifications
16	Trimming impeller

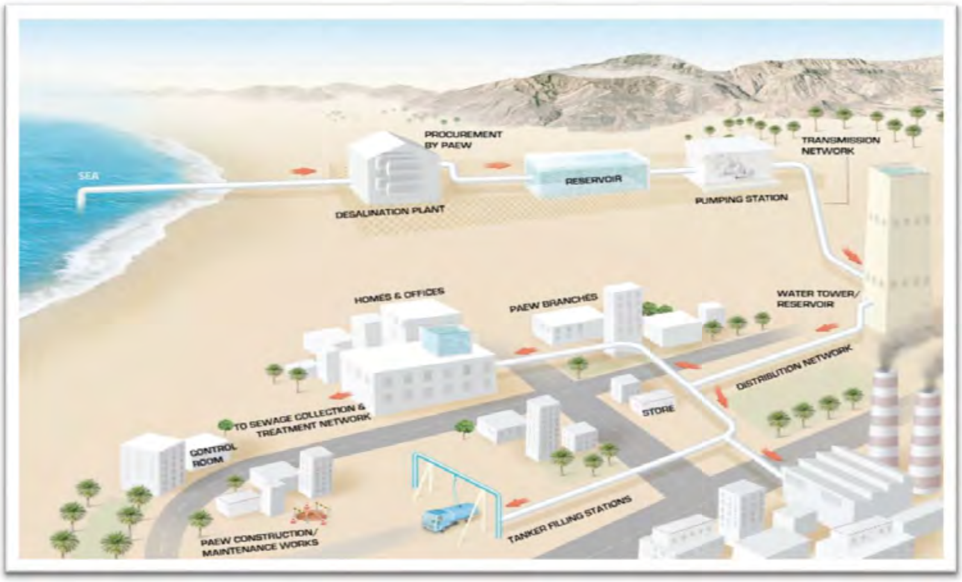

Fig. 1. Water supply system in Oman.

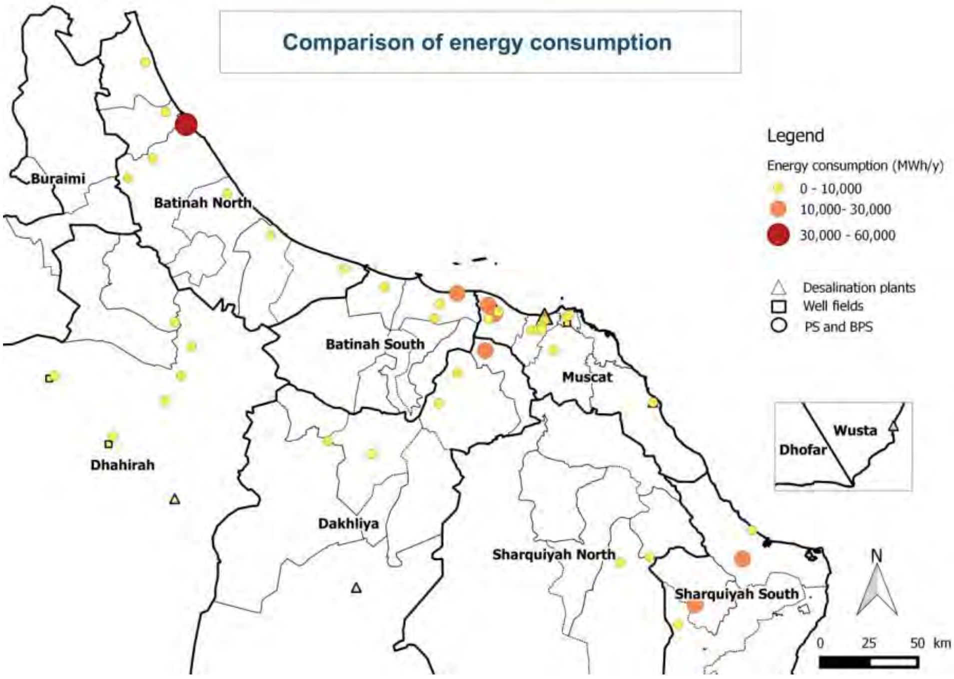

Fig. 2. Overall evaluation of the biggest energy consuming.

Name of the desalination plant	Type of raw water	TDS of raw water (ppm)	Recovery percentage	TDS of product water (ppm)	Specific Energy Consumption (kWh/m^3)
Adam DP	Brackish water	1,607	69%	386	2.37
Ghubrah DP	Sea water	40,000	36%	400	4.15
Hamra DP	Brackish water	2,910	67%	73	3.40
Lakbi DP	Sea water	27,500	34%	330	5.24
Quriyat	High brackish water	18,000	42%	480	3.97

Fig. 3. Desalination plants evaluation.

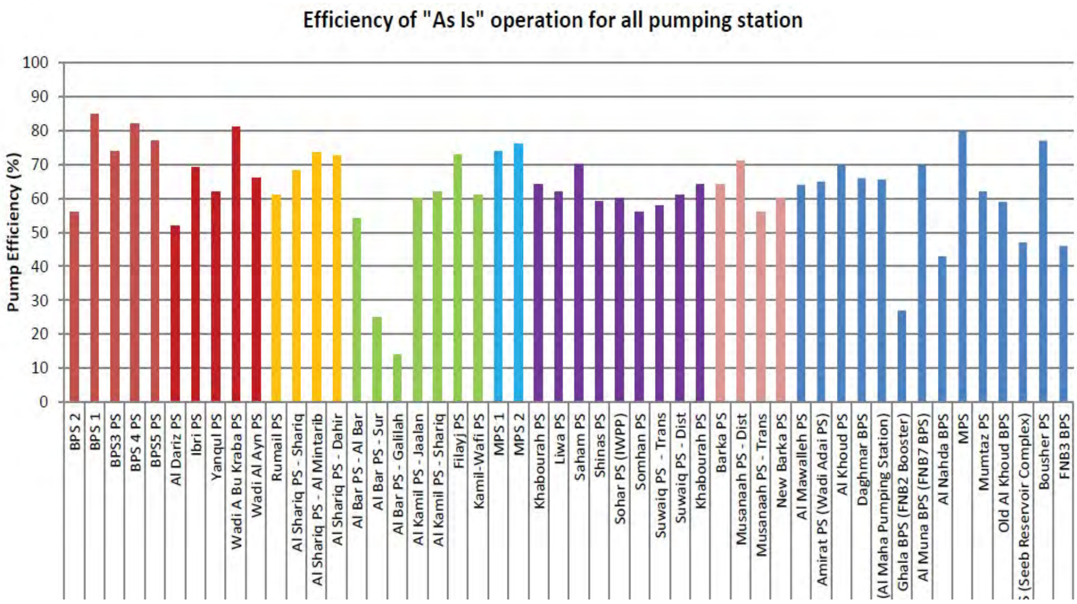

Fig. 4. Pumping stations energy evaluation.

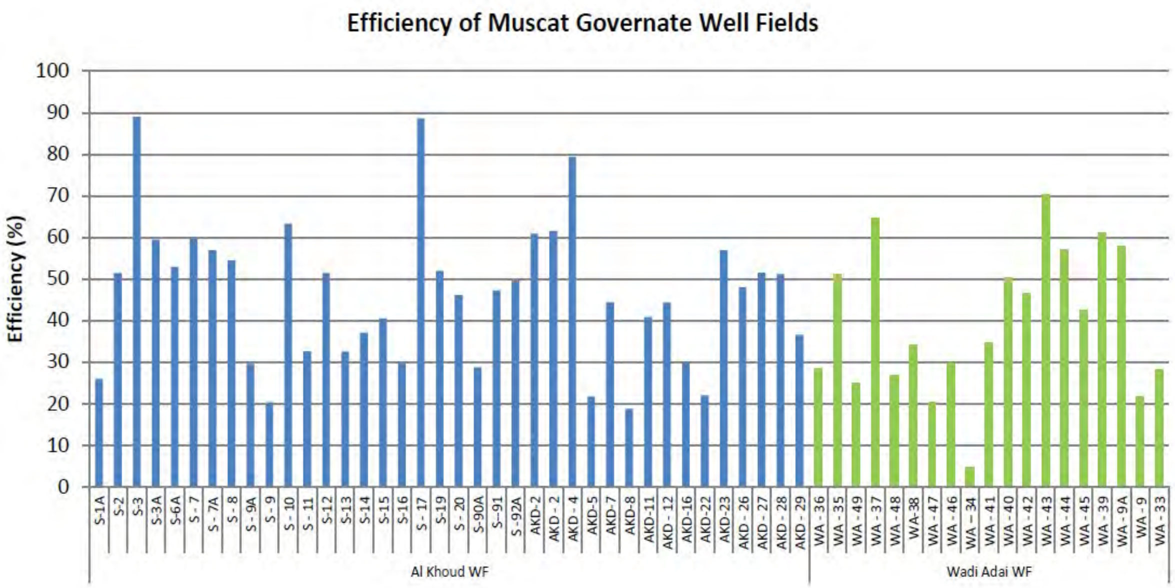

Fig. 5. Wells efficiency evaluation.

3. Case studies and initiatives

The Public Authority for Water in Oman (Diam) has implemented in 2017 and 2018 many successful solutions to optimize the energy usage. In this section, we will show few examples of the activities and initiatives done by operation teams.

Optimizing the pump-scheduling is an interesting proposal to achieve cost reductions in water distribution pumping stations. As systems grow, pump-scheduling becomes a very difficult task. In conventional water supply systems, pumping of treated water represents a major expenditure in the total energy budget. Because so much energy is required for pumping, a saving of 1% or 2% can add up to several thousand dollars over the course of a year. In many pump stations, an investment in a few small pump modifications or operational changes may result in significant savings (Christian von Lücken, n.d.).

3.1. Running the most efficient pumps in Mawalleh Pumping Station

In Mawalleh pumping station in Muscat governorate, the team selected the best scenario by using the most efficient pumps and stop the low efficiency pumps, the results are shown in Fig. 6 (Seeb Operation, 2018).

Al Mawalleh Pump Station			
Location	Month	Total Saving	
		KW	RO
Mawalleh Pump Station	Jan	603576	11,921.647
	Feb	837120	18,040.031
	Mar	158596	2,140.325
	Apr	398400	7,483.400
	May	461806	15,525.162
	Jun	252792	7,558.856
	Jul	371352	11,443.016
	Aug	527424	12,095.456
	Sep	504216	13,215.628
	Oct	237288	5,881.648
	Nov	251808	5,682.952
	Dec		
Total		4604378	110,988.121

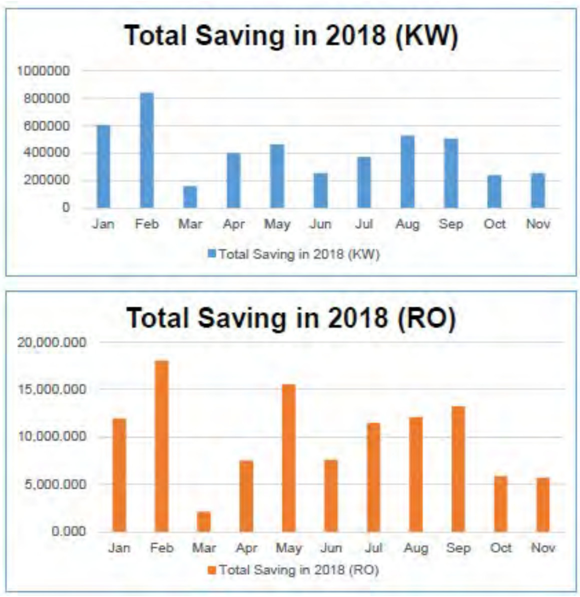

Fig. 6. Malallah pump station parameters 2018.

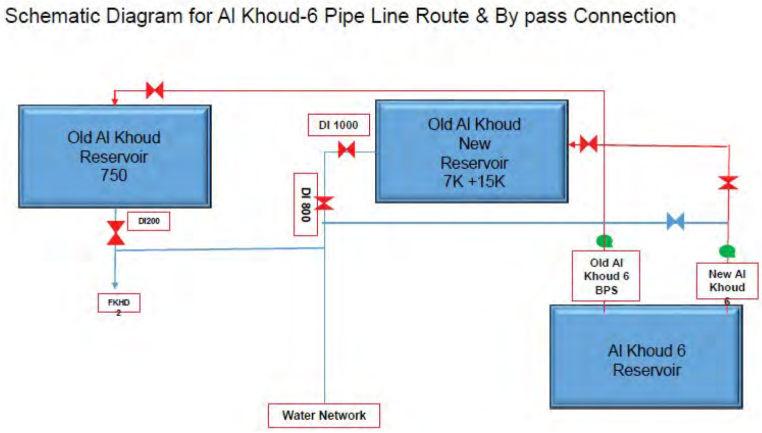

Fig. 7. Layout of Al Khoud pumping station roots.

Old Alkhoud Booster Pump			
Location	Month	Saving	
		Kw	RO
Old Al Khoud (Booster Pumps + Lighting + Guard room)	Jan	58830	1217.675
	Feb	12547	482.127
	Mar	-5036	-38.861
	Apr	67130	1466.553
	May	17225	646.299
	Jun	18639	697.042
	Jul	19661	718.168
	Aug	18693	522.737
	Sep	11131	319.042
	Oct	17367	401.809
	Nov	17463	412.502
Total		253650	6845.093

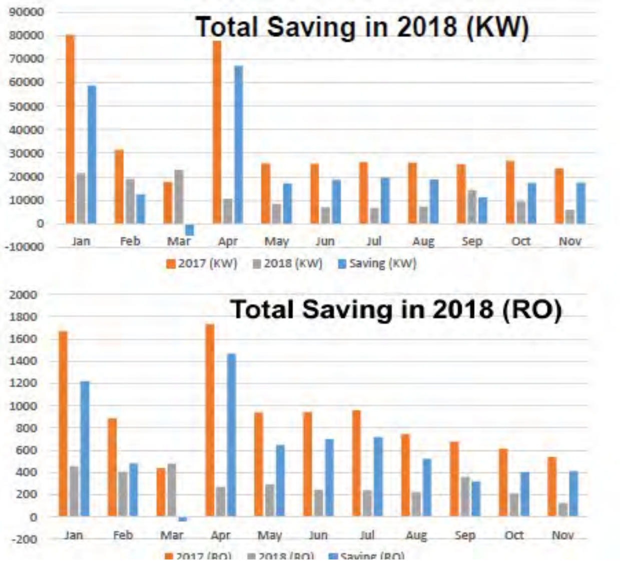

Fig. 8. Energy savings in Al Khould P.S.

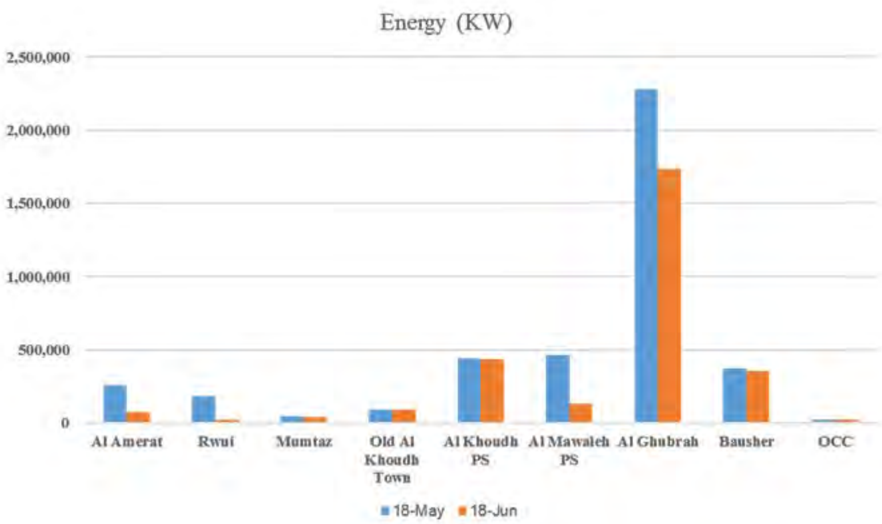

Fig. 9. Power saving in Muscat pumping stations.

3.2. Bypass the pumping station

The following figures shows the saving from stopping one pumping station (Al Khoud P.S.) and feeding the reservoir from other source, Schematic diagram for Al Khoud-6 Pipe Line Route & By pass Connection in Fig. 7 (Seeb Operation, 2018).

3.3. Energy optimization by avoiding the peak tariff time (CRT)

There was a successful activity to change the operation time in Jun-18 (Fig. 9) by rescheduling the pumping to avoid the high cost of electricity during peak time as per cost reflected tariff as shown in Fig. 10 (CCR, 2018).

3.4. Cleaning the strainers in wells

Due to the water quality of the produced water from wells, the strainers filled with dust and obstacles, which lead to low efficiency of the submersible pumps inside the wells with higher required power consumption.

3.5. Changing the old membranes in desalination plants

One of the interesting activities is changing the old membranes in the desalination plant. The following example is from Wusta area in Hima plant in Fig. 11, which indicates big saving in the consumed power.

Moreover, there are also many other activities that have been made for energy optimization in the water supply system in Oman. These include:

- Installing and utilizing variable frequency drives in pumping stations
- Installing and utilizing energy recovery devices in desalination plant
- Pumps maintenance and overhauling

TOD Register Identification	T1	T2	T3	T4
Register	Off - Peak	Weekday - Peak	Night - Peak	Weekend Day - Peak
Time Slot	02:00 – 13:00 17:00 – 22:00 16 Hrs	13:00 – 17:00 4 Hrs	22:00 - 02:00 4 Hrs	02:00 – 13:00 17:00 – 22:00 4 Hrs

	Off - Peak	Weekday - Peak	Night - Peak	Weekend Day - Peak
January - March	12	12	12	12
April	14	14	14	14
May - July	16	67	24	38
August - September	15	26	21	19
October	12	14	14	14
November - December	12	12	12	12

Note; all prices are in Biza per kw and above rates might be changed in yearly basis. The above table represents 2018 rates.

Fig. 10. CRT (cost reflected tariff in Oman) (Regulation, 2018).

Energy	Jan. to Nov. 2017	Jan. to Nov. 2018
Total consumption (KWh)	6,727,343.18	6,317,784.90
Power saving (KWh)	409,558.28	

Fig. 11. Hima desalination plant in Wusta.

4. Conclusion and recommendations

Operating water supply systems requires significant amount of energy. Thus, the discussed initiatives are implemented to optimize the power consumption that should be working to satisfy the water demand forecasting and system constraints at minimal operational cost. The results showed that the used energy optimization methods such as bypassing the pumping station, installing variable frequency drivers, overhauling pumps, changing operation scenarios, cleaning the strainers in the wells outlet, changing the old membranes in desalination plant and installing efficient energy recovery devices led into significant savings in the overall operational cost, and also led to considerable improvements in the system. All the obtained solutions are found feasible in terms of satisfying the system constraints, water demands, and hydraulic requirements. In order to measure the progress of energy savings actions, it is very important to do a close monitoring of energy consumption on PAW (Diam) operational sites by advanced tools and systems. Finally, it is recommended to continue the energy savings and optimizations actives to a next level by using a special software for power analysis to have clear data for each individual site from production to the networks.

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Evaluation of municipal water supply system options using water evaluation and planning system (WEAP): Jeddah case study

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ABSTRACT

Jeddah City is expected to experience water supply stress due to rapid population growth and expansion of urban developments. This paper aims to assess the impact of possible water demand on Jeddah water resources in 2030. To facilitate the analyses, a scenario-based modeling is used in conjunction with WEAP to find the best combination of scenarios that meet future water demands. For each scenario, the water resource implications were compared with a 2017 baseline. The model enabled analyses of unmet water demands, water demand, water delivered, and supply requirement for each scenario. The study identifies the year of unmet demand and calculates the reliability, resiliency, and vulnerability of the supply system. Results show that the gap between demand and supply will grow dramatically if current supply condition continues. An additional quantity of more than 504 MCM is needed in 2030 to satisfy water needs and development. The unmet water demand varies through years significantly according to the proposed scenario. The implementation of the leakage reduction measures proposed by the National Water Company (NWC), in conjunction with the application of reuse of treated wastewater and water conservation practices, can decrease the unmet demands and deficits to levels lower than, or similar to, those occurred in the 2017 baseline. However, in all cases, these involvements will be insufficient to completely meet the demands of all demand zones. A careful control of the population growth rate in future demands is necessary, although this may be difficult in a rapidly developing region such as Jeddah of Saudi Arabia.

Keywords: Demand management; Integrated water resources management (IWRM); Desalinated water; TWW; Water allocation; WEAP model; Jeddah

1. Introduction

Water shortage is a major challenge faced by Jeddah city. Rapid population growth, urbanization, expansion of development and the economic activities in Jeddah city exert pressure on available water resources (NWC, 2017; SGS, 2018). Therefore, water demand management plan should be considered to avoid future water scarcity. Jeddah city depends mainly on desalinated water from two existing desalination plants. Desalinated water provides City of Jeddah about 34 MCM per month, which represents 95% of the total water supply. Groundwater is another minor water supply source and represents 4% of the total water supply. Only 1% of treated wastewater (TWW) is used for Jeddah's industrial City (NWC, 2017), while 99% of the TWW is discharged into the Red Sea.

WEAP is a water allocation model and can be used at spatial and temporal levels. WEAP enables users to have interactive control on data input, model operation, and output display. It is capable of building and comparing different scenarios (SEI, 2001). The scenarios can be addressed on a wide range of "what if" questions. What if leakage reduction in the distribution system is reduced? What if water conservation in the household is implemented? What if various combinations of different water supply/demand options are implemented?

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The objective of this paper is to evaluate the existing condition related to the water supply system in the city of Jeddah and to evaluate the long-term impact of the proposed water management system using WEAP (SEI, 2001). It includes water supply/demand analysis for the city of Jeddah to analyze the current situation of water demand and propose water supply alternatives to improve the performance of water supply system considering different factors such as population growth, water conservation, leak reduction, and reuse of treated wastewater in agriculture. This is accomplished through evaluating the existing water demand and supply conditions and expected future demand and supply scenarios considering the different operating policies and factors that affect demand. The study identifies the year of unmet demand and calculates the reliability, resiliency, and vulnerability of the supply system. Moreover, the study is looking at the demand management approach as opposed to the traditionally practiced supply management approach and considered the first of its kind to be developed for Jeddah city.

2. Methodology

The study comprised of four stages. At first, all required data are collected from different water authorities (e.g., NWC, Jeddah municipality) and further processed using geographical information system (GIS). Then, GIS is employed to specify the spatial location of various water utilities to be incorporated in the WEAP model. In other words, the spatial coordination of the water utilities (i.e., reservoirs, Filling Stations, groundwater wells, desalination and wastewater plants) are taken from GIS and inserted into WEAP. Second, the current water system (supply/demand) for the city of Jeddah and future water management options are established. Third, assessment of various water demand management options is considered for the year 2030. Finally, the study also recognizes the year of unmet demand and estimates the reliability, resiliency, and vulnerability of the supply system.

3. Study area

Jeddah City is located on the west side of Saudi Arabia in the middle of the Red Sea with a total area of 5,460 km^2. The urbanized area of Jeddah city is about 1,765 km^2. The average temperature is about 28.69°C over the period 1981–2010 (DeNicola et al., 2015; Jeddah Municipality, 2017). In 2017, the population of Jeddah city was 4.69 million capita with a growth rate of 3.3% (General Authority for Statistics, 2017). Trends show that the population is expected to increase, and it is projected that the population will reach 7.0 million in 2030 (NWC, 2017).

3.1. Current water use

In this study, Jeddah city is divided into five zones (i.e., five demand zones) according to their geographical location and the existing water supply practices (Figs. 1 and 2). For each demand zone, the percentage of all allocated water in each demand zone is equal to 100%. The average quantity delivered to Briman zone in 2017 is 8,773,516 m^3/month (Table 1). Table 1 shows a detailed summary for the quantity of water allocated quantities from various sources across

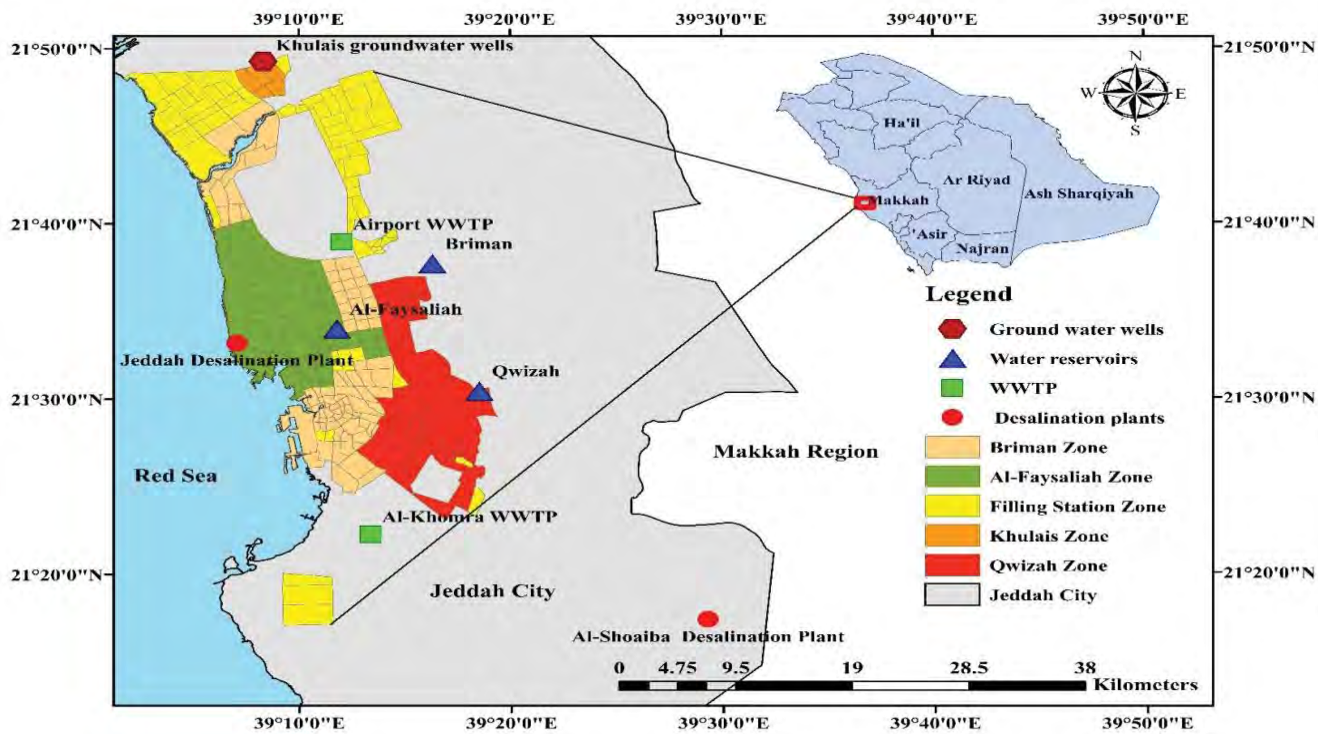

Fig. 1. Study area.

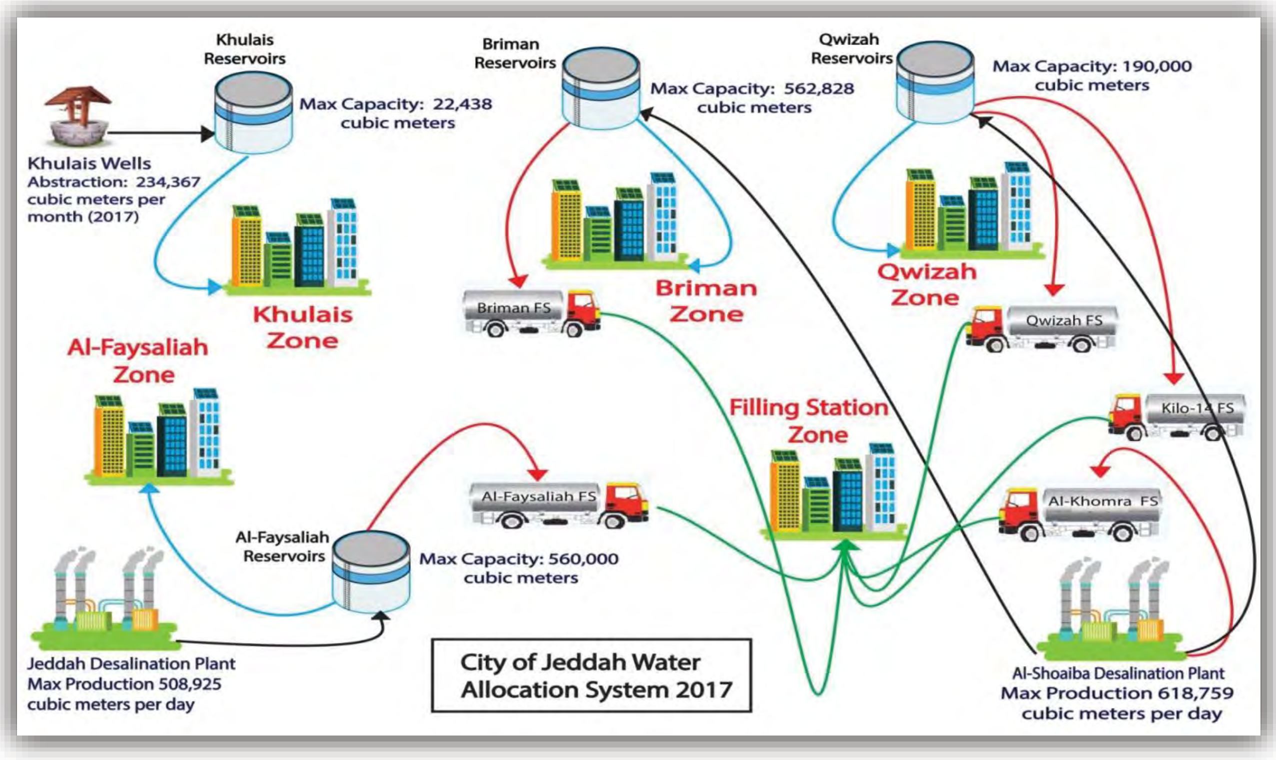

Fig. 2. Current water allocation system for all demand zones.

Table 1
Average water allocation in 2017 for Jeddah city (NWC, 2017)

Source	Supply	Type	Quantity m^3/month	Total quantity m^3/month	Total m^3/month
Jeddah Desalination Plant	Al-Faysaliah	Network	11,861,631	27,382,542	34,064,895
Al-Shoaiba Desalination Plant	Briman		8,773,516		
Al-Shoaiba Desalination Plant	Qwizah		6,513,028		
Groundwater Wells	Khulais		234,367		
Jeddah Desalination Plant	Al-Faysaliah	Filling Station	3,406,122	6,682,353	
Al-Shoaiba Desalination Plant	Briman		625,868		
Al-Shoaiba Desalination Plant	Qwizah		911,790		
Al-Shoaiba Desalination Plant	Al-Khomrah		426,722		

Jeddah city in 2017. Al-Faysaliah zone received an average water quantity of 11,861,631 m^3/month in 2017. Qwizah zone received a water quantity of 6,513,028 m^3/month in 2017. The fifth zone represents districts that are not connected to the water distribution network. This zone received water only from Filling Stations and water delivery tanks, with an average water quantity of 6,682,353 m^3/month in 2017. According to NWC, 10% of the Jeddah population in the first four zones will receive water from Filling Stations when the network failed to deliver water. Khulais reservoir takes its water from groundwater wells and finally distributes it to Khulais zone with a quantity of 234,367 m^3/month in 2017. Groundwater is being delivered to Khulais zone by water distribution system network. All zones obtain water from an existing 16 small reservoirs.

3.2. Desalination plants

The city of Jeddah has two major desalination plants, namely, Jeddah and Al-Shoaiba Jeddah desalination plant contain three reverse osmosis (RO) desalination units. They were constructed in 1994, with a total capacity of 255,248 m^3/d. This plant has another unit of desalination using evaporation and condensation of water with a capacity of 190,000 m^3/d, owned and operated by the Saline Water Conservation Corporation (SWCC, 2017). The second desalination plant is called Al-Shoaiba, with a capacity of 582,689 m^3/d. It is located about 110 km south of Jeddah City.

3.3. Wastewater treatment plant

The total capacity of the existing two WWTP is approximately 247 MCM/year (NWC, 2017). The treated effluent from both plants is primarily discharged to the Red Sea. Currently, less than 296,000 m^3/month of TWW is reused for some factories in Jeddah industrial City. Some of Jeddah districts are not connected to the sanitary sewer system. At present, domestic wastewater is discharged into the ground via cesspits without treatment.

3.4. Water reservoirs

Jeddah city has 23 reservoirs with a total capacity of 1,312,828 m^3 per day. Al-Faysaliah zone has 16 reservoirs, with a total volume of 560,000 m^3. Eight reservoirs have a capacity of 160,000 m^3 (i.e., 20,000 m^3 per each reservoir), while the other eight reservoirs have a capacity of 400,000 m^3 (50,000 m^3 per each reservoir). In Briman zone, there are four reservoirs with a total storage capacity of 562,828 m^3 (i.e., 140,000 m^3 per each reservoir). Qwizah zone has three reservoirs with a total storage volume of 190,000 m^3. Two reservoirs have a storage volume of 100,000 m^3 (50,000 for each one), while the third one has a storage volume of 90,000 m^3.

3.5. Water management scenario development

In this paper, two scenarios were set-up based on developing a process of Saudi National Water Company (NWC) and the Saudi Ministry of Environment, Water and Agriculture (MEWA). For each scenario, the water resource implications were compared with a 2017 base-case. The model allowed analyses of unmet water demands, water demand, water delivered, and supply requirement for each scenario. The supply requirements include water demand and losses. Table 2 shows brief details for the three water management scenario.

3.6. Basic assumptions for the base-case situation

The basic assumption in the Jeddah WEAP model included population, daily consumption (liter/day), annual water consumption (m^3/capita/year), growth rate (%), losses in the network (%), and treated wastewater reuse (%). The total population for all Jeddah zones in 2017 was 4.69 Million capita. The daily consumption of water was 309.0, 247.0, 175.0, 166.0, and 290.0 liters/day for Al-Faysaliah, Briman, Qwizah, Khulais, and Filling Station zones, respectively. According to NWC, the population growth rate is considered to be 3.3%. The current water losses in the network are assumed 20% due to leakage and illegal connections. The quantity of treated wastewater used for agriculture is 296,000 m^3/month. It represents 1.0% of the total treated wastewater quantity of 247 MCM/year. The other scenarios assumptions are listed in Table 2.

4. Results and discussions

4.1. Base-case scenario

WEAP result of water demand indicates that the water demand will increase from 335 MCM in 2017 to 779 MCM for the year 2030. Table 3 shows the WEAP output parameters for the base-case scenario. WEAP result of supply requirement indicates that it will increase (if no change in

Table 2
Scenarios and assumption of Jeddah city WEAP model

Scenario	Main assumptions
Base-case	The base-case scenario represents the current account that was initially set up for the year 2017. It represents the current system conditions including demand zone and water supply. Base-case represents a population growth rate of 3.3% with existing water allocation and policies and existing irrigation practices. In this case, the WEAP is executed for the next 13 years (starting from 2017 until 2030).
Scenario-1 (water conservation)	At present, the concept of water conservation is not applied in Jeddah city due to lack of awareness about the economic benefit of water conservation, and absence of a comprehensive plan to conserve water (MEWA, 2008). However, NWC is planning to implement water conservation to all existing and new building. Household retrofits aim to minimize the average consumption of water use per capita from 30% to 40% (NWC, 2017; MEWA, 2008).
Scenario-2 (water conservation and leak reduction)	NWC is planning to reduce leakage and implement water conservation plan according to SMWA guidelines. According to NWC, the water conservation plan with leakage reduction should be implemented from 2018. The current leakage in Jeddah's distribution system is more than 20% (NWC, 2017). This leakage is due to various reasons including unaccounted water, illegal connections, and leaks in the distribution system. In this case, the only change from the base-case scenario is to reduce the leakage in the water distribution network from 20% to 10%. NWC plans to establish new projects and to hire domestic and foreign companies to reduce leakage to 10%.

Table 3
Computed demand and supply requirements from WEAP for all scenarios

Scenario	Water demand MCM		Supply requirement MCM		Water delivered MCM		Unmet demand MCM	
	2017	2030	2017	2030	2017	2030	2017	2030
Base-case scenario	335	779	418	973	418	469	0	504
Scenario 1	335	513	418	641	418	469	0	172
Scenario 2	335	513	418	570	418	469	0	101

water supply) from 418 MCM in 2017 to 973 MCM in 2030 as shown in Table 3. The unmet demand is 504 MCM for all demand zones to be found in 2030. The increase in water demand is due to the increase in future population, while the supply of water remains constant. The supply requirement increased exponentially over demand years due to the increase in demand for water (Fig. 3). In this case, the maximum water delivered occurred in 2020 and remain constant until 2030. It indicates that demand zones will not receive more water in 2020 due to the maximum storage capacity of the water reservoirs (469 MCM). The unmet demand starts from the year 2018 and continues to increase exponentially until 2030. Therefore, there is a need to consider a new water demand/supply option to reduce the increase of unmet demands.

4.1.1. Scenario-1: water conservation

Results show that the implementation of water conservation in households as suggested by NWC has a major impact on future water demand. Water demands reduced for all demand years and all demand zones. It is reduced from 779 to 513 MCM in the year 2030 after introducing water conservation. The supply requirements (e.g., demand plus losses) decreased due to a reduction in water demand from 973 MCM in the base-case to 641 MCM in this case for all demand zones in 2030. In this case, water delivered reached its maximum capacity in 2028 and remained constant until 2030. When water conservation is introduced, reservoirs reached their maximum capacity in the year 2028. This means that NWC would require establishing new reservoirs to store more water to meet future demand started in 2026. Here, the unmet demand started in 2024 with a quantity of 3.8 MCM and reached 172 MCM in 2030. Results suggest that conservation is an important water management option to reduce unmet demand. WEAP result of unmet demand is reduced from 504 MCM in the year of 2030 to 172 MCM in 2030 after conservation implementation for the household.

4.1.2. Scenario-2: reduce leakages and water conservation

The result shows that the water demands have the most significant reduction throughout all demand years for all demand zones. The demand decreased from 779 MCM in the base-case to 513 MCM in this case for 2030 for all demand. The supply requirements decreased significantly from 973 MCM in the base-case scenario to 570 MCM after considering both conservation and leak reduction. Water delivery reached its maximum capacity of reservoirs in 2028 and remains constant until 2030. This means that NWC would require establishing new reservoirs in the year 2028 to meet future water demand. However, in the base-case scenario, water delivered reached its maximum capacity of reservoirs in 2025. Furthermore, the unmet demand started in the year 2023 with a quantity of 0.7 MCM and reached

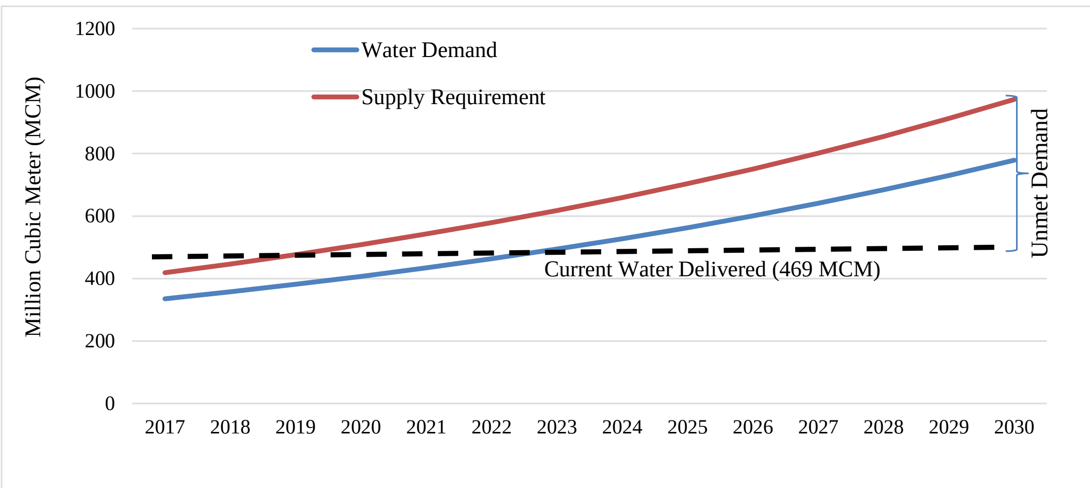

Fig. 3. Computed WEAP output parameters for the base-case scenario.

Table 4
Detailed selected results for the water system performance evaluation for the proposed scenarios

Scenario	Zone	(1) Total months	(2) Satisfactory state (months)	(3) Unsatisfactory (months)	(4) No. of successes	(5) Shortage of unsatisfactory months (MCM)	(6) Reliability = (2/1)	(7) Resiliency = (4/3)	(8) Vulnerability = (5/3)
Reference	Al-Faysaliah	168	49	119	5	733,460,230	29%	4.20%	6,163,531
	Briman	168	23	145	4	734,528,288	14%	2.76%	5,065,712
	Filling Station	168	12	156	0	639,665,336	7%	0.00%	4,100,419
	Khulais	168	23	145	4	49,212,048	14%	2.76%	339,393
	Qwizah	168	12	156	0	629,890,640	7%	0.00%	4,037,761
	(Sum)	168	12	156	0	2,786,756,541	7%	0.00%	17,863,824
Scenario 1	Al-Faysaliah	168	127	41	6	27,902,387	76%	2.33%	1,948,839
	Briman	168	100	68	4	138,280,515	60%	2.01%	2,033,537
	Filling Station	168	85	83	1	144,357,364	51%	0.00%	1,739,245
	Khulais	168	96	72	5	10,025,022	57%	2.00%	139,236
	Qwizah	168	87	81	0	144,066,385	52%	0.00%	1,778,597
	(Sum)	168	84	84	0	516,631,673	50%	0.00%	6,150,377
Scenario 2	Al-Faysaliah	168	157	11	5	5,144,497	93%	45.45%	467,682
	Briman	168	132	36	5	35,011,127	79%	13.89%	972,531
	Filling Station	168	120	48	0	48,129,079	71%	0.00%	1,002,689
	Khulais	168	131	37	4	2,992,618	78%	10.81%	80,882
	Qwizah	168	121	47	0	48,758,173	72%	0.00%	1,037,408
	(Sum)	168	120	48	0	140,035,494	71%	0.00%	2,917,406

101 MCM in the year 2030. Result suggests that this scenario is a very effective one to reduce unmet demand and supply requirements.

5. Evaluation of water system performance

In order to better assess Jeddah water supply system's performance and further show the system improvement from introducing the maximum supply available, the unmet demand analysis was analyzed over 13 years of supply and demand between 2017 and 2030. Reliability, resiliency, and vulnerability indicators are used to evaluate the current water delivery system's performance for Jeddah city (Hashimoto et al., 1982; Loucks and Van Beek, 2017). These indicators will be used to assess the selection of the best management water management scenario.

The result shows when implementing scenario 2, the reliability index of water supply which meets water demand achieved the highest reliability performance of 71% for all demand zones (Table 4). Results show that highest resiliency is achieved when implemented Scenario 2. Al-Faysaliah and Briman Zones achieved the highest reliability index of 93% and 79%, respectively. The highest reliability index of 93% has achieved for Al-Faysaliah zone. It indicates that 7% of the water, for Al-Faysaliah zone, was not delivered and considered unmet demand. Interestingly, the other zones in this scenario show the highest reliability when compared against reliabilities in same zones for other scenarios (Table 4).

The vulnerability index is found to be 6,150,377 MCM when water conservation is introduced (Scenario 2). In this case, the total shortage reached to 516,631,673 MCM and has occurred in 84 months for all demand zones. That is, shortages for all demand zones could reach 27,210,108 MCM per month. On the other hand, scenario 2 was found to be the less vulnerability of 2,917,406 MCM, with total shortages of 140 × 106 MCM occurred in 48 months. Reduction of a vulnerability index, in this case, refers to considering both leakage and water conservation. In scenario 2, the resiliency for Al-Faysaliah zone is 45.45% is the highest in this scenario. This could be referred to the fact that an Al-Faysaliah reservoir receives 11,861,631 m^3/month. It is considered the highest quantity of water to be delivered to this zone from Jeddah desalination plant.

6. Summary and concluding remarks

In this paper, a WEAP-based water resource simulation model is developed for the Jeddah City water supply system and included two water demand subsystems. The allocation of water resources among Jeddah City's zones was also considered as a finer-scale assessment. Furthermore, water resources supply and demand, as well as water saving potentials, were projected from 2017 to 2030 under different water resources development scenarios. The key findings of this study can be summarized as follows:

- The model gives a fair assessment of future water demand for Jeddah city based on existing information. The results revealed that an additional amount of more than 469 MCM would be required in 2030 to satisfy water needs and development.
- The results show that water demand would reach about 1,000 MCM in 2030 when the population increased to 4.3%. This necessitates establishing other water supply/demand management options to meet future water demand.
- The total water demand in 2030 reduced from 779 MCM in the base-case to 513 MCM when water conservation is applied. Further, water requirements also reduced from 973 MCM in the base-case to 641 MCM.
- The water demand could be reduced from 779 MCM in the base-case to 513 MCM when considering water conservation and leak management. The supply requirement would be reduced by 42%, from 973 MCM in the base-case to 570 MCM under these measures.
- The lowest unmet demand is found when introducing leakage management in conjunction with water conservation (i.e., Scenario 2). The unmet demand is reduced from 504 to 101 MCM. It is also worth to mention that unmet demand is only found in the years from 2026 to 2030.
- When considering leak reduction in conjunction with water conservation practices (i.e., Scenario 2), the results suggest that considering new water supply reservoirs has to be considered in 2030 to deliver water to all demand zones. This is because the water delivered in Scenario 2 has reached the maximum capacity of reservoirs storage (469 MCM) in 2030.
- The reliability analysis indicated that scenario 2 is the most reliable option to satisfy demand. In this case, the highest reliability of 71% of meeting demand is achieved for all demand zones. This indicates that 29% of the water is not delivered and considered unmet demand.

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Developing deterioration prediction model for the potable water pipes renewal plan – case of Jubail Industrial City, KSA

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ABSTRACT

The aim of this study is to identify the appropriate parameters for predicting the potable water pipes deterioration. The study evaluated the strength of some variables related to pipe breaks probability of failure based mainly on logistic regression model. The independent variables included in the study are static variables such as pipe diameter, pipe length and pipe material in addition to some dynamic (time-based) variables such as pipe age, water pressure and water velocity. The pipe break history (number of pipe breaks) for each pipe segment is used as dependent variable to be predicted in the statistical model. The resulted prediction equation is then used to calculate the failure probability for each pipe in the potable water network. Finally, prioritization of pipes is performed and the annual renewal plan is developed for the city of Jubail Industrial City in KSA based on the model results.

Keywords: Geographical information systems; Pipes; Renewal; Logistic; Regression

1. Introduction

The objective of the study is to identify priority pipes segments in community areas of Jubail industrial city for replacement program in the next 5 years. The study performed the screening process by evaluating all the pipes in the database of Jubail community areas. The statistical analysis such as logistic regression requires data for at least 5 years in order to provide reliable prediction of the pipe failures (Ambrose et al. 2008). The most cost-effective pipes replacement strategy gives approximately 2% annual return on investment (Moglia et al., 2005). The life cycle cost ranges from 100 years (Ambrose et al., 2008) to 200 years (Grigg, Fontane, & Zyl, 2013), which means that at least between 0.5% and 1% of the network length need to be renewed every year. However, the US national median of 1.7% for city pipeline replacement was reported by the American Water Works Association from aggregate data related to combined water utilities including transmission and distribution (AWWA;, 2017) which is more applicable to the study combined network.

2. Scope of work

Total number of the pipe segments under considerations is 29,658 with total length of 928.25 km that were built during years 1980 to 2017. Total number of 1,053 pipe break notifications and 847 affected pipe segments that were recorded during 01/01/2012 to 25/04/2018 in the study area. All key pipes information such as age, diameter size, material and length are recorded in the geographical information system (GIS). In addition, some of other support information such as average operating pressure and velocity are recorded. Other parameters such as soil types, customer complaints and water quality are currently out of the scope but gradually could be used in the future as input to the analysis. The study covered only the community area in Jubail industrial city including districts in Deffi, Fanateer, East Corridor, Jalmudah and southern part of Mutrafiah.

The study adopted the American Water Works Association target to renew 1.7% (AWWA, 2017) of the whole PW pipes network in the Jubail community areas each year in order to meet target life cycle of around 59 years of the

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whole network. The study aimed to identifying the most critical pipe segments (8.5% of the total network) that needs to be replaced during the next 5 years. In other words, the study attempted to identify the most critical 78.9 km of the current PW community pipes network where around 15.7 km need to be replaced each year.

3. Requirements, preparation and methodology

3.1. Data requirements

Table 1 shows the essential data requirement for the analysis where continuous variables are numeric and categorical variables are binomial (0 or 1):

3.2. Data preparation

The following are the procedures for preparing the data:

- Check for raw data completeness to be 100% for the study area
- Data cleansing and maintenance
- Ensure integrity and consistency of materials and diameters records and convert to binomial parameters.
- Calculate age of the pipes based on the installation year and classify age groups
- Calculate number of pipe breaks in each pipe segment and in each zone
- Conduct pipe break analysis of the pipes characteristics such as size, age, zone risk and pipe material
- Calculate absolute velocity values for the pipes
- Process pressure data logs, identify pressure zones and associate values to related pipes
- Recode some independent parameters to be categorical variables and make sure the dependent variable to be binary
- Use logistic regression analysis to identify significance and weights for the parameters

3.3. Overall process and methods

The method is partially inspired from the water distribution system risk tool for investment planning by Water Research Foundation, EPA and WERF (Grigg et al. 2013). This methodology has been customized according to the local situation of Jubail community network to accommodate local available data in GIS. The methodology is predictive method based on statistical analysis and ranking of multiple criteria from historical performance and failure. Logistic regression analysis has been selected to evaluate the strength of all parameters in predicting the occurrence of future pipe break events in all pipe segments. Following are main methodology steps:

- Identify criticality of residential zones
- Identify influence threat factors
- Specify probability of failure values based on logistic regression result
- Prioritization of critical pipes and plan renewal accordingly

4. Identify criticality of residential zones

The criticality rate is calculated for each district in the community areas as in the following equation:

Pipe breaks rate = (total # of pipe breaks in a district/network length of a district)/no. of monitoring years

Note that all districts of the study area have started to be monitored in the same year (2012) but many pipes are newly installed after 2012 which will have lower number of monitoring years. Therefore, it is required to divide by the number of monitoring year to get correct rate for all pipes segments. The result and thematic map showed the most critical residential districts in Jubail Industrial city that are facing highest rate of repeated pipe breaks per km of network length which are respectively: Huawailat (Camp 11) and Al Hijaz (B1), Al Kods (D2), Makkah (B2), JIC, Al Faiha (D3) and Camp 10. These are the areas, which got extreme risk and upper high risk. The result of the remaining districts can be seen in Fig. 1 for the high, medium and low risk.

5. Identifying influence threat factors

The data analysis is based on five main factors where three are considered as assets data related to the pipe (age, diameter and material) and two are operational hydraulic factors (pressure and velocity). These factors are the predictors that are used to get the probability of pipe breaks occurrence.

5.1. Asset data

5.1.1. Age of the pipe

Some statistics related to the age of pipes were extracted from the database (Table 2). It has been noticed that around 61% of the network length with age more than 26 years. Overall, the average of 1.1 pipe breaks per km was calculated. However, some of particular ages (29, 33 and 35) have the highest rate of 2 or more of pipe breaks per km.

5.1.2. Diameter size

Calculation and analysis of the diameter sizes of the pipes in the study area shows that diameters of smaller sizes (20 to 110 mm) represents around 21.6% of the network in the study area while pipes with the largest diameter sizes (450 to 1,400 mm) only represents around 4% of the network length. However, the majority of the pipes in the network falls in the middle class of diameters (150 to 400 mm) which represents 74.4% of the network length. This is reflected on the high number of pipe breaks (88% of the pipe breaks) in the diameters (150 to 400 mm) as seen in Fig. 2.

5.1.3. Material

The rate (PB/KM) in indicates if certain type of pipe material is breaking more often than the other types of material such as PVC, which has the highest rate of 1.32 PB/km among other types of materials (Table 3). Following comes

Table 1
Pipes data sources and parameters needed in the study

Data variable	Remarks	Input in logistic regression
	General required information	
Pipe ID	Unique GISID to differentiate each pipe segment and used to connect to the maps in GIS	No
Pipe length (km)	Length information of each pipe segment in kilometers	No
District boundary	Used for risk analysis and criticality calculation	No
	Dependent variable for logistic regression analysis	
No. of pipe breaks (PB)	Dependent categorical variable (0: no PB event; 1: PB event)	Yes
	Independent variables for logistic regression analysis	
Pipe age (years)	Continuous variable (Age = current year – installation year)	Yes
Pipe diameter (mm)	Used to classify 30 independent categorical variables (DIA_20, DIA_25, DIA_32, DIA_40, DIA_50, DIA_63, DIA_65, DIA_75, DIA_80, DIA_90, DIA_100, DIA_110, DIA_150, DIA_160, DIA_200, DIA_225, DIA_250, DIA_280, DIA_300, DIA_315, DIA_350, DIA_400, DIA_450, DIA_500, DIA_600, DIA_800, DIA_900, DIA_1000, DIA_1200 and DIA_1400)	Yes
Pipe material	Used to classify 8 independent categorical variables (M_AC, M_PVC, M_DI, M_FRP, M_GRP, M_uPVC, M_RCP and M_SCP)	Yes
Velocity (m/s)	Used to calculate continuous independent variable (absolute velocity). Extracted from hydraulic model. Blank records filled by average values.	Yes
Pressure (kPa)	Used to calculate 3 independent continuous variables (P_Mean, P_Max and P_Min). Extracted from field loggers.	Yes

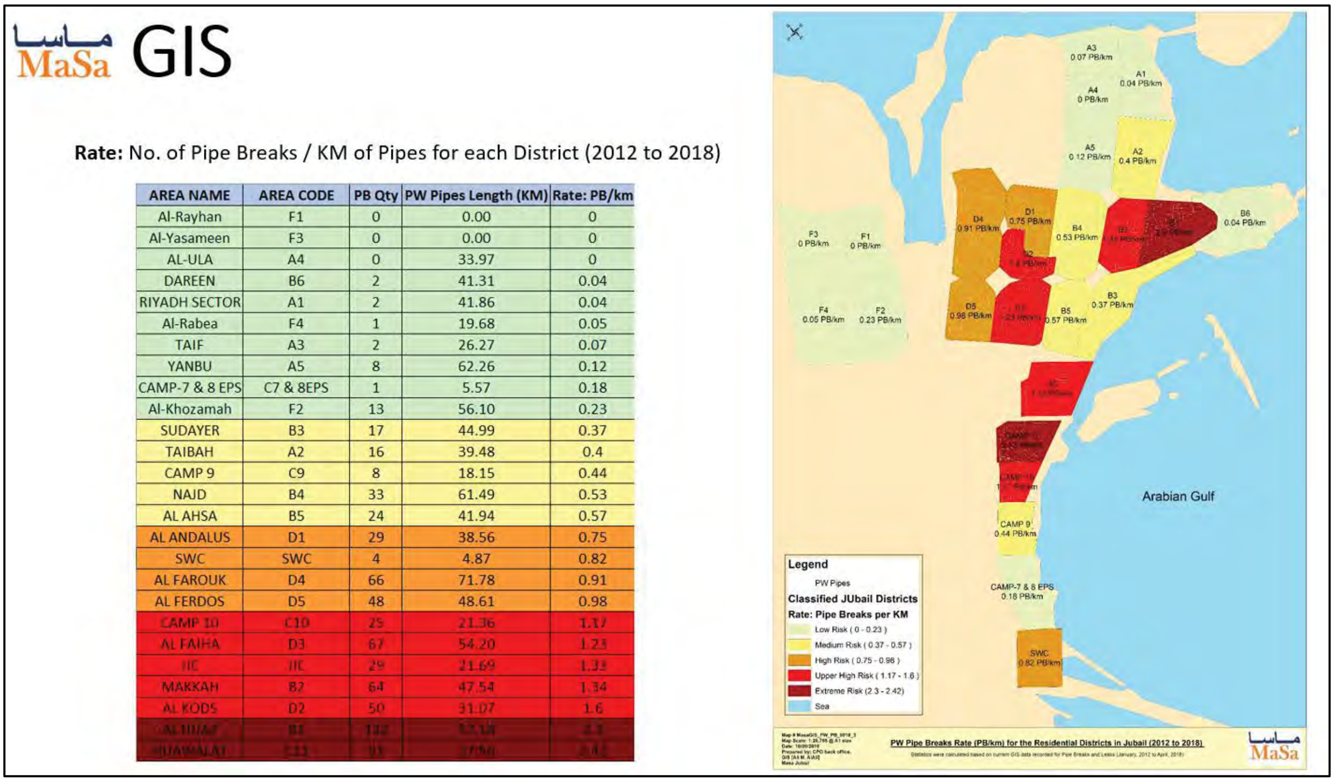

Fig. 1. Table and thematic map of the criticality analysis of pipe breaks per districts in Jubail Industrial city.

Table 2
Age groups and calculations of length and pipe break rates

Pipes age group	Length (km)	Total pipe breaks	Rate (PB/km)
Age Group 1: 1 to 26 years	363.02	115	0.31
Age Group 2: 30 to 38 years	565.23	938	1.65
Grand total	928.25	1053	Avg = 1.13

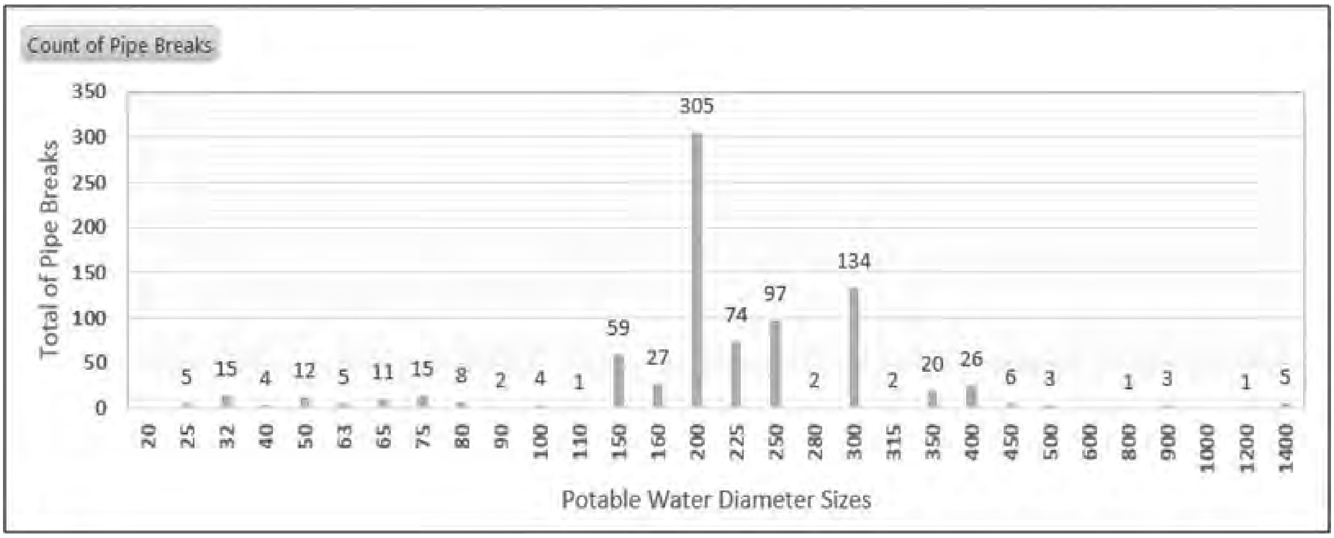

Fig. 2. Total potable water network pipe breaks according to the diameter sizes of the pipes.

the uPVC with approximately an average rate of 0.99 PB/km. On the other hand, FRP and RCP materials showed the lowest PB rates.

5.2. Hydraulic data

The hydraulic parameters include pressure and velocity. Velocity data were extracted from the main lines in the hydraulic model while the pressure data are extracted from 23 field data loggers.

5.2.1. Velocity (M/S)

The velocity data were exported from the hydraulic model and processed inside the developed GIS. The current hydraulic model provided calculations of velocity for the main lines only which represent only 20% of the total network length (187.2 km). Furthermore, only 202 pipe break events (23.8%) occurred on these main lines as indicated in Table 4. Records of the other pipes (740.4 km) were filled with the average absolute velocity value (0.089626 m/s) in order to be able to run the statistical model.

5.2.2. Pressure (kPa)

The pressure data were extracted from 23 field data loggers (Table 5) where a total of 6,543,563 logs for the period 17/07/2017 to 03/09/2018 were processed. The statistics were calculated for each data logger and Thiessen

Table 3
Calculations of length and pipe breaks categorized by material type

Material type	Length (km)	Total pipe breaks	Rate (PB/km)
AC	59.66	28	0.47
Dl	41.21	15	0.36
FRP	0.09	0	0.00
GRP	52.01	25	0.48
PVC	129.24	171	1.32
RCP	20.17	1	0.05
SCP	20.14	9	0.45
uPVC	605.74	598	0.99
Grand total	928.3	847	Avg = 0.91

Table 4
Length and pipe breaks of main lines categorized by velocity level

Velocity group	Length (km)	Total pipe breaks	Rate (PB/km)
Low velocity (<0.10 m/s)	116	135	1.16
High velocity (=>0.10 m/s)	71.8	67	0.93
Grand total	187.8	202	Avg = 1.07

Table 5
Network and pump stations data loggers used to measure pressure (kPa) parameter

Seq.	Logger Location	Logger Type	P_Max	P_Min	P_Mean	Date_From	Date_To	No. of Logs
1	T-230, Near Petrokemya, FH-90	KPI Logger	393.90	188.06	299.84	01/10/2017	31/10/2017	89,280
2	T-154, WWPS-7, Near SAFCO	KPI Logger	400.36	182.07	309.84	01/10/2017	30/10/2017	89,280
3	Ferdaus, T-Ahzab, FH-32	KPI Logger	280.73	125.54	230.79	01/10/2017	31/10/2017	89,280
4	T-Dammam/Dammam 17, FH-16	KPI Logger	262.06	117.75	227.46	01/10/2017	31/10/2017	89,280
5	Makkah, T-Sarat/T-Zamzam, FH 1-1	KPI Logger	295.40	153.78	254.41	01/10/2017	31/10/2017	89,280
6	Sudayer, Hawiyah 2, FH-15	KPI Logger	264.75	128.54	222.37	01/10/2017	31/10/2017	89,280
7	RC Building, backside visiter building	Network Logger	483.05	-0.97	371.08	12/07/2017	09/11/2017	345,826
8	T-Dammam, near Dammam 26, FH-1/3	Network Logger	290.96	67.02	230.41	17/07/2017	22/11/2017	368,714
9	T-Andulus/Andulus 9, FH-33	Network Logger	273.03	-1.38	211.18	17/07/2017	09/10/2017	242,039
10	T-Ferdaus/Ferdaus 20, FH-5	Network Logger	301.16	-1.38	228.99	13/07/2017	21/11/2017	378,028
11	T-Faiha/T-Khamees, near Faiha 27, FH-201	Network Logger	290.68	-1.65	226.28	13/07/2017	27/11/2017	394,700
12	Camp 11, T-Huwaylat/T-Dairie, St. 46, FH-01	Network Logger	251.80	61.09	179.81	12/07/2017	09/10/2017	255,979
13	T-Najd/Najd 16, FH 1-8	Network Logger	349.15	75.43	227.60	17/07/2017	22/11/2017	368,662
14	T-Faiha/Faiha 7, FH-62	Network Logger	273.31	-8.27	152.87	13/07/2017	27/11/2017	394,642
15	Kods 8/T-Khalil, in front of fire station, FH-30	Network Logger	292.75	91.84	214.29	17/07/2017	21/11/2017	366,384
16	T-Andulus/Andulus 23, FH-43	Network Logger	294.27	-3.72	220.20	17/07/2017	09/10/2017	241,924
17	Farooq, T-Karamah/T-Batra, FH-327	Network Logger	279.24	-0.55	217.25	13/07/2017	21/11/2017	377,771
18	T-Farooq/T-Sedieg, FH-37	Network Logger	280.62	72.95	224.38	13/07/2017	21/11/2017	377,773
19	Fanateer PS, Discharge line A	PS Logger	441.61	48.61	221.47	18/07/2017	27/11/2017	380,257
20	Fanateer PS, Discharge line B	PS Logger	448.50	52.06	245.81	18/07/2017	27/11/2017	380,204
21	Deffi PS, Discharge line A	PS Logger	315.44	26.54	229.78	18/07/2017	27/11/2017	380,240
22	Deffi PS, Discharge line B	PS Logger	317.16	-2.07	231.25	18/07/2017	27/11/2017	380,191
23	Jalmudah, T-6, after EXTRA mall, FH	PS Logger / RTU	339.56	32.75	225.05	17/07/2017	03/09/2018	374,549

polygons were created using GIS for the position of each data logger in order to cover the network pipes in nearest area to each logger. The mean, minimum and maximum pressure was associated with each pressure zone created from these polygons. Then, the mean, minimum and maximum pressure was associated to each related pipe segment within each pressure zone. The three pressure measures (P_Mean, P_Max and P_Min) variables were used as predictors for fitting the logistic regression model for all pipes' segments.

6. Statistical analysis

6.1. Research question

Failure predictions are thorough analysis of existing asset and failure data. Use of the failure predictions rather than just the historical performance when making pipes renewal decisions could reduce the predicted costs considerably. Statistical logistic regression analysis is required in order to get the prediction equation based on the explanatory variables. Therefore, the research question is: What is the impact of age, diameter, material, velocity and pressure on the probability of pipe breaks?

Overall Likelihood index of Failure = f (age, diameter, material, velocity, pressure)

6.2. Initial logistic regression analysis

Multiple duplicate records were created for pipe breaks occurred more than once in a single pipe segment in order to have only 0 or 1 in the response variable for each record, which provide binary response type using logistic function (Logit) model. Direct logistic regression was performed to assess the impact of all factors related to the function (age, diameter, material, velocity and pressure) on the likelihood that pipe break will occur. The model contained 43 independent variables as explained in Table 1. Result of the initial logistic regression analysis indicated that coefficients of two predictors (DIA_1400 and M_SCP) could not be defined by the model because of singularities. The low p-value out of the logistic regression model fitting result indicates that only the intercept and seven independent variables are statistically significant suggesting a strong association between them with the probability of pipe break event.

6.3. Analysis of variance

Analysis of variance (ANOVA) was also performed as statistical technique for investigating data by comparing the means of subsets of the data. The function compares the sequential logistic regression models which compares the smaller model with the next more complex model by adding one variable in each step. Each of those comparisons is done via a likelihood ratio test (LR test). Then, each coefficient against the full model containing all coefficients. ANOVA test of the 'main effect' for each independent variable which also explore the possibility of an 'interaction effect' among levels of independent variables on the dependent variable.

It has been noticed in the resulted analysis of deviance table which measure the goodness of fit that Resid. Dev is decreasing from 9,113 (at intercept level) and every time when new independent variable added to the model until it reaches 7,190.7 (at the full model level). The term was added sequentially from first to last where the deviance or the difference between null model and after adding the Age_Years variable = 670.18 was the largest deviance. The 2nd largest deviance was for DIA_150 = 509.14, followed by other DIA variables such as DIA_32, DIA_40 and DIA_50 with values (106.24, 111.34 and 107.74) sequentially. The probability of seeing a difference in Resid. Dev "Pr(>Chi)" indicated possible improvement in the model fit upon adding some variables is greater than what is expected by chance alone. These additional significant independent variables are DIA_63, DIA_65, DIA_90, DIA_110, DIA_160, DIA_225, DIA_250, DIA_300, DIA_400, DIA_450, M_AC, M_PVC, M_DI, M_GRP and P_Max.

6.4. Final logistic regression analysis

Direct logistic regression was performed again to assess the impact of significant factors after performing ANOVA on the initial logistic regression model as these additional factors showed possible improvement in the model fit on the likelihood that pipe break will occur (Table 6). The low *p*-value out of the final logistic regression model indicated that the model fit improved and the significant predictors increased from 7 to 16 independent variables which are statistically significant suggesting a strong association between them with the probability of pipe break event.

Out of the statistically significant predictors, it has been noticed that the intercept and nine diameter variables have negative coefficients suggesting that these variables being equal, the related pipe segments are less likely to have pipe breaks. In particular, the significant variables with negative coefficient are representing the relatively smaller diameter pipes as following: DIA_25, DIA_32, DIA_40, DIA_50, DIA_63, DIA_65, DIA_90, DIA_150 and DIA_160. Additionally, one material variable (M_DI) showed negative coefficient indicating that DI material pipes are less likely to have pipe breaks compared with other types of materials.

On the other hand, other types of material variables (M_PVC and M_GRP) have positive coefficient suggesting

Table 6
Model result of fitting logistic regression analysis in R

```
Call:
glm(formula = PB_Count.f ~ Renewal.data$Age_Years + DIA_25.f +
    DIA_32.f + DIA_40.f + DIA_50.f + DIA_63.f + DIA_65.f + DIA_90.f +
    DIA_110.f + DIA_150.f + DIA_160.f + DIA_225.f + DIA_250.f +
    DIA_300.f + DIA_400.f + DIA_450.f + M_AC.f + M_PVC.f + M_DI.f +
    M_GRP.f + Renewal.data$P_Max + Renewal.data$P_Mean, family = binomial(link = "logit"),
    data = modelldata)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-1.2615  -0.2056  -0.1398  -0.1026   3.8441

Coefficients:
                         Estimate Std. Error z value Pr(>|z|)
(Intercept)            -5.8679067  0.2118612 -27.697  < 2e-16 ***
Renewal.data$Age_Years  0.0894120  0.0045638  19.592  < 2e-16 ***
DIA_25.fDIA = 25       -2.9881975  0.4525545  -6.603 4.03e-11 ***
DIA_32.fDIA = 32       -2.4958960  0.2680098  -9.313  < 2e-16 ***
DIA_40.fDIA = 40       -3.2727430  0.4533895  -7.218 5.26e-13 ***
DIA_50.fDIA = 50       -2.5612037  0.2960059  -8.653  < 2e-16 ***
DIA_63.fDIA = 63       -2.1198955  0.4535722  -4.674 2.96e-06 ***
DIA_65.fDIA = 65       -1.6706617  0.2864155  -5.833 5.44e-09 ***
DIA_90.fDIA = 90       -1.8579021  0.7148429  -2.599 0.009349 **
DIA_110.fDIA = 110     -2.4019933  1.0069747  -2.385 0.017063 *
DIA_150.fDIA = 150     -2.0850377  0.1400334 -14.890  < 2e-16 ***
DIA_160.fDIA = 160     -0.7561222  0.2006584  -3.768 0.000164 ***
DIA_225.fDIA = 225     -0.1349843  0.1239883  -1.089 0.276292
DIA_250.fDIA = 250      0.3030320  0.1144329   2.648 0.008094 **
DIA_300.fDIA = 300      0.7815801  0.0978849   7.985 1.41e-15 ***
DIA_400.fDIA = 400     -0.2992226  0.2292412  -1.305 0.191800
DIA_450.fDIA = 450      0.9825621  0.4434521   2.216 0.026711 *
M_AC.fAC Material       0.4279170  0.2267588   1.887 0.059147 .
M_PVC.fPVC Material     0.4424478  0.0851588   5.196 2.04e-07 ***
M_DI.fDI Material      -1.1501682  0.2630056  -4.373 1.22e-05 ***
M_GRP.fGRP Material     1.0838486  0.2364036   4.585 4.55e-06 ***
Renewal.data$P_Max     -0.0011517  0.0008658  -1.330 0.183472
Renewal.data$P_Mean     0.0048819  0.0011928   4.093 4.26e-05 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 9113.0  on 29863  degrees of freedom
Residual deviance: 7238.7  on 29841  degrees of freedom
AIC: 7284.7

Number of Fisher Scoring iterations: 9
```

that these types of materials are more vulnerable to pipe breaks. Also, the larger diameter variables (DIA_250 and DIA_300) along with Age_Years and pressure mean (P_Mean) have positive coefficient suggesting that all other variables being equal, the relatively old and large diameter pipes with high pressure mean are more likely to have pipe breaks. Finally, M_AC material variable along with the other diameters, maximum pressure and velocity variables showed high *p*-values in the logistic regression model fitting results which indicate that all remaining variables are not statistically significant.

6.5. Probability of failure prediction

The equation of the final prediction model (Variable Pipe_Breaks) is:

Pred (Pipe_Breaks = 1) = exp(z) / [1 + exp(z)]

where;

$z = b_0 + b_1x_1 + b_2x_2 + \ldots\ldots + b_nx_n$

b_0 = the intercept constant
b_n = the regression coefficient of the n variables
Then;

z = –5.8679067 + 0.0894120 X Age_Years + –2.9881975 X DIA_25 + –2.4958960 X DIA_32 + –3.2727430 X DIA_40 + –2.5612037 X DIA_50 + –2.1198955 X DIA_63 + –1.6706617 X DIA_65 + –1.8579021 X DIA_90 + –2.0850377 X DIA_150 + –0.7561222 X DIA_160 + 0.3030320 X DIA_250 + 0.7815801 X DIA_300 + 0.4424478 X M_PVC + –1.1501682 X M_DI + 1.0838486 X M_GRP + 0.0048819 X P_Mean

The statistics of the predicted pipe breaks probabilities are: N = 29,658, Mean = 0.047756, Min = 0.000381, and Max = 0.530694. The final prediction model was tested on N = 837 pipes with previous real failure history where the mean of 0.047756 was used as decision boundary where values predicted above the mean will have 1 (predicted pipe break event) and prediction values less than the mean will have 0 (no predicted pipe break). The results showed that 74.3% of the pipe breaks were predicted correctly as in reality (Fig. 3).

7. Prioritization of critical pipes

The predicted pipe break probability values were calculated based on the final logistic regression model for each pipe segments in the whole network. Then, prioritization of the pipes was performed based on the highest probability values for the most critical 78.76 km of the complete potable water network. Table 7 and the map in Fig. 4 provide more details about the critical pipes chosen by the model to renew as priority in the next 5 years plan.

8. Discussion and conclusion

The methodology developed in this paper is essential for water utility companies in order to maximize utilization of all available asset and historical data to direct the huge pipes renewal investment in the right way. Out of the initial 43 independent variables, 16 predictors showed to have impact on the pipe break occurrence. In particular, the age, some diameter classes (250 and 300 mm), some material types (PVC and GRP) and the pressure mean showed positive correlation which could increase probability of pipe break events. Other variables showed tendency to decrease pipe breaks such as smaller diameter sizes and

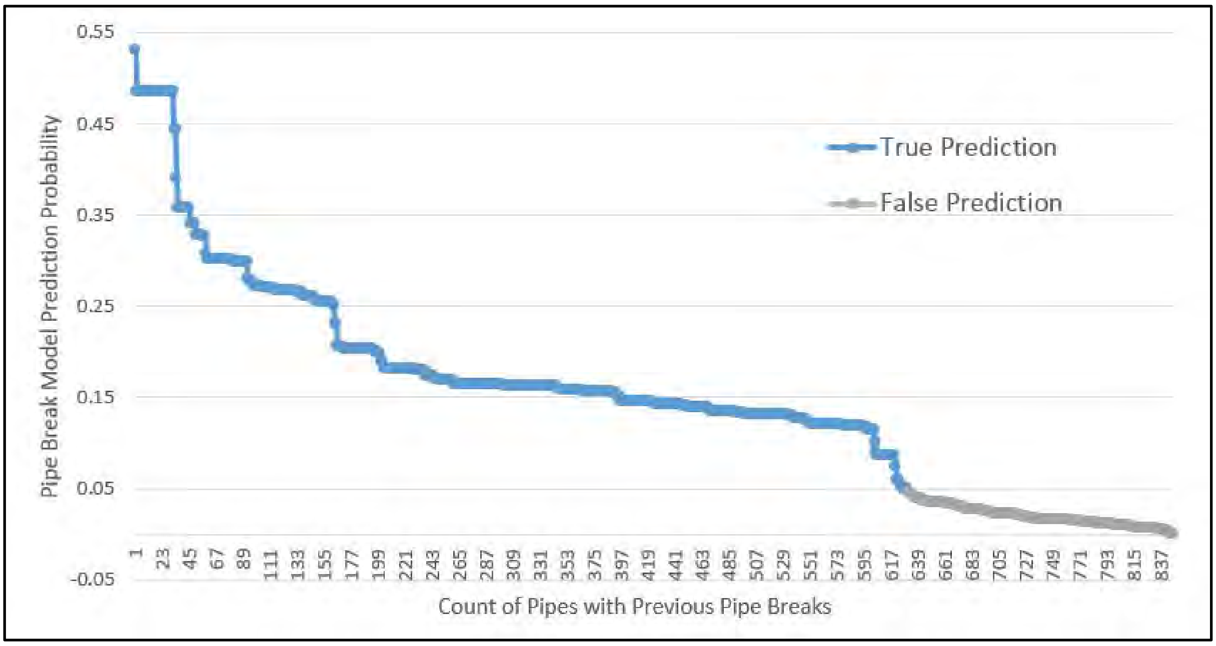

Fig. 3. Graph of the model predicted probability (0 to 1) as result of logistic regression prediction equation tested on real sample.

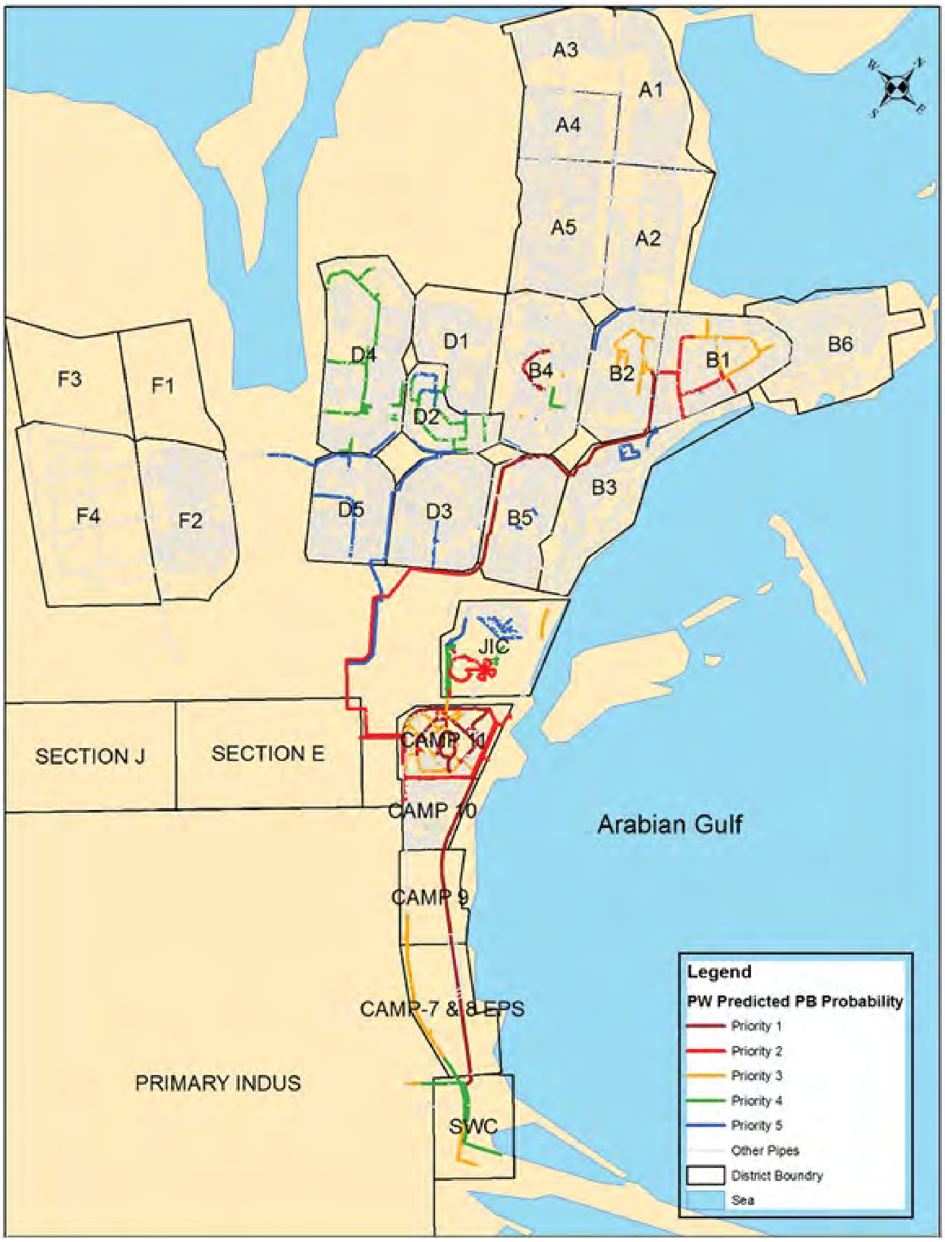

Fig. 4. Map of the potable water critical pipes based on high predicted pipe break probability, Pred (Pipe_Breaks = 1) = exp(z)/[1 + exp(z)].

Table 7
Priority levels for the annual critical pipes renewal plan

Priority Levels	Length (km)	Quantity of Pipes	Predicted PB probability range
Priority 1	17.28	110	0.358 to 0.530
Priority 2	15.69	150	0.302 to 0.358
Priority 3	14.65	305	0.267 to 0.302
Priority 4	15.68	259	0.251 to 0.267
Priority 5	15.46	206	0.204 to 0.251
Total	78.76	1030	0 to 1 pipe break probability

pipes made from DI material. Some literature (Hamidala & Sagar, 2016; Achim et al., 2007) found that pipe length has an important impact on the annual pipe break rate. Actually, the length was tested in the initial model and gave significant results as well with large positive coefficient but the authors decided to discard it from the model of this paper as its effect was clear on the final priority map covering only 121 main and long pipes on the network and consider them as most critical. The result of final model of this paper gave more detailed answer to the initial analysis of critical areas (Fig. 1) and provided higher resolution plan for the most critical 78.76 km pipes in the network (Table 7 and Fig. 4) as it can be seen that the priority 1 and 2 pipes are falling mainly on the most critical areas (B1 and Camp 11). Finally, the use of the GIS tool as a master repository for all key analysis information was very useful and efficient especially for detailed mapping and planning of the final results.

9. Future study improvement

The study used some assets and hydraulic parameters to estimate around the failure likelihood. However the study can be advanced in the future by improving some of the current parameters (such as more complete velocity based on GIS/hydraulic integration) and adding more explanatory variables. These parameters could include water temperature, ground water, weather condition, improper bedding, low stiffness, traffic vibration, water hammer, external vibration, corrosion issues, air pocket, operating condition, roots from trees, leakage and water loss, history of water quality complaints and bad joining. Root cause analysis findings and some previous studies/reports could help in addressing some of these additional factors. Furthermore, future studies could include estimation of the consequence of failures and getting the consequence rating scores (SAR) for each pipe segment. The cost of failure parameters could include number of affected facilities and customers, potential flooding, water loss, and cost of repair.

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استهلاك الطاقة في قطاع المياه البلدية بمملكة البحرين

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تعتبر قضية ترابط المياه والطاقة إحدى القضايا الهامة في دول مجلس التعاون لدول الخليج العربية لا سيما في ظل شح الموارد المائية ووفرة مصادر الطاقة الأحفورية والاعتماد عليها بشكل كبير في قطاع المياه. وهذا ما دفع دول المجلس إلى تبني مفهوم الترابط بين المياه والطاقة، الأمر الذي انعكس على أهداف الاستراتيجية الموحدة للمياه لدول المجلس. إذ ينص الهدف الاستراتيجي الأول على «*تحسين كفاءة استهلاك الطاقة في قطاع المياه*» وذلك عن طريق «*تقييم وتدقيق استهلاك الطاقة في قطاع المياه في جميع دول المجلس وإعداد دراسة مرجعية حول استهلاك قطاع المياه من الطاقة*». ويعتبر ذلك الخطوة الأولى نحو «*إعداد البرامج والأهداف لتحسين كفاءة استهلاك الطاقة في قطاع المياه*» بحسب الهدف الفرعي السادس المنبثق عن الهدف الاستراتيجي الأول. وفي هذا الإطار، تم حساب كمية الطاقة المستهلكة في قطاع المياه البلدية في مملكة البحرين ضمن مشروع إعداد استراتيجية المياه لمملكة البحرين. وتشير نتائج الدراسة إلى أن نحو ٨٪ من إجمالي الطاقة الكهربائية في مملكة البحرين في عام ٧١٠٢ قد تم استهلاكها في إنتاج مياه التحلية ومعالجة مياه الصرف الصحي. ولعل النصيب الأكبر من الطاقة قد تم استهلاكه في محطات تحلية المياه وذلك بنسبة ٧٨٪ من إجمالي الطاقة الكهربائية المستهلكة في قطاع المياه البلدية. حيث بينت الدراسة احتمالية وجود فرص علاية نسبياً لتحسين كفاءة استهلاك الطاقة في قطاع المياه البلدية، ذلك أن كمية الطاقة الكهربائية المستهلكة في إنتاج مياه التحلية ومعالجة مياه الصرف الصحي تفوق مثيلتها في دول العالم وذلك بحسب نوع تقنية التحلية والمعالجة المستخدمة. وتوصي الدراسة بضرورة أخذ معيار الطاقة المطلوبة للتحلية أو معالجة مياه الصرف الصحي بعين الاعتبار عند تقييم خيارات التقنية المتاحة لإنشاء محطات جديدة. كما وتوصي الدراسة أيضاً بقياس وتجميع البيانات المتعلقة باستهلاك الطاقة بشكل دوري في قاعدة بيانات وطنية موحدة، وذلك لتسهيل عملية حساب مؤشرات الأداء المتعلقة بكفاءة استهلاك الطاقة، ومراقبة الأداء، وتقييم التقدم المحرز نحو تحقيق أهداف تحسين كفاءة الطاقة الموضوعة. وثمة توصية أخيرة تتعلق بضرورة توعية أصحاب المصلحة بأهمية قضية الترابط بين المياه والطاقة، ذلك أن خفض كمية الطلب على المياه تعني خفض كمية الطلب على الطاقة، الأمر الذي ينعكس بصورة إيجابية على البيئة، الاقتصاد، واستدامة التنمية الاجتماعية والاقتصادية في مملكة البحرين.

الكلمات المفتاحية: ترابط المياه والطاقة، كفاءة استهلاك الطاقة، معالجة مياه الصرف الصحي، المياه المحلاة

1. المقدمة

حظيت قضية ترابط المياه والطاقة باهتمام كبير في الآونة الأخيرة لاسيما في دول مجلس التعاون لدول الخليج العربية. إذ ترتبط المياه ارتباطاً وثيقاً بالطاقة وذلك في ظل ندرة المياه ووفرة مصادر الطاقة الأحفورية، الأمر الذي انعكس على أهداف الاستراتيجية الموحدة للمياه لدول المجلس ٦١٠٢ - ٥٣٠٢ والتي تضمنت هذا المفهوم. حيث ينص الهدف الاستراتيجي الأول على «*تحسين كفاءة استهلاك الطاقة في قطاع المياه*» مما يستلزم «*تقييم وتدقيق استهلاك الطاقة في قطاع المياه في جميع دول المجلس وإعداد دراسة مرجعية حول استهلاك قطاع المياه من الطاقة*» وذلك بغية «*إعداد البرامج والأهداف لتحسين كفاءة استهلاك الطاقة في قطاع المياه*».

وتماشياً مع الاستراتيجية الموحدة للمياه لدول المجلس وفي إطار إعداد الاستراتيجية الوطنية للمياه لمملكة البحرين، فقد وجه مجلس الموارد المائية نحو حساب كمية الطاقة المستهلكة في قطاع المياه البلدية في مملكة البحرين وذلك تمهيداً للتعرف على الفرص المتاحة لتحسين كفاءة استهلاك الطاقة في قطاع المياه البلدية.

وبالإضافة إلى كونها ضمن متطلبات الاستراتيجية الوطنية للمياه لمملكة البحرين، فإن حساب وتحسين كفاءة استهلاك الطاقة في قطاع المياه البلدية يسهم في تحقيق الهدف الثالث المنبثق من الهدف السابع من أهداف التنمية المستدامة والذي ينص على أن تتم «بحلول عام

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٠٣٠٢ مضاعفة المعدل العالمي لتحسين كفاءة استهلاك الطاقة». كما ويسهم أيضاً في تحقيق الهدف المتعلق بكفاءة استهلاك الطاقة بشكل عام في مملكة البحرين والذي تم تحديده بنسبة ٦٪ بحلول عام ٥٢٠٢.

هذا، ويتيح حساب كمية الطاقة المستهلكة في قطاع المياه البلدية فرصة تحديد إمكانية استخدام الطاقة المتجددة في هذا القطاع، الأمر الذي يسهم في تحقيق الهدف الثاني والمنبثق من الهدف السابع من أهداف التنمية المستدامة والذي ينص على رفع حصة الطاقة المتجددة ضمن مزيج الطاقات المستهلكة وذلك بحلول عام ٠٣٠٢. كما ويتيح أيضاً فرصة تحقيق الهدف المتعلق بمساهمة الطاقة المتجددة ضمن إجمالي الطاقة المستهلكة في مملكة البحرين والذي تم تحديده بنسبة ٥٪ بحلول عام ٥٢٠٢.

يضاف إلى ذلك، فإن تحسين كفاءة استهلاك الطاقة في قطاع المياه البلدية يعني الحد من استهلاك الوقود الأحفوري، وبالتالي خفض إجمالي انبعاثات غازات الاحتباس الحراري. وهذا ما يسهم في تحقيق التزامات خفض الانبعاثات والمترتبة على اتفاقية باريس لتغير المناخ والتي قامت مملكة البحرين بالتوقيع والتصديق عليها في عام ٦١٠٢، في حين دخلت حيز التنفيذ في عام ٧١٠٢.

وبالنظر إلى هذه المنافع مع الأخذ بعين الاعتبار بأنه يجري إعداد هذه الدراسة للمرة الأولى في مملكة البحرين، فإن هذه الدراسة تهدف إلى التعرف على كمية الطاقة المستهلكة في قطاع المياه البلدية بمملكة البحرين. وعلى وجه الخصوص، فإنها تهدف إلى حساب كمية الطاقة المستهلكة في المراحل المختلفة لقطاع المياه البلدية، وحساب مؤشرات الأداء ذات العلاقة بالطاقة، وأخيراً مقارنة كفاءة استهلاك الطاقة في قطاع المياه البلدية بمملكة البحرين بعدد من الممارسات العالمية ذات الصلة.

2. المنهجية

٢. ٢. المنهجية المتبعة في هذه الدراسة

بشكل عام، هناك طريقتان لحساب كمية الطاقة المستهلكة في أي قطاع: نهج جمع البيانات من الأسفل الى الأعلى Bottom-up approach، ونهج جمع البيانات من الأعلى إلى الأسفل Top-down approach. فعند اتباع الطريقة الأولى لجمع البيانات، فإنه يتم تحديد كمية الطاقة التي يستهلكها كل جهاز أو آلة وذلك إما عن طريق قياس كمية الطاقة المستهلكة بشكل مباشر أو حسابها بالاستعانة بالخصائص التقنية للجهاز بالإضافة إلى ساعات العمل. أما في الطريقة الثانية، فإنه يتم تجميع البيانات المتعلقة بإجمالي استهلاك جميع المعدات أو الأجهزة للطاقة وذلك من خلال الاستعانة بقراءات عدادات الكهرباء. وتتيح الطريقة الأولى إمكانية تحديد فرص تحسين كفاءة استهلاك الطاقة بدقة بالإضافة إلى متابعة التقدم المحرز عند تطبيق إجراءات تحسين الكفاءة المختلفة. إلا أنه وفي المقابل، فإن البيانات المطلوبة قد لا تكون جميعها متوافرة الأمر الذي يحد من إمكانية التطبيق الكامل لهذه الطريقة. ومن هنا تأتي الطريقة الثانية لجمع البيانات، من الأعلى إلى الأسفل، لتحل هذه المشكلة لا سيما في ظل محاولة حساب كمية الطاقة المستهلكة وذلك للمرة الأولى.

وفي هذا الدراسة تمت محاولة اتباع الطريقة الأولى لجمع البيانات، إلا أنه ونظراً لغياب البيانات المطلوبة في قطاع المياه البلدية، فقد تم انتهاج الطريقة الثانية بشكل عام. إلا أنه تم استثناء ثلاث محطات لتحلية المياه إذ تعذر الحصول على البيانات المطلوبة باتباع الطريقة الثانية في حين توافرت البيانات المطلوبة بحسب الطريقة الأولى. وتقتصر حدود الدراسة على قطاع المياه البلدية فقط لتشمل إنتاج المياه بمراحلها الثلاث: إنتاج المياه، نقل المياه، وتوزيع المياه، بالإضافة إلى معالجة مياه الصرف الصحي والتي تتضمن: جمع مياه الصرف الصحي، معالجة مياه الصرف الصحي، وأخيراً نقل مياه الصرف الصحي المعالجة. هذا، ولا يدخل الاستخدام النهائي للمياه، سواء كانت مياه الشرب أو مياه الصرف الصحي المعالجة، ضمن نطاق هذه الدراسة. كما ويقتصر نوع الطاقة قيد الدراسة على الطاقة الكهربائية، ذلك أنها الأكثر استخداماً بالإضافة إلى توافر البيانات المتعلقة بها. حيث تم الحصول على عناوين المنشآت ذات العلاقة بقطاع المياه البلدية ومن ثم الحصول على كمية الطاقة الكهربائية المستهلكة خلال الفترة من يناير ٥١٠٢ وديسمبر ٧١٠٢ وذلك من هيئة الكهرباء والماء بمملكة البحرين. وتم اتباع المعادلة التالية بالاعتماد على البيانات التي تم تجميعها من الأعلى إلى الأسفل:

الطاقة الكهربائية المستهلكة في السنة في محطة ما = مجموع الطاقة الكهربائية المستهلكة في جميع أشهر السنة

وفيما يتعلق بمحطات تحلية المياه الثلاث: سترة والحد والدور، والتي تم حساب كمية الطاقة الكهربائية المستهلكة فيها باستخدام طريقة جمع البيانات من الأسفل إلى الأعلى، فقد تم اتباع المعادلات التالية:

القدرة الكهربائية (وات) = الجهد الكهربائي (فولت) * التيار (أمبير)

الطاقة الكهربائية (وات ساعة) = القدرة الكهربائية (وات) * عدد ساعات العمل (ساعة)

ثم تم حساب مؤشر كفاءة استهلاك الطاقة الكهربائية وذلك لمحطات تحلية المياه ومحطات معالجة مياه الصرف الصحي على النحو التالي:

مؤشر كفاءة استخدام الطاقة الكهربائية المحددة لمرحلة أو محطة معينة (كيلووات ساعة/ م^3) = مقدار استهلاك الكهرباء في فترة زمنية محددة / كمية المياه المنتجة أو مياه الصرف المعالجة في نفس الفترة

ومن ثم تمت مقارنة هذه النتائج بالممارسات العالمية ذات العلاقة. إذ تتيح نتائج هذا المؤشر إمكانية المقارنة بالممارسات المماثلة والمتبعة في دول مختلفة بالإضافة إلى كونها تمثل خطاً مرجعياً لمتابعة التقدم في تحسين كفاءة استهلاك الطاقة في قطاع المياه البلدية وذلك ما هدفت إليه الاستراتيجية الموحدة للمياه لدول المجلس.

٢. ٢. قطاع المياه البلدية في مملكة البحرين

تمر المياه البلدية في مملكة البحرين بمرحلتين: إنتاج المياه والتي تتضمن إنتاج المياه ونقلها وتوزيعها، ومعالجة مياه الصرف الصحي والتي تتألف من جمع مياه الصرف الصحي، ومعالجتها ومن ثم نقلها. وتتولى هيئة الكهرباء والماء مسؤولية إدارة المرحلة الأولى في حين تضطلع وزارة الأشغال وشئون البلديات والتخطيط العمراني بشؤون تسيير ومتابعة المرحلة الثانية. كما ويشارك القطاع الخاص في قطاع المياه البلدية وذلك من خلال ملكية وإدارة ثلاثة محطات لتحلية المياه: الحد والدور وألبا (جدول ١) بالإضافة إلى محطة واحدة لمعالجة مياه الصرف الصحي (محطة المحرق)، إلا أن الدولة تتكفل بشراء المياه المحلاة ومن ثم توزيعها على المشتركين، كما وتتكفل بتغطية تكاليف معالجة مياه الصرف الصحي.

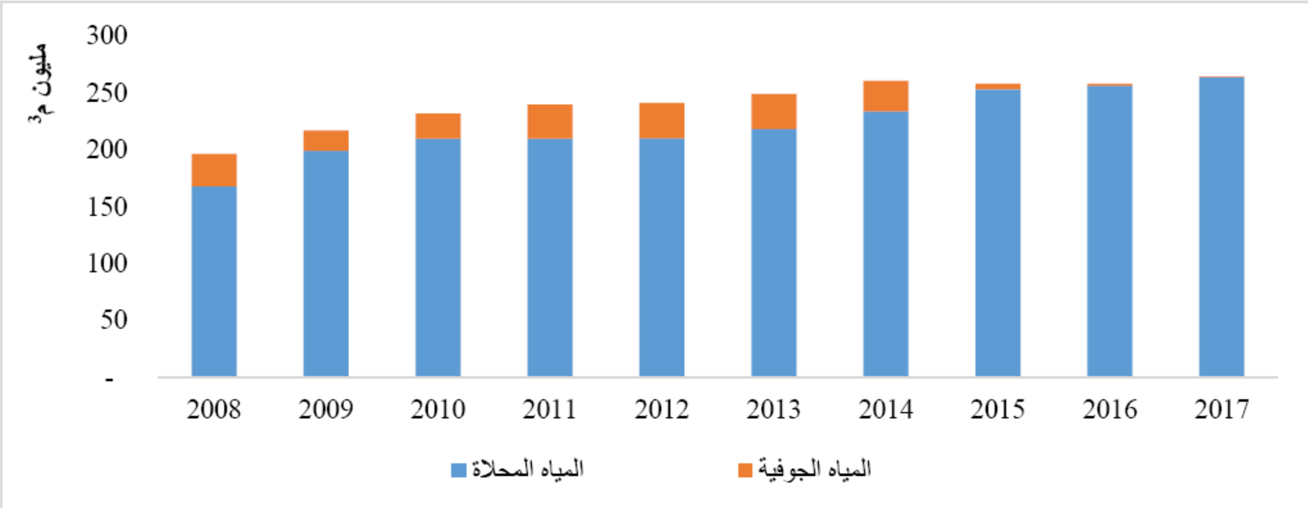
جدول ١: محطات تحلية المياه في مملكة البحرين (اتصالات شخصية، هيئة الكهرباء والماء)

المحطة	سترة	راس أبوجرجور	الحد	ألبا	الدور
سنة التشغيل	1975	1984	1999	2001	2012
ملكية المحطة	القطاع الحكومي	القطاع الحكومي	القطاع الخاص	القطاع الخاص	القطاع الخاص
مصدر المياه	مياه البحر	المياه الجوفية	مياه البحر	مياه البحر	مياه البحر
المنتج	المياه المحلاة والطاقة الكهربائية	المياه المحلاة	المياه المحلاة والطاقة الكهربائية	المياه المحلاة	المياه المحلاة والطاقة الكهربائية
التقنية المستخدمة	التبخير الوميضي المتعدد المراحل MSF	التناضح العكسي RO	التبخير الوميضي المتعدد المراحل MSF والتبخير بطريقة التأثير متعدد المراحل MED	التبخير بطريقة التأثير متعدد المراحل MED	التناضح العكسي RO
الطاقة الإنتاجية (ألف م٣/اليوم)	94.5	62.4	340.6	35.9	181.6

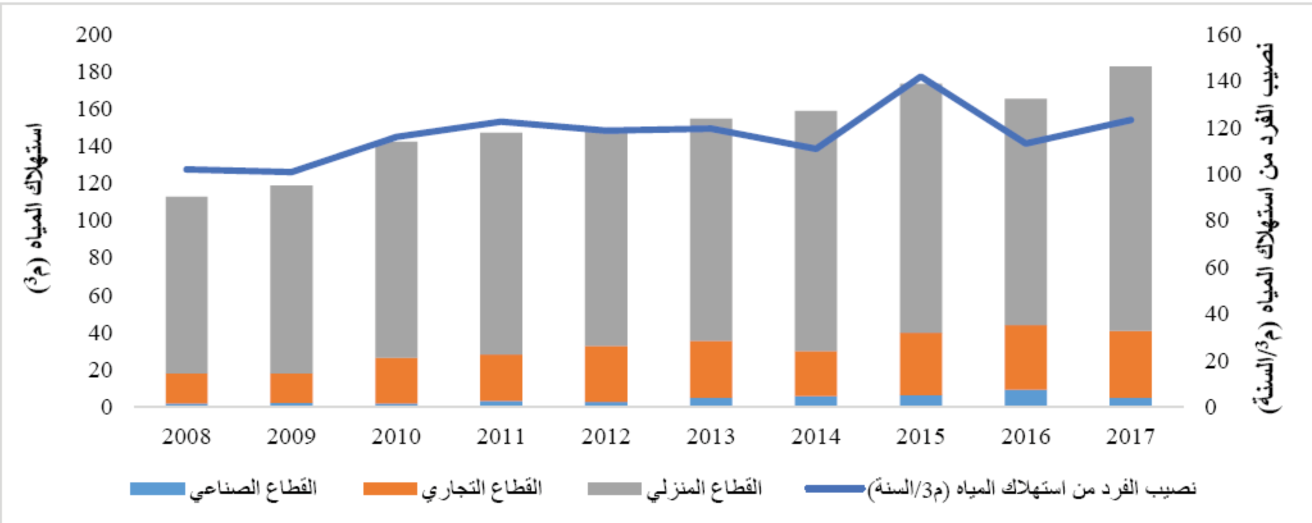
جدول ٢: محطات معالجة مياه الصرف الصحي في مملكة البحرين (اتصالات شخصية، *وزارة الأشغال وشئون البلديات والتخطيط العمراني*)

المحطة	سنة التشغيل	الطاقة الاستيعابية (م٣/اليوم)	الطاقة الفعلية (م٣/اليوم)	مصدر مياه الصرف الصحي	أعلى مستوى معالجة
توبلي	1982	200,000	300,000	سكني	ثلاثية
سترة	2008	16,500	15,457	سكني، صناعي	ثلاثية
عسكر	1997	288	487	سكني	ثنائية
الحد	2005	2,325	2,822	سكني، صناعي	ثلاثية
الجسرة	2006	340	726	سكني	ثلاثية
جامعة البحرين	1985	504	467	سكني	ثلاثية
جو	1992	408	494	سكني	ثنائية
جنوب ألبا	1994	900	1,135	سكني، صناعي	ثلاثية
جده	2008	25	23	سكني	ثلاثية
الدور	2003	70	153	سكني	ثلاثية
الهملة	2015	1,100	923	سكني	تقنية معالجة المياه بأغشية المفاعلات الحيوية MBR
المعامير	2010	2,250	1,863	سكني، صناعي	تقنية معالجة المياه بأغشية المفاعلات الحيوية MBR
المحرق	2014	100,000	71,000	سكني	طريقة المفاعلات الدفقية المتسلسلة SBR

ونظراً لمحدودية الموارد المائية في مملكة البحرين، ولتلبية الطلب المتنامي على المياه، فقد تم الاعتماد على تحلية مياه البحر بشكل أساسي. حيث ازداد إنتاج المياه من ٢٧١ مليون متر مكعب في عام ٨٠٠٢ إلى ٣٦٢ مليون متر مكعب في عام ٧١٠٢ (شكل ١). ويستهلك القطاع المنزلي النصيب الأكبر من المياه المنتجة وذلك بنسبة ٨٧٪ متبوعاً بالقطاع التجاري فالصناعي وذلك بنسب تبلغ ٠٢٪ و٢٪ على التوالي (EWA, 2017). أما فيما يتعلق بنصيب الفرد من استهلاك المياه، فقد كان متذبذباً خلال الفترة ٨٠٠٢-٧١٠٢، إلا أنه انخفض بشكل ملحوظ في عام ٦١٠٢ متأثراً بالإصلاحات المتعلقة بأسعار المياه (شكل ٢). وأما مياه الصرف الصحي، فيتم معالجة نحو ٥٧٪ من مياه الصرف الصحي معالجة ثنائية أو ثلاثية في محطة توبلي وذلك بإجمالي طاقة يومية تبلغ نحو ٣٠٠ م³/اليوم. وبالرغم من ذلك، فإنه لا يتم استخدام سوى نحو ١٣٪ من المياه المعالجة بهذه المحطة.



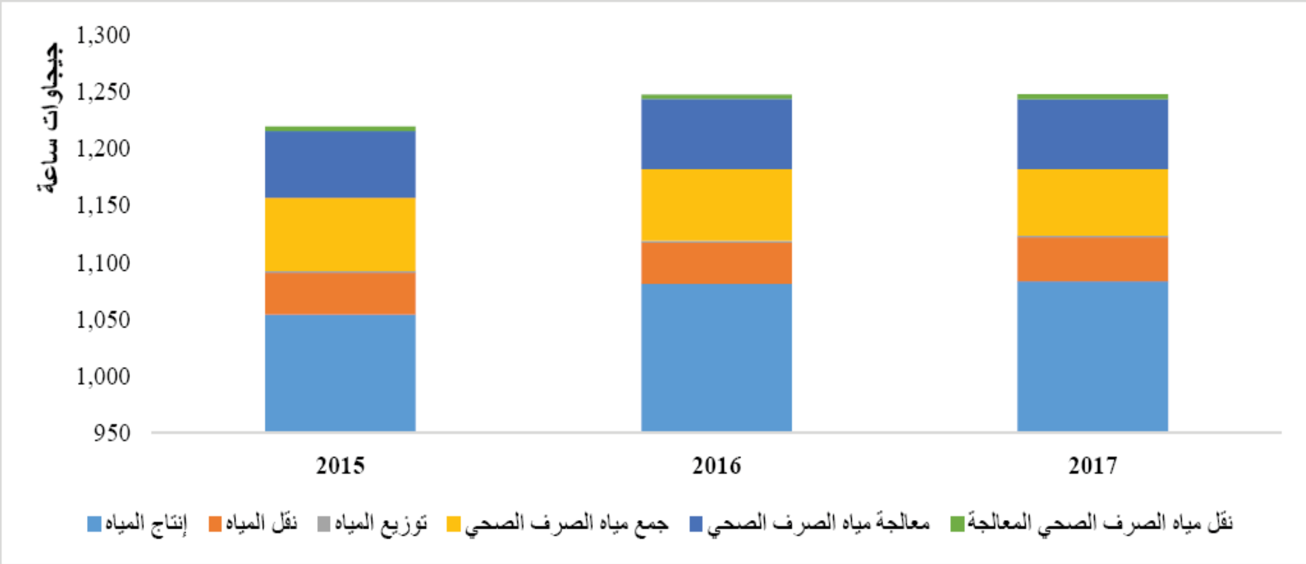
شكل ١: إنتاج المياه في مملكة البحرين في الفترة ٨٠٠٢-٧١٠٢ (EWA, 2017; IGA, 2016)



شكل ٢: استهلاك المياه حسب القطاعات في مملكة البحرين خلال الفترة ٨٠٠٢-٧١٠٢ (EWA, 2017; IGA, 2016)

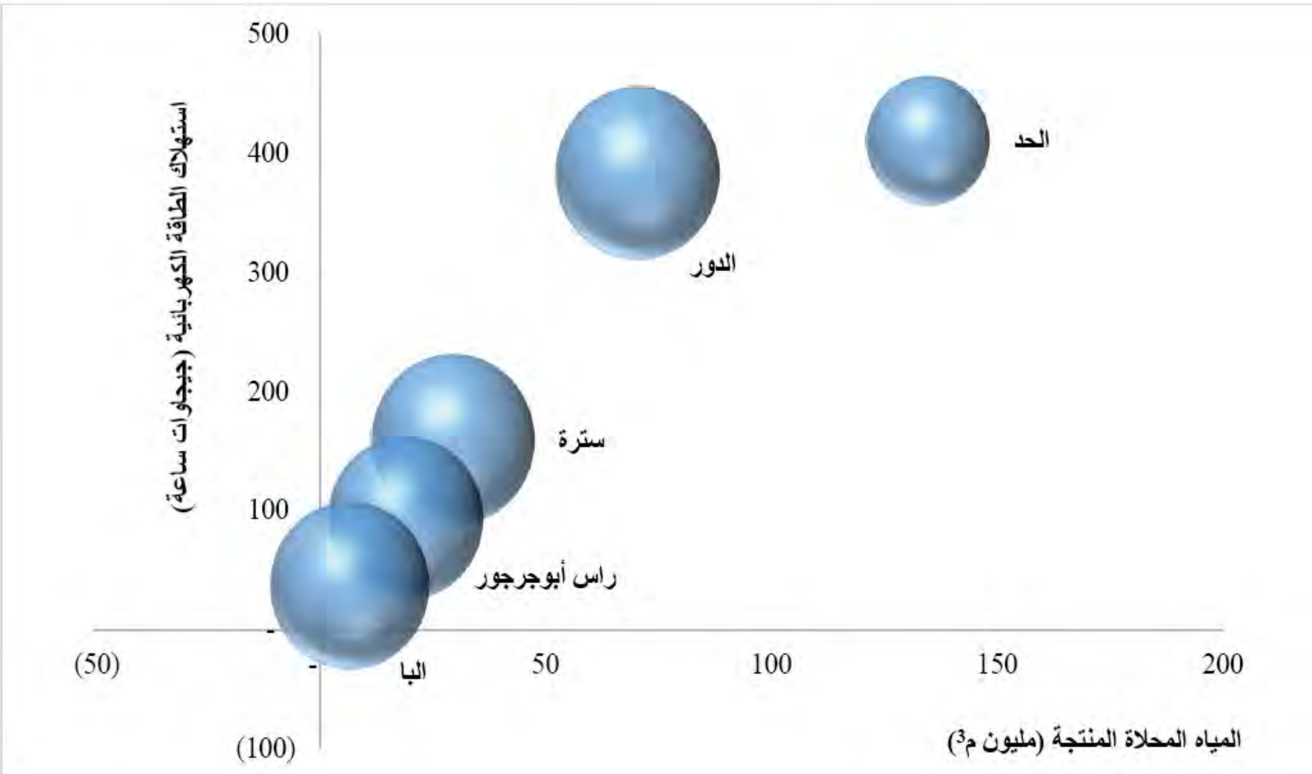
3. النتائج والمناقشة

استهلك قطاع المياه البلدية حوالي ٥,٧٪ من إجمالي الطاقة الكهربائية المستهلكة بمملكة البحرين في عام ٧١٠٢. حيث بلغت كمية الطاقة الكهربائية المستهلكة في قطاع المياه البلدية نحو ٧٤٢,١ جيجاوات / ساعة في عام ٧١٠٢ بزيادة قدرها ٣,٢٪ مقارنة بالطاقة الكهربائية المستهلكة في عام ٥١٠٢ والتي بلغت ٨١٢,١ جيجاوات / ساعة. وتستهلك مرحلة إنتاج المياه نحو ٠٩٪ من إجمالي الطاقة الكهربائية ذات الصلة بقطاع المياه البلدية (شكل ٣).



شكل ٣: الطاقة الكهربائية المستهلكة في قطاع المياه البلدية في مملكة البحرين خلال الفترة ٧١٠٢-٥١٠٢

وتستهلك محطات تحلية المياه نحو ٩٥,٦٩٪ من إجمالي الطاقة الكهربائية المستهلكة في مرحلة إنتاج المياه. وبالنظر إلى كفاءة استهلاك الطاقة في محطات تحلية المياه ذات التقنيات المختلفة، تبدو محطة الحد لتحلية المياه هي الأكثر كفاءة (شكل ٤). كما وتبدو كفاءة استهلاك الطاقة في محطات التحلية بمملكة البحرين متقاربة إلى حد ما بصرف النظر عن التقنية المستخدمة، وبالرغم من ذلك فإن استهلاك المحطات من الطاقة الكهربائية يزداد بزيادة كمية المياه المحلاة (مربع معامل الارتباط = ٤٨,٠).

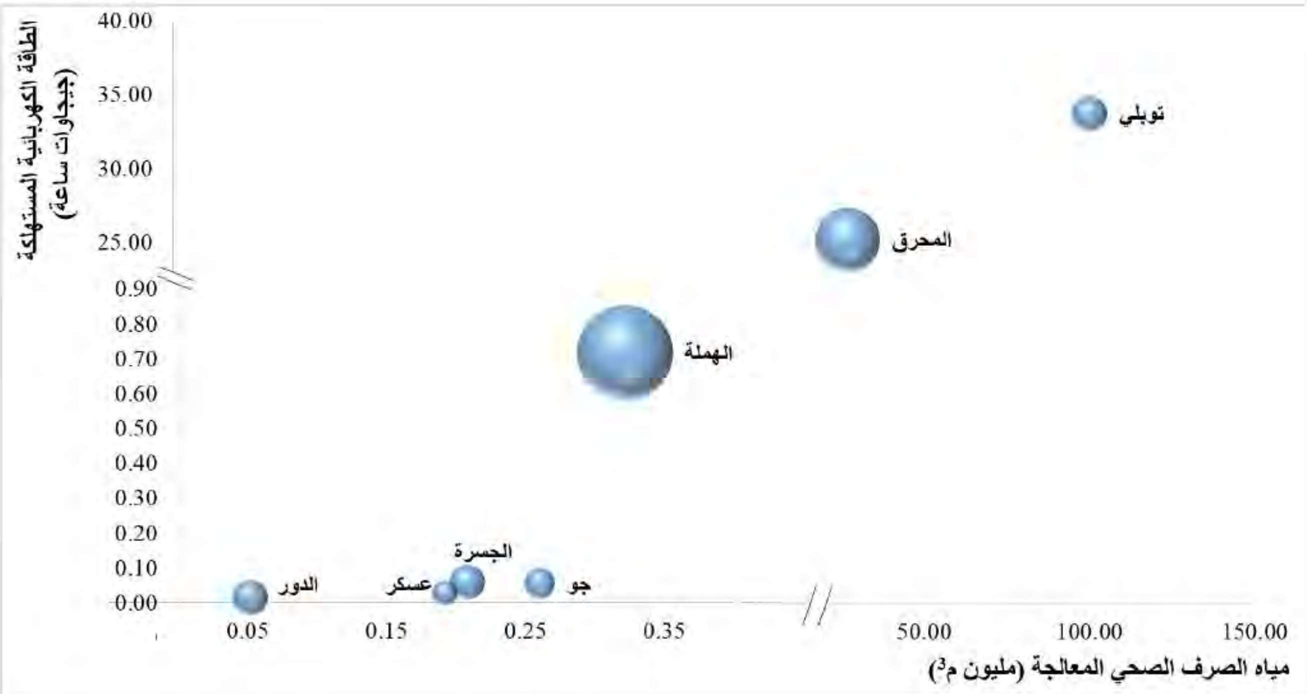


شكل ٤: إنتاج المياه المحلاة، الطاقة الكهربائية المستهلكة، وكفاءة استهلاك الطاقة الكهربائية في محطات تحلية المياه (ممثلة في حجم الدائرة) في مملكة البحرين في عام ٦١٠٢

وتأتي مرحلة نقل المياه الصالحة للشرب في المرتبة الثانية من حيث استهلاك الطاقة الكهربائية في إنتاج المياه وذلك بنسبة ٩,٢٪ متبوعة بتوزيع المياه وذلك بنسبة تقل عن ١,٠٪. وبالرغم من انخفاض نسبة الطاقة الكهربائية المستهلكة في توزيع المياه، إلا أن القيمة الفعلية المستهلكة بلغت أكثر من ٢٨٥,١ ميجاوات ساعة في عام ٧١٠٢ بزيادة قدرها ٣١١ ميجاوات ساعة مقارنة بعام ٥١٠٢.

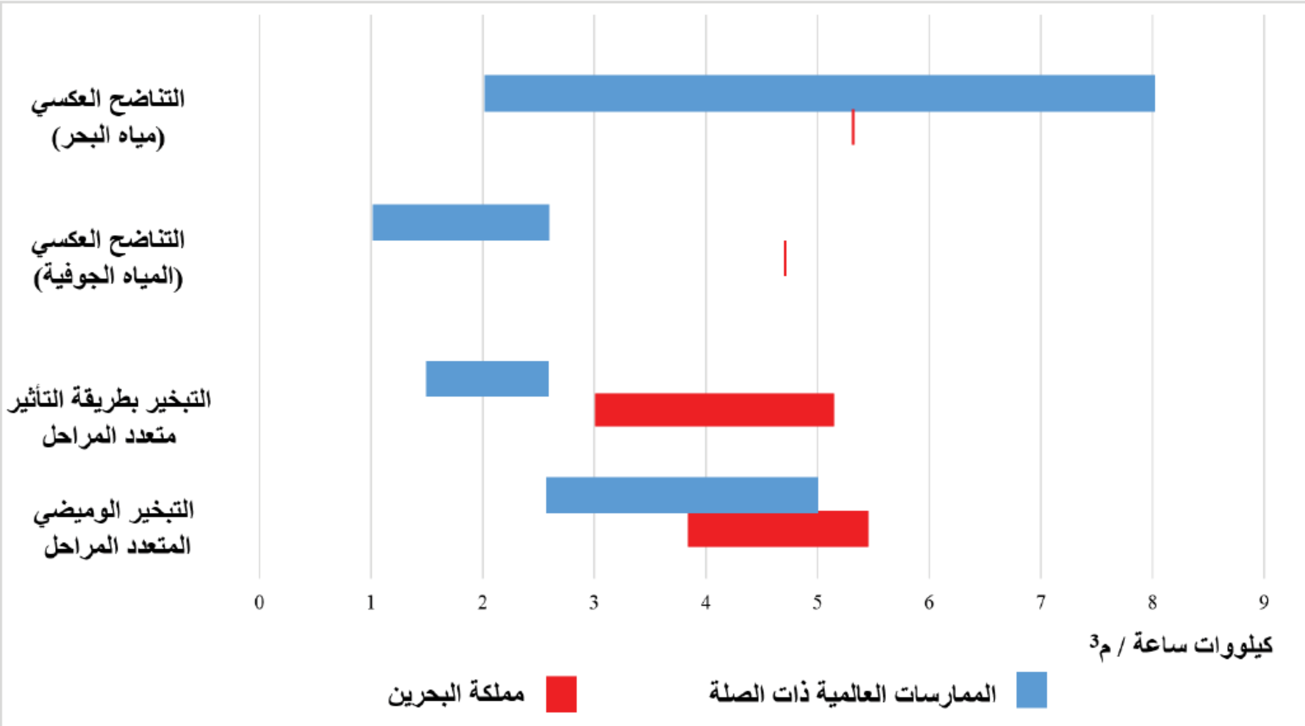
وأما فيما يتعلق بمرحلة معالجة مياه الصرف الصحي، فقد استهلكت ٤٢١ جيجاوات ساعة في عام ٧١٠٢ وذلك بما يعادل نحو ٩٪ من إجمالي الطاقة الكهربائية المستهلكة في قطاع المياه البلدية. وتم استهلاك النسبة الأكبر في جمع ومعالجة مياه الصرف الصحي وذلك بنسبة ٥,٦٩٪، في حين تم استهلاك النسبة الباقية في نقل مياه الصرف الصحي المعالجة وذلك بنسبة ٥,٣٪.

وبحساب كفاءة استهلاك الطاقة الكهربائية في محطات معالجة مياه الصرف الصحي، يتضح أن معظم المحطات تستهلك ما يقل عن ٣,٠ كيلووات ساعة وذلك لمعالجة ١ م^3 من مياه الصرف الصحي، في حين تستهلك محطتي المحرق والهملة نحو ٩,٠ و٢,٢ كيلووات ساعة على التوالي وذلك لمعالجة الكمية ذاتها من مياه الصرف الصحي (شكل ٥). ويرجع ذلك لاختلاف تقنية المعالجة المستخدمة في المحطتين والمتمثلة في تقنية معالجة المياه بأغشية المفاعلات الحيوية MBR في محطة الهملة وطريقة المفاعلات الدفقية المتسلسلة SBR في محطة المحرق. وعلى غرار محطات تحلية المياه، فإن كمية الطاقة الكهربائية المستهلكة في محطات معالجة مياه الصرف الصحي تزداد بزيادة كمية المياه المعالجة (مربع معامل الارتباط = ٢٨,٠).

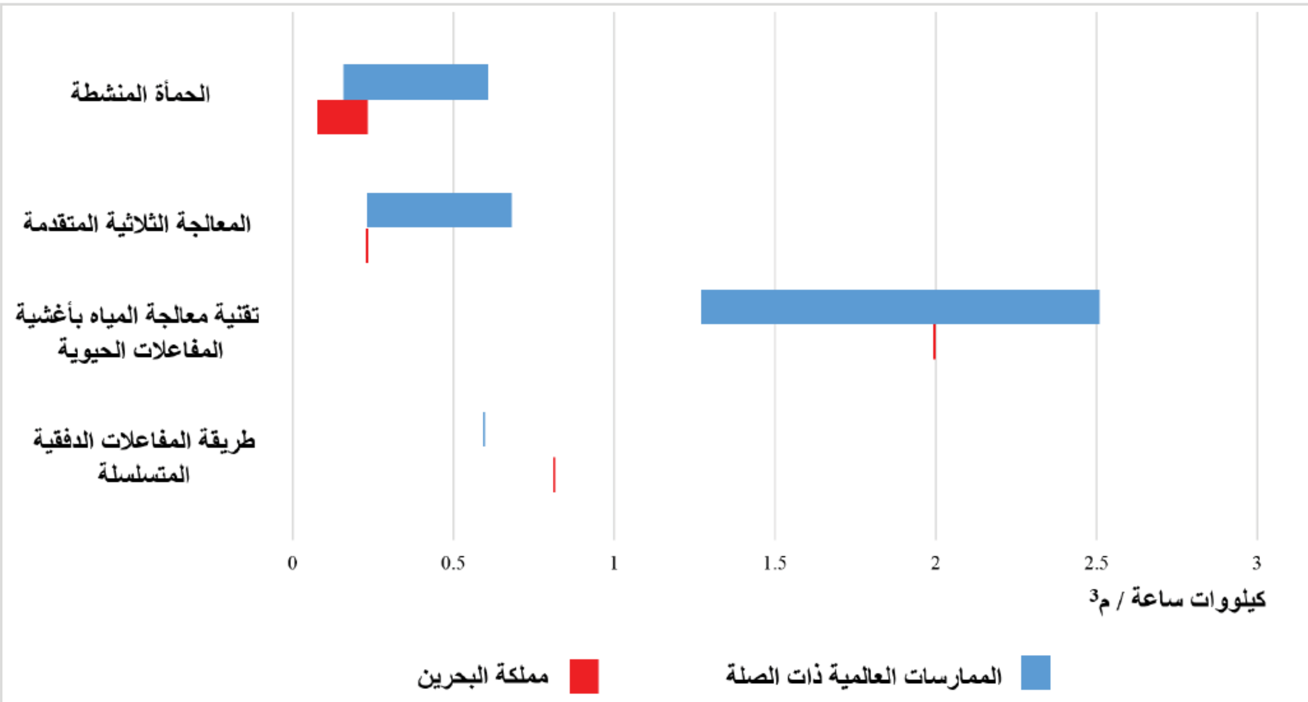


شكل ٥: مياه الصرف الصحي المعالجة، الطاقة الكهربائية المستهلكة، وكفاءة استهلاك الطاقة الكهربائية في محطات معالجة مياه الصرف الصحي (ممثلة في حجم الدائرة) في مملكة البحرين في عام ٧١٠٢

وبمقارنة كفاءة استهلاك الطاقة الكهربائية في محطات تحلية المياه ومعالجة مياه الصرف الصحي في مملكة البحرين بمثيلاتها كما ورد في الدراسات السابقة، فيتضح أنها ضمن نطاق الممارسات العالمية بشكل عام. إلا أن احتمالية تحسين كفاءة الاستهلاك تظهر بوضوح وذلك فيما يتعلق ببعض التقنيات كما هو موضح في شكل ٦ و شكل ٧.



شكل ٦: مقارنة كفاءة استهلاك الطاقة الكهربائية في محطات تحلية المياه بحسب التقنية في مملكة البحرين مقارنة بالممارسات العالمية (ESCWA, 2017; Shahzad et al., 2017; Siddiqi & Anadon, 2011)



شكل ٧: مقارنة كفاءة استهلاك الطاقة الكهربائية في محطات معالجة مياه الصرف الصحي بحسب التقنية في مملكة البحرين مقارنة بالممارسات العالمية (ES-CWA, 2017; Shahzad et al., 2017; Siddiqi & Anadon, 2011)

4. الاستنتاجات والتوصيات

يرتبط قطاع المياه البلدية ارتباطاً وثيقاً بالطاقة في مملكة البحرين، حيث قامت هذه الدراسة وللمرة الأولى بحساب كمية الطاقة المستهلكة في إنتاج المياه ومعالجة مياه الصرف الصحي في المملكة. كما وبينت هذه الدراسة كفاءة أداء محطات تحلية المياه ومعالجة مياه الصرف الصحي من حيث استهلاك الطاقة الكهربائية مقارنة بالممارسات العالمية وذلك بحسب التقنية المستخدمة. وتتمثل أهمية هذه الدراسة في تقييمها للوضع الحالي وذلك تمهيداً لتحسين كفاءة استهلاك الطاقة في قطاع المياه البلدية. وبالرغم من أهمية هذه الدراسة، فإنها تقتصر على قطاع المياه البلدية فحسب وبالتالي فإنه يمكن إجراء دراسات أكثر شمولية في المستقبل وذلك لحساب وتقييم استهلاك الطاقة في قطاع المياه الصناعية والزراعية. كما ولم تتطرق هذه الدراسة إلى كفاءة استهلاك الطاقة لدى المستهلك النهائي للمياه، الأمر الذي يمكن تغطيته في مسوحات مستقبلية لتشمل المستهلك النهائي لمياه الشرب والمستهلك النهائي لمياه الصرف الصحي المعالجة.

وتوصي هذه الدراسة بضرورة الأخذ بمعيار كفاءة استهلاك الطاقة وذلك خلال عملية اتخاذ القرار المتعلقة بتقنيات تحلية المياه أو معالجة مياه الصرف الصحي. كما وتوصي الدراسة أيضاً بضرورة توفير البيانات المتعلقة باستهلاك الطاقة وذلك للمراحل المختلفة المتعلقة بإنتاج المياه ومعالجة مياه الصرف الصحي. هذا بالإضافة إلى ضرورة حساب المؤشرات ذات العلاقة بكفاءة استهلاك الطاقة وإعداد دليل ارشادي حول إدارة الطاقة في قطاع المياه بشكل عام والمياه البلدية بشكل خاص. وتوصي الدراسة أيضاً بتوعية المستهلكين بأهمية ترشيد استهلاك المياه، وذلك لخفض كمية المياه المنتجة بالإضافة إلى خفض كمية الطاقة المستهلكة في إنتاج المياه ومعالجة مياه الصرف الصحي مما يسهم في الحفاظ على الموارد الطبيعية والبيئة.

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Sustainable cities in the GCC countries

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Water sectors are under pressure from growing demand, cost of new infrastructures, increasing energy prices and aging water systems. Through intelligent water network solutions known as Water-Smart Cities, water utilities will be, remotely, monitored, maintained and managed, and consumption will be evaluated, assessed and optimized. These solutions will, accurately, map losses due to leaks, waste and evaporation, and take targeted corrective action.

Smart Cities is a new concept for modern cities using cutting-edge technologies to monitor and supply information which is used to manage assets and resources efficiently. This includes water and power plants, water supply networks, wastewater management, traffic and transportation systems, information systems, government and private buildings, and other community services.

This paper will highlight the effects of poor management of water resources on the sustainability and prosperity of cities. Without proper water quality and quantity no civilization will be initiated or even maintained. Smart water policy is the first step towards water-smart city; it will promote water efficiency regulations and improve water management practices. New technologies, strategic policies and effective implementation of demand management are the key issues for a successful water-smart city.

Climate change effects resulted in more frequent droughts and floods, unpredictable temperature variations, in addition to growing populations and high consumption would lead to insecure water resources. Therefore, the need for rapid, cost-effective actions that can save water on a large scale became a necessity.

Combination of information and communication technologies and internet of things (IoT) is the heart of smart cities to optimize the operation efficiency of the city services and connect officials and citizens to consumption data and other data, allowing for real-time responses.

The IoT as a technology holds great potential to solve water scarcity through smart, instant and predictable management. In every part of the water cycle, IoT can be utilized to manage water resources better and reach efficient and optimal results. It includes cloud connection for real-time analyses and automated alerting sensors and meters that enable data capture over large distances.

Water-Smart City includes all related sectors; residential, industrial and agricultural. The three sectors share the main features of water-smart city including remote alert, quality track, central control and smart metering systems. Water solutions are one of the main solutions of the smart city concept and should have more emphasis from the water specialists as it is the future management tool for water resources.

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جمعية علوم وتقنية المياه
Water Sciences and Technology Association

Water and wastewater service performance monitoring in Palestine: An economic instruments for service efficiency improvement and sustainability

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The water sector in Palestine as well as in a number of Arab Countries is highly fragmented with approximately 500 water and wastewater service providers in the West Bank and Gaza Strip of varying types including utilities, municipal departments, joint service councils, NGOs and private service providers.

Given all above, the sector and in addition to the Israeli control over water resources is facing serious challenges including:

- One of the lowest per capita water availabilities in the region
- Territorial fragmentation leading to different approaches and different water service providers
- Operational inefficiencies lead to interruption, high NRW and pollution
- Insufficient customer satisfaction
- Chronic under investment for infrastructure development
- Insufficient ring-fencing of revenues in the water sector
- Insufficient corporate governance

It is clear from the foregoing that the country needs a well-defined regulatory framework that can respond to the challenges facing the sector, in particular if the long-term vision of "access to safe, adequate and sustainable water supply for all by 2025" is to be achieved.

In December 14th, 2009, the Cabinet of Ministers of the Palestinian National Authority endorsed the "Action Plan for Reform" towards the definition and implementation of a comprehensive program of institutional and legislative reform in the Palestinian water sector. The establishment of a Water Sector Regulatory Council was proposed. WSRC is to monitor operational performance related activities of water service providers including production, transportation, distribution, consumption, wastewater collection, treatment and disposal, and reuse of treated wastewater for irrigation.

Basic functions of the economic regulator in Palestine

- Approval of water prices and construction costs of water and sanitation services.
- Issue operational licenses to S.P's.
- Supervise and inspect compliance with the conditions, requirements and indicators stipulated in the licenses.
- Develop performance incentives systems.
- Monitor operation processes related to the production, transport, and distribution of water and wastewater.
- Make sure that costs of production, transport, distribution and wastewater treatment protect the interests of all concerned parties.
- Monitor Water Supply Agreements.
- Set and disseminate quality assurance standards for technical and administrative services provided by S.Ps.
- Create a database with technical, financial and statistical information.
- Addressing complaints between service providers and consumers.

Characteristics of a sound economic regulatory framework

The WSRC has completed reporting the "financial and commercial viability of water and wastewater service providers in Palestine" describing the findings and recommendations for developing the Action Plan (Road Map) for a fully sustained service. This road map, although prepared for Palestine, still, other SP can make use of it, and drivers for improvements can be implemented elsewhere.

Effective economic regulation benefits the sector through improved performance, increased coverage and enhanced private sector participation.

Performance monitoring aiming at SP sustainability

The WSRC performance monitoring, although covers technical, financial, quality and other indicators including gender and governance, it gives high attention to economic-related issues and indicators including: tariff calculation, reviews and adjustments, collection efficiency, operational costs (personnel, energy, purchased water cost, O&M, and working efficiency), Service providers indebtedness, incentives, and Israeli deductions from the general taxes.

Based on all above, the council has completed the 2014, 2015, 2016 and 2017 service providers performance reports coupled with time-based comparative reports for the same period.

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The 2017 performance report issued in December 2018 has covered 90 water and wastewater service providers in the West Bank and the Gaza strip; 22 key performance indicators were used in addition to 9 sub indicators covering the technical, financial and quality issues. In addition, indicator on staff efficiency and gender is included.

A decline in the percentage of collection of water fees for a large percentage of service providers was noted, this will inevitably have a negative impact on the overall performance and increase the burden of debt whether for the PA, and the decline in the follow up on maintenance of water systems or the capacity to develop and improve performance in general. The noticeable decline was in the increase in water losses which we noted for most of the service providers. Cost of energy and staff per cubic meter of water is still on a rise for several service providers. This is one of the direct reasons behind the increase of the total cost per cubic meter of water, and necessitates an immediate audit of the electricity systems and a quick review of the employment policy of SPs.

Summary of the above can be as follows

Low fees collection rates, limited cost coverages, non-approved tariff structures, unsuitable billing and accounting systems, limited assets and depreciation data, limited water quality in a number of localities including Gaza. The above findings are key instrument for prioritization of interventions, planning and policy update. The presentation will show data regarding the above and a list of recommendations and follow up measures to be considered by related stakeholders.

Drivers for SP sustainability and economic viability

The council has recommended the following drivers for service providers:

- Regrouping service providers in larger and autonomous units, such as utilities and JSC;
- Defining SP individual targets based on national targets and benchmarks;
- Strengthening public awareness and stimulating client orientations;
- Increase the prepaid meters coverage;
- Strengthening management and operational capacities;
- Strengthening billing and collection procedures and system, including updating customer database;
- Carry out value chain analysis of the operators to see where cost reduction and performance improvement could be achieved;
- Review the options for outsourcing activities and possibly PPP;
- Target asset management and valuation, which would form the basis for defining the depreciation of assets;
- Reduce the percentage of non-revenue water, through institutional, operation and maintenance planning.

Session 8

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Development of benchmarking system for the wastewater sector in the Kingdom of Bahrain

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ABSTRACT

International benchmarking procedures are useful and effective tools to assess the performance of wastewater services. Wastewater treatment plants (WWTPs) are large resource consumers and are perceived as a promising effort to detain the global resources crisis through sustainable action. The economics of wastewater management and treatment is the subject of growing interest to protect the environment from the adverse effects. According to international water bodies, the challenges facing the governments are rapid population growth, worsening of the climate, severity of freshwater scarcity, rising costs, aging infrastructure, increasingly stringent regulatory requirements, and a rapidly changing workforce, varying influent due to storm water, etc. are global challenges. In this study, wastewater collection, treatment and discharge related to Tubli sewage treatment plant at Tubli Water Pollution Control Center were analyzed with the aim of developing key performance indicators, which are used for benchmarking purposes. This analysis helps improving the understanding of how individual scores of efficiency and operating variables are related. The study describes the development of a benchmark for the evaluation of control strategies in WWTPs. This study is intended to be useful to decision-makers in the wastewater treatment sector. The benchmarking methodology and empirical application developed by performance indicators (PIs) for wastewater services published by International Water Association (IWA) is used for improving the management of WWTPs and contribute to save operational costs. The study assessed the benchmarking of the wastewater services in the Kingdom of Bahrain. Performance assessment and benchmarking have developed as key aspects of WWTP management. Benchmarking is a data-driven process, and can only be successful if careful consideration is given to data availability and accuracy. Four teams have contributed to the development of the benchmark and have obtained results. The only data readily available and accurate are supplied for regulatory purposes. There are 184 PIs detailed by IWA. In the study 25 PIs were analyzed for the year 2017 where the data are readily available. The results indicated that, without sufficient data, assessing the accuracy of the data and identifying comparable WWTPs, the PIs analysis becomes increasingly complex. Improved data management practices can be achieved through WWTP benchmarking. Enabling the successful benchmarking in the present-day can (i) accelerate the improvement of data collection practices, (ii) improve WWTP management practices and (iii) lead the way to the inclusion of more advanced benchmarking applications in the years to come, when data availability and accuracy issues are corrected. Optimizing the investments and developing regional experiences are key factors to promote the scientific research.

Keywords: Benchmarking; Treatment plant; Efficiency and effectiveness; Stakeholders; ACWUA; IWA

1. Introduction

Sanitation services in Bahrain are provided at commendable rates reaching more than 90% of the population. Sanitation services are delivered at high professional standards and are operating modern treatment facilities with high standards for tertiary and advanced treatment capabilities. However, these services are provided to the public with highly subsidized rates with almost zero cost recovery, despite the government many attempts to charge for its sanitation services. These conditions make sanitation services

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almost completely dependent and captive to government funding and allocations, which ultimately affects the sector financial sustainability and hence its performance.

According to the GCC Unified Water Sector Strategy (GCC UWS) 2015–2035, sanitation authorities find themselves in stressful working conditions. These conditions do not provide the authorities with an opportunity to look at the overall utility management and performance in terms of the many attributes of effectively managed utilities (EMU), which help utilities, respond to both current and future challenges and ensure their sustainability. These EMU attributes and performance measures include environmental, personnel, physical, operational, quality of services, economic and financial aspects of wastewater. By 2035, the GCC countries shall establish sustainable, efficient, equitable, and secure water resources management systems contributing to their sustainable socio-economic development. This shall be achieved through GCC supreme council for water with the support of technical advisory committee. To achieve the highest management standards for sanitation utilities the GCC countries shall adopt and implement the best practice benchmarking system for sanitation utilities. The benchmarking rank of sanitation utilities in the GCC countries shall be in comparison to those countries which use benchmarking in the world. In this regard, benchmarking of the sanitation sector becomes crucial to improve its sustainability and enhance its services. International experiences have proven that benchmarking can be a good instrument to stimulate performance wastewater management. Therefore, adopting an EMU approach and principles can help wastewater utilities enhance the stewardship of their infrastructure, improve performance in many critical areas, and respond to current and future challenges.

Sanitation services in Bahrain are provided to the public with free of charges. These services are provided in a professional standard to meet the public satisfaction. The cost recovery for the sanitation services has to be collected from the public. Although the government is trying to charge the public for the services, still the full subsidy is in force. Presently sanitary utilities in Bahrain do not follow the best practices for benchmarking/quality assurance system for the wastewater utility management. To begin with, the approach of Arab Countries Water Utilities Association (ACWUA) is well-thought-out initially as a gap analysis. The ACWUA is a global center of excellence that partners with water supply and wastewater utilities in the Arab Countries on building capacities within the utilities and on instituting best practices in order for the utilities to achieve their objectives. In this sense, this survey explored the current situation in sanitary wastewater services in the Kingdom of Bahrain. This represents Phase 1 of the study. Phase 2 of the study utilized the manual - performance indicators (PIs) for wastewater services – International Water Association (IWA) to analyze and select the most appropriate benchmark.

- To achieve the highest International Standards of Water and Wastewater Services
- Identifying key PIs as per the manual for best practices
- Implementing effective water governance
- Providing the capability for utilities to identify targets associated with each leading practice
- Developing a benchmarking framework and assessment methodology
- Developing a supporting benchmarking tool
- Making the tool available for the use and benefit of the water sector

The National Master Plan for Sanitary Engineering Services (NMPSES) that conforms to the National Planning Development Strategies (NPDS, 2007) provides a more holistic view of the entire Sanitary Engineering Services (SES) in the Kingdom of Bahrain, to ensure that the SES meet the current and projected loads for the next 20 years. In 2008, following a two year process of research, analysis, consultation and design, the related “Bahrain 2030 NPDS” was published (GTZ, 2008)

The wastewater management system is a foundation of modern public health and environment protection. PIs are used to identify where organizational performance is meeting desired standards and where performance requires improvement. It is to encourage meaningful sustainability, best practices and industrial benchmarking to establish within the wastewater management community. Survey has been conducted to gather information about current handling of wastewater system to identify the gaps. Further sanitary department shall identify PIs to measure and monitor the performance. The indicators shall be aligned with international best practices for benchmarking. A framework of PIs are developed to identify a reasonable set of environmental, social, economic and technical indicators for wastewater treatment by following IWA best practices (Matos, et al., 2012).

The objective of this study is to develop/adopt and implement a benchmarking system that is suitable to Bahrain sanitation sector, and compare the findings with that from the best practices in the world. Moreover, within the framework and in line with the implementation plan of the GCC UWS, this will serve the 3rd policy of the 4th strategic objective aiming at “achieving the highest International Standards of Water and Wastewater Services”, which calls for “adopting and implementing the highest benchmarking system for sanitation utilities in the GCC countries”. A first step to achieve this policy is to develop a national benchmarking system in each GCC country as a prerequisite to the establishment of the joint GCC wastewater benchmarking system.

2. Methodological approach

The development of a benchmarking system for the sanitation sector in Bahrain would involve the adoption of generally accepted procedures and methodologies, able to provide decision makers with an overall perception of the utility performance as a sound basis for making strategic choices from water organization bodies and the best international practices. In the literature, there are three relevant references available for the approach of EMU; these are namely:

- The ACWUA - TSM – Arab requirements for wastewater treatment facilities
- PIs for wastewater services, operations and maintenance specialist group - IWA

- Performance benchmarking for effectively managed water utilities – Water Research Foundation (WRF)

Presently there is no benchmarking/quality assurance system for the wastewater utility management in Bahrain. To begin with, the approach of (ACWUA, 2015) will be accomplished initially as a gap analysis exercise. This will represent phase 1 of the study. Phase 2 of the study will utilize the literatures in determining the PIs using the IWA manual (Matos, et al., 2012) to analyze and select the most appropriate benchmark based on their relevance to the sanitation sector in Bahrain.

2.1. Phase 1: gap analysis (ACWUA Survey)

Any undertaking needs to strive for high degree of efficiency and effectiveness to achieve its management goals. In addition, other stakeholders, such as regulators or customers require assurance that the undertaking is performing appropriately (Merkel, 2002; Matos et al., 2012). In this frame, a survey was launched by Ministry of Works, Municipalities Affairs and Urban Planning (MOWMAUP), Sanitary Engineering Department to obtain the facility staff feedback regarding the performance management of the wastewater system in the Kingdom of Bahrain. The survey was based on the guidelines of (ACWUA, 2015). Technical sustainable management (TSM) (Arab) is a quality management system (QMS). TSM (Arab) requirements aims at the development of water and wastewater facilities in the members countries of ACWUA to reach conformity to the Arabian regulations, codes, laws and standards in fields of management of the following activities:

- Human resources
- Occupational health and safety
- Operation
- Maintenance
- Quality assurance

ACWUA QMS questionnaire shall be considered as the survey form. The questionnaire shall be sent to all the sanitary units to gather the information. The survey questions had four options namely yes, no, I don't know and not applicable. Based on the observed responses out of ten if five or more respondents replied yes it was considered normal. On the other hand if four or less respondents replied yes, it is considered as a gap. The main objective of the survey is to assess the current management of wastewater system:

- Align existing PIs with international best practices for benchmarking by using the manual PIs for wastewater services published by IWA.
- To follow applicable PIs from the manual PIs for wastewater services published by IWA.
- To benchmark the performance of sanitation services from collection, treatment, transmission and distribution of treated effluent and compare the findings with that from the best practices in the world.

The survey was administered face to face by Ministry of Works (MOW) engineer from July 23, 2017 until August 28, 2017. The analysis was done in two steps:

- Review all the literatures, conduct workshops, group discussions and surveys
- Analyze, find gaps, identify data source, identify data owner, data accuracy, data reliability, data forms

2.2. Framework

The survey questionnaires are based on TSM requirements which aim at the improvement of water and wastewater facilities in the member countries of ACWUA. The main purpose of the survey by ACWUA is to reach conformity to the Arabian regulations, codes, laws and standards in fields of QMS. The survey questions are published by: the ACWUA under the guidance of the ACWUA task force (QMS)/(TSM-Arab) with support from the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH – December 2015.

The survey questionnaires are grouped by the following categories:

- Human resources
- Occupational health and safety
- Operation
- Maintenance
- Quality assurance/quality control

The targeted positions for the survey are chiefs, heads and potential senior engineers from sanitary engineering operation and maintenance directorate (SEOMD) as a pilot survey. Information requested in this questionnaire refers to activities relating to collection, treatment, transmission and distribution of treated effluent. This survey was conducted with the following four sections in the directorate with total ten respondents:

- Sewage network section
- Treatment plants section
- Treated sewage effluent section
- Quality control group

3. Results of phase 1

The results of the survey are shown in Figs. 1 to 5. Based on the survey results, the categories of identified gaps are shown in Table 1.

3.1. Phase 2: determining the PIs using the IWA manual and select the appropriate benchmark

Using IWA manual of best practice for wastewater services (Matos et al., 2012), the performance shall be evaluated using key PIs. PIs are measures of efficiency and effectiveness of the delivery of services by an undertaking that result from a combination of several variables. A PI consists of a value which is a ratio between variables expressed in specific units. PIs can be analyzed interpreted and compared by taking into consideration context information and the quality of data for each utility.

3.2. Performance indicators

PIs may be considered as providing key information needed to define the efficiency and effectiveness of the

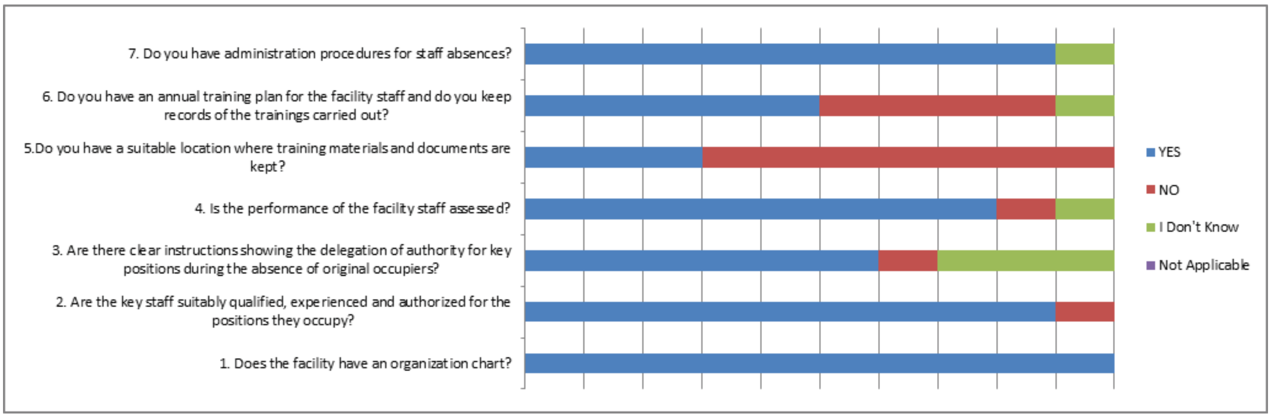

Fig. 1. Human resources.

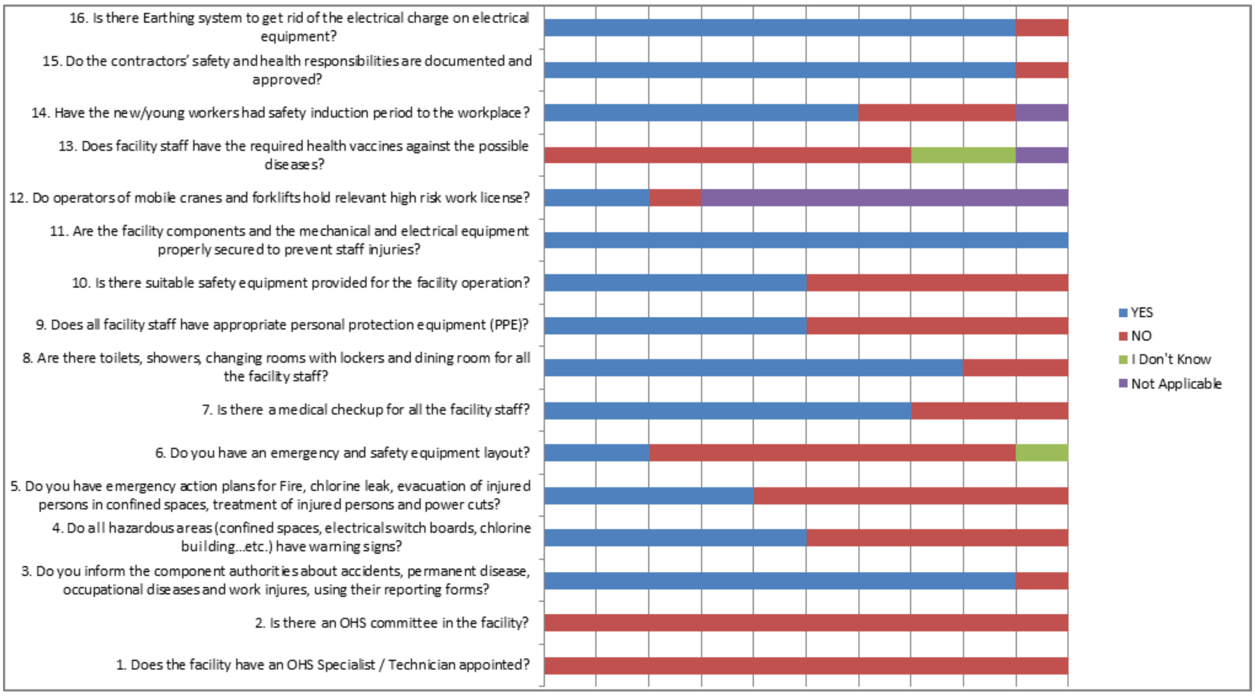

Fig. 2. Occupation health and safety.

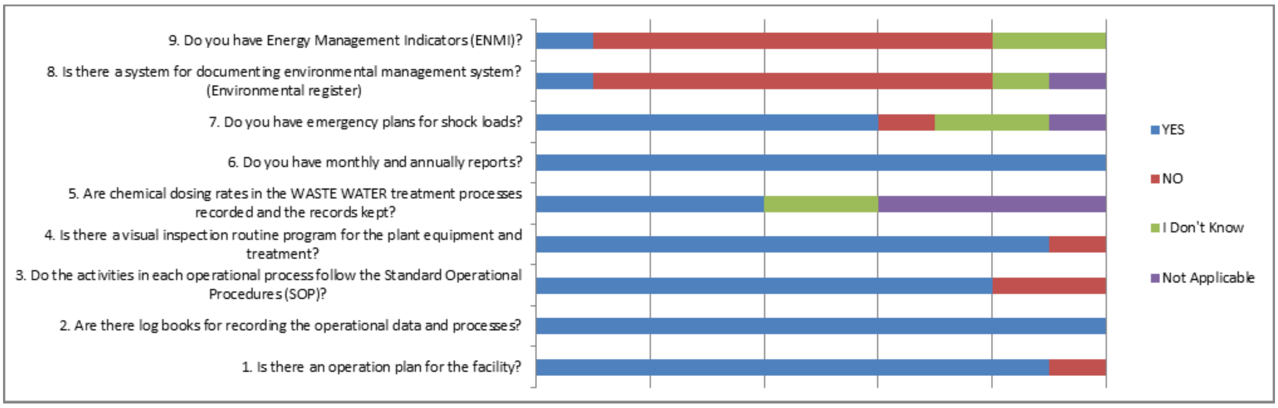

Fig. 3. Operation.

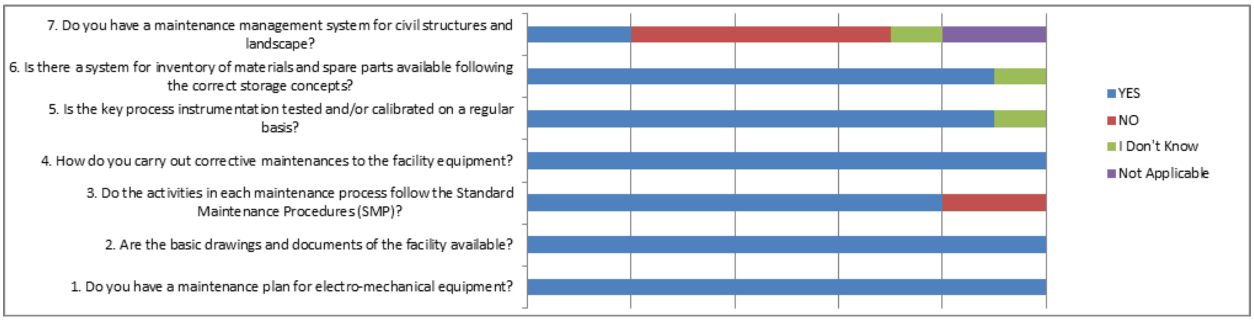

Fig. 4. Maintenance.

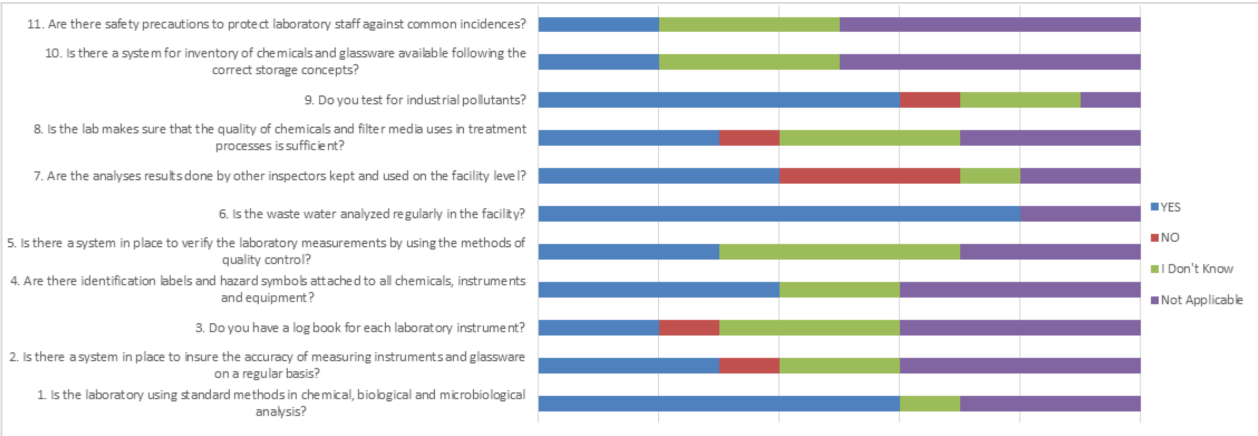

Fig. 5. Quality assurance and quality control.

delivery of services by an undertaking (Deb and Cesario, 1997). Efficiency is the extent to which the resources of an undertaking are utilized to provide the service, for example, maximizing service delivery for the minimum use of available (possibly natural) resources. Effectiveness is the extent to which declared or imposed, objectives, such as levels of service, (specifically and realistically defined) are achieved. PIs may also be considered as providing information for metric benchmarks (quantitative comparative assessment of performance) (Larsson et al., 2002). The actual comparison of performance between similar service provision is undertaken via process benchmarking (examining business processes, comparing the activities of different organizations and seeking to identify best practices). A PIs may thus be used as a quantitative (or in some cases qualitative) measure of a particular aspect of an undertaking's performance or standard of service. PIs may be used to compare performance historically, or against some pre-defined target (Matos et al., 2012). PIs are pieces of information that summarize the characteristics of a system or highlight what is happening in a system. They are often a compromise between scientific accuracy and the information available.

3.3. Benchmarking process

Benchmarking is the systematic process of searching for best practices and effective operating procedures that lead to increased performance and the adaption of these practices to improve the performance of one's own organization (Cabrera et al., 2009; Parena et al., 2002). However, despite the importance of benchmarking of the water sector in the GCC countries to evaluate performance and identify best practices, it has not been developed and adopted yet in the municipal water utility services, especially in the sanitation (wastewater) sector. Treated wastewater are considered as a promising water source and has large potential in alleviating the global water crisis, being pressured by an ever-increasing demands and reduction of freshwater resources due to pollution and depletion. Currently, the economics of wastewater management and treatment is the subject of growing interest to protect the environment from the adverse effects, and also to contribute to meeting water demands. Wastewater treatment plants (WWTPs) typically operate continually and are subject to several pressures (e.g. population changes, varying influent due to storm water, more stringent environmental regulation, and other pressures), making the implementation of resource efficiencies uniquely challenging. In this present study, wastewater collection, treatment and discharge of wastewater related to Tubli sewage treatment plant at Tubli Water Pollution Control Center were analyzed with the aim of developing some key PIs, which is used for benchmarking purposes. Performance assessment is a key area of WWTP management; a common method of conducting performance assessment is through the use of key performance indicators (Alegre et al., 2009).

Table 1
Categories of identified gaps

S. No.	Gaps	Validation
	Human resources	
1	Suitable location for training materials and documents	Confirmed
	Occupation health and safety	
2	OHS specialist/technician appointment in the facility	Confirmed
3	OHS committee in the facility	Confirmed
4	Emergency action plans for fire, chlorine leak, evacuation of injured persons in confined spaces, treatment of injured persons and power cuts	Confirmed
5	Emergency and safety equipment layout	Confirmed
6	Operators of mobile cranes and forklifts hold relevant high risk work license	Confirmed
7	Staff health vaccinations against the possible diseases	Confirmed
	Operation	
8	Chemical dosing rates in the wastewater treatment processes records	Confirmed
9	System for documenting environmental management system (environmental register)	Not confirmed
10	Energy management indicators (ENMI)	Confirmed
	Maintenance	
11	Maintenance management system for civil structures and landscape	Confirmed
	Quality assurance/quality control	
12	Accuracy of measuring instruments and glassware	Not confirmed
13	Log book for each laboratory instrument	Not confirmed
14	Identification labels and hazard symbols for all chemicals, instruments and equipment	Not confirmed
15	Verification of the laboratory measurements by using the methods of quality control	Not confirmed
16	Record of the analyses results by other inspectors	Not confirmed
17	Quality of chemicals and filter media in treatment processes	Not confirmed
18	System for inventory of chemicals and glassware available following the correct storage concepts	Confirmed
19	Safety precautions to protect laboratory staff against common incidences	Confirmed

This analysis helps improve the understanding of how individual scores of efficiency and operating variables are related. This study describes the development of a benchmark for the evaluation of control strategies in WWTPs. This study is intended to be useful to decision-makers in the wastewater treatment sector. The benchmarking methodology and empirical application developed by PIs for wastewater services published by IWA is used for improving the management of WWTPs and contribute to save operational costs. The first step is to assign relative significance levels to each PI depending upon the objective and context of the PI application by the wastewater undertaking. This should be done in consultation with the various stakeholders to:

- Comparing the processes and performance metrics to industrial best practices.
- Measurement of the quality of an organization's policies, products, programs, strategies, etc. and their comparison with standard setup.
- Quantitative comparative assessment that enables utilities to track internal performance over time and to compare this performance against that of similar utilities.

Overall objective of the benchmarking process is to trigger implementation of appropriate actions that will improve its current performance (http://www.businessdictionary.com/definition/benchmarking.html)

- To determine what and where improvements are essential
- To analyze how other organizations achieve their high performance levels
- To use this information to improve performance

This is to benchmark the performance of sanitation services from collection, treatment, transmission and distribution of treated effluent and compare the findings with that from the best practices in the world. This is also to adopt generally accepted procedures and methodologies, able to provide decision makers with an overall perception of the utility performance as a sound basis for making strategic choices from water organization bodies and the best international practices. The following international four benchmarking practices were considered to select an appropriate one for ministry approach.

3.3.1. Effective utility management (EUM) (a primer for water and wastewater utilities)

The effective utility management (EUM): a primer for water and wastewater utilities ("primer") is the foundation of EUM. It is designed to help water and wastewater utility managers make informed decisions and practical, systematic changes to achieve excellence in utility performance in the face of everyday challenges and long-term needs for the utility and the community it serves. EUM can help utilities respond to both current and future challenges and support utilities in their common mission of being successful 21st century service providers. Based on these challenges, EPA and six national water and wastewater associations signed an historic agreement in 2007 to jointly promote EUM based on the ten attributes of effectively managed water sector utilities (M. Matichich, 2014):

- Product quality
- Customer satisfaction
- Employee and leadership development
- Operational optimization
- Financial viability
- Operational resiliency
- Community sustainability
- Infrastructure stability
- Stakeholder understanding support
- Water resource adequacy

3.3.2. European benchmarking co-operation (EBC) - 2012 water and wastewater benchmark

European benchmarking co-operation (EBC's) benchmarking- and improvement program offers participants a comprehensive analysis of the performance of its utility in comparison with colleague utilities from across Europe. This "fitness check" helps participants finding improvement areas and -priorities in a structured and objective way (EBC, 2016)

3.3.3. Metric benchmarking

It is a numerical measurement of performance levels and comparison with other water undertakings to identify areas needing improvement (e.g. staffing numbers/connection, % leakage level, % supply coverage, etc.), the steps are (D. Milnes, 2006):

- Identification of those areas where there is an apparent performance gap.
- Understanding of explanatory factors, such as physical characteristics, geography, weather, population, all key to understanding the apparent performance gap, and may add to or diminish that gap, generating a real performance gap.
- All metric benchmarking data should therefore be treated with a degree of caution and not necessarily taken at face value.

3.3.4. PIs for wastewater services - IWA - operations and maintenance specialist group

The manual of best practice PIs for wastewater services provides guidelines for the establishment of a management tool for wastewater utilities based on the use of PIs. The focus is on those PIs considered to be the most relevant for the majority of wastewater utilities, to be used routinely at management level and potentially for metric benchmarking practices. Phase 2 of the study utilized the manual - PIs for wastewater services – IWA (Matos et al., 2012) to analyze and select the most appropriate benchmark due to the following reasons. The IWA PI system for water services is now recognized as a worldwide reference. Since it first appearance in 2000, the system has been widely quoted, adapted and used in a large number of projects both for internal performance assessment and metric benchmarking. Water professionals have benefited from a coherent and flexible system, with precise and detailed definitions that in many cases have become a standard. The system has proven to be adaptable and it has been used in very different contexts for diverse purposes. The PIs system can be used in any organization regardless of its size, nature (public, private, etc.) or degree of complexity and development. It contains a reviewed and consolidated version of the indicators, resulting from the real needs of water companies worldwide that were expressed during the extensive field testing of the original system. The indicators now properly cover bulk distribution and the needs of developing countries, and all definitions have been thoroughly revised. The confidence grading scheme has been simplified and the procedure to assess the results- uncertainty has been significantly enhanced. In addition to the updated contents of the original edition, a large part of the manual is now devoted to the practical application of the system. Complete with simplified step-by-step implementation procedures and case studies, the manual provides guidelines on how to adapt the IWA concepts and indicators to specific contexts and objectives.

3.4. Benchmarking approach

The data collection and benchmarking were conducted with the following four sections in the directorate with total 11 team members: sewage network section; treatment plants section; treated sewage effluent section and quality control group. To avoid any bias or spurious misinterpretation of the benchmarking results, it is strongly recommended that only those PIs based on variables with 1 year data record should be used for benchmarking performance with other undertakings. In this study, the following steps were performed to:

- benchmark the performance of sanitation services from collection, treatment, transmission and distribution of treated effluent and compare the findings with that from the best practices in the world.
- collect data and align with international best practices for benchmarking by using the manual PIs for wastewater services published by IWA.
- follow applicable PIs from the manual PIs for wastewater services published by IWA.

4. Results of phase 2

The performance shall be evaluated using PIs as per IWA. PIs are measures of efficiency and effectiveness of the delivery of services by an undertaking that result from a combination of several variables. A PIs consists of a value which is a ratio between variables expressed in specific units. PIs can be analyzed interpreted and compared by taking into consideration context information and the quality of data for each utility. There are six categories with a total of 182 PI as per IWA manual (Matos et al., 2012):

- Environmental indicators (wEn)

  Environmental indicators evaluate the performance of the undertaking regarding environmental impacts, including the compliance with wastewater discharge standards, intermittent overflow discharges and final disposal of solid wastes (sludge, sediments and screenings). The environmental indicators include 15 PIs.
- Personal indicators (wPe)

  Personal indicators assess efficiency and effectiveness of the wastewater undertaking personal, considering functions, activities and qualifications. Matters like training, health and safety and absenteeism are also taken into account. Correct interpretation of these personal indicators entail a cross-reference to outsourcing

Table 2
Performance indicators categories

S. No	Category	Total PI	PI - data available
1	Environmental indicators	15	8
2	Personal indicators	25	1
3	Physical indicators	12	2
4	Operational indicators	56	13
5	Quality of service indicators	29	1
6	Economic and financial indicators	45	0
Total		182	25

Table 3
Performance indicators results

S. No.	PI	PI description	Unit	Result
1	wEn1	WWTP compliance with discharge consents	%/year	20.636
2[a]	wEn2	Wastewater reuse	%	29.933
3	wEn6	Sludge production WWTP	Kg DS/p.e/year	3.963
4	wEn7	Sludge utilization	%	0.000
5	wEn8	Sludge disposal	%	100.000
6	wEn9	Sludge going to landfill	%	100.000
7	wEn10	Sludge thermally processed	%	76.785
8	wEn11	Other sludge disposal	%	0.000
9	wPe12	Wastewater quality monitoring personnel	(No/(1000 tests/year))	0.228
10	wPh1	Preliminary treatment utilization	%	176.911
11	wPh3	Secondary treatment utilization	%	153.836
12[b]	wOp2	Sewer cleaning	%/year	25.261
13	wOp34	Sewer blockages	No/100 km sewer/year	249.351
14	wOp37	Flooding from sanitary sewers	No/100 km sewer/year	15.365
15	wOp44	Wastewater quality tests carried out	(-/year)	0.995
16	wOp45	BOD tests	(-/year)	0.992
17	wOp46	COD tests	(-/year)	0.980
18	wOp47	TSS tests	(-/year)	0.996
19	wOp48	Total phosphorus tests	(-/year)	0.784
20	wOp49	Nitrogen tests	(-/year)	0.988
21	wOp50	Fecal *E.coli* tests	(-/year)	0.996
22	wOp51	Other tests	(-/year)	0.999
23	wOp52	Sludge tests carried out	(-/year)	0.622
24	wOp53	Industrial discharges tests carried out	(-/year)	0.781
25*	wQS9	Tertiary treatment	%	36.697

[a]Volume of wastewater treated by undertaking -the data is for the wastewater collected from Tubli WPCC only.
[b]Measured for main lines only.

data. Employees include every person who works for the undertaking in return for a wage. The personal indicators include 25 PIs.

- Physical indicators (wPh)

  Physical indicators aim to evaluate if wastewater treatment and sewerage assets still have enough capacity (headroom) to operate correctly and safely, assuring that their service targets can be attained. The utilization of preliminary, primary, secondary and tertiary treatment is considered as well as the degree of surcharging in the sewers. Pumping capacity utilization and automation and the degree of control are also included. The physical indicators include 12 PIs.
- Operational indicators (wOp)

  In this group, PIs are intended to assess the performance of the undertaking as regards operation and maintenance activities. The areas to be assessed include sewers, ancillaries, pumps and pumping station inspection and maintenance, equipment calibration, electrical equipment inspection, energy consumption, sewer and pump rehabilitation, inflow/infiltration/exfiltration, failures, wastewater and sludge quality monitoring, vehicle availability and safety equipment. The operational indicators include 56 PIs.
- Quality of service indicators (wQS)

  Quality of service PIs measure the level of service provided to customers. Areas include level of service coverage, flooding and relations with customers, such as reply to requests, complaints, third party damage and traffic disruption caused by undertaking activities. The quality of service indicators include 29 PIs.
- Economic and financial indicators (wFi)

  Indicators in this group deal with the effectiveness and efficiency of the use of financial resources. Additionally, they provide means to interpret the business management, indicating the company financial behavior and ability to expand. Revenues, costs, composition of running costs per type of cost, per main function and per technical activity, composition of running costs per type of cost, leverage, liquidity and profitability indicators are included. The economic and financial Indicators include 45 PIs.

The team members provided the data for benchmarking regarding the PIs related to their units. In order to collect the data a simple template was sent to the team members based on the understanding and for easy approach. Some of the team members provided the data in the template form. Some team members provided the data in the available format for them.

Benchmarking procedures are useful tools to assess the performance of these facilities and help identify best practices to ensure the management of efficient facilities and improve the sustainability of these facilities and enhance their services in the present and future. With the available data for 25 PIs for the year 2017, the data for benchmarking were used. In the future, the other related data shall be recorded to benchmark all the necessary requirements as per IWA manual of best practice for PIs for wastewater services (Tables 2 and 3).

In fact, the availability of the data/information is a crucial factor in the metrics of benchmarking. In this regard, future additional data and information collection should be identified for the continuous implementation of the benchmarking system in Bahrain.

5. Conclusion

Each year, the network of participating wastewater utilities is growing further, but the goal is not to grow as large as possible. It is more important to keep individual utilities for a longer period, since performance improvement is a continuous activity. This requires that the constant development to fulfil the needs and expectations of the participants and to introduce new elements that are relevant from internal- or external perspectives. For instance, PIs are accustomed determine wherever structure performance is meeting desired standards and wherever performance needs improvement. It is to encourage meaning property, best practices and industrial benchmarking to ascertain among the waste product management community and to spot an inexpensive set of environmental, social, economic and technical indicators for waste product treatment by following IWA best practices.

This study assessed the benchmarking of the wastewater services in the Kingdom of Bahrain. Performance assessment and benchmarking has developed as a key aspect of WWTP management. Benchmarking is a data-driven process, and can only be successful if careful consideration is given to data availability and accuracy. Four teams have contributed as data owners and have provided the data. The only data readily available and accurate is that which is supplied for regulatory purposes. Without sufficient data, assessing the accuracy of the available data and identifying comparable WWTPs becomes increasingly complex. Improved data management practices can be achieved through WWTP benchmarking. Enabling the successful benchmarking in the present-day can (i) improve WWTP management practices, (ii) accelerate the improvement of data collection practices and (iii) lead the way to the inclusion of more advanced benchmarking applications in the years to come, when data availability and accuracy issues are corrected. With the available data for 25 PIs for the year 2017, the data for benchmarking were used. In the future, the other related data shall be recorded to benchmark all the necessary requirements as per IWA manual for PIs for wastewater services. The main recommendations of the study are:

- Gap analysis shall be conducted in detail for the non-confirmed gaps
- Continue with the 25 PIs measurement and to improve the performance wherever applicable
- Set action plan to collect data for remaining PIs
- Secure and archive the collected information for future use and analysis

Use of SIGMA Lite professional software by IWA developed by ITA to enter the PI data and obtain the results with the following features;

- Incorporation of the complete set of PIs from the IWA as a stand-alone PI evaluation system

- Facility to export the results to MS-Excel spread sheet for further interpretation and processing
- Easy to operate with automatic calculation of PIs

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Virus removal from treated wastewater in modified garden soil columns, Kuwait

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ABSTRACT

A research study was conducted to determine the addition of garden soil to natural soil for removal of coliphage viruses from treated wastewater. Treated wastewater containing viruses was passed through soil columns filled with soil collected from Sulaibiya area, Kuwait. The four soil column experiments were under operation for eight months. The first and second soil columns filled with natural soil, while the third and fourth soil columns filled with modified soil consist of Sulaibiya soil mixed with 1% garden soil. All soil columns had soil depth of 0.1 m and with constant hydraulic head of 0.1 m above soil surface. For each experimental condition, two identical columns were set up, so that the reproducibility of the results can be evaluated, producing four columns. For all columns, the tests were conducted under alternating 1 d flooding and 1 d drying conditions. Influent and effluent water samples were collected and analysed following cycles of flooding periods. The coliphage virus counts in the treated wastewater ranged between 0 and 62,800 pfu/100 ml. The laboratory results revealed that coliphage removal for Sulaibiya soil ranged between 58% and 100% with average value of 88.4%, while their removal efficiency for modified columns was between 60% and 100% with average value of 92.3%. The presence of garden soil mixed with the soil relatively increased the coliphage removal from treated wastewater.

Keywords: Coliphage viruses, Treated wastewater, Soil column experiments, Effluent

1. Introduction

Kuwait is a modern industrialized nation that meets most of its domestic, commercial and industrial water needs by desalination of seawater. However, while desalination technologies demonstrated a remarkable progress in recent years, they still do not present a viable economical option for wide agricultural use. Therefore, countries with limited water resources carry on research effort into agricultural use of wastewater since recycling of renovated wastewater generates a valuable water resource.

As Shahalam et al., (2017) points out, Kuwait produces 1 million m^3 of tertiary treated wastewater per year, of which only 40% is used for irrigation, while the remainder is being discharged to the Arabian Gulf. The volume of tertiary treated wastewater is set to increase in line with growing population and escalating water needs. In this context, the methods that can restore the wastewater quality to usable levels will be gaining and ever increasing importance.

Water for agriculture needs to meet stringent quality criteria, which include absence of pathogens like virus and bacteria, and low nitrogen levels (Elkayam et al., 2018). These parameters are difficult to achieve within economic realms of existing purification technologies. Therefore, researchers concentrate on efficient ways of improving the quality of wastewater using natural environments, for example soil.

Coliphage viruses (i.e. viruses that uses *Escherichia coli* bacteria cells as host) were selected for this study because their structure, composition, morphology and size closely resemble that of enteric viruses, they are easily grown on bacteria cultures, and only simple materials and equipment are needed for coliphage detection and quantification by plaque

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forming units (pfu), (APHA, 2005). Also, coliphage viruses are chlorine resistant microorganisms and considered as indicators for wastewater viruses.

Soil aquifer treatment (SAT) technique is an economically attractive method for the treatment of wastewater for restricted and unrestricted irrigation (Shahalam et al., 2017). These systems are operated to use underground formations as a treatment facility, and thus are called SAT or geo-purification systems. While significant research effort has been applied to SAT throughout the world, there is an evident need to test this technique with local Kuwaiti soils, wastewater, and climatic conditions. A laboratory study concentrated on the tertiary treated wastewater from the Sulaibiya wastewater treatment plant, treated by sandy soils from Kuwait.

Adsorption appears to be the predominant factor in virus removal by soil (Yanji et al., 2001; Park et al., 2016). Thus, factors influencing adsorption phenomena will determine not only the efficiency of short-term virus retentions, but also the long-term behavior of viruses in the soil. Such factors include soil composition, and the presence of soluble organic matter. Viruses are readily adsorbed to clays under appropriate conditions, and the higher clay contents of the soil, the greater the expected removal of viruses (Al-Haddad et al., 2018). Sandy loam soils and other soils containing organic matter are also favorable for virus removal. Soils with a low surface area do not achieve good virus removal (Kauppinen et al., 2018). Soluble organic matter competes with viruses for adsorption sites on the soil particles, resulting in the decreased virus adsorption. The objective of the study was to assess the removal of coliphage viruses from treated wastewater using natural soil and modified soil column experiments in Kuwait.

2. Methodology

2.1. Soil collection and properties

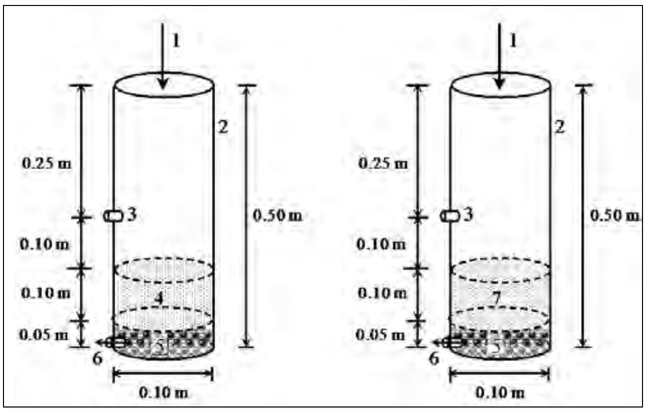
One type of soil that was used in column experiments included soil collected from Sulaibiya area, Kuwait. Soil samples from the top 10 cm from the Sulaibiya area were used to fill four soil columns. Each 5 cm of soil inside the column was compacted until filled the required total soil length and this compaction method will produce density (1.8 g/cm^3), specific gravity (SG) (2.63) similar to their values in the field. Modified soil was prepared by mixing 1.374 kg natural soil with 13.88 g (i.e., 1%) garden soil. Sample of this mixture was collected using sample divider to determine its properties and to confirm even distribution of 1% garden material in the soil. Bentonite clay was selected for this study because it mainly consists of organic content (more than 900.0 mg/kg-TOC) that have a reasonable specific surface area (SSA).

2.2. Design and column construction

Four soil columns were constructed to study removal of viruses from tertiary treated wastewater using different natural soil and mixed soil containing 1% clay. The columns were constructed using polyvinyl chloride (PVC) pipes of 0.1 m diameter. These columns were practical for water sampling in the laboratory, easy to fabricate, cheap and used in other researches (Al-Haddad et al., 2015) in the field of SAT system, and allowed to correlations of the results of this study with the work of the pervious researches under the similar laboratory conditions. The PVC pipes reduce contamination and interaction between coliphage and the column walls. The total length of 0.5 m contained 0.05 m of gravel, 0.1 m of natural soil, 0.1 m of constant wastewater head and allowed a margin of safety (Fig. 1). The depth of the natural soil was selected as the optimum depth for virus removal, following the practices of previous researchers (Al-Haddad et al., 2015). The gravel in this study was used as a filter zone to prevent the passing of fine materials through the outlet. The column numbers one and two were filled up with natural material and three and four were used for modified soil. The grain size distribution, SSA, total organic carbon content (TOC %), total carbonate content (CO_3 %), cation exchange capacity, density, SG, porosity (P) and fine materials (silt and clay) content of the soil were determined for both types of soils (natural and modified) using standard methods described by (Page et al. 1982).

2.3. Column operation and maintenance

The tertiary wastewater was pumped daily from the Sulaibiya Data Monitoring Center to a high level 1.89 m^3/L capacity tank through a PVC line. The tertiary wastewater was fed to all the soil columns simultaneously. The tertiary treated wastewater header tank, and all the feeding PVC lines were flushed and cleaned regularly during drying and maintenance periods of column operation. Constant head of 0.1 m of treated wastewater was used in measuring the removal of coliphages. These constant head was maintained for the soil columns by overflow outlets above the soil surface. For each experimental condition, two identical columns were set up, so that the variability of the results can be assessed. The coliphage tests were studied only under alternating flooding and drying conditions. All columns were subjected to short flooding and drying cycles of 1 d of flooding alternating with 1 d of drying for eight months. During the drying periods and at the end of each month, the maintenance of



1- Influent
2- PVC Column
3- Overflow Outlet
4- Soil
5- Gravel
6- Outlet for Sample Collection
7- Soil with Garden Soil Materials

Fig. 1. Design of soil column experiments.

the soil columns was carried out by scratching organic layer on top of soil surface using long plastic forks and removing this layer to increase the infiltration rate. The infiltration rate was measured for columns at the beginning of the flooding period, and calculated according to the following equation (Al-Haddad et al., 2015):

$$\text{Infiltration rate}\left(I\right)=\frac{V}{At} \quad (1)$$

where V is the volume of the outflow in time t and A is the cross-sectional area of the soil column. In this study, infiltration rate was expressed in m/d. In the field, the infiltration rates of the treated water through the aquifer will be affected by presence of impermeable layers such as silt, clay and carbonate layers beneath the wastewater recharge spreading basins.

2.4. Wastewater sampling and analysis

Samples of influent and effluent were collected 24 h after the flooding periods. Each sample was separated into two subsamples, and measurements of the coliphage content of each subsample were carried out to ensure the accuracy of the analyses. Samples were collected using sterile 100 ml glass bottles with glass stoppers, and they were analyzed within 4 h of collection. Any sample kept for 4 to 24 h was cooled to at least 10°C. Virus samples were analyzed in the laboratory of Water Research Center Laboratory (WRC) at Kuwait Institute for Scientific Research (KISR) using the standard methods for the examination of water and wastewater (APHA, 2005). Fresh bacteria and coliphage media were prepared at the end of each month. Modified tryptic soy agar (MTSA) media and *Escherichia coli* C (host culture, WARD'S No. 85W1662) were used for detection of coliphage viruses (APHA, 2005).

3. Results and discussion

The result of grain size distribution for Sulaibiya soil is plotted in Fig. 2. The *S*-shaped grain size graph indicates rather poorly sorted distributions spanning the gravel, sand, and fine classes. The soil tested consisted of sandy soils with different percentages of fines (i.e., silt and clay). Al-Haddad (2000) reported that Sulaibiya soil consists of 97.5% sand, 1.5% silt and 1% clay. The mean value of fines for the natural soil samples was 2.5% and that for modified soil was 3.10%. The amount of fines was found to be an important factor for the removal of virus by adsorption. The mean values of P, SSA and the TOC for natural soils were found to be 33%, 8.22 m^2/g, and 343.23 mg/kg, respectively. The same for the modified soils were 44%, 5.88 m^2/g, 5.88 m^2/g and 907.18 mg/kg for the modified soils. The mean value of carbonate content for both types of soil was 5.5%. Soils with high contents of fines, organics and carbonates are expected to adsorb more viruses from treated wastewater.

The soil columns were recharged with treated wastewater from August 2004 to February 2005. During the period August 2004–20 November 2004, tertiary treated wastewater was used for recharge. After this period, there was a change in the quality of water used for recharge due to the mixing of tertiary treated wastewater from Al-Jahra wastewater plant with reverse osmosis (RO) treated wastewater from Sulaibiya Plant Utility Company at Sulaibiya area(Al-Haddad et al., 2005). On 14 February 2005, only the RO treated wastewater was passing through the soil columns. The coliphage virus count in the treated wastewater ranged between 0 and 62,800 pfu/100 ml during the study. However, the coliphage counts decreased when the tertiary treated wastewater was mixed with RO treated wastewater, and coliphage counts fell to nil in the RO treated wastewater at the end of soil column experiments.

The effects of natural and modified soil types on coliphage virus removal from the treated wastewater are presented in Figs. 3–5. The coliphage counts in the treated wastewater after passing natural and modified soil ranged between 58 and 100 pfu/100 ml; and between 75 and 100 pfu/100 ml, respectively (Figs. 3 and 4). At the same time, the coliphage removal using Sulaibiya soil ranged between 58% and 100% with average value of 88.4%, while their removal efficiency using modified soil vary between 60% and 100% with average value of 92.3% (Fig. 5). This data support that idea that addition of organics in the soil increases

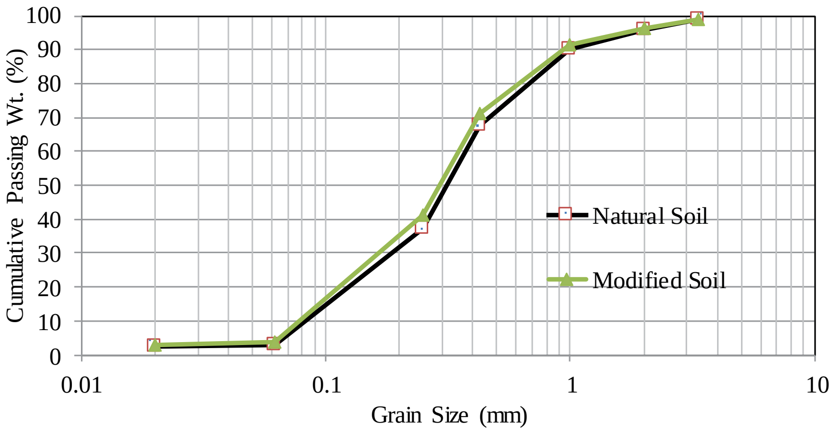


Fig. 2. Grain size distribution for natural and modified soils.

Fig. 3. Coliphage viruses before and after passing modified soil.

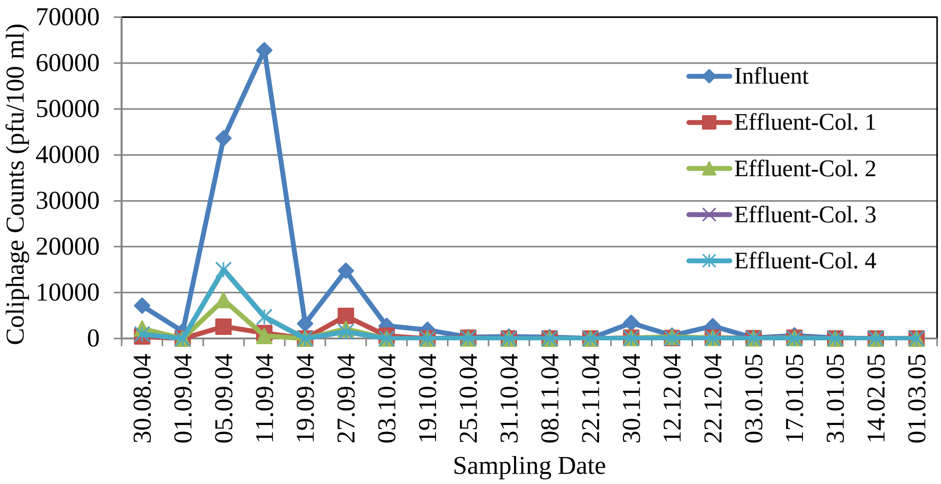


Fig. 4. Coliphage counts using natural soil (columns 1 and 2) and modified soil (columns 3 and 4).

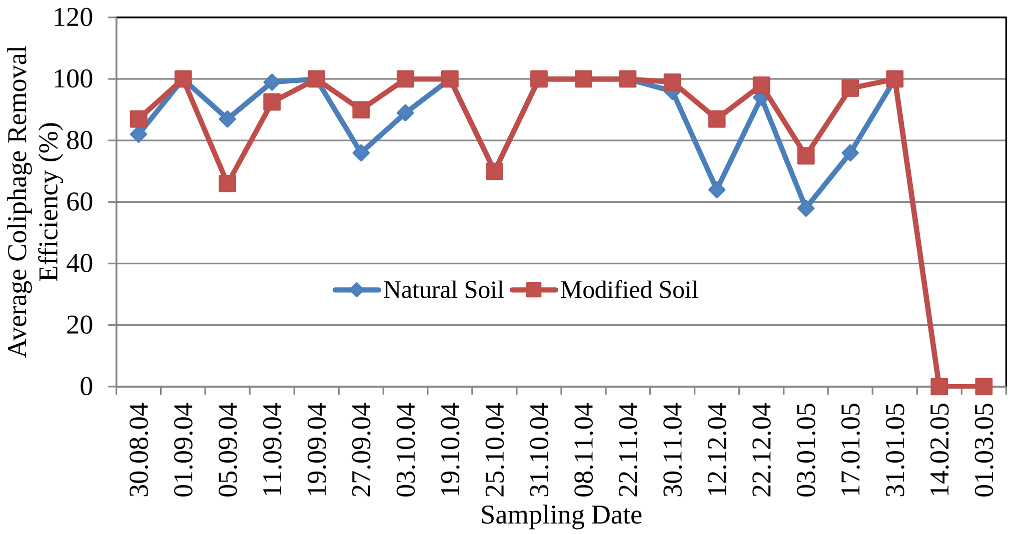


Fig. 5. Coliphage removal efficiency after passing natural and modified soil columns.

the coliphage removal from treated wastewater. A similar soil column experiment was carried out by Al-Haddad et al. (2018) where they reported that viruses were mostly adsorbed at the top 5 cm of soil. The results obtained in the present study confirm this conclusion. The infiltration rates for Sulaibiya natural soil ranged between 0.4–10.9 m/d with an average value of 2.3 m/d, while those rates for modified soil (soil with added organics) ranged between 0.2–8.9 m/d with an average value of 2.0 m/d. It is clear that infiltration rate was reduced due to addition of bentonite clay in the modified soil column. The reduction in the infiltration rates produced longer contact time between the viruses in the treated wastewater and the soil particles, which later reflected in high values of coliphage removal efficiency from treated wastewater.

4. Conclusions

Soil column experiments were carried out to determine removal of coliphage viruses from the treated wastewater using Sulaibiya natural soil and amended soil mixed with garden soil materials. Total of four soil columns were constructed at the KISR wastewater research building in the Sulaibiya area. Soil samples were collected to fill the columns and to determine their properties. All soil columns had soil depth of 0.1 m and with constant hydraulic head of 0.1 m above soil surface. The treated wastewater was pumped daily from the tank and fed to all the soil columns. All columns were subjected to short flooding and drying cycles of 1 d of flooding alternating with 1 d of drying for eight months. Samples of influent and effluent water were collected 24 h after the flooding periods.

High counts of coliphage viruses were found in the tertiary treated wastewater (62,800 pfu/100 ml) and their counts was reduced after mixing it with RO treated wastewater. The laboratory results revealed that coliphage removal for Sulaibiya soil ranged between 58% and 100% with average value of 88.4%, while their removal efficiency using modified soil was 60% and 100% with average value of 92.3%. The soil properties such as amount of fines, organics, and the infiltration rates were important factors that increased the coliphage removal from the treated wastewater. Based on the laboratory experiments, following recommendations are forwarded:

- Removal efficiency of bacteria and viruses (enteric viruses) from the wastewater using the SAT system should be determined in the field. The field study should be conducted over a period of several years and conclude with a detailed presentation of all expected benefits and shortcomings of SAT in terms of technical, environmental, social and economic returns. This study should also provide a set of detailed guidelines on use of SAT in Kuwait.
- Operation of SAT system should be applied separately for both the RO-treated wastewater, and tertiary treated wastewater to compare the bacteria and virus removal efficiency from both types of water.
- In agricultural areas, the treated wastewater should be passed through a filter zone of sandy soil mixed with 1% organics (organic fertilizer) before this water is used for irrigating the agricultural areas. In addition, this mixture of soil can be added at the base of surface spreading basins recharged by treated wastewater to remove the pathogen.

Acknowledgments

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A practical step towards sustainability: decentralised wastewater management in Oman

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ABSTRACT

Oman has undergone major transformations during the past few decades, which have resulted in growing water scarcity and an increase in the domestic wastewater production. To align with UN Sustainable Development Goal (SDG) number 6: "Ensure availability and sustainable management of water and sanitation for all", the government spending on wastewater services dramatically increased over the past two decades aiming to extend sanitation services all over Oman. However, the expansion of the wastewater infrastructure will have to address the conditions of rural and suburban settlements in order to reduce network and pumping requirements and the risk of technical failure to the minimum and to ensure cost efficiency. To achieve this goal, a pilot project has been set up to develop an integrated system solution for decentralised wastewater management in Oman. The main objective of the project is to establish a research, demonstration and training facility aiming at developing, promoting and facilitating the implementation of sustainable and effective sewage and reuse management solutions for suburban and rural communities in Oman. The procedure applied for designing the facility was comprised of two parts; the comparative analysis, which gathers forms and ranks information into a knowledge basis, on which the designer can make a decision and the engineering design process. With the geographic information system (GIS)-based assessment tool assessment of local lowest-cost wastewater solutions (ALLOWS) the project compares different scenarios for regional wastewater management options. ALLOWS features two main components: (1) Spatial analysis, and (2) cost assessment using net present value calculation for different scenarios for a lifetime of 80 years. In a case study, different sanitation scenarios were developed for Al Mizarih village, near Qurayyat, Oman. This preliminary assessment indicates that under current conditions a solution on household level is the most cost-effective option. However, semi- and decentralised scenarios gain in cost-effectiveness, when future population growth and settlement patterns are anticipated in the analysis.

Keywords: GIS-based assessment, ALLOWS, rural, sewage, suburban, wastewater management

1. Introduction

Oman experienced fast economic growth and demographic change over the past two decades causing more stress on its limited water resources. In 2015, the population reached about 4.2 million with 56% Omanis and 44% expatriates. As a result, the national demand for water already exceeds annually recharged resources by 316 million m^3/year (Al-Barwani 2016). Furthermore, by the year 2040, the total population is projected to increase by 2.4 million National Centre for Statistics and Information's (NCSI, 2015). Consequently, sewage production will also further increase as a result of population growth. However, improper sewage treatment can affect groundwater quality if undesired

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substances infiltrate into the aquifers and can thus result in serious pollution, which might cause adverse effects on human health and the environment. Possible groundwater pollution from sewage effluent has already been observed in Oman (Al-Bahry et al., 2014). Such pollution can result from leaking septic systems on household level or from the improper operation and maintenance (O&M) of sewage treatment plants (STPs) and improper sewage treatment and quality of treated effluents (Baawain et al., 2014).

In 2015, the Ministry of Regional Municipalities and Water Resources (MRMWR) signed an agreement with Oman Wastewater Services Company, SAOC (Haya Water) on managing, operating and maintaining sewage facilities of the ministry across the entire country, except for the Dhofar governorate. Subsequently, MRMWR has already transferred 63 STPs connected to sewer and treated effluent networks with a total length of about 750 km in various governorates to Haya Water (Haya Water, 2016). In 2016 Haya Water has floated a consultancy service tender to update its sewage management master plan and to include the additional nine governorates in the Sultanate in its master plan (ZAWYA, 2016). However, the introduction of new sewage infrastructure in remote rural and suburban settlements faces several major challenges, most importantly, capital cost, regulatory, planning, and technical bottlenecks as well as citizens' concerns over adverse effects from STPs. To overcome these bottlenecks and to ensure countrywide acceptance of new sewage infrastructure as well as the safe and sustainable treatment and reuse schemes, exceptional efforts are required to focus on:

- Cost-efficiency and reliability of treatment technologies under Omani conditions
- Ensuring adequate skills of operations and maintenance personnel responsible for different STP types in remote areas
- Involving rural and suburban communities and homeowners in the planning for sewage treatment and reuse infrastructure. Experiences in several countries (UN, 2017) have shown that engaging national sectors and stakeholders is a prerequisite for a sustainable sewage management system
- Promoting sewage treatment and reuse as essential themes for the future of Oman
- Improving the image and acceptance of sewage treatment and reuse for all Omani citizens and residents
- And finally, sewage management is a task of national interest

A collaborative discussion between The Research Council of Oman (TRC), Haya Water and the Helmholtz Centre for Environmental Research (UFZ, Germany), has been set up to develop an integrated system solution for decentralised approaches to sewage management in suburban and rural areas of Oman. It has been agreed that the above challenges require a multifunctional facility that provides the environment for technology testing, certification, and development, research on resource recovery and reuse, as well as outreach to the general public and capacity building all provided at one location.

1.1. Traditional sewer extension approach vs. integrated management approach

Sewage treatment management can be designed specifically to fit local sanitation needs for individual homes and rural communities. For remote areas and especially in mountainous areas and in urban areas where existing infrastructure inhibits extension (re-densification), local sewage treatment systems provide economic benefits, due to the reduction of pumping and network requirements, as well as ecological benefits from water reuse and groundwater protection. To realize these benefits, Haya Water aims at an integrated approach, which can effectively combine safe and economical treatment for different types of settlements, ranging from villages to cities and provide treated effluent and nutrients for reuse.

Integrated sewage treatment and reuse is defined as the collection, treatment, and reuse (or disposal) of sewage in the most cost-efficient and beneficial manner in the local context. In an integrated approach growing rural and suburban areas without sewage infrastructure as well as re-densifying urban areas where spatial limitations inhibit the growth of the existing centralized infrastructure can be

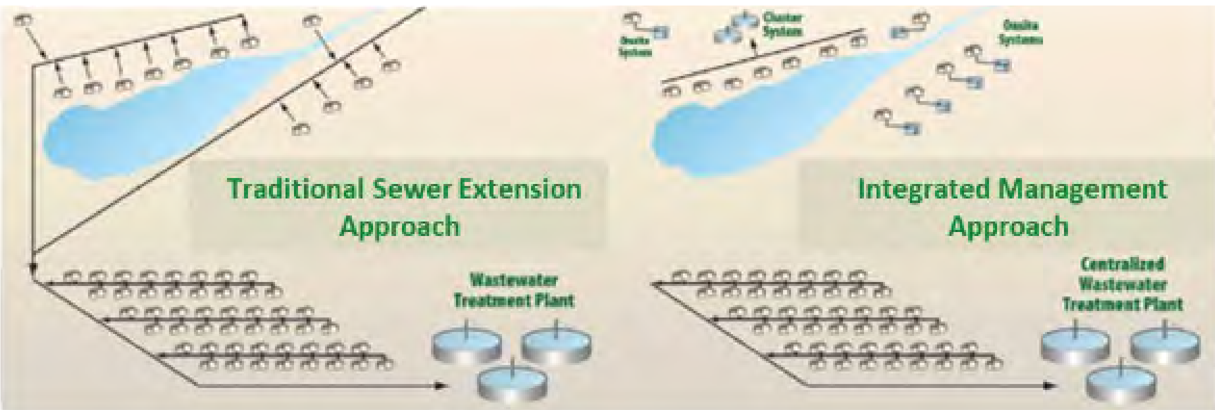

Fig. 1. Traditional sewer extension and integrated management approach that uses a variety of system scales to provide treatment that matches the context (WERF, 2010).

served at relatively low cost. For remote locations, the costs associated with the sewer construction (between the village and the closest STP) can become prohibitive, particularly in mountainous landscapes. Integrated sewage management provides local communities with additional benefits in the form of locally available water, nutrients and organic resources for reuse and improved sanitary and environmental conditions. Integrated solutions focus on cost-efficiency by designing treatment systems specifically to fit local sanitation needs for individual homes and rural communities thus combining small and large infrastructure.

1.2. Key components of an integrated management approach

Integrated wastewater treatment and reuse systems, independently of the technical solution selected, are all constituted of the following components:

- *A sewage collection system* that conveys sewage from its point of origin to its place of treatment. In integrated solutions, it is usually expected that the network length between household connections is as short as possible either and preferably gravity-fed to reduce operation and maintenance cost (OMC).
- *A sewage treatment system* that removes pollutants to a level determined by regulation. It usually includes, at least, a primary and secondary treatment step. A wide range of technologies is available to perform at any treatment level. Typically, national regulations pre-select some technologies that can be used to meet the level of treatment based on the given local context (population connected, sewage quality, reuse purpose, etc.). However, the one sewage treatment technology that would fit all possible contexts does not exist till now. Each technology has advantages and limitations and one of the main challenges for sewage infrastructure planners is identifying a technical solution that is best under given local constraints.
- *A reuse or disposal solution* that allows safe discharge of the treated effluent. Controlled reuse of treated effluent provides additional benefits (irrigation and fertilization of agricultural fields, landscaping, soil restoration, etc.). When reuse is not feasible, the safe disposal of treated effluent is required, e.g. controlled discharge or managed aquifers recharge.
- *An O&M framework* so that O&M tasks are regularly carried out to ensure that the treatment systems meet regulatory requirements throughout their operational life. For remote locations, O&M requirements are key criteria in the choice of the treatment technology to be installed. Most important is to ensure, that O&M is being performed properly for all sizes of treatment plants. In many countries, this is ensured by certifying O&M companies and the platform is designed to enable Haya Water to conduct certified training for O&M personnel.
- *Governance* that ensures regular monitoring of STPs and proper performance of O&M contractors. Also, general regulations regarding the set of treatment technologies that can be implemented in Oman as well as requirements for reuse and discharge need to be determined and monitored.

1.3. Why we need research and testing facility?

Innovative sewage product designers and manufacturers have begun developing technologies to treat and reuse water while keeping it onsite. This type of decentralized treatment and reuse offers a solution that is sustainable, efficient, cost-effective, and highly practical. For a particular location and specific effluent quality and in the absence of a technology certification procedure, it is usually difficult to select the most appropriate technology from among the set of available technologies. Factors like cost, efficiency, site requirements as well as sustainability criteria such as robustness and O&M requirements and their interdependencies are involved in the decision-making process. However, selecting the most appropriate technology might be difficult for decision-makers in administrations, government, and engineering companies as they may not possess comprehensive knowledge of their individual features. It is also important to acquire the experience with their O&M in order to be familiar with these technologies and be able to choose from the extensive range of commercially available technologies before the implementation in a specific location. This is particularly the case for technologies applied in more remote areas with unique challenges.

In addition, it is obligatory for all sewage treatment systems operated in Oman to meet the Omani treatment, reuse and disposal standards. However, such obligation does not secure the required treatment efficiency, stability, ease of O&M nor a wide range of important technological features (robustness, behavior under Omani climate conditions, tolerance to shock loads, sludge generation, etc.). Therefore, the proposed research and testing facility is planned to be a world-class infrastructure, enabling Oman to get to the next level of wastewater management. It will create new and singular opportunities for improving sewage management in Oman at all scales in particular by introducing cost-effective sanitation systems for rural remote areas, by providing a training center for technical training, thus securing best O&M skills, and by increasing the range of beneficial reuse of treated effluents.

2. Methodology

2.1. Design of research and testing facility for decentralised wastewater

A comparative analysis was carried out to gathering and comparing information, experiences, and conclusions from existing research and testing sites, which are similarly designed to fulfill one or more of the research objectives. Four different sites were chosen on the basis of their primary driver or purpose, which closely matched a study objective. These sites are listed below, with their corresponding primary objective;

- The UFZ Eco-technology Research Facility at Langenreichenbach (LRB). Langenreichenbach, Germany.
- The BDZ Decentralised Sewage Treatment Training and Demonstration Centre (BDZ) - Training and Demonstration. Leipzig, Germany.
- The SMART Project Research, Demonstration and Training Facility, Fuheis, Jordan.

- The PIA Testing Institute for Wastewater Technology GmbH – Testing and Certification. Aachen, Germany.

2.2. Creating sanitation scenarios

The assessment of local lowest-cost wastewater solutions (ALLOWS) tool (Manfred van Afferden et al., 2015) has been used to create sanitation scenarios for rural regions in Oman. The methodology has two general components:

- Spatial analysis methodology
- Cost assessment methodology

The methodology enables wastewater asset planners to plan different sewage management scenarios in a spatially explicit way using geographic information system (GIS) and technical drawing software (e.g. ArcGIS, AutoCAD) and compare the costs of the different scenarios on the basis of a dynamic cost comparison methodology using standard software (e.g. MS Excel, Python, R, Matlab). To be able to exercise this methodology on a case study (e.g. a specific village), a set of spatial and cost data are required. Depending on the envisioned level of detail, additional data regarding building regulations and standards should be used. Fig. 2 shows the required input data, the spatial analysis and the cost assessment workflow in general.

3. Results

3.1. Multi-functional national platform

An area of 6,000 m^2 has been allocated within Haya Water premises, at Al Ansab STP, for establishing this platform. To serve its purpose, the proposed platform is conceived as a facility that accommodates the major sewage and reuse stakeholder groups in Oman. This allows the pursuit of specific objectives in the area of integrated sewage management and will create new collaboration opportunities and synergies. Thus, the platform provides a holistic environment for testing and certification and technology development, embedded in a park-like landscape citing the cultural and natural heritage of Oman that will appeal to visitors and stakeholders. The platform also includes infrastructure for technical training, research, demonstration, capacity development, all designed specifically for the Omani context. In addition, the platform activities and services will have the potential to extend to the GCC region and beyond so as to open new market opportunities for Oman.

3.2. Designing options

Three different designs are prepared for the proposed "National Platform for Advanced Integration of Water Reclamation and Resource Recovery Technologies", with a particular and in-depth focus on the components and technical details of the facility. Key components of each design are also presented to show how they satisfy the facility's objectives and activities.

3.3. Main features and benefits

The potential applications of the platform will include the following facilities and benefits:

- *Facilities for testing and certification of sewage and sludge treatment/stabilization technologies (box concept)*: These important facilities will help Haya Water and other sewage service providers in their evaluation and pre-selection of sewage treatment systems that are most reliable, effective and sustainable under Omani conditions (technology selection and adaptation). This infrastructure will serve as a condenser in order to enhance collaboration between industry, academia, and policymakers.
- *Facilities for technology development and adaptation*: These facilities - technical hall and workshop, mixing and dosing station to produce different sewage qualities and field laboratories combined with the existing Haya laboratories - will help in transferring new research outcomes to concrete applications or sewage treatment products ready for commercialization. These products are expected to be cutting-edge innovative, cost-effective and simple-to-operate. Furthermore, they are expected to provide essential and forward-looking sewage services such as provision of treated effluent for reuse from different sewage qualities, reduction of local side-effects (e.g. odor) to acceptable levels, effective removal of pathogens and micro-pollutants, nutrient (phosphorus) and organic carbon recovery, production of bio-energy and energy-self-sufficient treatment, etc. These facilities will be designed to play a pivotal role in promoting spin-offs in the sewage treatment and resource recovery sectors thus contributing to job creation, in-country value creation, and sustainable economic growth.
- *Facilities for applied research on reuse*: To increase the opportunities for successful applied research and training of graduate, postgraduate, and postdoctoral researchers in agricultural irrigation using treated effluent qualities. Such facilities will also support policymakers in revising and where necessary amending existing legal provisions and standards to ensure safe reuse and economic feasibility of Omani sewage infrastructure and management.
- *Environment for capacity development and technical training*: The platform is designed to provide a variety of capacity building infrastructure, in particular, a water reclamation and management learning path, media-equipped classrooms, and exhibition and demonstration facilities,

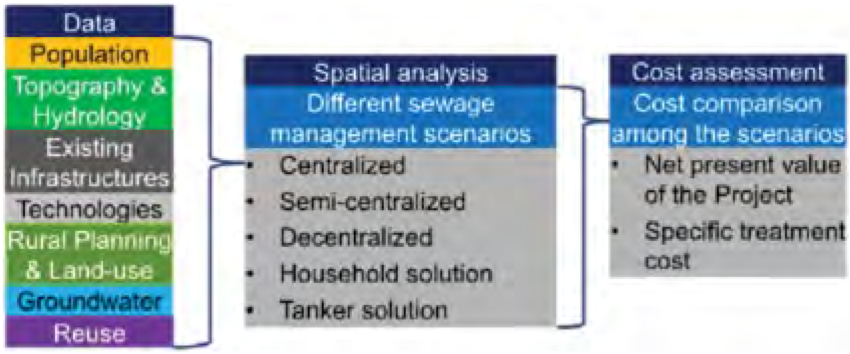

Fig. 2. ALLOWS 3-step process: (1) General data collection, (2) Spatial analysis and (3) Cost assessment.

to conduct capacity building programs for technical staff, graduates and school students in order to enhance practical, technical and scientific knowledge about and overall acceptance of sewage infrastructure and related topics, e.g. water reuse and water saving, environmental protection and sustainability of water resources.

- *Demonstration of different sewage treatment technologies in operation (demonstration plots)*: Demonstration does not focus on specific technologies, but on a long-term operation, treatment efficiency and stability, and hence on the appropriateness of investment, resources, capacities, and framework conditions. Through the demonstration projects and subsequent seminars, conferences etc., decision-makers will be informed about the advantages and challenges of different treatment technologies and management options. Bottlenecks and weaknesses of the existing regulatory and legal frameworks become apparent and indicate the improvement of framework conditions. This will also help in conducting education and outreach activities in order to contribute to the strategic social involvement objectives of Haya Water.

3.4. Technical key features proposed for the national platform

- *Concrete cased testing boxes (plug and play)*: Eight closable and partly extendable testing boxes (2 × 30 m^2, 6 × 20 m^2) fitted with an array of inlet and outlet pipes, in addition to monitoring and control devices allowing for testing, certification, and researching the housed technology unit. Boxes are designed with removable internal and external walls allowing customizing the box volume and to ease and increase the safety of technology installation.
- *Open testing boxes*: Two boxes of designated open areas for the testing, certification, and research of containerized, modular or 'package STPs' using identical operational infrastructure to the closed testing boxes.
- *Primary sewage* distribution system: Sewage line fitted with pumps, dosing, and control systems providing sewage to the open and closed testing boxes.
- *Mixing and dosing station with secondary artificial sewage distribution line*: Infrastructure allowing for the distribution of artificial sewage to the testing boxes.
- *Combined office and meeting space*: Designated space and equipment for staff operating/ researching at the platform, in addition to facilities dedicated to hosting meetings and conventions.
- *Technical hall*: The technical hall, also connected to the real and artificial sewage distribution systems, allows for the development of technologies via lab experiments, research, and development of bioprocesses and biotechnology in addition to providing technical infrastructure for conducting training programs.
- *Media-equipped education and training room*: Designated space for the technical training of target groups (engineers, O&M technicians, farmers, scientists, and students).
- *SCADA*: A system to control, monitor and operate the platform systems which also provides a human-machine

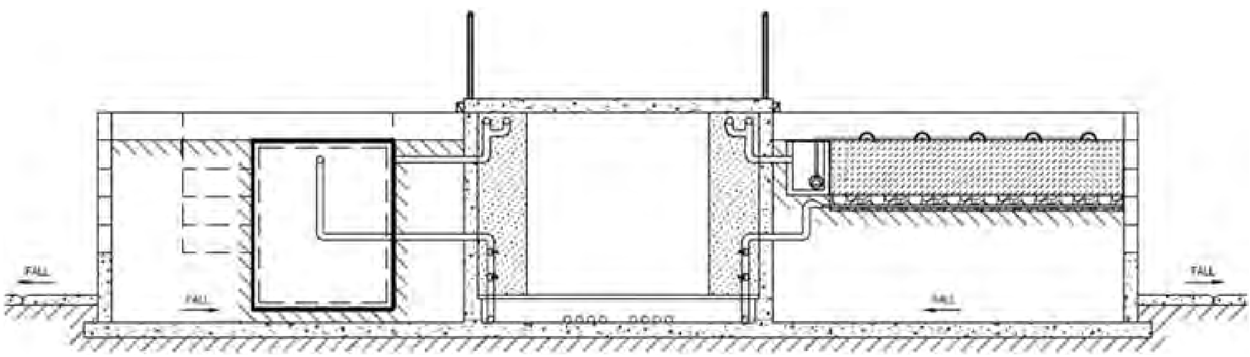

Fig. 3. Cross section of the box and corridor concept (Wetzlar, 2017).

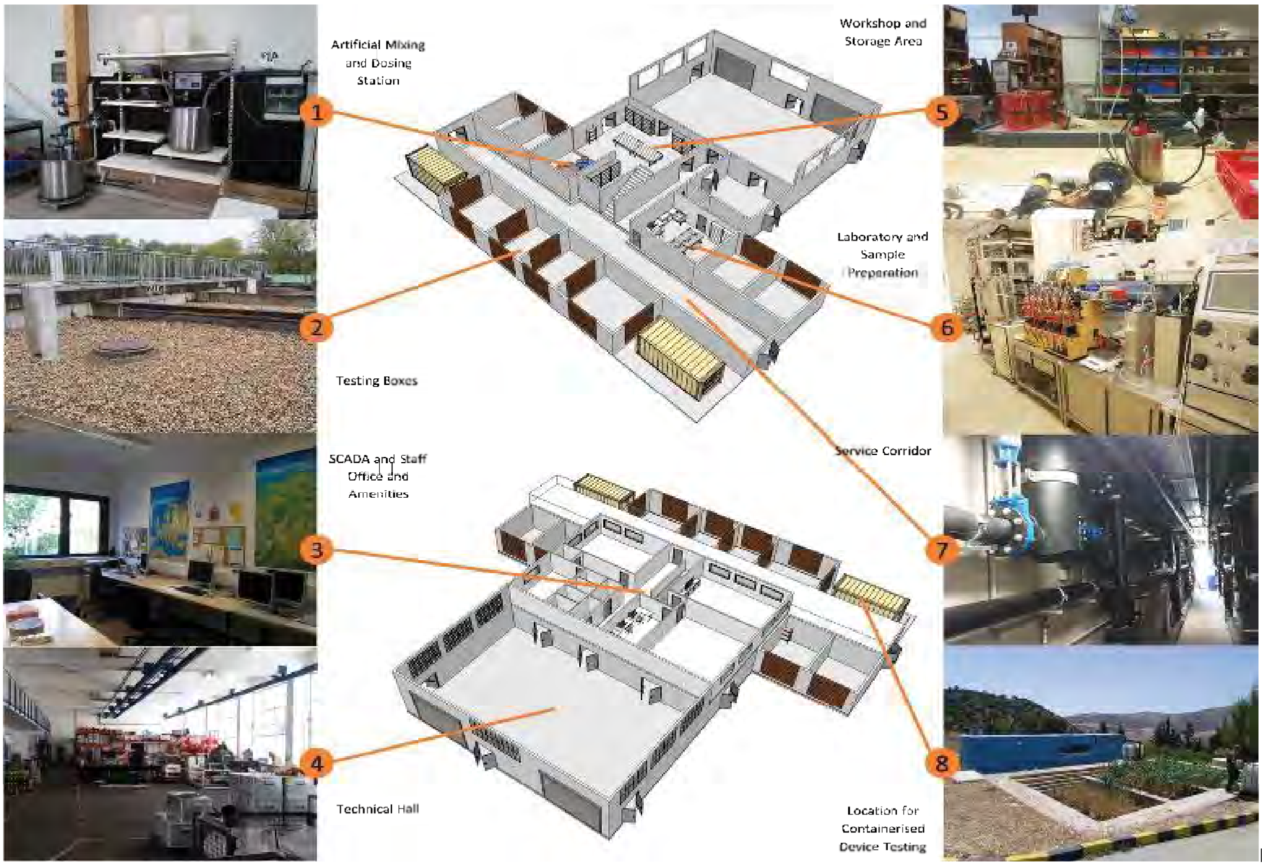

Fig. 4. Preliminary 3D overview indicating technical key features of the Platform. A multi-functional Design Option has 8 testing boxes, 2 containers connections, artificial sewage dosing unit, samples preparation room, offices, training room, big technical hall, workshop, sewage and reuse storage room (Wetzlar, 2017).

interface, allowing staff to access and visualize data onsite or remotely.

- *Auto-sampling*: Auto-samplers are proposed to be installed for all test boxes to improve sampling flexibility, provide automated data entry and to prevent sample degradation.
- *Service Corridor*: An air-conditioned corridor housing the two distribution lines, operational and maintenance equipment and distribution, 'Switch Area'. The corridor is proposed to include a false floor and air-conditioning to facilitate a comfortable, easy to access and safe working environment for operators, scientist, and visitors.
- *Collection Tanks*: for numerous treated, untreated, and artificial sewage supply.

3.5. Integrated management scenarios: Al Mizarih case study

Different sanitation management scenarios have been designed for Al Mizarih village as a case study:

- *Centralized scenario*: Sewer system with a conveyance of the sewage to the central STP
- *Semi-centralized scenario*: Sewer system connected to a local STP in Al Mizarih
- *Decentralised scenario*: Reduced sewer network, six small STPs and household STPs
- *Only single household solution*: Household STPs
- *Disposal via vacuum tankers*: All households are serviced by tankers

3.6. Spatial analysis

The first step of the spatial analysis involves data processing. Despite bringing the data into a uniform format, spatial resolution, as well as a uniform projection, different processing steps have to be computed based on the input data. For Al Mizarih we started with satellite images and some basic information, namely the population size of about 2,000 inhabitants. Fig. 5 shows a high-resolution satellite image of Al Mizarih that shows the close vicinity of the settlement to the Daykah dam and a map inlay that visualizes the surrounding region including the distance to the next largest city, Qurayyat. In Fig. 6, the main data layers namely: the digital elevation model (DEM), as well as the buildings and roads are depicted.

Figs. 7 and 8 depict processed data based on the DEM and the buildings. For Al Mizarih the populated area has an elevation range of about 90–160 m a.m.s.l and about 437 buildings. Fig. 7 shows the hydrological Wadi network as well as the micro-catchments based on the natural flow direction that enables planners to divide settlements into suburbs that can be connected to a treatment unit based

Fig. 5

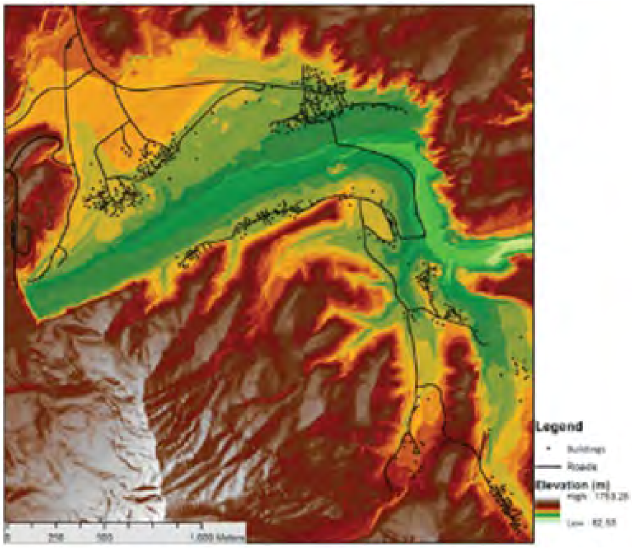

Fig. 6

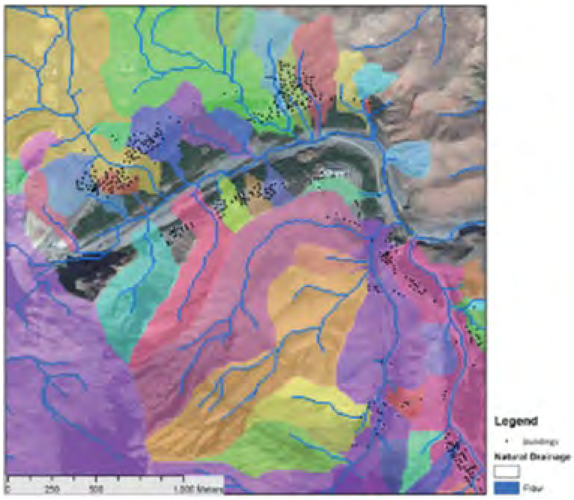

Fig. 7

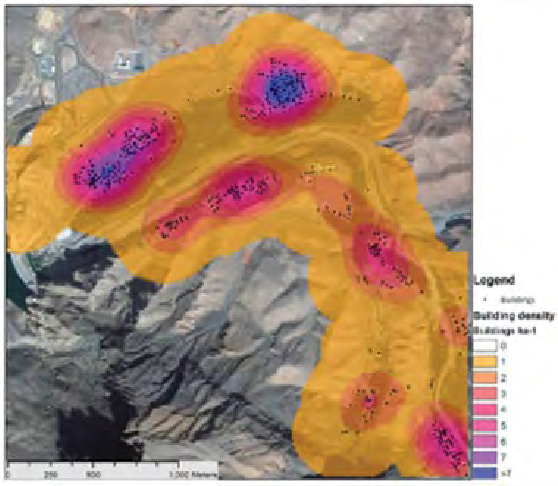

Fig. 8

on gravity flow rather than on pumping. In the case of Al Mizarih, however, it is obvious that the village is divided by a large Wadi bed which also means that the buildings along the Wadi bed are separated into many small catchments. A separation into small clusters that can have a pure gravity based network, therefore, is difficult. Therefore, the demand for pump stations will accordingly increase in this particular case. Fig. 6 shows a density map that was processed using the individual buildings. The building density allows analyses such as building density vs. network length and is a tool to cluster the settlement into treatment units.

Following the data processing, the sewer design is the next step. The sewer network is designed according to the German guideline ATV-A 200 using technical drawing software (e.g. AutoCAD Civil 3D). The elevation data requires some network assumptions that are listed below:

Horizontal alignment of the sewer network:

- Roads used as a potential route for sewer network
- The maximum distance between manholes: 60 m
- Wadi: Special sewer structure to cross Wadi
- Water consumption ca. 150 L/d

Vertical alignment of the sewer network:

- Minimum slope: 0.5%
- Maximum slope: 12%
- Minimum cover: 0.8 m
- Depth ≥5 m: pump station

3.7. Sewer network (AutoCAD)

The sewer network is designed using AUTOCAD civil 3 d (2011) pipe network creation tool. First, the pipe properties for the gravity and pressurized pipes are defined in accordance with the German norm DWA-A 139. Then the manhole properties are defined according to DWA-A 139. Based on the preliminary data for water consumption in Al-Mizarih, the DIN 200 concrete pipe is selected as the minimum diameter pipeline. Following the set up the assumptions for the vertical alignment (e. g. min. and max. slope) is set as a rule for the network creation tool. The tool then enables to create sewer network by converting the horizontal alignment (in this case the roads as the potential route) into the sewer network. The pump stations are placed on the sewer line when the depth of the sewer line reached 5 m. The pump stations are designed according to the German guideline ATV-DVWK-A 134. Depending on the elevation the pressurized pipelines were designed manually.

In a first step, a sewer network is designed that is connected to all households (Fig. 9). Based on this, the centralized scenario is designed that connects the settlement to the next available treatment plant. In the case of Al Mirazih this is the STPs in Qurayyat (Fig. 10), meaning the wastewater will be conveyed by 30 km long combined (gravity and pressurized) sewer line and 6 pump stations to the STP in Qurayyat. In the semi-centralized scenario all households are considered to be connected as well, however, a 2,000 person equivalent (PE) STP within the settlement is planned (Fig. 11). The construction and O&M of the sewer network and pump station are cost-intensive factors. Therefore, in the decentralised scenario, the sewer network and pump stations are minimized by creating clusters depending on the density of the buildings (Fig. 12). The correlation between the density of the town and the specific sewer network length is analyzed as it is shown in Fig. 13. The specific sewer length (m per household or m per capita) increases in low-density areas, whereas the opposite occurs in the higher populated area. Based on this analysis, the sewer network is then minimized, leaving the building in low-density areas out and serving only the building in high-density areas (Fig. 14). Then the pump stations are replaced with STPs (size of 150–500 PE). The remaining buildings are considered to have their own single household solutions (6 PE STPs). The next scenario is the single household solution,

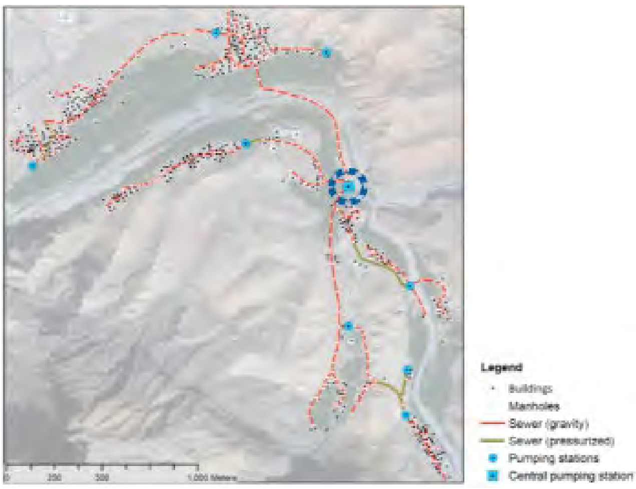

Fig. 9

Fig. 10

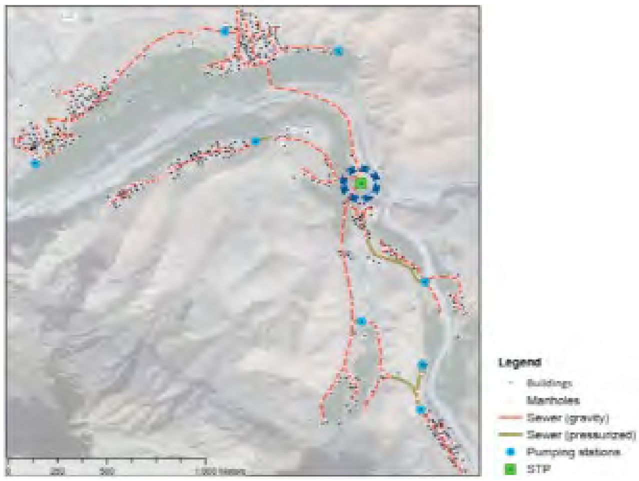

Fig. 11

meaning that all buildings are considered to have their own small STPs (6 PE). The last scenario is the tanker solution, where the entire buildings are considered having storage tanks and serviced by tankers.

3.8. Cost assessment

Following the spatial analysis, the spatial data for each scenario is extracted for the cost assessment. The cost assessment is carried out in accordance with the German guidelines for the application of dynamic cost comparison calculations. The methodology allows to add the different types of costs (investment cost (IC), reinvestment cost (RIC), and O&M cost) in order to find the net present value of the project over the analysis period.

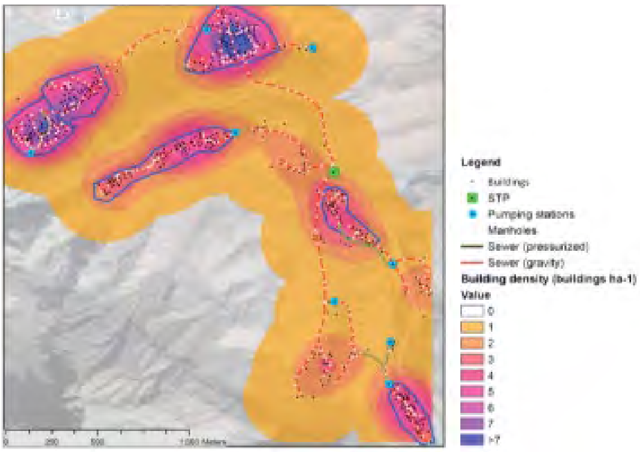

Fig. 12

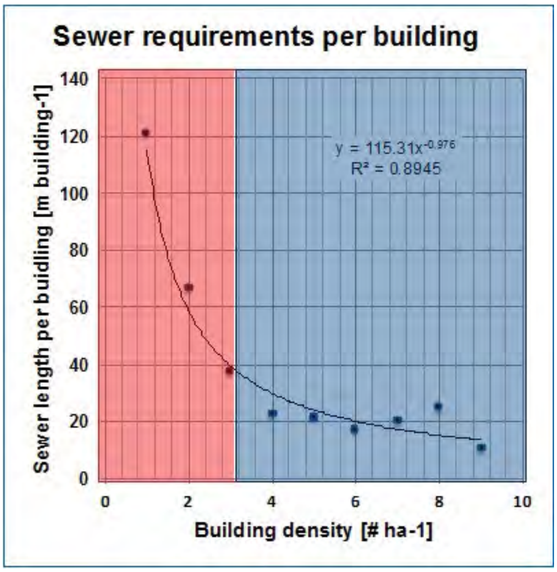

Fig. 13

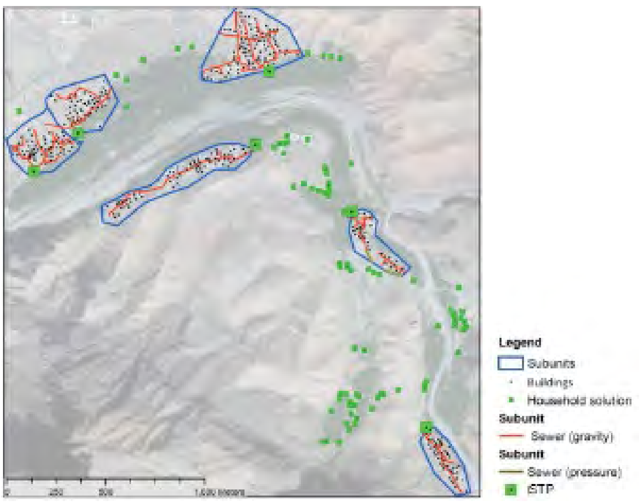

Fig. 14

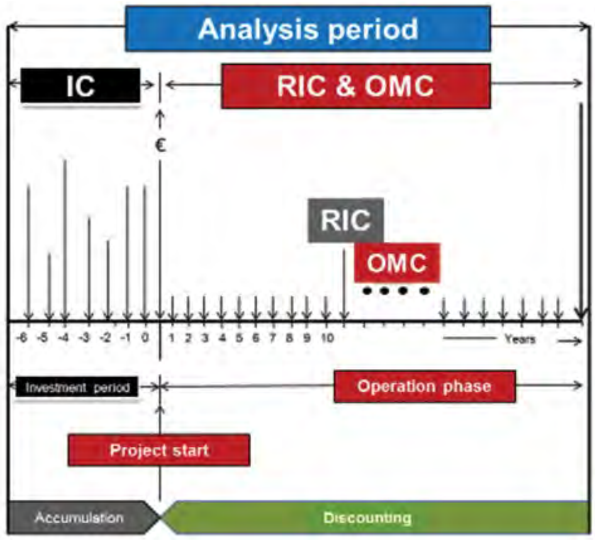

Fig. 15

Then the stations were designed according to the German guideline ATV-DVWK-A 134.

The IC includes the cost of construction, planning, and other costs (such as land price, contingency etc.). This is then calculated at the beginning of the project (present). The RIC is the cost spent for routine renovation and replacement (e.g. a pump is replaced every 5 to 8 years). The OMC is the annual cost for energy consumption, maintenance work, salary etc. The latter cost (RIC and OMC) are calculated for the future and converted in present values. There are two important aspects of the cost assessment, the analysis period and discount factor. Both are used for estimating the present values of the cost, which arises in the future.

The analysis period depends on the lifetime of the individual infrastructures such as STPs and sewer network. For example, the lifetime of sewer network is assumed to be 80 years while package STPs are often planned to last for 40 years and household STPs only 25 years. In the case of Al Mizarih, the period is chosen as 80 years in order to appreciate the lifetime of the sewer network, which is the most influential cost factor. The discount factor is basically the interest rate and is used for determining the present value of the future cost. This depends on the prognoses economic analysis and varies mostly between 3%–7%.

4. Conclusion

Innovative sewage product designers and manufacturers have begun developing technologies to treat and reuse water while keeping it onsite. This type of decentralised treatment and reuse offers a solution that is sustainable, efficient, cost-effective, and highly practical. However, improper treatment before water reuse can create public health issues. This study outlines the plan for setting up and operating the national platform for advanced integration of water reclamation and resource recovery technologies. The main purpose of this platform is to develop, promote and facilitate the implementation of sustainable and effective sewage and

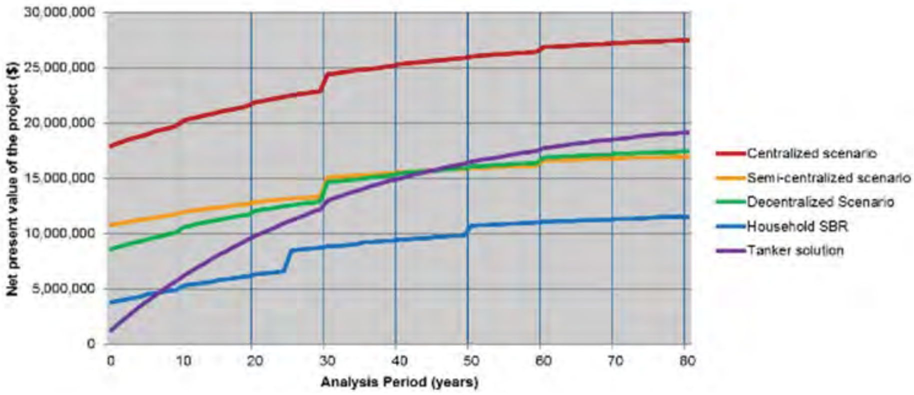

Fig. 16. Net present value of the different scenarios over the 80 years of analysis period. The preliminary assessment shows that the household solution might be an attractive option. However, it has to be mentioned, that future development of the town is not considered at this stage. Under growing population, the semi-centralized and decentralised scenarios might become attractive.

reuse management solutions for suburban and rural communities in Oman. The proposed designs have been postulated to integrate the various yet essential multi-functional activities concerned with the development of adequate and context-specific sewage management options. For example, testing and certification activities are designed for technology selection and adaptation to the Omani conditions and regulations, while training activities shall be designed for long-term sustainable development that will gradually and consistently add value to the local communities by building the capacity of local human capital. In addition, the platform will also provide space for a variety of research programs on different sewage treatment technologies and agricultural reuse in order to contribute towards strategic investment objectives of Haya Water and to play a leading role in further developing in-country value. The GIS-based decision support tool (ALLOWS) enables applying scenario analysis by comparing the total value project lifecycle of different sanitation management options.

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Seasonal variations of the growth of filamentous bacteria in Kuwait's wastewater treatment plants

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ABSTRACT

If not controlled, excessive sludge bulking can lead to a complete failure of the entire wastewater treatment process. Selection of an appropriate control measure requires information about the filaments type, level of dominance and the most probable causes. The main aim of this paper is to present the filamentous bacteria identified in Kuwait's wastewater treatment plants and to compare their seasonal levels of dominance. Wastewater samples were collected weekly from Riqqa and Um-Al-Haiman activated sludge systems in Kuwait for eight months. Vermicon identification technology, a molecular method, was used for the identification and quantification of the following six filamentous bacteria: Type 1851, H. hydrossis, Nocardioform, Type 021N/Thiothrix, N. Limicola and M. parvicella. The obtained results indicated that the rapid growth of the filaments was triggered by the sharp drop in water temperature during winter (January). Further, most of the filaments dominate the systems almost all through the year. Furthermore, Microthrix was found to have the highest rate of fluctuations.

Keywords: Wastewater, Activated sludge systems, Filamentous bacteria, Sludge bulking, Control measures

1. Introduction

Kuwait has no natural freshwater resources other than scarce amounts of brackish groundwater that is over-exploited. Due to the scarcity of natural freshwater resources, Kuwait depended for a long time on the expensive processes of seawater desalination to satisfy almost all of its water demands. To maintain the sustainable development and lifestyle, therefore, Kuwait has recently adopted a vigorous campaign to reuse treated municipal wastewater in mainly agricultural and greenery landscape irrigations (Al-Shammari and Shahalam, 2005).

Kuwait treats the municipal wastewaters at four main activated sludge wastewater treatment plants located in Kabd, Riqqa, Sulaibiya and Umm Al-Haiman areas. All these plants, except the Sulaibiya wastewater and reclamation plant, are encountering severe filamentous sludge bulking and foaming problems particularly during the winter season. Sludge bulking and foaming usually results in poor effluent quality, odor nuisances and sludge management problems (Metcalf and Eddy, 2003; Nielsen et al., 2009; Posavac et al., 2010; Li et al., 2010). If not properly controlled, excessive sludge bulking and foaming can lead to even a complete failure of the entire wastewater treatment process (Soltysik et al, 2011).

Filamentous microorganisms grow naturally in activated sludge systems (Madoni et al., 2000). It provides a backbone for other types of bacteria to grow (Jenkins et al., 1993). However, the imbalance between the floc-forming and filamentous microorganisms often results in sludge bulking and foaming problems. In solving these problems, identification of the type of the dominant filaments and their cause is very important steps.

Sludge bulking and foaming problems are generally complex problems that are often caused by a multitude of interrelated factors. They can be linked to the substances

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in the influent, the plant operating variables and/or the environmental conditions (Chua and Le, 1994). Therefore, the correlation of filamentous bacteria types with specific causative conditions is very useful in developing specific control measures for sludge bulking and foaming episodes frequently encountered in activated sludge systems (Switzenbaum et al., 1992).

Considerable effort has been made worldwide to identify the dominant filamentous bacteria and their probable causes. This effort, however, is almost limited to cold developed countries such as European countries, United States of America, South Africa and Japan (Mino, 1995). In particular, there is very little information about the filamentous bacteria growing in activated sludge systems of the countries that are located in tropical and desert climatic zones. Published literature about the filamentous bacteria responsible for sludge bulking and foaming of the activated sludge plants in the Gulf region is limited to the preliminary studies done by Safar and Abusam (2007) and Faheem and Khan (2009). Safar and Abusam (2007) attempted to identify the filamentous bacteria dominant in Jahra plan in Kuwait, while Faheem and Khan (2009) tried to characterize the filaments abundant in Al-Aweer activated sludge plant in Dubai.

Identification of filamentous bacteria growing in wastewater treatment systems is usually achieved through conventional microscopic identification method which is based on the morphological characteristics of the filaments. This conventional method usually requires laborious preparation of pure culture inoculums from mixed cultures and lengthy microscopic characterization procedures. In addition, these methods have been recently proven to be unreliable (Mielczarek et al., 2012). In contrast, the molecular techniques, which have been developed in the last decades, have revolutionized the procedures of filamentous bacteria identification and tremendously increased the reliability of its results (Fourest et al., 2004; Sanz and Kochling, 2007).

To obtain accurate information about the filamentous bacteria proliferating Kuwait activated sludge systems, Vermicon identification technology (VIT), which is based the molecular biology techniques, was used in this study.

2. Materials and methods

1,000 ml grab samples of sludge-mixed liquor were collected weekly from three locations along the Riqqa and Umm Al-Haiman activated sludge systems during the period from January to September 2014. The sampling locations were: the influent stream, the aeration tank and the secondary effluent stream. In-situ measurements of temperature (Temp.), electrical conductivity and hydrogen ion concentrations (pH) were immediately carried out before transporting the collected samples to the laboratories of Sulaibiya Research Plant (SRP) of Kuwait Institute for Scientific Research (KISR) for further analysis. At SRP, filamentous bacteria were identified and quantified using VIT kits purchased from Vermicon Inc., Munich, Germany. At SRP routine wastewater quality parameters were also determined according to APHA (2012) standard methods. Finally, Excel software was used to carry out statistical analysis of the obtained results. More details of the analytical methods can be found in Abusam et al. (2016).

3. Results and discussion

Figs. 1 and 2 present the abundance profile expressed in VIT scores for the six filamentous bacteria found in Riqqa aeration tank samples. As shown in these figures, the identified filaments started from almost none (scale 0) in the first half of January 2014 and rapidly became abundant (scale 4) or even excessive (scale 5) in only few weeks. It is also clear from these figures that the concentrations of the filaments were fluctuating over time. Further, Fig. 1 shows that the concentrations of Microthrix and Nocardioform had the highest rate of fluctuations over time. Both figures, however, shows that, except for the abrupt drops in the scores of Microthrix and Nocardioform during the warmest months (June-August), there were no apparent seasonal shifts in population of the filaments.

Figs. 3 and 4 show that filaments identified for the samples collected from Umm Al-Haiman aeration tank had the same rapid trend of growth and almost the same flocculation in population dynamics as that for the filaments identified in the Riqqa aeration tank. Further, they also show that Microthrix and Nocardioform were highly affected by the increase in water temperature during the months June to August. Similar seasonal shift in the population of these filaments was also observed by Wanner et al. (1998).

Figs. 1–4 also shows that filamentous bacteria started to grow in the activated sludge systems of both Riqqa and Umm-Al-Hayman at the beginning of the winter season (January). That is to say, they were triggered by the drop

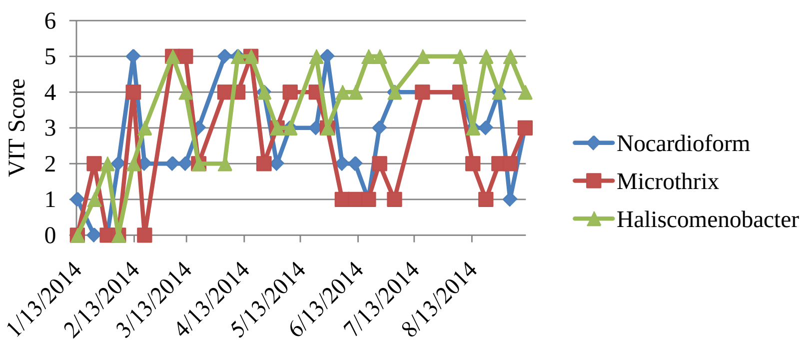

Fig. 1. Profile of Nocardiaform, Microthrix and Haliscomenbacter concentrations in Riqqa aeration tank.

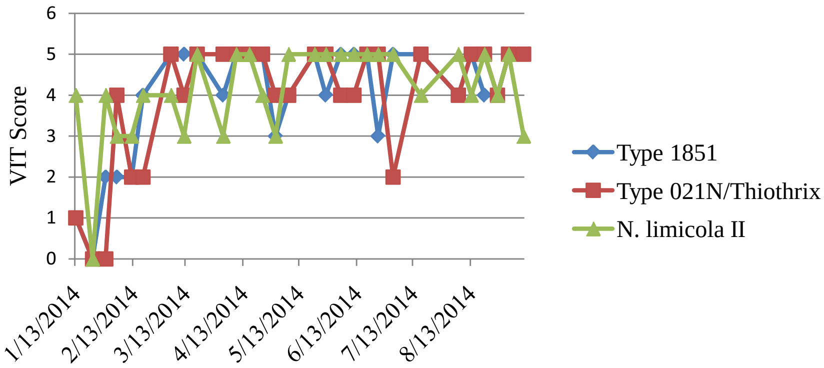

Fig. 2. Profile of Type 1851, Type 021N/Thiothrix and N. limicola concentrations in Riqqa aeration tank.

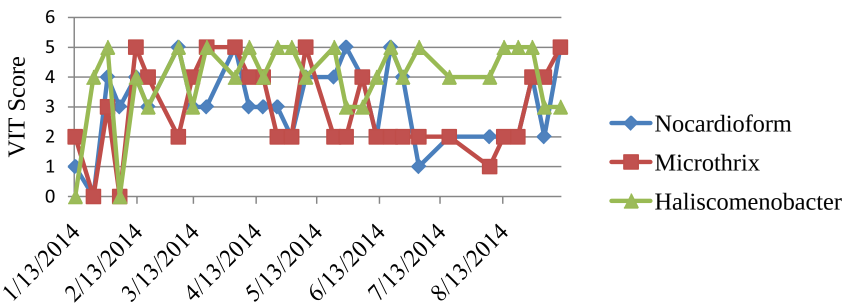

Fig. 3. Profile of Nocardioform, Microthrix and Haliscomenbacter concentrations in Umm Al-Haiman aeration tank.

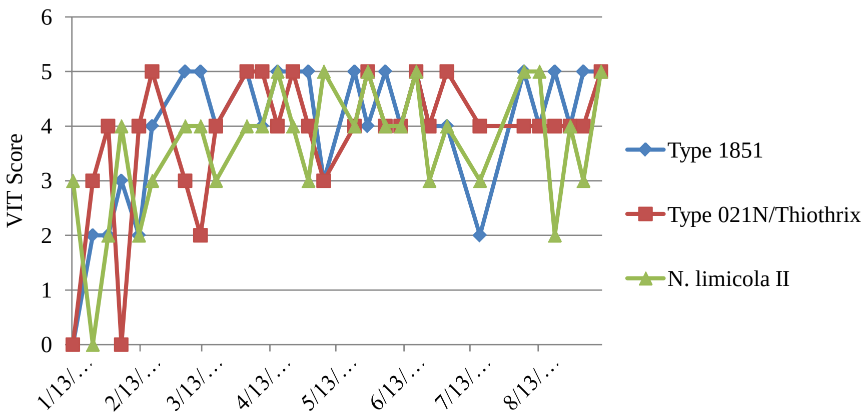

Fig. 4. Profile of Type 1851, Type 021N/Thiothrix and N. limicolla concentrations in Umm Al-Haiman aeration tank.

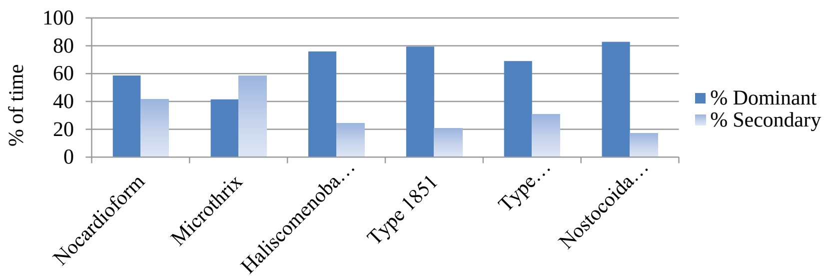

Fig. 5. Percent of time of dominant and secondary filaments in Riqqa Aeration Tank the whole sampling period.

of wastewater temperature drop to about 22°C. In contrast, filamentous bacteria were found to start grow in temperate conditions when wastewater temperature is well below 20°C (Wanner et al., 1998; Madoni et al., 2000; Graveleau et al., 2005; Cao and Lou, 2016).

Filaments are usually considered dominant when they score three or more. However, they are considered to be secondary when their score is less than three. Fig. 5 compares the percent of times when the filaments were dominant (score ≥ 3) to that when they were secondary (score < 3) in the aeration tank of Riqqa activated sludge system. It is clear from this figure that Nostocoida limicola II, Type 1851, Haliscombacter and Nacordioform were dominant for more than 70% of the time. Figs. 6 shows that the aforementioned findings were also true for the aeration tanks of Umm Al-Haiman activated sludge system. However, the only exception here is the dominance of Type 021N/Thiothrix in Umm Al-Haiman system during the entire period of sampling and analysis.

Figs. 7 and 8 compare the seasonal dominance of the filaments (score ≥ 3) as a percentage of time for Riqqa and Umm-Al-Hayman systems, respectively. It is clear that, for

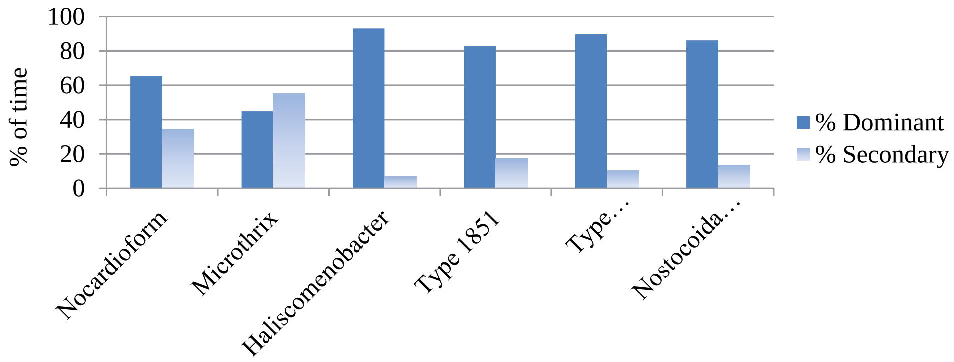

Fig. 6. Percent of time of dominant and secondary filaments in Umm Al-Haiman aeration tank.

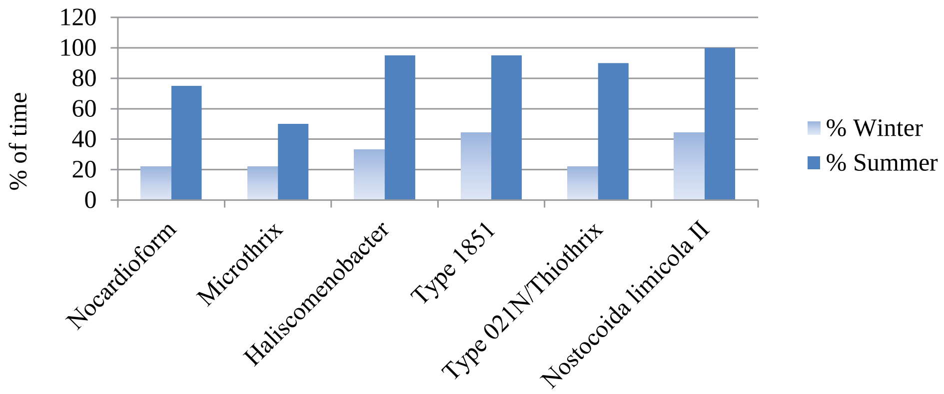

Fig. 7. Percent of time of winter and summer dominance of the filaments in Riqqa aeration tank.

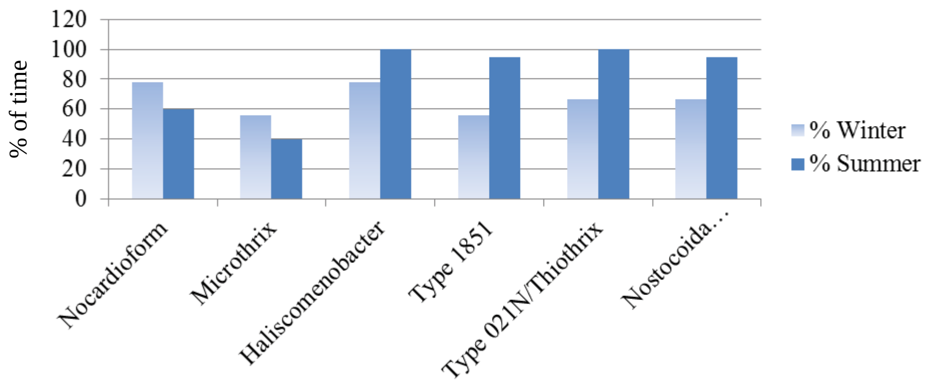

Fig. 8. Percent of time of winter and summer dominance of the filaments in Umm Al-Haiman aeration tank.

both systems, filamentous bacteria were more dominant during the summer season than during the winter season. The rank of the most dominant filaments (>70% of time) during the summer season were as follows: Nostocoida limicola II, Type 1851, Haliscombacter and Nacordioform.

Excessive growth of filamentous bacteria is usually correlated to the influent quality, the plant operating mode and/or the environmental conditions (Chua and Le, 1994). These correlations and the most probable causes are given in Abusam et al. (2017).

4. Conclusions

- The types of filamentous bacteria dominating in Riqqa and Umm Al-Haiman-activated sludge systems were identified using VIT kits (VIT, Munich, Germany).
- An analysis of the identification results obtained indicated that the following four types of filamentous bacteria were dominant (>70% of observation time) in both systems: N. limicola II, Type 1851, Haliscombacter and Nacordioform.
- Dominance of these filaments was found to be higher during the summer season than the winter season

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Removal of odorous compounds from hospital wastewater

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ABSTRACT

A study was carried out to assess the removal efficiency of odorous compounds from the wastewater of hospitals in Kuwait using aeration with activated sludge technique. Samples were collected from the outlet of wastewater from Maternity Hospital. The collected samples were transferred to the laboratory of Sulaibiya Research Plant (SRP) of KISR. Each sample was divided into three parts: the first part of the sample was analyzed to obtain characteristic of hospital wastewater, while the second and third samples were mixed with activated sludge from Kabd wastewater treatment plant and underwent aerobic treatment for 12 and 24 h periods in two bioreactors using a different intensity of aeration. In the first bioreactor, the dissolved oxygen (DO) was kept on the level of 2 mg/L, while in the second 4 mg/L. Wastewater and effluents samples were analyzed for the examination of the following parameters: temperature, pH, electrical conductivity, chemical oxygen demand (COD), ammonium, nitrite, nitrate, organic nitrogen, total nitrogen (TN) and sulfides. Based on obtained results of analyses, the removal efficiency of wastewater parameters were calculated mainly for COD, NH_4–N, sulfides and TN. The laboratory results indicated that after a hydraulic retention time (HRT) of 24 h, the mean values of sulfide removal efficiency increased from 82.54% to 93.85%, when DO increased from 2 to 4 mg/L, respectively. Under the same previous operating conditions, the mean value of ammonium removal efficiency was increased from 85.96% to 97.44%. To obtain the best effluents the biological process should be extended aeration type with HRT 24 h at DO 4 mg/L. The obtained results will be recommended as the base for treating wastewater from hospitals in package units before discharging to sewage network.

Keywords: Dissolved oxygen; aeration, ammonium, sulfides and wastewater

1. Introduction

Sulaibikhat Bay in Kuwait suffers from water pollution due to the discharge of sewage to the bay. There is suspicion that the part of incoming sewage belongs to nearby hospitals, so it was decided to check the wastewater from Maternity Hospital and its treatability in the process of aeration with activated sludge method. The most convenient way to solve the problem is to install package units to treat the sewage from hospitals on site. In Kuwait, Al-Haddad et al., 2014 studied the removal of hydrogen sulfide from groundwater by an aeration technique. The goal of the project presented was to find out how much aerobic activated sludge can reduce the concentration of pollutants responsible for odor as well as other organic pollutants, which can be treated by microbiological processes. In Kuwait, all of the hospital wastewater is treated in municipal sewage treatment plants. Hospital wastewater flows by gravity to the nearest wastewater pumping station and is pumped to wastewater treatment plant afterwards. The oxidation of odorous compound as ammonium and sulfides can be done in biological way. For ammonia, there is a reaction called nitrification. Two types of bacteria are responsible for nitrification: nitrosomonas and nitrobacteria. Nitrosomonas bacteria oxidize ammonia to nitrite product (Metcalf & Eddy, 2003). Nitrite is afterwards converted to nitrate by nitrobacter. Approximate equations for these reactions can be expressed as follows:

$$55NH_4^+ + 76O_2 + 109HCO_3^- \rightarrow C_5H_7O_2N + 54NO_2^- + 57H_2O + 104H_2CO_3 \quad (1)$$

$$400NO_2^- + NH_4^+ + 4H_2CO_3 + HCO_3^- + 195O_2 \rightarrow C_5H_7O_2N + 3H_2O + 400NO_3^- \quad (2)$$

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Hydrogen sulfide as a main case of sulfides can be biologically oxidized to sulfuric acid as follows:

$$H_2S + 2O_2 + \text{bacteria} \rightarrow H_2SO_4 \quad (3)$$

The hospital wastewater in Kuwait is treated only in municipal wastewater treatment plants but the effluents obtained contain residues of pharmaceuticals (Carballa et al., 2004; Kolpin et al., 2002; Kummerer 2001 and Snyder et al., 2003). Efficiency of hospital wastewater treatment were investigated all over the world (Amouei et al., 2012; Alrhmoun et al., 2014; Beirer et al., 2012; Mohammed and Al-Rassul Ali, 2012; Kootenaei and Rad, 2013; Kovalova et al., 2012; Mesdaghinia et al., 2009; Prayitno et al., 2014; Prayitno et al., 2013; Spinova et al., 2013; Su et al., 2015 and Razaee et al., 2005). From their works, there is confirmation that conventional wastewater treatment systems usually do not have the satisfactory efficiency and researchers indicate necessity of pretreatment of such healthcare institutions' effluent before discharging to municipal plants. Su et al. (2015) indicates advantage of rotating biological contractor over conventional methods. Beier et al. (2012) have found many advantages of membrane bioreactor technology for treatment of hospital and healthcare institutions' wastewater. In the frame of this project, activated sludge method will be studied as most economical among existing methods. Wiest et al., 2017 carried out the study of specific hospital wastewater treatment for two years confirming that pharmaceuticals are not completely removed by conventional activated sludge method and they recommended separate treatment of such wastewater preferably on-site of hospitals. Tuc et al., 2016 investigated how antibiotics are treated in wastewater treatment plants and how they behave in sewage network. They found that a major part of antibiotics is not treated and they flow out with effluents. Verlicchi et al., 2012 investigated distribution and concentration of pharmaceuticals in hospital effluents. The authors indicated that municipal wastewater treatment plants have significant amount of antibiotics in their effluents. According to Kummerer, 2001, in wastewater treatment plant effluent the concentration of antibiotics is usually 50 μg/L. In accordance with above the output of antibiotics in product water of Sulaibiya wastewater treatment and reclamation plant is around 7.3 kg/year. It is significant amount of antibiotics in product water, which is applied for irrigation purposes all over the Kuwait. The parameters discussed of hospital wastewater are not acceptable for discharging to the sea in accordance with KEPA requirements, so such wastewater have to be treated in biological method of activated sludge by aerobic technique.

2. Materials and Methods

Before starting experiments two bioreactors of organic glass (plexi-glass) were constructed in KISR's workshop. To deliver oxygen for aeration process, the laboratory scale compressor was applied (model Condor MDR2/11 bars from Peak Scientific Company).

For ensuring bubbling of air in mixed liquor special air stones were applied (fine bubble diffusers). Bioreactors were placed on special stands only to allow emptying them in an easy way. Samples were taken from wastewater outlet (manhole) from Maternity Hospital in Kuwait on a weekly basis. The installation of aerobic bioreactors is presented in plate 1.

2.1. Plate 1. bioreactors for aerobic treatment of wastewater

The sampling was carried out according to the standard operation procedure, which was in accordance with standard methods for water and wastewater examination (APHA, 2012). Sampling was carried out manually using a cylinder made of steel with volume of 6 L which was hold by a rope (10 m long). Samples for laboratory analyses were collected into glass bottles. Beside a manhole, the following field tests were carried out: temperature, conductivity, pH and dissolved oxygen (DO). Moreover multi-gas detector delivered data for impurities of ambient air above wastewater as follow: hydrogen sulfide, methane, carbon dioxide and oxygen. Total volume of samples (20 L) were collected and divided to 2 L samples, which was taken for laboratory analysis to get characterization of tested wastewater and the remaining 18 L of sample was divided into two sets of samples which were placed in two bioreactors and were mixed with the same volume of activated sludge from Kabd wastewater treatment plant. Obtained mixed liquors were aerated with two different levels of DO; the first reactor was tested for DO level as 2 mg/L while in the second one, the DO was 4 mg/L.

Aeration was done in two steps for 12 and 24 h, so the results were obtained for two periods of aeration to determinate which hydraulic retention time (HRT) is better for a discussed process. For fresh samples of wastewater and for samples of effluent after 12 and 24 h of aeration, the following analyses were carried out: temperature, pH, chemical oxygen demand (COD), DO, electrical conductivity (EC), sulfides, NH_4^+–N, organic nitrogen, nitrate, nitrite and total nitrogen (TN). For collected samples and activated sludge as well as mixed liquor total volatile solids were examined. All analyses were carried out in accordance with standard methods for water and wastewater examination (APHA, 2012).

3. Results and discussion

All of the results were collected in spreadsheet. The pH value of the collected raw wastewater from Maternity Hospital ranged between 5.94 and 7.50, with mean value of 6.80. These data indicated a slight acidic wastewater environment. On the same manner, the DO value ranged between 0.42 and 3.35 mg/L, with mean value of 1.17 mg/L. The collected wastewater of manhole revealed a low oxidized environment. EC of raw wastewater was ranged from 551 to 941 μS/cm, with the mean value 710 μS/cm. In general, the raw wastewater was characterized by slightly acidic, reduced environment of freshwater source.

The collected samples also showed high COD values which ranged between 400 and 750 mg/L, with a mean value of 633.28 mg/L. The quality of raw wastewater with respect to COD values was in agreement with of Iranian wastewater tested by Amouei et al, 2012. The minimum, mean and maximum values of NH_4–N were found to be 11.3, 20.64 and

38.90 mg/L, respectively. On the other hand, the maximum value of TN reached 188 mg/L, while its minimum value was 26 mg/L, (mean value of 65.06 mg/L). In general the NH_4–N is the main odor compound contained in raw wastewater. Notice that the mean concentration of TN was found to contain mainly (95%) of organic nitrogen and ammonium nitrogen.

The sulfide gas concentration of raw wastewater was ranged between 0.015 and 0.796 mg/L with mean value of 0.105 mg/L. The relatively high values of sulfide were observed only in a sampling dated 24 January 2017. In general, these values indicated a low decomposition of organic matter producing sulfides and hydrogen sulfide. Moreover, the sulfide gas concentration was significantly lower than ammonium gas concentration in raw wastewater.

The laboratory results of NH_4–N in raw wastewater and effluents for hospital samples exposed to 12 h aeration at DO 2 mg/L were plotted in Figs. 1 and 2. This set of experiment was planned to fix the DO at 2 mg/L, however, it was difficult to control the level of DO at the bioreactor. Therefore, the mean value of DO was found to be 3.06 mg/L. The chosen DO levels of experiment were in agreement with practical industrial values applied in wastewater treatment plants in Kuwait (set points for DO are in the range from 3.0 to 4.0 mg/L).

3.1. Changes of ammonium concentration in raw wastewater and effluent after 12 and 24 h of aeration at DO 2 and 4 mg/L

The NH_4–N concentration in effluent ranged between 0.0 and 32.95 mg/L, with mean value 10.48 mg/L for the first option of parameters (HRT 12 h at 3.21 mg/L as mean value for DO). The NH_4–N removal efficiency ranged between 11.74% and 100%, with a mean value at 66.08 mg/L (Table 1). It should be also highlighted that the first experiment was carried out as a blind, with the absence of activated sludge. Therefore, the obtained results for efficiency represent only effect of aeration process without the standard biological treatment. Regarding the second set of experiment which was carried out at HRT 24 h and DO 2 mg/L, the results were presented in Fig. 1. Moreover, the ammonium of the effluent was found in the range from 0.00 to 14.85 mg/L, with a mean value of 3.29 mg/L. The minimum, maximum and mean value of the removal efficiencies were found as 85.96%, 100% and 76.53% respectively.

In the third set of experiments, DO was fixed for 4 mg/L and HRT 12 h. Ammonium concentration in effluent ranged from 0 to 27 mg/L with a mean value of 6.42 mg/L (Fig. 2). The removal efficiency values were ranged from 9.85% to 100% with a mean value of 76.53%. In general, the ammonium concentration in the effluent (6.48 mg/L) was lower than the value (16 mg/L) set by KEPA (2001) for irrigation purposes.

In experiments with DO 4 mg/L and HRT 24 h, the ammonium removal was the best; it ranged between 77.88% and 100%, with the mean value 97.44% (Fig. 2). Moreover for this case, the concentration of ammonium in effluent was ranged from 0 to 23.1 mg/L, with a mean value of only 2.24 mg/L (Fig. 2 and Table 1). The improvement of NH_4–N in concentration of an effluent was due to the nitrification processes (Eqs. (1) and (2)).

3.2. Concentration of sulfides in raw wastewater and effluents after 12 and 24 h of aeration at DO 2 and 4 mg/L

The concentrations of sulfides in an effluent after activated sludge process were very low, and thus it can be considered that they are efficiently removed. The changes of sulfides concentration were presented in Fig. 3 and Table 2), which show a low concentration of sulfides in both the cases when DO was at 2 and 4 mg/L. The mean, maximum and minimum values for the sulfides concentration in raw

Plate 1. Bioreactors for aerobic treatment of wastewater.

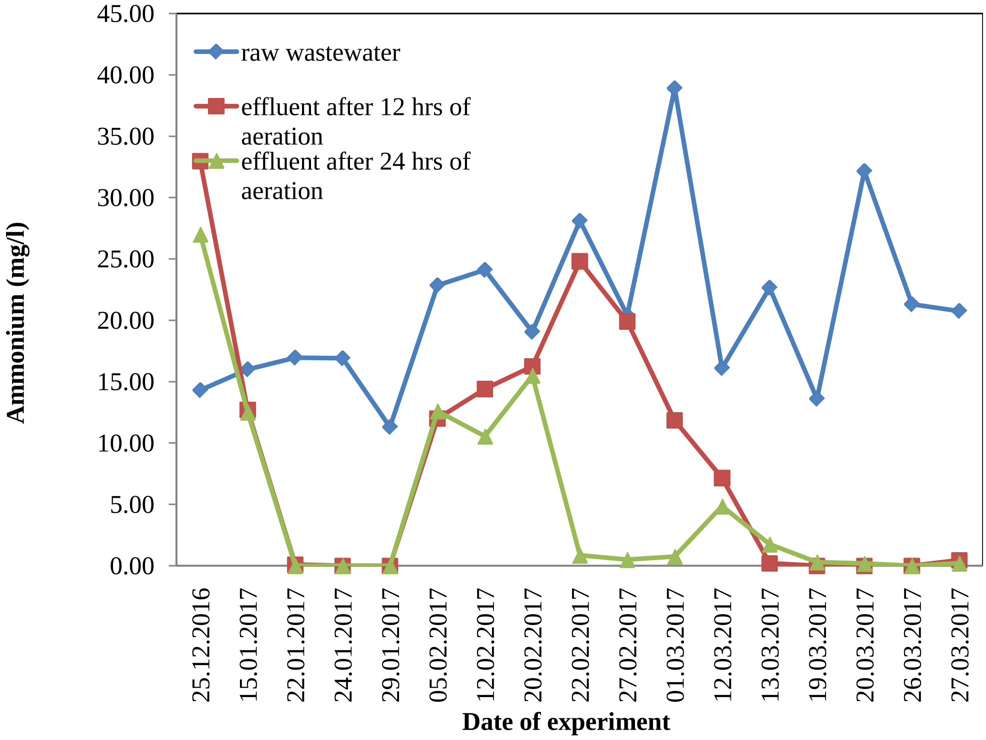

Fig. 1. Ammonium in wastewater and effluents after 12 and 24 h of aeration at DO 2 mg/L.

Table 1
Statistical analysis of NH_4–N concentration in raw wastewater and effluents after 12 and 24 h of aeration at DO 2 and 4 mg/L

	Raw wastewater	12 h @ 2 mg/L DO	12 h @ 4 mg/L DO	24 h @ 2 mg/L DO	24 h @ 4 mg/L DO
Range	9.45–38.9	0–32.95	0–27	0–14.85	0–23.1
Mean	19.98	9.43	6.48	3.29	2.24
STD	7.2	9.8	8.5	4.9	5.8
CV (%)	36	103	131	148	259
% Mean removal efficiency	–	66.08	85.96	76.53	97.44

DO = dissolved oxygen; STD = standard deviation; CV = coefficient of variation.

wastewater was found as 0.105, 0.796 and 0.015 mg/L respectively (Table 2). There were little differences between sulfides concentration in effluents for HRT 12 h, (0.016 mg/L) and HRT 24 h (0.009 mg/L). For the first option of parameters (HRT 12h at DO 2 mg/L), the sulfides concentration ranged between 0.000 and 0.109 mg/L, with a mean value of 0.016 mg/L (Fig. 3, Table 2). The removal efficiency for this option ranged from 32.04% to 100%, with the mean value of 76.76% (Table 2).

For the second option of process parameters (HRT 24 h at DO 2 mg/L), the concentration of sulfides in effluent ranged from 0.000 to 0.058 mg/L, with mean value 0.009 mg/L and removal efficiency was from 40.78% to 100 mg/L, with mean value of 83.64% (Table 2, Fig. 3). In third options of parameters (HRT 12 h at DO 4 mg/L), the sulfides concentrations were ranged from 0.000 to 0.061 mg/L, with a mean value of 0,011 mg/L. The removal efficiency ranged from 43.69% to 100%, with mean value was 82.54%. The improvement in the sulfide concentrations in discussed effluents was due to the oxidation of sulfides to sulfates (Eq. (3)).

For fourth option (HRT 24 h at DO 4 mg/L), sulfides concentration were ranged from 0.000 to 0.057 mg/L, with mean value was 0.006 mg/L. The removal efficiency ranged from 72.73% to 100%, while mean value of 93.85%. It was found that an increment HRT from 12 to 24 h improved removal efficiency by 10% (Table 2).

3.3. Changes of COD for wastewater and effluents after 12 and 24 h of aeration at DO 2 and 4 mg/L

The COD values for raw wastewater ranged from 400 to 750 mg/L with a mean value of 633.28 mg/L. As shown in Figs. 4 and 5, the COD was reduced in significant way.

Table 2
Statistical analysis of sulfides concentration in raw wastewater and effluents after 12 and 24 h of aeration at DO 2 and 4 mg/L

	Raw wastewater	12 h @ 2 mg/L DO	12 h @ 4 mg/L DO	24 h @ 2 mg/L DO	24 h @ 4 mg/L DO
Range (mg/L)	0.015–0.796	0–0.109	0–0.061	0–0.058	0–0.057
Mean (mg/L)	0.105	0.016	0.011	0.009	0.006
STD (-)	0.2	0.03	0.02	0.02	0.01
CV (%)	200	150	200	200	100
Mean removal efficiency (%)	–	76.76	82.54	83.64	93.85

DO = dissolved oxygen; STD = standard deviation; CV = coefficient of variation.

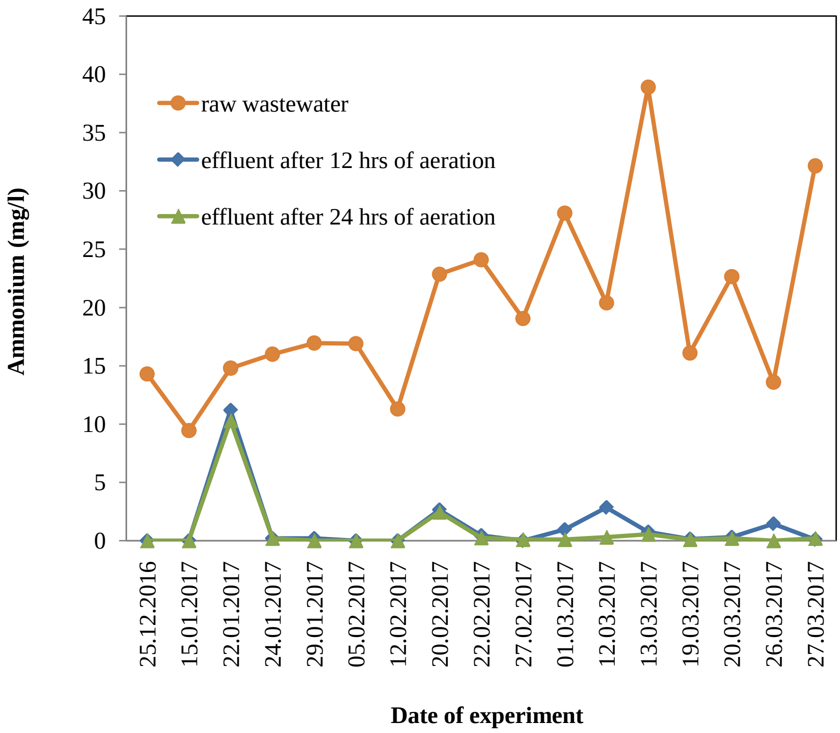

Fig. 2. Ammonium in wastewater and effluents after 12 and 24 h of aeration at DO 4 mg/L.

For an effluent after 12 h aeration at DO 2 mg/L, the mean value was found to be 59.06 mg/L (Fig. 4). The removal efficiency for this option of parameters ranged from 76.41% to 97.47%, while mean value of 93.03%.

For the second option (DO 2 mg/L, HRT 24 h), the COD mean value ranged from 15 to 139 mg/L, with the mean value of 30.7 mg/L. The removal efficiency for this case ranged from 72.89% to 97.87%, with a mean value of 93.97%. At the third set of conditions (DO 4 mg/L at HRT 12 h), the mean value was 51.93 mg/L (Fig. 5). Removal efficiency for the same parameters ranged from 75.53% and 97.73%, with a mean value of 94.67%.

For the fourth option of process conditions (HRT 24 h at DO 4 mg/L), the mean COD value was 29.31 mg/L (Fig. 5), while the minimum and maximum values were between 11 and 174 mg/L respectively. The removal efficiency for the last group of parameters ranged from 69.37% to 98.13%, with a mean value of 95.02%. These results indicated that the effluent can be used safely for irrigation purposes, if only COD values were considered.

3.4. Removal efficiency of pollutants in wastewater after aeration

The obtained results were analyzed to evaluate the effectiveness of pollutant removal. All of the results were statistically evaluated and they were presented in graphs and tables. Moreover, the efficiency was calculated for basic parameters using the following formula:

$$\text{Efficiency} = \frac{C_{\text{raw ww}} - C_{\text{effl.}}}{C_{\text{raw ww}}} \times 100\% \tag{4}$$

Where:

$C_{\text{raw ww}}$ = concentration in raw wastewater in mg/L,
$C_{\text{effl.}}$ = concentration in effluent in mg/L.

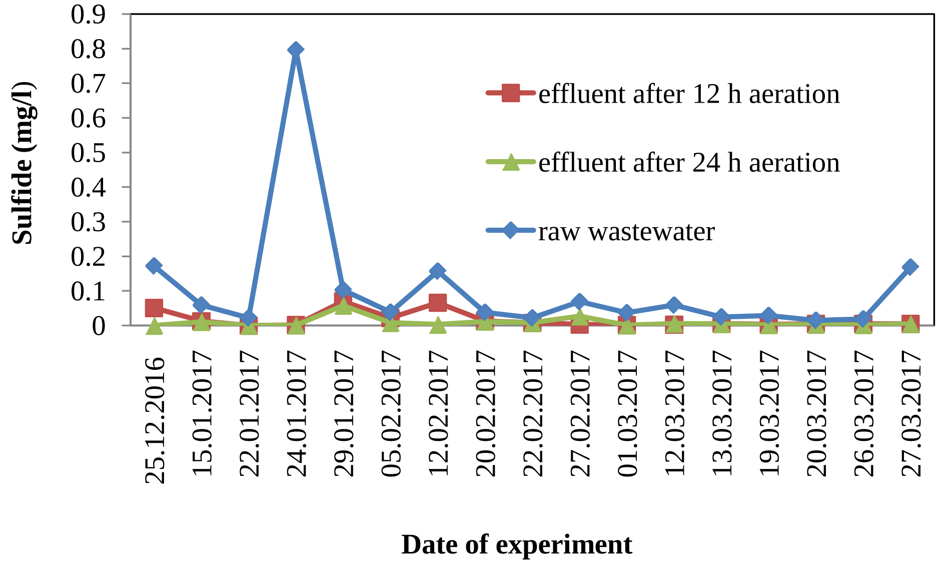

Fig. 3. Sulfides in wastewater and effluents after 12 and 24 h of aeration at DO 2 mg/L.

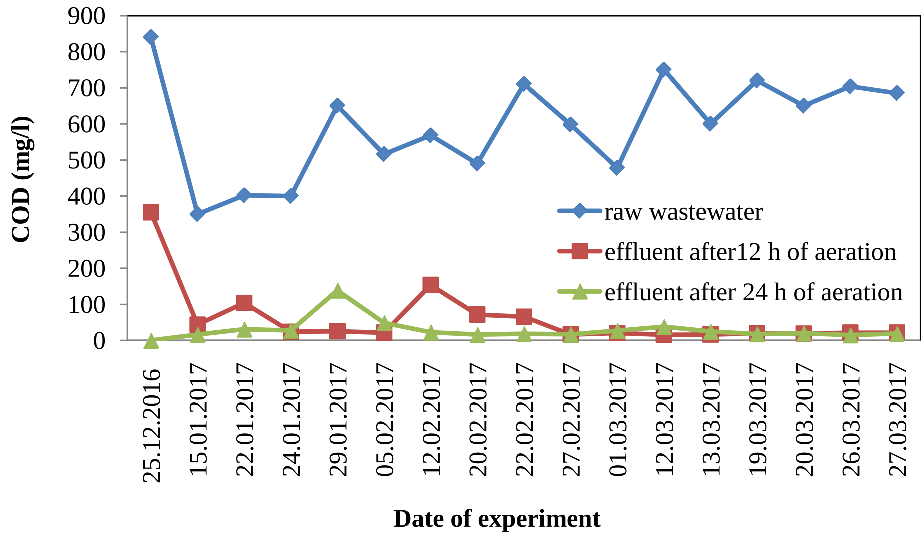

Fig. 4. COD in wastewater and effluents after 12 and 24 h of aeration at DO 2 mg/L.

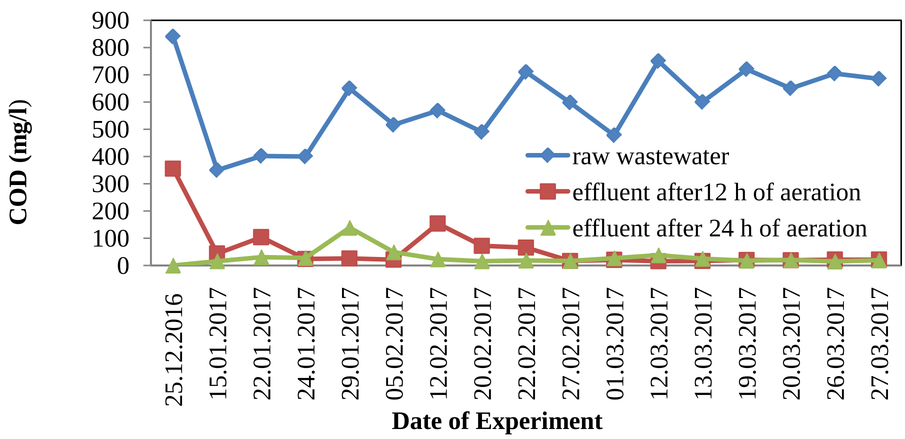

Fig. 5. COD in wastewater and effluents after 12 and 24 h of aeration at DO 4 mg/L.

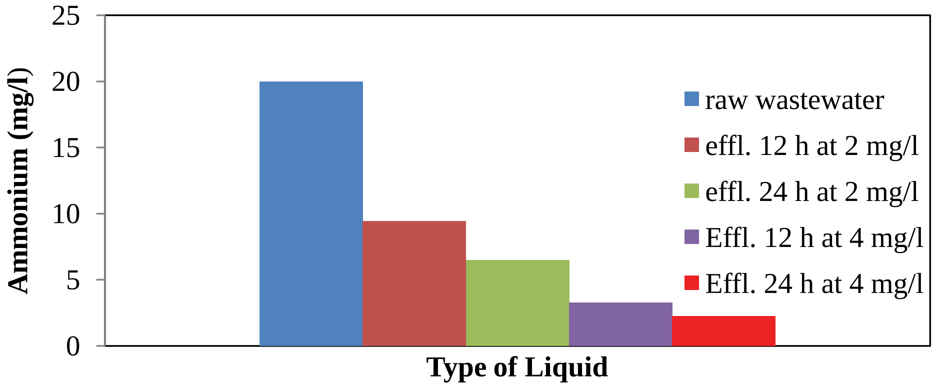

Fig. 6. Mean concentrations of NH_4–N in raw wastewater and effluents after 12 and 24 h of aeration at DO 2 and 4 mg/L.

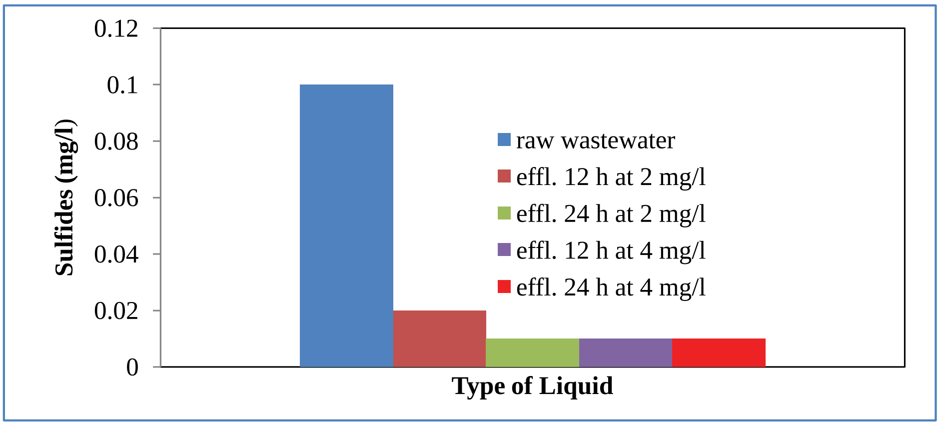

Fig. 7. Mean concentrations of sulfides in wastewater and effluents after 12 and 24 h of aeration at DO 2 and 4 mg/L.

KEPA requirements for maximum COD of irrigation water is 100 mg/L. Therefore, the obtained effluents are of acceptable values (effluent COD 29.31 mg/L and removal efficiency for HRT 24 h at DO 4 mg/L was 95.02% as mean value). It should be highlighted, that the obtained effluents for the discussed experiments had much lower COD values than KEPA (2001) effluent water standards in Kuwait.

3.5. Statistical analysis for ammonium results

As it is presented in Fig. 6 and Table 1, the mean removal of ammonium was fully satisfactory and its mean removal efficiency was found above 97% for the case of aeration for 24 h at DO for 4 mg/L. The standard deviation and variation coefficients are shown in Table 1.

3.6. Statistical analysis for sulfides results

The sulfides results were changed significantly to the value of 0.01 mg/L and removal efficiency was reached 93.85% (HRT 24 h and DO 4 mg/L). The results support the decision for HRT 24 h and DO 4 mg/L due to fact that removal efficiency for the case with HRT 12 h and DO 2 mg/L was only 76.76% (Table 2 and Fig. 7).

The obtained results for ammonium and sulfides removal were better than the results reported in previous studies. In the current study, the ammonium was removed with mean removal efficiency 97.44%, and sulfides with 93.85% (Kootenaei and Rad, 2013 reported that the mean removal efficiency values for ammonium and sulfides were ranged 88% and 79% respectively). These obtained in discussed experiments values lead to the statement that removal of odorous compounds was fully satisfactory. Amouei et al., 2012 reported mean removal efficiency for COD as 76% while the obtained results from the current study was 95.02%. Moreover the quality of effluent with respect to NH_4–N and sulfide, all met KEPA (2001) standards for irrigation purposes.

4. Conclusions

The output results of this study can be summarized as follows:

- Mean removal efficiency for ammonium nitrogen reached 97.44%.
- Sulfides, these mean values exceed 83% for 12 h of aeration and 93% for 24 h aeration if DO was fixed for 4 mg/L.

- Mean removal efficiency for COD was above 97%.
- Obtained results of parameters: NH_4–N, sulfide and COD, all met KEPA standards for irrigation water in Kuwait.

The study recommended the following:

- Construction of an onsite treatment unit near the Maternity hospital with capacity of 1,200 m^3 for operation condition of DO at 4 mg/L and HRT should be 24 h.
- Performance of bioreactor can be evaluated for extra wastewater parameters such as: antibiotics, pharmaceuticals, microbes (bacteria and viruses).
- Periodic monitoring of wastewater parameters before and after treatment should be carried out on a daily, monthly and yearly basis.

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The potential of wastewater reuse in the Arab region as a management option for water security under climate change condition

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Water resources scarcity, accessibility, and environmental degradation are the major challenges facing most of the Arab region. This region has already run out of renewable freshwater decades ago and is unable to meet their food requirements using the available water resources. Water reuse features prominently amongst other innovative integrated water management approaches and reuse of treated domestic wastewater is becoming a common source for additional water in several Arab regions and many of these countries have included wastewater re-use in their water planning. This will narrow the gap between freshwater supply and demand in different water-use sector. The major challenge in using marginal-quality waters in agriculture is to maximize the benefits for the farmers and society while minimizing adverse environmental and health impacts. Therefore, pre-use treatment, and/or appropriate soil-water-crop management strategies are needed for using treated wastewater for irrigation in agriculture through efficient, environmentally acceptable, cost-effective and sustainable strategies, and enabling policies and institutional support. This paper will address the integrated approach for reclamation and reuse of treated wastewater? How wastewater has been managed successfully for safe reuse in some Arab countries? What are the institutional and the organizational involved in the safe reuse of wastewater? How some Arab policymakers adapted the wastewater management agenda to their country's economic context?

Findings demonstrate that water reuse can help in addressing water problems and challenges, particularly when decision-making are from a systems perspective. When ecosystem services are taken into account and are valued properly, water reuse is a sustainable practise that can also be financially profitable.

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Using Bayesian networks (BNs) for mapping stakeholders behaviors in integrated water resource management with a focus on irrigated agriculture in Al Batinah region of Oman

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ABSTRACT

The problems of water resource management and its interaction with society have to be tackled from an integrated perspective taking into account the interdependence of environmental, political, social and economic factors. The conventional approaches being currently used, to study water resources management (WRM), lack to reflect the mutual relationship between water resources and societies. However, varieties for approaches to developing models of complex systems are available. Bayesian networks (BNs), is an approach, which can integrate data and knowledge of different types and from different sources in which, causal links join the variables. A BN is a type of decision support system based on a probability theory that implements Bayes' rule. This work is focusing on the case of Al-Batinah coastal plain in Oman where lots of small-scaled farms practice agriculture. There is no control over the water amounts abstracted from the coastal aquifer. Therefore, the coastal aquifer is at risk due to seawater intrusion. Since groundwater replenishment is limited, the region is facing a problem of water deficit, which also influences the sustainability of agricultural production. Based on a social survey conducted regarding the Al Batinah case, the existing situation generates conflicts between different stakeholders (SHs) which have different interests regarding water availability, sustainable aquifer management, and profitable agricultural production. Therefore, the development of appropriate management strategies for a transition towards a stable and sustainable future hydrosystem states is required. This work aims to evaluate the implementation potential of several management interventions and their combinations by analysing behaviors and opinions of relevant SHs (farmers and decision makers) in the region. This should support decision makers (DMs) in taking more informed decisions. Data were collected through a social survey. Differences were examined statistically between opinions of farmers and decision makers regarding potential interventions.

Additionally, the approach of BN was used for mapping stakeholders' behaviors and to show the strength of a relationship between dependent and predictor variables. The findings suggest that BNs provided an enhanced understanding of the presence and strength of causal relationships. The hypothesis for most of the variables, in the structure of the network, worked logically. Moreover, it is possible to determine the implementation potential of management interventions regarding their acceptance, and additionally, triggers can be identified to increase this potential. Nevertheless, management interventions should also be evaluated regarding economic and environmental criteria.

Keywords: Decision support system (DSS); Stakeholder; Potential interventions; Bayesian Network; Oman

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1. Introduction

In the field of WRM, the decision is surrounded by multiple actors (Simonovic & Fahmy, 1999), with contradicting interests and vision about the potential management options. In addition to that, the number of alternatives might be very high and the selection of a suitable one with the satisfaction of most of the stakeholders needs many efforts. Therefore a sustainable WRM is essential, to ensures the integration of social, economic, and environmental issues into all stages of WRM (Sun et al., 2016). This should be done with the consideration of the associated uncertainties of water resources. In this regard, many decision systems have been built to help users to understand uncertainty issues in water resources. However, for a decision process in areas with high demand to succeed, an integrated water resources management (IWRM) approach is recommended. This should allow the assessing of different management policies and interventions. Moreover, it should include the application of a participatory approach which allows the participation of the relevant stakeholders in a system. The environmental decision makers need to be supported with a good decision support system (DSS) to help them to take more informed decisions.

This work is focusing on a real management problem of the coastal agricultural region in South Al Batinah plain in the northern Oman where lots of small-scaled farms practice agriculture. There is no control on the amounts abstracted from the aquifers. The wells' owners pump as much groundwater as they want, from the main aquifer along the coast, without any restriction (Al-Shaqsi, 2004). Therefore, the coastal aquifers are at risk due to seawater intrusion and the region is facing a problem of water deficit, which also influences the sustainability of the agricultural production.

The work aims to evaluate the implementation potential of several management interventions and their combinations by analyzing behaviors and opinions together with the responses of relevant SHs in the region. Data and results were obtained for several types of stakeholders, for example, water professionals, farmers from the study area and decision makers of different organizations and ministries by using either face to face interviews or distribution of questionnaires. Among others, they have been asked regarding several management interventions such as water quotas, subsidise, crop pattern changes, modern irrigation systems which reveal in partly contradicting opinions between stakeholders.

Data were analysed statistically by using the SPSS (Statistical Package for Social Science) software package. This included using Independent Sample T-test, which allows comparing the means for two different groups to find out whether the difference between group means is statistically significant. Additionally, the approach of BN was used for mapping stakeholders' behaviors and to show the strength of a relationship between dependent and predictor variables. The results of the social survey and BN application allow evaluating management interventions from the social perspective. It is possible to determine the implementation potential of management interventions regarding their acceptance and additionally triggers can be identified to increase this potential.

2. Background – the study area

The Sultanate of Oman is an arid country and relies on groundwater as a source of fresh water, typically in shallow alluvial unconfined aquifers (Stoery, 1995). Agriculture is the leading consumer of groundwater, around 53%, of total cultivated areas in the country, is concentrated in Al Batinah (MAF, 2005) mainly because this region is characterised of soils that are more fertile and easier access to water, in the form of groundwater, compared with other administrative areas in the country. As a result, the groundwater abstraction exceeds the rate of recharge which affects the social and economic situation of farmers as well as the environment. The imbalance between the abstraction rates (ca. 120 Mm^3/y), and recharge rates (ca. 50 Mm^3/y) led to a dramatic decline in groundwater levels accompanied with saltwater intrusion into the coastal aquifer of the region. Agriculture is also facing challenges in Al Batinah. The study done by MRMWR in 2011 (MRMEW, 2011), reported that the land area effected by salinity above 10,000 μS/cm, in Al Batinah, has increased with time since the year 1995 by 14,500 fd. Several agricultural lands of the coastal areas have become unsuitable for cultivation (MAF, 2011) and some farms have become abandoned (Zekri et al., 2010). This is a typical example of a social dilemma (common-pool resources dilemma). The groundwater aquifer is a common source for the farmers to irrigate their farms but farmers are only focusing on their individual profit and immediate satisfaction rather than behave in larger societal best or long-term interests.

The main part of interest for the work, consists of two; Wadi catchments; wadi Bani Kharus and wadi Ma'awil (Fig. 1). The study area comprises two Wilayat (villages) Al Musana'a and 'Barka' where the farms are located near the coast line and the aquifer is affected by the salinity intrusion. Several interventions (e.g., construction of groundwater recharge dams, a ban on construction of new wells without permission) are practiced by the government to maintain the groundwater aquifer. However, the situation is getting worse and may require more effective management interventions which may range between the extremes of stopping all agriculture activities to recover the local aquifer system, and producing as much as possible as long as water and soil are available (Subagadis et al, 2014).

2.1. Common approaches in supporting the decision-making process in IWRM

Varieties of approaches to develop models of complex systems are available. Following are some of the common known integrated approaches in supporting decision making processes in water resource management;

- *Coupled component models*: employed when integrating different components of hydrological, economic, social and environmental processes (Grundmann et al., 2013).
- *Bayesian Networks (BNs)*: employed for management and decision-making applications in which stakeholder participation and uncertainty is a key consideration (Ticehurst et al., 2011).
- *Multiple criteria decision analysis*: This is a type of an integrated modeling approach for prioritizing or scoring

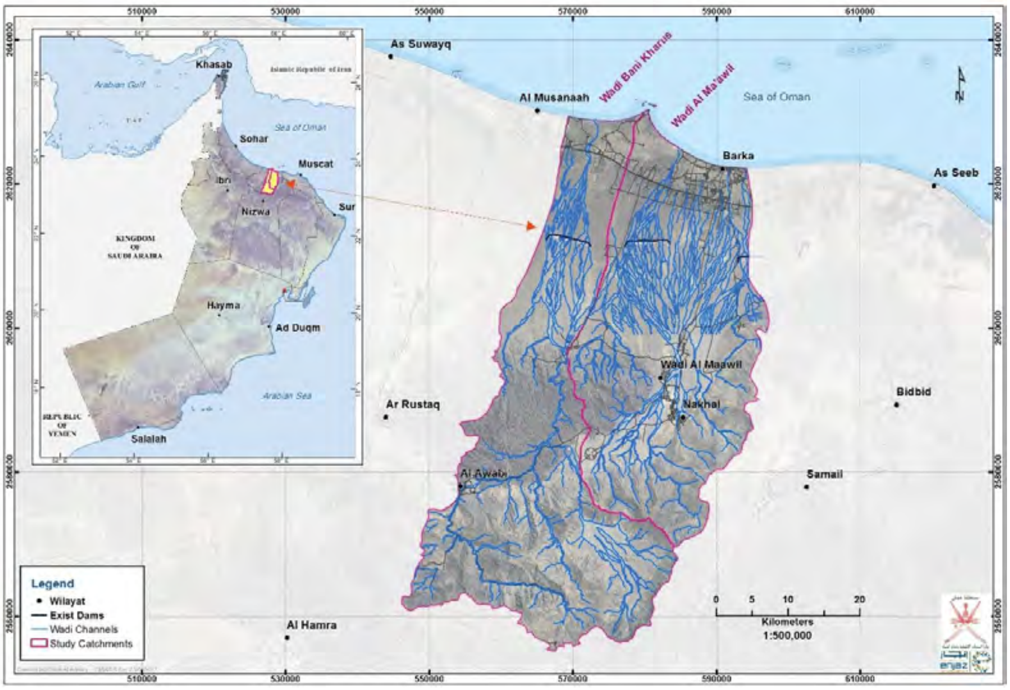

Fig. 1. Location of Wadi Bani Kharus and Wadi Ma'awil – Map provided by MRMWR (2017).

the overall performance of decision options against multiple criteria or objectives (Afshar et al., 2011).

- *System dynamics*: these are dynamic system models which are used to study the dynamics, feedbacks and evolving interaction in a system over time (Akbar et al., 2013).
- *Agent-based models and knowledge-based models*: These are simulation models partly driven by increasing demand from decision makers to provide support for understanding the potential implications of decisions in complex management systems (Rounsevell et al., 2014).

Subagadis (2015) argued that BNs are the most appropriate for modeling complex systems under uncertainty. Castelletti and Soncini-Sessa (2007) developed an integrated model of a water reservoir network by using a BN structure coupling to a hydrological model. BNs were used to describe, in a probabilistic way, the behavior of farmers within an irrigation district in response to some planning actions. Ticehurst et al. (2011) presented findings from a study done to explore the benefits of combining BNs with conventional statistical analysis. BNs were used with conventional statistical analysis to examine landholders' adoption of conservation practices for Wimmera region in Australia.

2.2. Summary

Models are highly used in the field of water resources. However, BN model applications have not been widely used in studies related to agriculture irrigated by groundwater in coastal areas, which are affected by saline water intrusion. Although such types of models are helpful in extending knowledge, they require additional efforts. Moreover, they have not been used, so often, in exploring the influence of social factors on the adoption of management options related to water resources in those particular regions. In Oman, no social research studies have been done associated with behavior analysis of both decision makers (DMs) and farmers in the field of IWRM with a focus on irrigated agriculture. Moreover, modeling approaches, applied as decision support tools, have not been introduced yet in such fields. The work introduced through this paper intends to explain the dilemma of limitation in successes of the already applied solutions concerning the behavior of the stakeholders. It outlines how IWRM can encompass social issues. It elaborates ways for prediction and estimation of the implementation potential of selected interventions by analyzing opinions and responses of the relevant stakeholders. It is an attempt to bring closer the views of the stakeholders to achieve the goal of accepting the proposed interventions gradually.

3. Methodology

3.1. Data, information and knowledge collection

Data, information and knowledge were collected by performing a social survey, and questionnaires were designed to collect data from different groups of SH's.

The information collected for this work is a combination of environmental, social and economic data. Following are the type of information which was decided to be collected for the study purposes:

- Information related to water availability and water quality
- Farm size, irrigation sources and irrigation methods
- Information related to opinions of farmers and DMs

- Information related to knowledge about water and agricultural management
- Information related to training and subsidies
- Information related to suitable interventions and stakeholders participation in water management

3.1.1. List of interventions for agriculture and water management

The primary goal, for the management interventions, is that groundwater levels are to be stabilized in conjunction with maintaining the social and economic interests of the relevant SH's. Based on this idea, a list of interventions was constructed and included in the questionnaires.

The list of the intervention was constructed based on different sources;

- Literature review (some were used in similar studies, not only in Oman, but also in different other regions).
- Some of them were suggestions from expert consultation through the project meetings.
- Some of them are results of an analysis of a pre-test survey

The general specifications of the management options and interventions either focus on water demand-side measures (e.g., an implementation of water quotas and subsidies) to reduce water consumption and use the resources more efficiently, or on water resources side measures (e.g., climate conditions and artificial recharge) to increase the availability of water.

3.2. Data analysis

Data analysis was performed in different ways; statistically by applying descriptive statistics, cross tabulation and independent samples *t*-test. Descriptive statistics such as frequencies, means, medians, standard deviation (SD), correlation and percentages are used to analyse the answers of particular questions. Both, data collection and data analysis are performed in order to explore if the impacts can be quantified. Then all this is followed by the modeling part. This is an advanced step, to explore if models can be used to reproduce the relations in the data, and for allowing future forecast. In other words, to forecast how the different groups of stakeholders will behave with changing conditions.

3.2.1. Modeling

The modeling part includes two different analysis:

- *Discriminant analysis (DA)*, which is performed to identify the drivers influencing farmers' opinions regarding different intervention measures.
- *Bayesian network (BN)*, which are techniques used to represent a probabilistic dependency model. They are graphical models for reasoning under uncertainty in a domain (Ticehurst et al., 2011).

For the purpose of this paper, we will focus more on the analysis procedure and results of the BNs modeling part.

Bayesian networks (BNs) are one of the techniques used to represent a probabilistic dependency model. They are graphical models for reasoning under uncertainty in a domain (Ticehurst et al., 2011). Each BN consists of nodes and arcs, but there is another hidden part which is a set of local conditional probability distributions. The two parts together can represent the joint probability distribution of a domain and explain or show the cause and effect between the variables and outcomes throughout the network. Therefore, the basic idea of BNs is Probabilistic reasoning.

The network was developed by using GeNIe (Graphical Network Interface) software[1], which is a development environment for building decision networks. It was constructed manually, based on experts' opinions on factors that are believed to be affecting farmers' decision regarding implementation of specific interventions. Variables included representing the economic situation, water resource situation, knowledge situation and trust or confidence situation of the community.

The BN was developed by following eight major steps:

Step 1: Define the focus issue

The selected intervention to be the intervention analysed through the network.

Step 2: Develop an influence diagram (manual step of determination of the variables and conditions)

Variables and links were assigned and a proposed BN map was developed.

Step 3: Review influence diagram (validation of the structure of the BN)

During a pre-test survey, performed in earlier steps of the work, an example of the proposed BN was distributed to the water experts and decision makers from water-related organizations in Oman who participated in the pre-test survey.

Step 4: Define states for the framework variables (assignment of conditional probabilities to input/output variables and learning of conditional probability table for the manual variables)

Data were used to develop a spreadsheet (generate data file in GeNIe) containing data and information for each variable in the network. Then the relationships between variables were quantified by conditional probability distributions.

After that, the data in the spreadsheet were merged with the network. The full network (Fig. 2) then consists of the three main elements:

1. The nods which are the variables that represent the factors relevant to the implementation of a particular intervention measure:
    - The input variables (green in color)
    - The intermediate variables (blue in color)

1. (http://genie.sis.pitt.edu/)

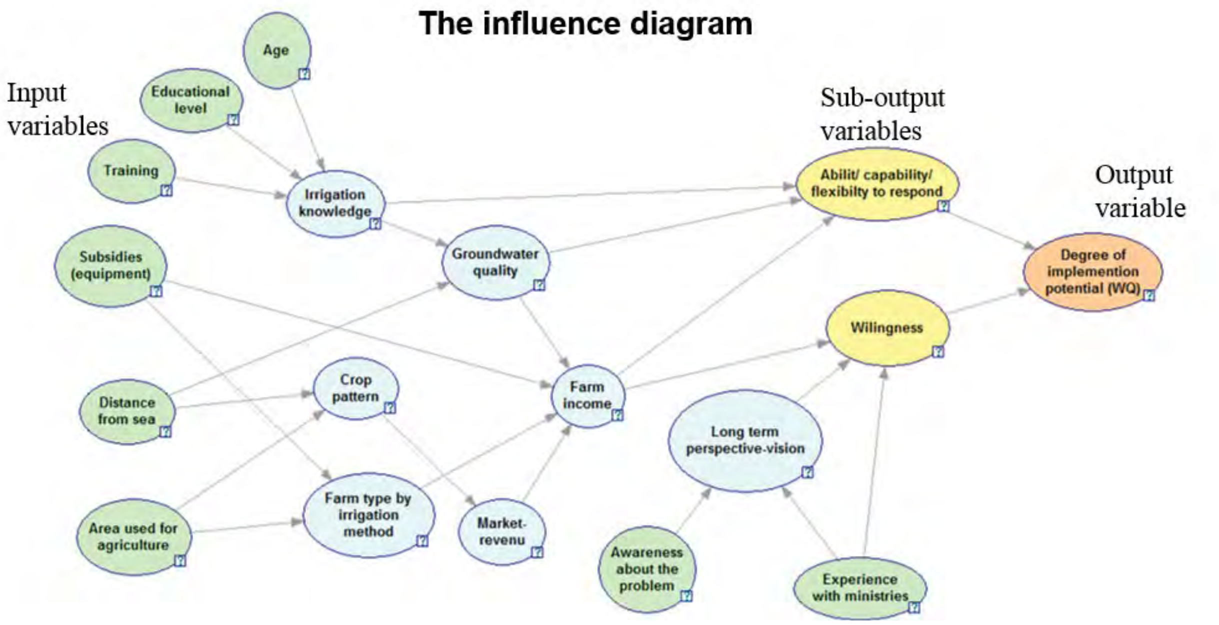

Fig. 2. Suggested influence diagram for the Batinah case.

- The sub-output variables (yellow in color)
- The output variable (orange in color).

2. The arcs (the arrows) which represent the relationships between the variables that quantify the links between them.
3. The CPTs, which are used to calculate the states of the variables. A CPT is attached to each variable. This table is representing the relationship between the node (variable) and its parents based on a prior information or knowledge and experience. The table should include all the possible combinations between the values of the node of interest and values of its parents' nodes.

The first two elements can be seen from the BN diagram, while the third element is hidden behind.

Steps 5 and 6: Validation of the variables and links between variables (Performance of the BN)

Running of the method should allow investigating the linkage and feedbacks between hydrological and socio-economic interactions for the management problem of Al Batinah. The first simulation was run to evaluate if the network represents the current situation and the outputs (re-production) are similar to the ones obtained by statistical analysis. The results obtained from the first simulation are compared with the statistical results obtained from analysing the intervention table. This is how the performance of the network was validated.

Steps 7 and 8: Sensitivity analysis – monitor and observe

Afterward, the model is used for further simulation to investigate the effects of the selected variables on the implementation and acceptance of interventions (Hypothesis: Identify how the network should behave if some adjustments are made to some variable).

A sensitivity analysis was performed to create a set of scenarios. Those scenarios were then used to determine how changes in one variable(s) will impact the target variable. For example; if an update is made on one variable (say crop pattern), other variables in the BN might change probabilities after the update. This enables to check whether the output results of other variables in the BN make sense and are justifiable and realistic after the update of a particular variable. Then the variables, play a role in farmers' opinions can be ranked according to the level of influence on the target variables.

4. Results and discussion

The study population consisted of 131 respondents, combining 64 farmers from the study area, 12 water professionals from different research centers, and 55 water experts from different water and agriculture-related organizations (e.g., groundwater, agricultural water use, WRM and planning, surface and sub-surface hydrology, climate change, environment protection, and others) in Oman. Since the group of water professionals was too small and for analysis purposes, water professionals were combined with the group of water experts to be treated as one group. The survey covered at least 80% of the total number of farmers included in a list of the registered farms, provided earlier by the Ministry of Agriculture and Fisheries.

4.1. Modeling

For the validation of the structure of the BN, water quota was considered to be the intervention to be tested through the network. The reason is that there is a high variation in opinions regarding water quotas implementation within the group of farmers. The variables (Table 1) to be included in the network were decided based on knowledge obtained through the description and evaluation of the

Table 1
Assumptions behind the variables used in the structure of the Baysian Network model (BN)

Variable	Definition – the idea	Impacts on	Assumption	Data available or not (A/N)
Degree of implementation potential of water quotas	Water quota is defined to be, the allocation of the resources in an equitable way. Implementation of water quotas to the groundwater used for irrigation in the study area is essential to control the problem of water shortage and saline intrusion in the coastal aquifer. The idea is to test the degree of implementation potential through evaluating variables affecting behaviors and opinions of different stakeholders.	N/A	N/A	A
Ability/capability/flexibility to respond	Ability and capability of the stakeholders In the matter of money.	1) degree of implementation potential	According to the factors influencing farmer's capability, to accept or reject the idea.	A
Willingness/attitude	This is to test the level of willingness of accepting or rejecting the idea.	1) degree of implementation potential	Increase the level of acceptance	A
Farm income/month	Net income from the farm (O.R/month)	1) ability/capability/flexibility to respond 2) Willingness	If there is an income from the farm, it means more money is available for the adoption of better management activities.	A
Market- revenue	Farm production sold (percentage)	1) farm income/month	Increasing monthly income from the farm production	A
Ground water quality/salinity range	Recorded salinity range for the ground water in the farm	1) ability/capability/flexibility to respond 2) farm income/ month	Good water quality helps the farmer to increase the cultivated area and produce more products.	A
Crop pattern	Type of cultivated crops in the farms (trees, forage & clover, vegetables)	1) marketing	Deciding the percentage of total farm production sold and make a profit.	A
Irrigation knowledge	If farmers have good irrigation skills	1) farm classification 2) ability/capability/flexibility to respond	This should allow farmers to manage their farms in a good way and adopt new irrigation methods. Also, farmers become more likely to respond	A
Farm type	Classified by irrigation method used	1) farm income/month	A modern farm with new irrigation techniques is more likely to have more income compared to a traditional one.	A

The area used for agriculture	Percentage of the area used for agriculture on the farm.	1) crop pattern 2) farm type (by irrigation method)	Effects the type of cultivated crops and type of irrigation methods to be used.	A
Distance from sea	Distance between the farm and the coastline.	1)groundwater quality/ salinity range 2) crop pattern	Near to the sea, more water salinity problems.	A
Subsidies	Government support (equipment). Farmers will be able to have new irrigation equipment in their farms and upgrade their farms from being traditional to modern ones.	1) farm type (by irrigation method) 2) farm income/month	Reduction in water used for agriculture	A
Training	Training and education in different aspects of water & agricultural management	1) irrigation Knowledge	1) By training, farmers can gain more information on farm and water management; then their irrigation skills will improve.	A
Educational level	Respondent's educational level	1) irrigation knowledge	A good education helps to introduce new technologies in irrigation.	A
Age	Age of the Respondents	1) irrigation knowledge	long experience in water management and farming will impact the irrigation knowledge	A
Long-term perspective	The vision and perspectives of the respondent about future alternatives	1) willingness	A respondent with a long-term vision for the situation will be more willing to respond.	A
Experience with ministries	The level of trust between farmers and governmental water and agricultural organizations.	1) long-term perspective 2) willingness	Experience with Ministries: representing the level of trust between farmers and governmental water and agricultural organizations. Availability of good cooperation with water and agriculture organizations, farmers, are more likely to respond. The more the farmers trust these organizations, the more willing to support optimization.	A
Awareness about the problem	Awareness of the respondent about water management, limitation of resources and the environmental problems.	1) long-term perspective	A farmer with a good knowledge of the situation will be able to evaluate what is best for the future.	A

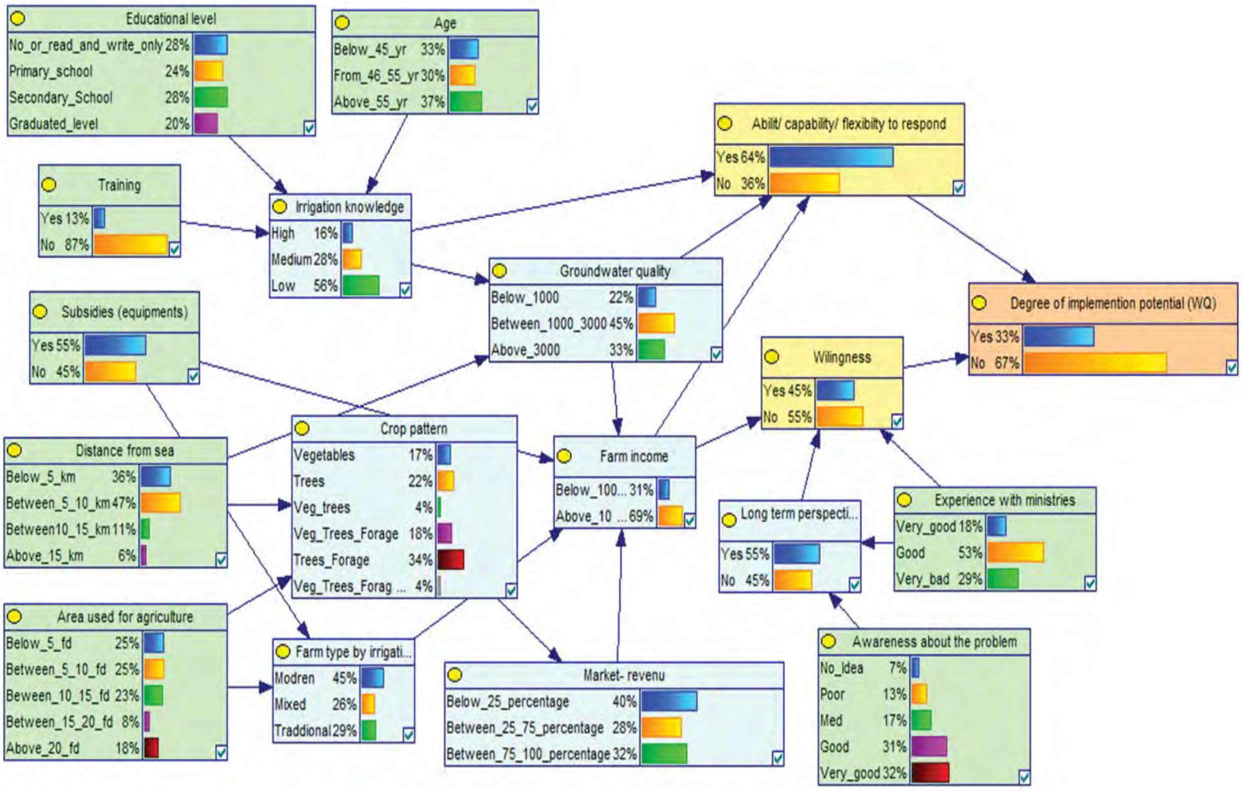

Fig. 3. Structure of the BN (implementation of water quotas).

problem, the statistical results and by using expert opinions. The stakeholders (decision makers and scientists) through meetings and workshops reviewed the structure of the BN.

The data initiated in the network were directly formed from the answers of the responses to the survey questions. Almost all the collected data and information were useful and applicable even the qualitative ones. The missing data were very few in the data set, so the interpolation option was used to fill the gaps in the spreadsheet.

The statistical approaches were used to identify the key variables influencing farmers' willingness and capability to change. These were represented as nodes in the BN and described using states relevant to the survey responses. An initial representation of the causality links between the key factors was developed. Then the BN was automatically learnt from the dataset. The algorithm used was clustering, which is the default algorithm of the software, and according to literature, for example (Jongsawat et al., 2008), it should be sufficient for most applications. The software used in this study (GeNIe) automatically normalises any values entered. Each variable is assigned with its CPT. The BN structure and results of the first round simulation are presented in Fig. 3.

The results obtained through the validation step indicated that the reproduction by using BN was performing well and other simulation can be carried out by making some adjustment to the network.

During the sensitivity analysis, an increase/decrease in the probabilities of some parent nodes (input nodes) was made to explore the result in the effect of relative increase/decrease on the output nodes' probabilities. As an example of the results, we will illustrate in the following figure (Fig. 4) the impacts of "training" and "subsidies"[2]:

The probabilities of "training" and "subsidies" were increased to 100% for the 'Yes' state and decreased to 0% for the 'No' state. The results showed that the node "training" is not influencing the target output node "degree of implementation potential" and regarded as having a less influencing effect on the sub-output node "ability/capability/flexibility to respond".

Moreover, the node "subsidies" is not influencing any of the output nodes. It has a slight impact on the node "farm income" and "farm-type by irrigation method." The increase in the probability of "farm-type by irrigation method" changed from 45% for 'modern' to 48%. Also, the "farm income" which is 'above 1000 Omani reals' increased from 69% to 71%.

Six rounds of simulations were carried out, and the preliminary results from the BN model showed that:

- The hypothesis for most of the variables worked logically.
- The impacts of the input variables on the implementation potential of water quota (the output variable) were limited.
- Some variables (e.g., subsidies from the government) might be related to the adoption of water quota.

2. The adjusted variables are surrounded by blue circles and the influenced variables are surrounded by red circles.

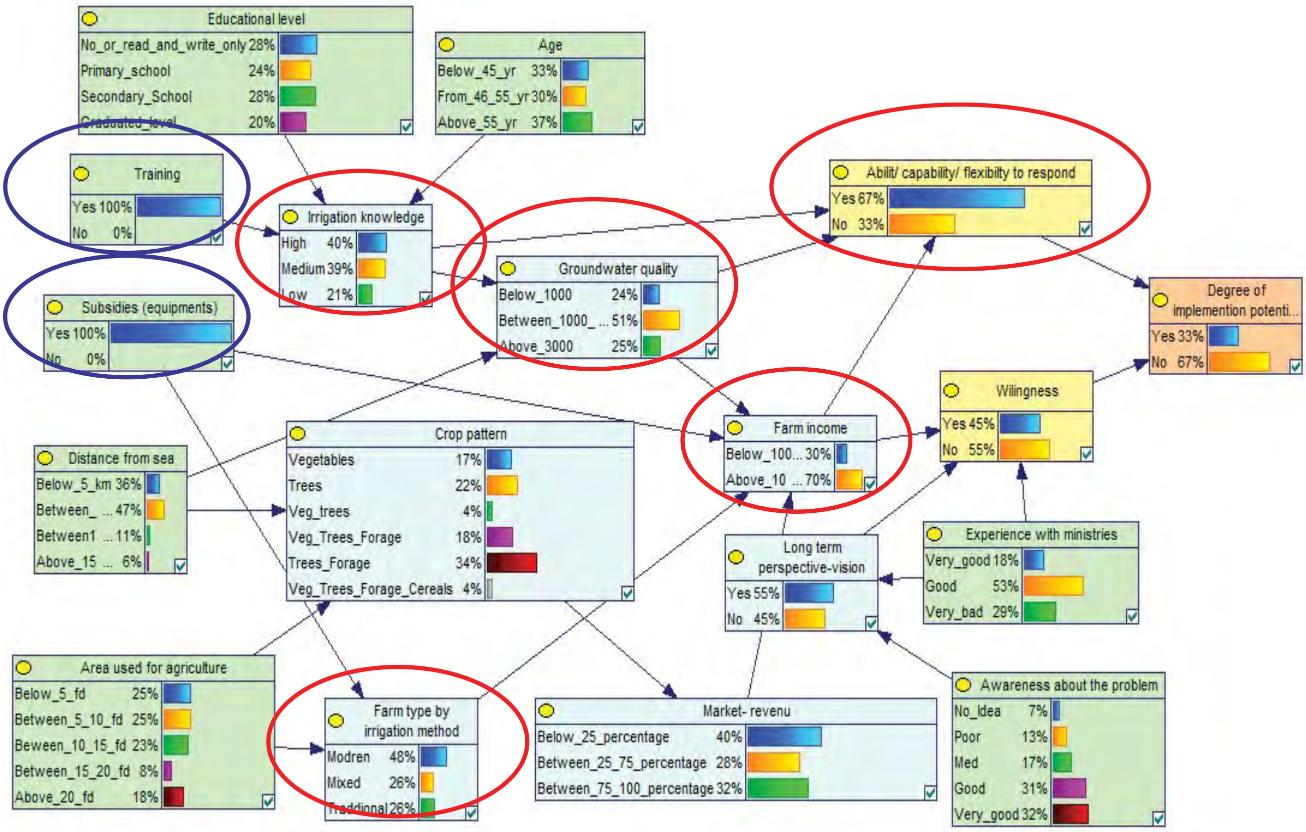

Fig. 4. Impacts of "training" and "subsidies" on the output variables.

- The variables, which are very close to the variable of interest, have more influence than those variables which are far away from the output or the variable of interest.

It was also noticed that, if the BN is too big, there are no much effects on the output. The reasons might be that some variables are misplaced[3] , or the sample size might be too small, and improvement of the database set is needed. This spots the light on the importance of the care which should be taken while developing such a network in order to construct the best model from the data. In this regard, Neil et al. (2000) argued that although tools are available to construct large BN, there are no guidelines on building those networks.

5. Conclusion and outlook

BNs are one type of techniques of using computer technology for dealing with probabilities to integrate data, experience, knowledge, and information along with their uncertainties from different sources. They provide a useful tool for inferring hypotheses from the available information by transmitting probabilistic information from the data to various hypotheses (Suermondt, 1992).

The application of the BN approach, in this study, is a matter of transfer the statistical results to an explanation model. The scenarios should form the basis to increase the acceptance of different interventions. Therefore, the network can be used as a DSS enabling DM's to identify what is possible to be implemented from the social point of view.

In this work, the future forecasting ability was quite limited by the structure of the BN. The evidence were very low (not so clear) and the limitation was high. BNs are complex and sometimes consist of too many connections and relationships, dependency and CPT are not strong enough, or even the sample size is not enough. The level of missing data also has a significant impact on the results of a BN. Therefore, the improvement of the database (extension of the survey) is a potential future task. Moreover, another BN model can be developed with different connections and relationships. But one should be aware that if there are major changes, over time, in the structure of the institutions, then the BN cannot deal with such evolution of the behavior. It is hard to understand the behaviors of people; the techniques used can be limited to the type of data available, characteristics of the selected region, sample size. In this work, the implementation of cost and law and regulations issues was not considered. Therefore, additional research, taking into consideration those issues, is required. Finally, for the case of South Al Batinah, both groups agreed that the water situation is at risk. However, there are difficulties in implementing the intervention, and it is not easy to

3 There might be more than one possible structure of the BN for the problem we are trying to solve.

predict which one is the most suitable with a good chance to be implemented from the social point of view.

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Towards efficient water management in nuclear power plants

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ABSTRACT

Nuclear power plant projects require securing a sustainable source of water for the different stages of the projects, including construction and flushing, cold and hot testing, the condenser cooling operation, including the primary coolant make-up system, as well as the safety inventory and discharge from the radioactive liquid waste treatment system. Hence, efficient water management is crucial during all phases of construction, operation, and maintenance of any nuclear power plant. In some cases, the use of water resources has developed into an environmental issue resulting in stringent regulations which limit the possibility of water withdrawal as well as water discharge. Recent experience has shown that nuclear power plants are susceptible to prolonged drought conditions, forcing shut down of the reactors or reduction of power to a minimal level. Due to water scarcity and concerns associated with climate change affecting available water resources, nations of the world are operating or considering nuclear power plants should assess the different strategies of efficient use of existing water supplies for the needs of nuclear power plants. Also, the consideration of alternative water sources; including desalination, water reclamation, or other water recycling strategies should be considered in securing sustainable water supply for the nuclear power project. Due to the importance of efficient management of water at nuclear power plants during the entire phases of construction, operation, and maintenance; the IAEA Water Management Programme (WAMP) was developed to enable member states to assess various types of cooling systems and the need for cooling water and other essential systems in water-cooled nuclear power plants. The program estimates the water needs for cooling and other essential systems. Moreover, it helps in the selection process of cooling systems by assessing three different criteria: water resources, environment, and economics. WAMP enables users to perform comparisons of different cooling systems, reactor technologies, and at different site conditions. The reported results include water withdrawal and consumption estimation; and estimation of economics (capital and operating costs) for cooling systems. This paper highlights the aspects of and strategies towards efficient water management in nuclear power plants, focusing on two crucial strategies: the use of nuclear desalination and water reclamation for achieving efficient water management in nuclear power plants. Also, the main features of the IAEA tools in support of nuclear desalination and water management are discussed.

Keywords: Nuclear; Desalination; Water management

1. Introduction

To approach sustainable development, while there are ongoing increasing risks of global water scarcity, and concerns over environmental impact along with population growth in arid and semi-arid regions of the world, it is necessary to adopt proper and efficient water management strategies and techniques in conjunction with the implementation of the sustainable and reliable energy plan. Water management is a crucial strategy during the entire phase of the construction, operation, and maintenance of any nuclear power plant. This emphasizes the importance of considering innovative solutions and alternatives for securing sustainable water resources when considering nuclear power projects. Using nuclear energy for producing fresh water from seawater has been drawing broad interest among Member States of IAEA due to acute water issues in many arid and semi-arid areas

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worldwide. Several demonstration programs on nuclear desalination have been taken up to confirm its technical and economic viability under country-specific conditions with the technical coordination and support of the IAEA, which continue to support its Member States with achieving sustainability of water through nuclear desalination and efficient water management.

This paper discusses the water-energy nexus in the light of nuclear power plants and highlights the IAEA current and future activities in support of nuclear desalination and efficient water management, and the related IAEA tools and toolkits which are developed to provide support to Member States with more understanding of the economic viability as well as thermal performance of nuclear desalination technologies and efficient nuclear water management.

2. Water for nuclear power plants

Water demands for nuclear power plants vary depending on different factors: cooling system utilized, the thermal efficiency of the plant, the need for service water, safety and non-safety system designs, as well as the waste disposal techniques. It is important to select a site where suitable cooling water is available, and/or atmospheric conditions are suitable, all allowing higher plant efficiencies at lower water withdrawal rates. Different cooling technologies can reduce the water use and consumption. However, it depends on the tradeoff with cost when choosing nuclear power implementation and benefit analysis.

Current nuclear power plants demand more cooling water compared to those of fossil fuel power stations by about 25% on average. This is due to their lower thermal efficiency, as they operate at lower pressures and temperatures of generated steam. These parameters can be increased, but only to a limited extent, because of the limits imposed by the frequent use of zircaloy as a material for fuel cladding and coupled neutronic and thermal-hydraulic considerations in conventional light water reactors. Also, manufacturing capabilities of the main reactor, heavy components are another limitation. Table 1 shows the water use for different cooling technologies in nuclear power plants and other power plant types for comparison.

In addition to the water withdrawn and consumed during the major phases in the lifetime of nuclear power plants, that is, during construction, commissioning, operation, shutdown, and decommissioning, providing water for potable and industrial use during all the pre-mentioned stages is of great importance importance (Khamis and Kavvadias 2012). Two innovative approaches to efficient water management in NPPs are hybrid nuclear desalination and water reclamation.

3. Nuclear desalination

Among several other promising alternatives and techniques for efficient water management in nuclear power plants is seawater desalination using nuclear energy for industrial and potable water production for securing water needed for the plant (IAEA). The main currently available and mature technologies of seawater desalination are multi-stage flash (MSF), multi-effect distillation (MED), and seawater reverse osmosis (RO). In addition, a hybrid desalination concept, which is the combination of two or more processes to provide better performance at lower cost is eyed as the most optimized for consideration in nuclear power projects involving desalination (Khamis and El-Emam 2016). Hybrid desalination plants combine the advantages of the main desalination processes, both membrane-based (i.e., RO which required electric power for pumping the feedwater to the osmotic pressure) and distillation (i.e., MSF and MED). The quality of water produced from MSF or MED is proper for industrial uses including the water needs for a nuclear power plant operation and through its lifetime. The water product of RO is of potable quality and proper for domestic use. The water produced from the hybrid desalination plant can be blended for improving the quality of water produced from RO.

In a nuclear desalination project employing a hybrid desalination plant, the electricity-driven RO technology can cover the water demands for construction purposes as well as covering the demands of the community serving the construction plant. In operation phase, the waste heat rejected at the condenser of the secondary cycle of the NPP can drive a thermal-based desalination plant to provide water for covering the makeup water demands, while the RO plant covers the potable water demands or other needs. In case of an accident, the RO would serve as an efficient route to ensure sustainable reactor cooling if required, considering the electric power to be provided from the grid electricity or standby generators. In addition, RO can be used during wet decontamination (e.g., full flush of the primary system).

4. Water reclamation

Another proven approach for efficient water management is the recycling of wastewater after being chemically treated against any contained solid impurities or other contaminations. The usage of recycled water depends on the degree of treatment it passes through. In general, recycled water is used for irrigation, fire suppression, or dust control. However, In Singapore and California, reclaimed water can be used indirectly for potable use after being processed

Table 1
Water use for different cooling systems (m^3/MWh)

	Once-through (withdrawal)	Cooling pond (consumption)	Cooling towers (consumption)
Nuclear	95–230	2–4	3–4
Fossil-fuelled	76–190	1–2	2
Natural gas/oil cc	29–76	–	1

through advanced treatment. This approach is very promising to be applied in the NPPs, especially in water-stressed and arid regions and desert locations, mainly for the cooling of the power plant. This technique has been successfully implemented in Palo Verde NPP in California, where 100% reclaimed water is used for cooling.

5. IAEA tools and toolkits on nuclear desalination and water management in NPPs

The IAEA has developed different tools in support of analyzing and understanding the feasibility of different options involving water desalination and water uses and consumption in nuclear power plants. These tools are available on the IAEA website.

5.1. Desalination economic evaluation program (DEEP)

The IAEA DEEP software can be used for performance and cost evaluation of various power and seawater desalination co-generation configurations. DEEP provides detailed cash flow analysis of dual-purpose desalination plant, showing a detailed overview of the project financing; and is capable of conducting sensitivity analysis (Kavvadias et al. 2010). Also, DEEP is suitable for conducting a comparative assessment, among different plants, fuels and desalination technologies including MSD, MSF, RO, and hybrid options. It includes the formulation of different alternatives such as different turbine configurations, backup heat, intermediate loop, water transport cost, and carbon tax (Fig. 1).

5.2. Desalination thermodynamic optimization program (DE-TOP)

DE-TOP developed by the IAEA for performing thermodynamic and optimization analyses of nuclear cogeneration systems. It simulates steam power cycle of different water-cooled reactors or fossil plants, and the coupling with other applications (currently with options for nuclear desalination and district heating applications) (Sánchez-Cervera et al. 2013). With an intuitive graphical user interface and flexible system configuration, The user can select different arrangements between power plant and the coupled plant (single steam extraction, multiple steam extraction, back-pressure operation, etc.; Fig. 2).

5.3. Water management program

Due to the importance of efficient management of water at nuclear power plants during the entire phases of construction, operation, and maintenance; the IAEA Water Management Programme (WAMP) was developed to enable Member States to assess various types of cooling systems and the need for cooling water and other essential systems in water-cooled nuclear power plants. The program estimates the water needs for cooling and other essential systems. Futhermore, it supports the choice of cooling systems by assessing three different criteria: water resources, the environment, and economics. WAMP enables users of performing comparisons of different cooling systems, reactor technologies, and at different site conditions. The reported results include water withdrawal and consumption estimation; and estimation of economics (capital and operating costs) for cooling systems (Fig. 3).

6. Conclusion

The high consumption of water for power generation is a major concern that faces nuclear power plants. Desalination and wastewater reclamation and treatment are currently utilized and of strong potential to increase as sources of freshwater, and these are considered as effective techniques to be implemented in the nuclear power sector. It is imperative to improve the efficient treatment and the use of water. The

Fig. 1. Interface of the IAEA desalination economic evaluation program (DEEP).

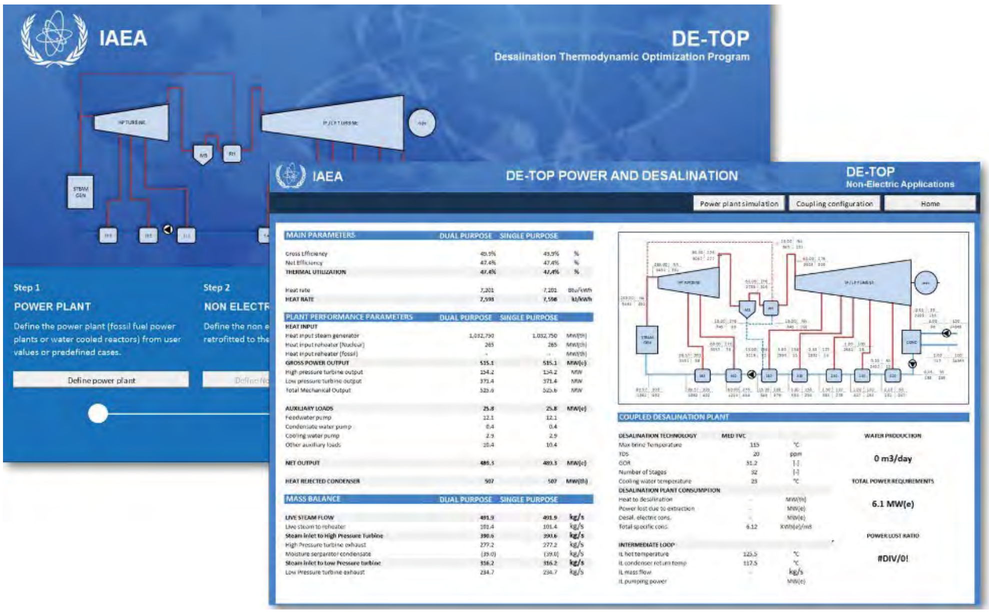

Fig. 2. Interface of the IAEA desalination thermodynamic optimization program (DE-TOP).

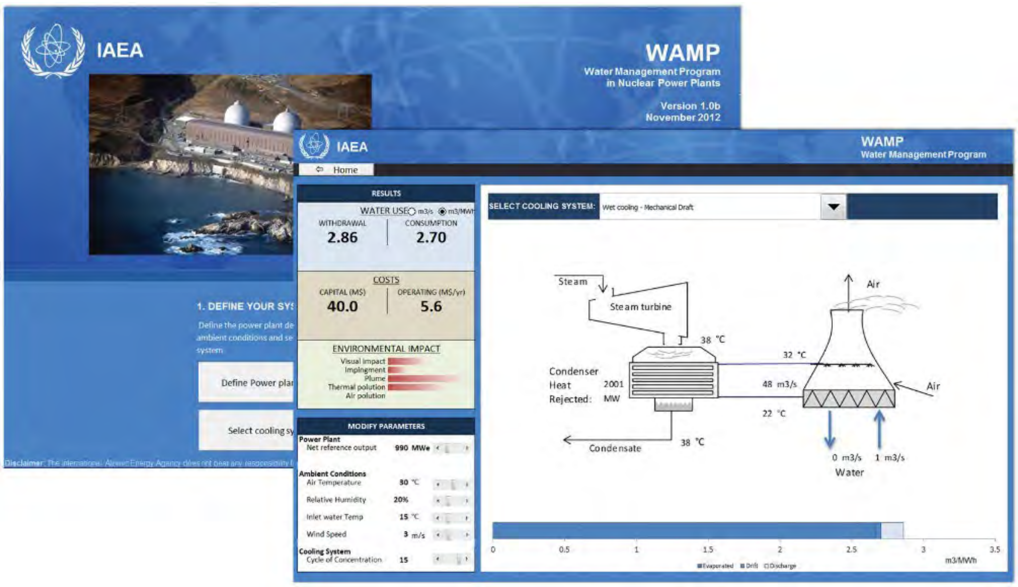

Fig. 3. Interface of the IAEA water management program (WAMP).

IAEA conducts several activities on the nuclear cogeneration of desalination applications as well as for efficient water management in nuclear power plants. The IAEA developed several tools to enable interested Member States to investigate the economics of such projects and determine their thermodynamic performance.

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Role of Oman Water Society in water resources conservation

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ABSTRACT

Oman Water Society (OWS) is a non-profitable non-governmental organization (NGO) found by professionals working in both the government and private sectors who are involved in the water management, water supply, and water projects. OWS was an official launch on April 14, 2010. The society aims to establish a platform for professionals with interest in water to exchanging ideas, researches, discuss challenges, enhancing their knowledge and expose themselves to the latest technology in the field. It is to the interest of the country as well as the Water Sector to have all (stakeholders) or at least most of the professionals working in the water and wastewater field in this society. Being an NGO, Oman Water Society (OWS) is becoming the focal point for all water-related issues to be discussed. Local, regional as well as International organizations are participating in events organized by the Society. Oman Water Society organized a series of seminars conducted by experts in the water sector. It has also organized several workshops in water-related issues and training programs to the young engineers in the on-going projects by coordination with the consultants and contractors working the water projects. The society is encouraging all interested parties to participate in the above-mentioned events. In addition to that, the public sector very well addresses to take part in such activities although for non-members. Country related topics are given priority in delivering the water seminars and events. For instance cyclones, climate changes, groundwater, desalinization, agricultural development and other new water resources te innovations. OWS believes such related topics will not only encourage professionals to participate but also the other stakeholders (i.e., public, farmers, etc.). Moreover, young professionals are considered to be an available source to increase the number of associates within the society. Therefore, OWS is focusing on such new/young professionals by introducing society to them. The society is offering them associates membership until they obtain the full membership after their graduation. Oman Water Society is working hard to achieve its goals by approaching specialists in the concerned public and private sectors. As well, it is looking forward to connecting with all segments of society in order to create a link between all partners concerned with the water sector, whether they are from the water consumers or decision makers. The OWS is doing this in order to intensify efforts in all aspects of water resources and its preservation. The venues of most of the symposiums and seminars organized by OWS are selected at the governorate where particular water-related problem or challenges in order to have all concerned stakeholders including the general public. As a result of these efforts, it has been possible to tackle many water-related challenges and come up with good recommendations. Furthermore, good networking is taking place during the OWS events, which are playing a role in setting goals for water management and conservation in the country.

Keywords: Oman Water Society (OWS); Water conservation; Public participation

1. Introduction

The Oman Water Society was established on 29th Rabi' al Thani 1431 (14th April 2010), thus becoming the first Omani society in the Sultanate to specialize in water and the second in the Arabian Gulf. It has a range of goals designed to promote water-related concepts. Its vision for the future includes studies and research that will help develop local potential, provide expertise for Omani nationals and improve proficiency and performance levels in areas that are of interest to the society (OWS Website, 2018). The society setup the following goals:

- The OWS is contributing to the country's development in collaboration with the competent authorities.

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- Encouraging scientific research, studies and training programs and developing the local potential in the various water sciences-related fields.
- The society is collaborating with universities and scientific research centers.
- It is also fostering co-operation between bodies, institutions, and individuals involved in the water sector.
- Encouraging and providing studies, data and statistics on water-related matters and publishing them in the media.
- Helping to promote awareness about rationalizing water consumption and making the best possible use of available water resources.
- Working with the competent authorities to draw up and develop the best possible specifications and standards for the water sector.
- Collaborating with the competent authorities to conserve ground and surface water stocks from depletion and pollution.
- Encouraging the use of scientific methods for developing water sources such as desalination, wastewater treatment, and recycling.
- Providing technical, scientific, economic and legal consultation services on water-related matters to such bodies as request it.

2. Benefits of membership

The members who will join the society will enjoy the following benefits:

- Members can be represented on committees set up by the Council for various purposes such as organizing lectures, events, and scientific and recreational field visits.
- Active members are appointed to represent the Society at conferences, symposiums, and exhibitions at home and abroad.
- Support is provided for member participation in conferences, seminars, workshops, and other activities. Members have access to study grants and training courses.
- Members can improve their cultural and scientific/academic standards by attending lectures and seminars organized by the society.
- Members can benefit from facilities and [price] reductions obtained by the society in international forums.
- Members and participants can exchange ideas and information.
- There are opportunities for contacts and interaction between experts and participants.
- Through ongoing co-operation and coordination, there are opportunities for members to deal with problems

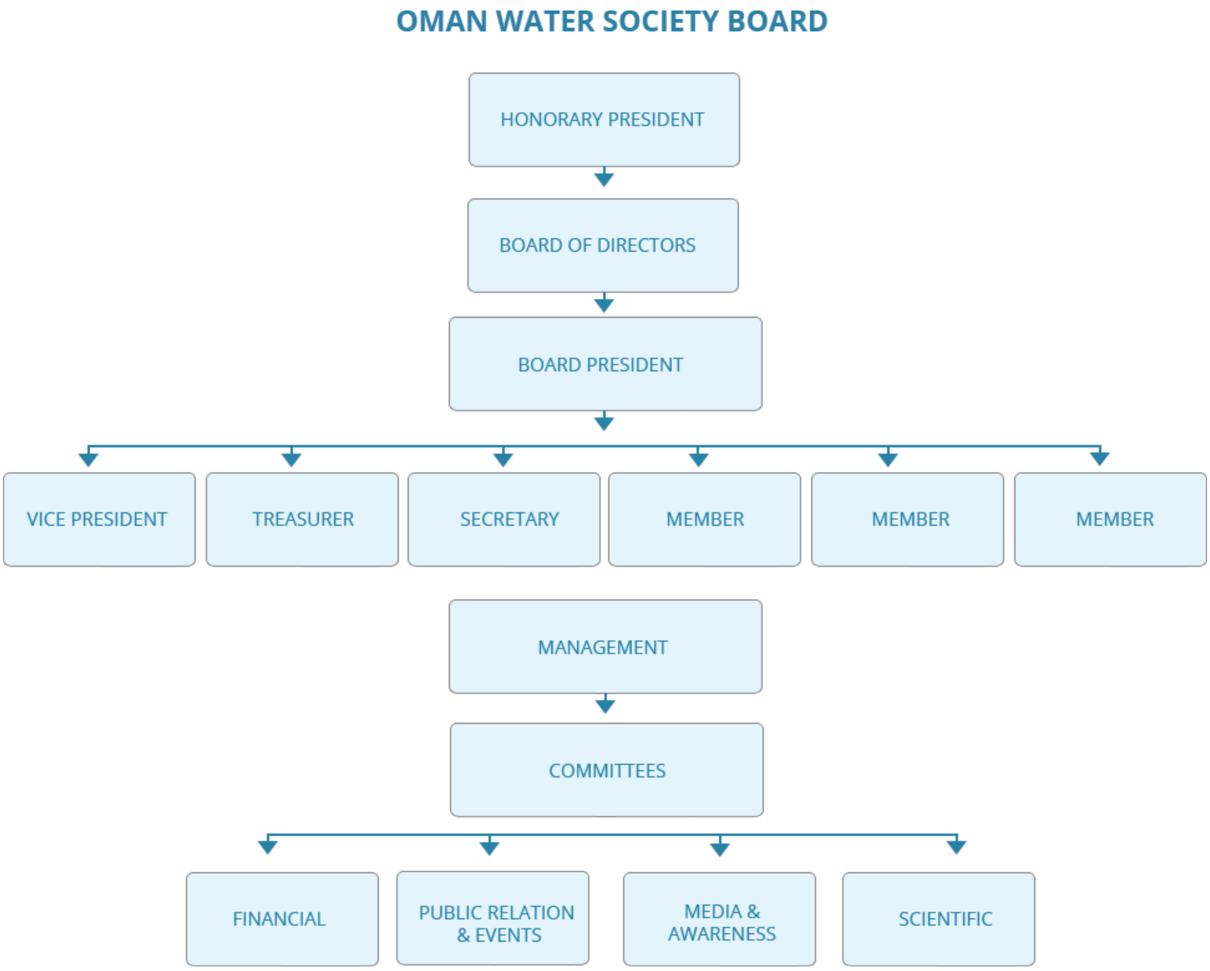

Fig. 1. Organization chart of the Oman Water Society.

Fig. 2. OWS film water in the leader's vision.

Fig. 3. OWS symposium brochures.

and benefit from the expertise available among the membership.
- Members have access to the latest water technology.
- The society organizes study groups and seminars for the benefit of its members.
- The society enjoys contacts and interaction with other relevant societies and bodies.
- The society provides a platform for consultation on water science-related issues.

3. Organizational chart

The Board of Directors constitutes the executive authority of the society. It must implement the society's bylaws together with the resolutions and directives approved by its ordinary and extraordinary general meetings and to make recommendations and take decisions by the society's objectives provided that these are also within the Board of Directors' competences.

According to Article (24) of a bylaw of the society: The Board of Directors shall be composed of seven members of the society who have active members who shall be elected by the general meeting for a term of two years, subject to renewal. The following organizational chart represents the society set up.

4. Society activities

Since its official launch, the society has worked very hard and accomplished many activities to achieve its objectives. Summary of how the OWS operates are listed below:

- Through the implementation of symposiums and workshops in the Sultanate's multiple governorates, by the end of 2018, 14 symposia were completed.
- Launching of specialized awareness campaigns (schools, farmers and universities).
- Participation in festivals, scientific and commercial exhibitions.
- Participation in local and international conferences.
- Participation in government committees and specialized working groups (e.g., agriculture and mining strategy and Oman Vision 2040).
- Production of documentaries and cultural films (e.g., water in the leader's vision and film on man and water).

5. OWS symposiums

The Oman Water Society organized 14 symposiums distribute to all governorates of the Sultanate. These symposiums were attended by more than 2,000 participants from all water stakeholders where very important water issues were addressed. The symposiums are listed below:

- First Cyclone Symposium on Tropical Cyclones (Preparedness and Risk Reduction held in Muscat on 21st June 2011.
- Second Cyclone Symposium on Tropical Cyclones (Tropical Cyclones and its effects on Community) held in Sur on 6th June 2012.
- Symposium of Fog Collection held in Salalah on 24th September 2012.
- Water Resources in Musandam (Challenges and Solutions) held in Khasab, Musandam Governorate on 2nd to 3rd March 2013.
- Third Cyclone Symposium on Tropical Cyclones (Hand-in-hand to reduce the risk of tropical cyclones, what is my role? Held in Muscat on 5th June 2013.
- Water for Sustainable Tourism Industry held in Nizwa on 23rd to 24th September 2013.
- Produced Water in Sustainable Development Plans of Al Wusta Governorate held at Duqm, on 9th to 10th December 2013.
- Industrial Waste Water Treatment (Challenges and Re-use) held at Sohar on 1st to 2nd December 2014.
- Aflaj, Cultural Heritage and Development Necessity held at Ibra on 8th–9th June 2015.
- Best Practices and its impacts on Water Resources Sustainability held at Ibri on 25th to 26th January 2016.
- Offshore springs in Sultanate of Oman held at Quryat on 7th to 8th November 2016.
- Sustainable Water Management in Fragile Mountain Ecosystems held in Jabel Al Akhdhar on 12th to 13th April, 2017.
- Small Desalination Units for Agricultural Sustainability (Challenges and Opportunities) held at Barka on 5th to March, 2018.
- The fourth Workshop on Tropical Cyclones and Flash Floods (Evaluation of the Sultanate's Experience and Lessons Learned after Guno and Phet Cyclones).

Fig. 4. Awareness campaigns for students.

Fig. 5. Lectures delivered to farmers by one of the OWS members.

Fig. 6. Partnership with Sultan Qaboos University in Research Projects.

6. Awareness programs

The society continuously is arranging and organizing lectures by professionals on all related water issues. The lectures are delivered in schools, universities, Oman Women Associations and all other public gathering (Al Sulaiman, 2018). The members of the society would deliver these lectures and in some occasions experts and officials from government and non-government organizations are invited to deliver the lectures on behalf of the OWS.

Agriculture in Oman is the major consumption of the water resources, therefore it is very important to involve the farmers in conservation of the water resources of the country. The OWS arranges lectures especially to the farmers.

7. Research and innovation support

The Oman Water Society has recognised the importance of research and scientific innovations related to water and hence supported as much as it could the especially the young scientists and help them to accomplish their ambitions.

8. Participation in conferences

The participation in international events is very important for the exchange of experiences and the transfer of technology. Therefore, the society seeks to support the participation of its members and to submit papers in the conference and also participation in exhibitions.

Fig. 7. Meeting with researchers at the OWS premises.

Fig. 8. Innovation initiative and supporting the innovators.

Fig. 9. OWS members participation in the international events.

9. Water champions initiative

OWS offered an initiative to raise awareness among students about the importance of water and its conservation by making groups of students in schools and teaching them how to become champions water (OWS, 2015). The Champion of Water is any girl or boy of all ages who dedicate their efforts to protect water sources that we have. They should know all that is relevant to water preservation and share that knowledge with others. Despite their gender or age, they are all participants in the one thing that they are committed to water sources preservations. The initiative also targets the administrative and teaching staff and supervisors who will oversee the implementation of the field plan for the initiative as well as observers of the initiative the following year and students' parents. Necessary approvals have been taken and now securing the budget needed to start the project, where the search for financial support for the project.

10. Conclusions and recommendations

Conservation of the country water resources and involve all the stakeholders have always been a concern for the society and its members. Within a short time since its establishment in 2010, Oman water society has achieved most of its goals and developed its business plan in a very systematic approach. The plan addressed the short-, medium- and long-term requirements as seen fit by the society board. OWS at its short-term plan has already delivered the following:

- Organized a series of seminars and workshops that were conducted by experts and invited speakers from within Oman and also abroad in the Water Sector.
- Conducted training programs to the young engineers in the on-going projects by coordination with the consultants and contractors working the Water projects.
- The society encouraged all interested parties to participate in the above-mentioned events. Public sector such as farmers and school students are very well addressed and have been encouraged to take part in such activities although for non-members.
- Country-related topics have taken priority in delivering water seminars and events. For instance cyclones, climate changes, groundwater, desalinization, agricultural development, etc. OWS believes such related topics will not only encourage professionals to participate but also the other stakeholders (i.e., public, farmers, etc.).
- Young professionals have always been an available source to increase the number of associates within the society. Therefore, OWS has been targeting such new/young professionals by introducing society to them. The society offered them associates membership until they obtain the full membership after their graduation.

It is recommended that the OWS continues its efforts on its short- and long-term as mentioned above. It should also encourage the public especially those who have water expertise, as well as water users to join the society. The members of society enjoy many benefits and therefore these should be further extended to encourage the member to be very active in the society ativities in the future. Public participation and capacity building has proved to be a very effective way of water resources conservation; it is recommended that OWS extends its efforts to all the water stakeholders.

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SDG goal 6 monitoring in the Kingdom of Bahrain

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ABSTRACT

The 2030 Agenda for sustainable development goals (SDGs) is an ambitious, aspirational, and transformational in nature global development plan. It is comprised of 17 holistic, indivisible, and universally applicable goals that embed and integrate the three dimensions of sustainable development – the economic, social, and environmental dimensions. These goals are supported by 169 integrated targets and 232 global indicators to enable global monitoring and reporting on their implementation progress. Goal 6 (SDG 6) of this agenda – the water and sanitation goal – aims to ensure availability and sustainable management of water and sanitation for all. As opposed to goal 7 of the Millennium Development Goals (MDGs), which was limited to access to water and sanitation facilities, SDG 6 of the sustainable development goals covers the entire water – cycle in an integrated manner. It is extended to address drinking water, sanitation and hygiene, protection of water-related ecosystems, water use efficiency and scarcity, and water management at both national and trans-boundary levels. Water and sanitation services are at the very core of the 2030 Agenda; thereby SDG 6 is cutting across all the other goals on both targets and indicator levels. This paper attempts to establish a baseline and methodological mechanism for monitoring and reporting on SDG 6 in the Kingdom of Bahrain. A trend analysis approach was used for tracking progress towards meeting the SDG 6 targets. According to the monitoring results, progress varies considerably. Bahrain has fully achieved the targets of increasing the coverage of the population having access to safely managed drinking water and sanitation services, and halving the proportion of untreated wastewater, well ahead of the agenda deadline. Progress on attaining the targets associated with the protection of water-related ecosystems and water use efficiency and water scarcity are, however, falling short at various degrees of implementation. The monitoring efforts also reveal that, despite the modest progress made on enhancing the institutional structures and capacity building in the water sector, implementation of integrated water resources management (IWRM) is still facing enormous challenges. In general, our analyses have shown that the natural water scarcity, high population growth rates, accelerated socio-economic development, non-efficient water use, shortages in financial outlays, and the lack of adequate technical and institutional capacities are the crucial factors hindering or decelerating progress on achieving SDG 6. Although sufficient data were made available for our analysis, data gaps were inevitable and require focused attention during the 2030 Agenda time frame. Among others, a set of potential management measures and policy interventions that may help fill these gaps and accelerate progress are recommended.

Keywords: Sustainable Development Goals; SDG 6; Kingdom of Bahrain; Water and Sanitation; Sustainable Water Management

1. Introduction

In September 2015, the United Nations adopted resolution 70/1, "Transforming our world: the 2030 Agenda for Sustainable Development". The vision enshrined in this Agenda is ambitious, aspirational, and transformational in nature (UN-ESC, 2016). The 2030 Agenda comprises 17 integrated, indivisible, and universally applicable goals that embed the three dimensions of sustainable development – the economic, social, and environmental dimensions. The importance of the integration and interlinkages concept within the 2030 Agenda is well-documented by UN-Water (2017a) "If these interlinkages are recognized and actively managed, implementing one target can assist with

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implementing many others, thereby optimising the use of existing resources and capacity and realising the purpose of the 2030 Agenda". These 17 goals are supported by 169 integrated targets and 232 global indicators to enable global monitoring, streamlining, and reporting on their implementation progress.

The Kingdom of Bahrain has paved its way for sustainable development by launching its development strategy in 2008 "Bahrain's Economic Vision 2030" – the guiding principles of which are: sustainability, competitiveness, and fairness (EDB, 2008). This vision was then translated into a comprehensive strategy "National Economic Strategy 2009–2014" (EDB, 2008). Both initiatives are strongly in line with the global 2030 Agenda for SDGs in terms of vision, guiding principles, objectives, and development initiatives.

In alignment with the 2030 Agenda, the government led parliament to ratify the "Government Action Plan 2015–2018". This action plan is a short-term national development programme that aligns its objectives and national priorities with those of the SDGs (Bahrain Government, 2015). By way of example, targets 6.1, 6.4, and 6.5 of SDG 6 are consistent with and covered by the national priorities and strategic programmes contained in the infrastructure and environment and urban development pillars of this action plan. A resolution decree No. 21/2015 was issued by the Cabinet to establish a "National Information Committee".

SDG 6 – the water and sanitation goal – aims to ensure equitable and safely managed water and sanitation services for all, preserve healthy ecosystems, and address water use efficiency and availability. It also calls for promoting IWRM at all levels, protecting and restoring water-related ecosystems, expanding international cooperation and capacity building in water and sanitation-related programmes, and supporting a participatory approach in water and sanitation management. SDG 6 comprises eight targets (six technical targets and two means of implementation targets), and eleven global indicators (nine core indicators and two additional indicators).

These targets are closely interlinked in the form of target-level linkages to ensure sustainable and integrated management of water and sanitation for all. A few examples of these interlinkages include: providing safe drinking water for all (target 6.1) which is directly related to the quality of the raw and ambient water (6.2, 6.3, and 6.6), and is strongly dependent on the water management being adopted (6.5) and efficiency of use (6.4). Also, sound water recycling practises and safe wastewater reuse (6.3) improve water use efficiency (6.4); and according to UN-Water (2016a), a safely managed sanitation service (6.2) is essential to protect the environment and water related ecosystems (6.3 and 6.6), or potential sources of drinking water (6.1). In addition, expanding international cooperation and capacity-building support to developing countries in water – and sanitation-related activities and programmes (6.a), and strengthening the participation of local communities in improving water and sanitation management (6.b) are fundamental elements to achieve IWRM (6.5).

Water and sanitation are at the very core of sustainable development (UN-Water, 2016) because safe drinking water and adequate sanitation services and hygiene are pillars of human health, social and economic well-being, food, energy and industrial production, environment and ecosystems protection, and climate change (UN-Water, 2016b). Therefore, SDG 6 links and cuts across all the other 16 sustainable development goals, also at target-level. The vast majority of target-level linkages across the 2030 Agenda with SDG 6 are positive (synergetic), meaning that implementing SDG 6 targets mutually supports a large number of other targets, and vice versa (UN-Water, 2016b). Some SDG 6 targets, however, have conflict or trade-off relationships with other SDGs targets, but this may provide countries with opportunities and challenges for improving their management procedures and decision-making processes.

This paper draws upon a comprehensive work (Al-Noaimi, 2018b) that sought to monitor progress on achieving SDG 6 in the Kingdom of Bahrain, and set out the baseline and methodological mechanism for progressive SDG 6 integrated monitoring up to the 2030 Agenda deadline, using a trend analysis approach. In this paper we collect, evaluate, analyse, and monitor data-sets on SDG 6 targets, mainly covering the time-span 2000–2016, with the year 2016 being considered as the baseline year against which progress up to 2030 will be evaluated.

The key challenges and obstacles faced, barriers to progress, data gaps, and performance deficiencies were also identified and briefly assessed. Our main findings have shown that progress achieved on SDG 6 monitoring varies significantly, with the main targets of providing safe and affordable accesses to drinking water supply and sanitation services being considerably attained. Inevitably, however, there are areas where progress is lagging behind to various degrees. The paper stresses the importance of re-shaping some of the water policies and management measures, including strengthening of the national statistical systems to address monitoring requirements and improvements in data reporting mechanisms, enhancing adoption of IWRM approaches, and optimising the proportions of wastewater reuse.

2. Baseline monitoring of SDG 6 targets and indicators

Tracking progress on the sustainable development goals requires the collection, processing, analysis and dissemination of an unprecedented amount of data and statistics at all levels, including those derived from official statistical systems and from new and innovative data sources (UN-ESC, 2016). Therefore, a robust, harmonised, and internationally comparable statistical framework (to facilitate reliable data sharing and dissemination at the regional and global levels) will need to be established at national, subnational and regional levels to streamline and optimise monitoring and reporting mechanisms on the sustainable development goals.

The Kingdom of Bahrain has established a comprehensive, consolidated, consistent, and timely data storage and management system – the Bahrain Water Resources Database (BWRDB). The database contains detailed quantitative and qualitative water and water-related statistics and information, with a set of computed indicators and variables. These data are disaggregated, standardised, and adjusted for global comparability, with rigorous data validation, refinements and improvement processes, and well-established reporting mechanisms. The BWRDB is a work-in-progress project and is currently being reviewed and expanded in terms of concept, structure, and methodology to fulfil the SDG 6 monitoring needs and to address the specific requirements of the Bahrain National Water Strategy and the Gulf Countries Unified Water Strategy and Implementation Plan (Al-Noaimi, 2018a).

In the context of the 2030 Agenda, a global indicator framework has been broadly defined to track progress towards the SDGs at the global level (UN-Water, 2017). Countries are, however, encouraged to devise their own additional national, sub-national, and perhaps regional indicators, bearing in mind the level of development, available resources, existing capacity, national priorities and so on for each country. The core element of the global indicator framework is the disaggregation of data and the coverage of specific groups of the population (ethnic, gender, marginalised, migratory status, and other groups characteristics) to fulfil the main principle of the 2030 Agenda of leaving no one behind (UN-ESC, 2016).

The BWRDB has offered reasonable and appropriately disaggregated time series data for integrated monitoring and tracking progress on SDG 6 targets and global indicators. Our monitoring efforts are mainly based on the suggested metadata for global monitoring of SDG 6 (UN-Water, 2016c) and the integrated monitoring guidelines and methodologies for SDG 6 targets and global indicators (UN-Water, 2017 and GEMI, 2017). We have also closely followed the various step-by-step methodological and guidance notes and institutional information recommended for measuring each of the SDG 6 global indicators.

The following discussion outlines progress attained towards the implementation of the SDG 6 eight global targets (six technical targets and two means of implementation targets) in the Kingdom of Bahrain. It also highlights the status of data availability, the degree of indicator applicability, and key challenges and opportunities.

3. SDG 6 technical targets

Technical targets are those used to monitor real progress on the SDGs. As mentioned earlier, SDG 6 consists of six technical targets (targets 6.1–6.6) supported by nine core indicators to facilitate global monitoring.

3.1. Target 6.1 drinking water supply

By 2030, achieve universal and equitable access to safe and affordable drinking water for all. Target 6.1 builds on target 7.C of the MDGs on drinking water, though the former is broadened to the extent that it calls for universal and equitable access for all and specifies that drinking water should be safe and affordable.

3.1.1. Indicator 6.1.1 percentage of population using safely managed drinking water services

Target 6.1 is measured by the global indicator 6.1.1 which specifies the share of the population using safely managed drinking water services from the total population. In order to meet the criteria for a safely managed drinking water service, people must use an improved drinking water source that should be: accessible in premises, available when needed, and free of contamination (WHO and UNICEF, 2018). The service levels for drinking water are divided by the Joint Monitoring Programme (JMP) into five parameters: safely managed, basic, limited, unimproved, and surface water.

Sufficient data were made available on this indicator from the official administrative records, annual statistical reports, and population statistics. The data have shown that, between 2000 and 2015, the average proportion of the population using improved and safely managed drinking water services (piped drinking water in premises) was 99%. In 2016, the proportion of people who had gained access to piped supplies reached the 100% mark. Fig. 1 shows the proportion of the population using safely managed drinking water sources from 2000 to 2016. According to the service provider, the lesser proportions (less than 100%) during 2000–2015 are attributed to pending applications, but this may also be partially due to illegal connections.

Fig. 2 shows that, during the 12-year period spanning 2005 to 2016, drinking water quality has significantly improved, thanks to the expansion in the desalination capacity. Total dissolved solids (TDS) content decreased from 1,528 to 294 mg/L between 2005 and 2016. In 2016, for instance, sodium and chloride contents fell considerably to 42 and 58 mg/L, respectively – well below the recommended allowable limits. Throughout the same period, trace metals content also recorded concentration values well below the international standards. However, data on drinking water quality lack analyses on fluoride, arsenic, and mercury, which are essential for assessing drinking water quality. Inclusion of these parameters in the routine drinking water monitoring programme is essential for enhancing the progressive monitoring efforts.

The graph in Fig. 3 compares the percentages of bad and good samples for samples collected at the distribution points for the period 2000–2016. The trend is remarkably positive, showing compliance of between 98.2% and 99.5%. From 2000 to 2015, the average of bad samples was less than 0.99%. During 2016, the proportion of polluted samples was only 0.9%. As presented in Table 1, which compares the proportion of good and bad samples for samples collected at the consumer outlets for the period 2000–2012, the percentage of bad samples ranges from 1.6% in 2000 and 2011 to 5.8% in 2008. This translates into compliance of between 94% and

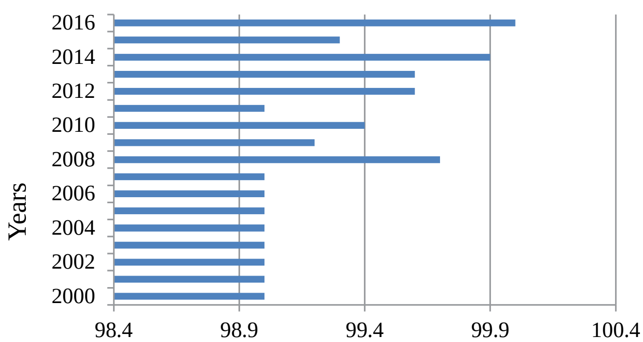

Fig. 1. Percentage of population using safely managed drinking water services (%).

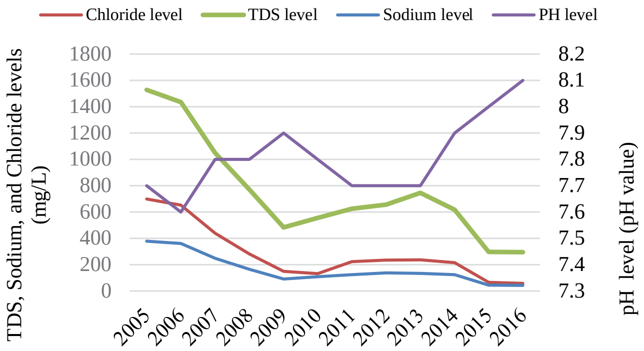

Fig. 2. TDS, Sodium, Chloride, and pH levels in drinking water 2005–2016.

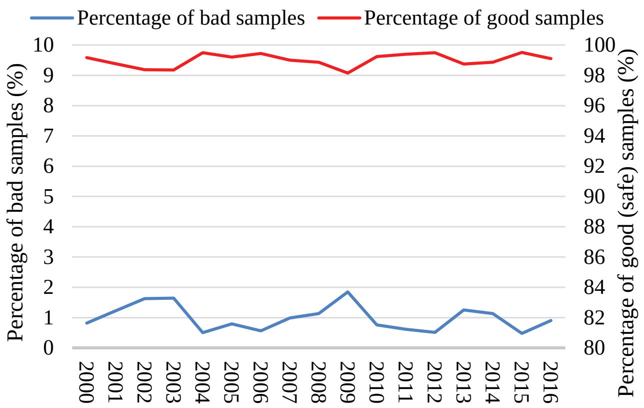

Fig. 3. Graphical representation of the good (safe) and bad drinking water samples 2000–2016.

Table 1
Percentages of good (safe) and bad samples at the consumer outlets 2000–2012

Years	Total samples	Sample status		Percentage of the good (safe) and bad samples	
		Safe	Bad	Safe	Bad
2000	1,340	1,318	22	98.4	1.6
2001	1,665	1,617	48	97.1	2.9
2002	1,666	1,630	36	97.8	2.2
2003	1,704	1,673	31	98.2	1.8
2004	1,565	1,544	21	98.7	1.3
2005	1,188	1,154	34	97.2	2.8
2006	1,134	1,083	51	95.5	4.5
2007	601	580	21	95.5	3.5
2008	447	421	26	94.2	5.8
2009	570	552	18	96.8	3.2
2010	502	484	18	96.4	3.6
2011	319	314	5	98.4	1.6
2012	674	662	12	98.2	1.8
Total	13,375	13,032	343	97.4	2.6

98%. On average, only 2.6% of the samples analysed at premises were found to be not suitable for drinking purposes.

In spite of the achievements made on the monitoring of drinking water quality, a significant drop in the number of samples analysed is noted (Table 1), falling to 674 samples in 2012, which represents a nearly 61% decline since the peak of 1,708 samples in 2003. Moreover, the reported data for 2013 to 2016 were unreliable for further evaluation and had been omitted from our analyses. These deficiencies reflect a decline in monitoring performance that needs to be seriously addressed. Performance must be maintained over time to support routine monitoring and to allow for more effective and standardised water quality monitoring, including the upgrade of sampling frequency and measurement procedures.

The majority of the drinking water in Bahrain originates from desalination sources. According to the 2016 estimate, 98.5% of the drinking water supplied to consumers is desalinated water. A study shows (Al-Noaimi, 2004) that consumers in Bahrain pay only 30% of the true unit cost of domestic water (i.e., the subsidy reaches around 70%); this is based on a calculated average unit cost of BD 0.113/m^3 (BD = 2.64 US$). Although water tariff restructuring has been implemented since 2017, subsidies are likely to remain an essential part of the tariff system, implying that payment for drinking water services does not and will not represent a burden at least to the national consumers. Affordability in SDGs is, however, still a debatable issue as further work is required to establish a commonly agreed method that will allow more systematic and consistent monitoring of affordability in the future (UN-Water, 2018; WHO and UNICEF, 2018).

The typical characterisation of the population to rural and urban areas is not precisely applicable to the Bahrain situation. Additionally, the drinking water distribution networks in the country are designed in a way that drinking water is distributed to mixed distribution areas, making it difficult to differentiate consumers based on their living areas. This indicates that progress accomplished represents the urban and rural population coverage (i.e., national coverage), meaning that Bahrain has fully achieved the target of increasing the coverage of the population having universal, equitable, and affordable access to safely managed drinking water services.

It needs to be noted, however, that bottled water is widely used in Bahrain, but only for drinking purposes. Even though, data from household surveys on the accessibility of this source were not made available, virtually all the population drinking bottled water or using any other type of packaged water (water tankers only supply drinking water in rare emergency cases) have access to piped and safely managed water sources. For this reason, the use of bottled water was not assessed here separately. This appears to confirm the need for greater clarity on a global level on this aspect of target 6.1.

3.2. Target 6.2 sanitation and hygiene

By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable *situations*. This target also builds on target 7.C of the MDGs that calls for halving, by 2015, the proportion of people without sustainable access to basic sanitation. Target 6.2 addresses the use of safely managed sanitation services and ending open defecation practices to protect the health of the individual, community, and environment. It also highlights the importance of hygiene and handwashing facilities on premises to avoid the spreading of communicable diseases. More importantly, it pays special attention to the needs of women and girls, and to other marginalised groups and calls for providing them with equal services and necessary protection.

3.2.1. Indicator 6.2.1 percentage of population using safely managed sanitation services of wastewater safely treated

Indicator 6.2.1 is adopted globally to evaluate target 6.2. This global indicator seeks to specify the proportion of the population using safely managed sanitation services and those having handwashing facilities with soap and water. Because, as mentioned earlier, JMP has produced separate categorisation for hygiene service levels, indicator 6.2.1 is normally divided into two sub-indicators: 6.2.1a Proportion of population using safely managed sanitation services, and 6.2.1b Proportion of population using a handwashing facility with soap and water.

The updated ladder for sanitation services (WHO and UNICEF, 2018) includes five steps, namely: safely managed, basic, limited, unimproved, and open defecation, while the new ladder of the JMP for hygiene disaggregates handwashing facility on premises to three service levels: basic, limited, and no facility.

When viewed over the period from 2000 to 2016, the average proportion of the population having access to safely managed sanitation services via direct sewer systems was 77.5%. As shown in Fig. 4, the progress on 'population with direct connections to the sanitation services' has been erratic. While it rose by nearly 6% from 2000 to 2002, it fell considerably from 77% in 2002 to 65% in 2008, or a drop of around 16%. Progress remained almost constant between 2003 and 2005, but then slowed down until 2008. The most significant progress was made between 2008 and 2014, jumping from 65% in 2008 to 90% in 2014, corresponding to an increase of 39%. During 2016, the trend reversed, as the percentage of people with piped sewer systems dropped to 85%; this was less than in 2014 by approximately 6%.

The high population growth rates and rapid urbanisation developments appeared to have outpaced – at some stages – the rate of expansion in wastewater and sewerage infrastructures. It is evident that the compound effects of these factors contributed to this inconsistent trend. Much work remains to be done to accelerate progress on this target, as will be recognised when assessing progress on achieving target 6.3.

For SDG 6 monitoring, JMP defines safely managed sanitation services as those provided via piped sewer systems or on-site facilities such as septic tanks or pit latrines. In Bahrain, the population who lack access to direct connection to piped sewer networks, 15% in 2016 for example, enjoy safely managed sanitation services through on site sealed septic tanks (Fig. 4). These septic tanks are regularly emptied, and effluents are transported and delivered to treatment plants. The delivery of these effluents follows rigorous environmental standards and procedures to prevent risk to human health and the environment. This means that progress on meeting SDG target 6.2 of increasing sanitation coverage is fully accomplished in Bahrain well prior to the target deadline of 2030.

Another point worth mentioning is that both public drinking water consumers and industrial firms in Bahrain do not pay sewerage and/or discharge (pollution) charges. Farmers also receive tertiary treated wastewater for reuse for

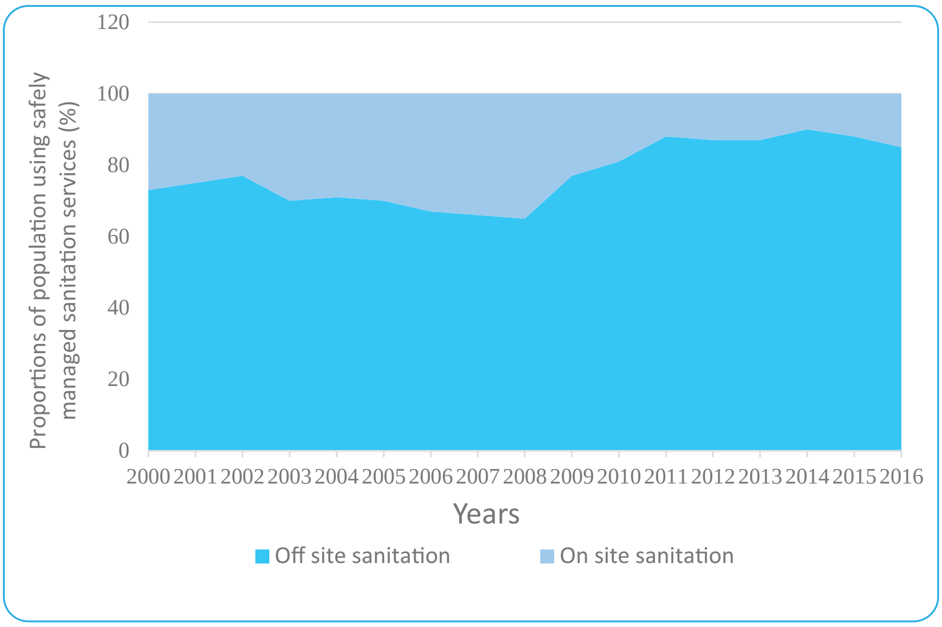

Fig. 4. Proportions of population having access to safely managed sanitation services 2000–2016 (In percentage).

restricted irrigation and sludge as fertiliser free of charge. However, proposals are being discussed in parliament regarding the imposition of a uniform tariff on connections to the sanitation services.

Statistical data on handwashing facilities that are usually collected through household surveys and censuses are not available to track progress on the sub-indicator 6.2.1b. The standard of socio-economic development in Bahrain may suggest that access to these facilities is assumed to be universal. It can thus be argued that this sub-indicator is not applicable to the situation in the country, or at least it should be monitored in integration with SDG 1 on poverty and SDG 3 on health with possibly inter-ministerial and coordinated monitoring efforts.

At global level, however, to overcome the data gaps for middle and high-income countries for future reporting on this sub-indicator, JMP will develop a suitable proxy for the availability of handwashing facilities in the home, drawing on data that are more likely to be available for high-income countries, such as 'availability of piped water supplies, hot water, showers or bathroom in premises' (WHO and UNICEF, 2018).

3.3. Target 6.3 water quality and wastewater

By 2030, improving water quality by reducing pollution, eliminating dumping and minimising release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally. The focus in target 6.3 is on the protection of water-related ecosystems and human health by eliminating, minimising, and significantly reducing all types of pollution into water bodies. The target also calls for substantially increasing recycling practices and safe reuse of treated wastewater as a means for (1) reducing the amount of water discharged (normally untreated or partially treated) into water bodies, and (2) decreasing freshwater withdrawal and increasing water use efficiency.

Progress on target 6.3 is closely linked to that of indicator 6.2.1 as both are part of the so-called sanitary chain, and also contribute to safe drinking water (6.1.1) as water pollution limits opportunities for safe and productive use of drinking water sources (UN-Water, 2018; WHO and UNICEF, 2018). Target 6.3 is currently being measured by two global indicators: namely, indicator 6.3.1 which focusses on the safe treatment, reuse, and disposal of wastewater, and indicator 6.3.2 which concerns with the ambient water quality in certain water bodies.

3.3.1. Indicator 6.3.1 proportion of wastewater safely treated

Indicator 6.3.1 measures the percentage of wastewater safely treated compared with the total wastewater generated. It has two components: wastewater generated by households and wastewater generated by other economic activities (industrial), based on the ISIC Rev. 4 Coding (UN-DESA, 2008). Consequently, the indicator can be disaggregated by source into two sub-indicators – 6.3.1a Proportion of wastewater safely treated in urban wastewater treatment plants, and 6.3.1b Proportion of wastewater safely treated in industrial wastewater treatment plants.

Disaggregated data on municipal water supplies, volume of domestic wastewater collected, volume of domestic wastewater treated, and volume of domestic wastewater disposed of to the sea were made available from the BWRDB. These data were used to develop a set of important national indicators signifying the collection rate, treatment rate, reuse rate, and the rate of discharge. Table 2 provides quantitative data on these variables from Tubli Water Pollution Control Centre (TWPCC) – the main wastewater treatment plant for the years 2000–2016. The table also offers proportionate information on the proposed national indicators.

On average, the collection rate (proportion of the volume of wastewater collected to total municipal water supply) is nearly 49% – falling short of the global collection rate of 60%. Over the period of interest, the trend varies widely. While falling from 47.5% in 2000 to 40.3% in 2006, it substantially rose from 40.3% in 2006 to 51.4% in 2007, or by about 28%, yet it dropped again by 6% between 2007 and 2012. The recent years 2013–2016 have shown a positive trend. In 2016, the collection rate reached almost 58%, or within close reach of the global threshold value, up from roughly 48% in 2012.

The most significant progress has been made on the national indicator treatment rate (proportion of the volume of wastewater treated to the volume of wastewater collected), which recorded a proportion of 100% throughout the comparison period and implies that all the collected wastewaters are being treated normally at least to secondary or tertiary levels of treatment.

The proportion of wastewater reused to the volume of wastewater treated – the reuse rate, gradually increased from 20% in 2000 to around 41% in 2008, or a slightly more than double rise of 105%. In the subsequent years, 2008–2015, progress slowed considerably to reach the 20% mark in 2015. After that, in 2016, it rose again by almost 31% compared with the 2015 level. Between 2000 and 2016, the volume of treated wastewater reused averaged at only 28%. It thus becomes clear that this rate of progress is insufficient and that a strong push is needed to reverse this trend by improving the existing sewerage infrastructures and the adoption of a more efficient wastewater management programme.

In the reference period from 2000 to 2016, the proportionate volume of wastewater treated and disposed of to the marine and coastal environment, or the so-called discharge rate, also developed a highly fluctuated trend similar to that of the reuse rate, naturally in opposite directions. The considerable increase in the proportion of discharge rate observed from 2014 onward is mainly due to the commissioning of the Muharraq Sewerage Treatment Plant (Muharraq STP), a BOOT scheme that collects around 73,000 m^3/d (27 Mm^3/year) of wastewater and treats it to tertiary level. Of this quantity only 2 Mm^3/year is currently being used for landscape irrigation; the remaining volume is dumped to the environment due to the absence of an effective wastewater reuse strategy.

An average discharge rate of 72% indicates that significant amounts of secondary and tertiary treated effluents are being discharged to the environment, which represents major lost opportunities for augmenting freshwater supplies, especially under the prevailing water scarcity conditions in Bahrain.

The accelerated socio-economic development and high population growth rates continue to overtake expansion in

Table 2
Wastewater collected, treated, reused, and disposed of to the sea from urban wastewater treatment plants 2000–2016

Years	Description								
	Municipal water use(2)	Wastewater collected(3)	Wastewater treated(3)	Wastewater treated and reused(4)	Wastewater treated and disposed of to the sea(5)	Percentage of wastewater collected to the municipal water use	Percentage of wastewater treated to wastewater collected	Percentage of wastewater reused to wastewater treated	Percentage of wastewater treated and disposed of to sea to wastewater collected
2000	128.0	60.8	60.8	12.4	48.4	47.5	100	20.4	79.6
2001	136.1	61.1	61.1	12.8	48.3	44.9	100	21.0	79.0
2002	138.1	64.7	64.7	13.1	51.6	46.9	100	20.3	79.7
2003	146.0	62.2	62.2	15.1	47.1	42.6	100	24.3	75.7
2004	152.6	64.1	64.1	15.1	49.0	42.0	100	23.6	76.4
2005	157.4	66.1	66.1	14.8	51.3	42.0	100	22.4	77.6
2006	164.7	66.3	66.3	26.1	40.2	40.3	100	39.4	60.6
2007	169.0	86.8	86.8	31.6	55.2	51.4	100	36.4	63.6
2008	197.4	97.7	97.7	39.6	58.1	49.5	100	40.5	59.5
2009	216.0	108.4	108.4	38.2	70.2	50.2	100	35.2	64.8
2010	231.5	115.2	115.2	35.4	79.8	49.8	100	30.7	69.3
2011	240.8	116.9	116.9	37.6	79.3	48.6	100	32.2	67.8
2012	242.4	116.7	116.6	36.7	79.9	48.1	99.9(6)	31.5	68.5
2013	248.6	124.0	123.95	32.4	91.55	49.9	99.95	26.2	73.8
2014	258.6	148.6	148.53	31.4	117.13	57.5	99.95	21.1	78.9
2015	256.7	145.7	145.7	29.6	116.1	56.8	100	20.3	79.7
2016	257.8	148.2	148.2	39.2	109.0	57.5	100	26.5	73.5
Average values for wastewater indicators (in percentage)						48.6	99.99	27.8	72.2

Notes:
All in Mm^3/year, unless otherwise stated.
Not includes municipal water used for agriculture.
Not includes wastewater collected and treated in other plants (industrial).
Not includes wastewater reused in other plants, wastewater reused within premises at TWPCC, as well as sea outfall or TSE surplus quantities.
Includes secondary and tertiary treated wastewaters.
The difference represents wastewater lost within plants operations.

the sewerage infrastructures, resulting in high infiltration rates and deficiencies in treatment performance particularly in events of hydraulic overloading (partially treated wastewater often being dumped to the surrounding environment in such events). The design capacity of TWPCC is 200,000 m^3/d, with a peak design capacity of 220,000 m^3/d. In 2016, for example, the plant received 303,000 m^3/d, or a hydraulic overload of 52%. During the years 2007 to 2016, the average daily flows received by the plant amounted to 291,000 m^3/d; this represents a daily carryover volume of 91,000 m^3, or an overload of 46%.

Although major improvements have taken place over the last 10 years, these limitations call for further actions to enhance the wastewater collection and treatment infrastructures. Among others, these may include improving the treatment and collection facilities, conveyance systems, and reuse transmission networks. A wastewater reuse programme with a clear national policy on Treated Sewage Effluents (TSE) reuse and an effective inter-ministerial coordination mechanism should be established at the national level to plan and substantially increase the reuse of wastewater for irrigation, industry, and perhaps groundwater recharge.

As illustrated in Table 3, quality of the secondary treated effluent from TWPCC has shown elevated concentrations with respect to total suspended solids (TSS), volatile suspended solids (VSS), total coliforms, *E. coli*, and parasites, considerably exceeding the national and local guidelines values. Notably, in 2016, abnormally high values were reported for TSS, VSS, turbidity, biological oxygen demand (BOD), and chemical oxygen demand (COD). However, the TDS content decreased significantly from 3,641 mg/L in 2004 to 1,352 mg/L in 2016.

The table also shows that, apart from the slightly elevated values of total coliforms, *E. coli*, and parasites, the tertiary treated effluent from TWPCC is generally of good quality, with the TDS level being remarkably reduced from 3,423 mg/L in 2004 to 1,060 mg/L in 2016, thanks to the improvement observed in the drinking water quality as revealed in Fig. 2.

Sufficient and good quantitative and qualitative data were made available to monitor progress on the component of wastewater flows in industry (indicator 6.3.1b). These data were collected from five industrial firms and include volumes of wastewater collected, volume of wastewater treated, volume of wastewater reused, and volume of wastewater discharged of to the coastal and marine environment. These industries comprise oil and gas, aluminium, petrochemical, steel, and ship repairs economic activities, and represent the only industrial firms owning private wastewater treatment plants.

The data have shown that the total volume of industrial wastewater collected reached 9.6 Mm^3 in 2016, up from only 0.192 Mm^3 in 2005 (Table 4). A similar trend is observed with the volume of wastewater treated, jumping from 0.175 Mm^3 in 2005 to around 7.8 Mm^3 in 2016. The majority of treated industrial wastewater is treated up to the secondary level, reaching 6.8 Mm^3 in 2016. By contrast, during the same year, only 0.60 Mm^3 or 8% of the industrial wastewater was treated to the tertiary level. The total volumes of industrial wastewater treated and reused increased significantly to 0.76 Mm^3 in 2016 as compared with 0.175 Mm^3 in 2005.

Despite the fact that almost 90% of the wastewater treated in the industrial plants is disposed of to the marine environment (6.7 Mm^3 in 2016), evidence has shown that such a practice is not causing damage to the environment. Table 5 presents data on annual average values of selected parameters of wastewater collected and treated at three industrial firms for the year 2016. It is evident that the treated effluents from industry are of good quality, showing values complying with the environmental standards set out by the Supreme Council for Environment – the agency which regulates and control industrial effluent quality and

Table 3
Analysis results of selected parameters for secondary and tertiary treated effluents from TWPCC for selected years

Parameters	Secondary treated effluent			Tertiary treated effluent		
	2004	2011	2016	2004	2011	2016
Total dissolved solids (TDS)	3,641	2,200	1,352	3,423	2,407	1,060
Total suspended solids (TSS)	11.8	11.7	90.4	11.0	4.0	5.1
Turbidity (NTU)	23	1.3	36.1	2.2	0.8	0.5
Volatile suspended solids (VSS)	109	7.9	58.2	2.0	1.3	1.9
Biological oxygen demand (BOD)	1.0	6.8	38.4	0.9	5.0	3.0
Chemical oxygen demand (COD)	–	23	91.6	29.0	16.0	19.6
Nitrite (NO_2)	1.9	2.4	2.8	1.46	1.0	2.4
Phosphate (PO_4)	–	3.2	2.3	–	1.25	1.77
Total Coliform (count/100 mL)	–	0.62×10^6	3×10^6	1.0	13.2	18.0
E. coli (Count/100 mL)	–	0.32×10^6	2.6×10^{6}*	–	2.2	3.2
Parasite (worm) (worm/litre)	–	815	333*	–	1.2	1.3

Notes:
All in mg/L, unless otherwise stated.
All are annual average values.
A dash indicates no data.
*Data of 2015.

disposal procedures as well as the issuing of effluent discharge permits (see Resolution No. 3/2001 Regarding the Environmental Standards (Air and Water)).

As highlighted above, though some positive steps have been attained, progress on monitoring the urban component of indicator 6.3.1 is falling short to some extent, as challenges and problems responsible for the marginal reuse rate and high discharge rate are yet to be solved. The quality of the secondary treated effluent remains a major challenge and poses a risk to marine and coastal environments.

In contrast, Bahrain has achieved commendable progress with regards to the component related to the proportion of safely treated industrial wastewater flows. The major industries have their own wastewater treatment plants and their effluents are disposed of in compliance with the standards.

Table 4
Volumes of wastewater collected, wastewater treated, wastewater reused, and wastewater disposed of to the sea for selected years from the industrial wastewater plants

Description	Years		
	2005	2013	2016
Wastewater collected	0.192	0.71	9.6
Wastewater treated	0.175	0.691	7.42
Of which:			
Treated to the secondary level	0.011	0.149	6.82
Treated to the tertiary level	0.164	0.542	0.60
Wastewater treated and reused	0.175	0.68	0.76
Wastewater disposed of to the sea	0.0	0.012	6.7

Notes:
All in Mm^3.
The difference between the collected and treated wastewater quantities represents wastewater lost within plant operation.
Total wastewater treated does not equal the volumes of wastewater reused and wastewater discharged to the sea due to rounding.

3.3.2. Indicator 6.3.2 proportion of bodies of water with good ambient water quality

Indicator 6.3.2 is closely interlinked with indicator 6.3.1 as increasing levels of wastewater treatment, and reuse of wastewaters improve ambient water quality in water bodies, while unsafe disposal of wastewaters into water bodies damages ecosystems and poses risks to public health. To report on this indicator, water bodies are classified into three types: rivers, lakes, and groundwater.

Ambient water quality refers to untreated natural water in river, lakes, and groundwater, and represents a combination of natural and anthropogenic influences (UN-Water, 2018). The indicator is concerned with water pollution or the evaluation of human and development impacts on the ambient quality in these water bodies, and measures the

Table 5
Analyses of selected chemical, nutrients, and microbiological parameters from wastewater plants of three major industrial firms 2016

Parameters	BAPCO	ALBA	FOULATH	Guideline values
Temperature (°C)	33.6	–	28.7	3 + TRW
Acidity (pH – Unit)	7.7	7.2	8.1	6–9
Total dissolved solids (TDS)	30,948	–	491	NGV
Total suspended solids (TSS)	1.1	0.3	4.5	35
Turbidity (NTU)	0.6	0.6	4.4	75
Residual chlorine (RC)	0.02	0.002	<0.05	2
Biological oxygen demand (BOD)	4.8	8.0	8.2	50
Chemical oxygen demand (COD)	91.1	18.8	26.2	350
Ammonia – Nitrogen (NH_3 – N)	0.74	0.16	0.44	3
Phosphate (PO_4)	0.58	0.08	0.83	2
Total Kjeldahl Nitrogen (TKN)	2.63	2.2	1.4	10
Total organic carbon (TOC)	–	1.8	5.5	50
Oil and grease	5.8	0.2	<1	15
Phenols	0.06	0.01	<0.002	1
Lead (Pb)	0.03	0.001	<0.05	1
Total Coliform (MPN/100 mL)	12	ND	<1.8	1,000

Notes:
All values are in mg/L, unless otherwise stated.
A dash indicates no data, ND value not detected, and NGV indicates no guideline value suggested.
TRW = Temperature of receiving water.
BAPCO is Bahrain Petroleum Company (Oil industry), ALBA is Bahrain Aluminium Company (Aluminium industry), FOULATH is Bahrain Steel Company (Steel industry).
Guideline values are based on Table 4 "Standards for Effluent Discharge from Industry" of the Resolution No. 3 (2001) regarding the amendments to the tables attached to Resolution (10) /1999 regarding the Environmental Standards (Air and Water) amended by Resolution No.2 (2001).

proportion of all water bodies that have good water quality compared with the total water bodies in the country.

Globally, in order to evaluate and examine indicator 6.3.2, a number of core parameters have been selected for each of the water bodies under investigation. The selection of these core parameters is mainly based on the simplicity of measurement and the assumed basic technical capacity. Countries are, however, encouraged not only to set their own standards for the definition "good ambient quality" depending on their specific conditions but also to improve their monitoring programmes over time by increasing the number of data points and frequency of measurements, and inclusion of more progressive monitoring parameters as national capacity increases.

With regard to the Bahrain situation, out the water bodies of concern, only groundwater body is applicable. Shallow groundwater bodies in the country are represented by two aquifers: the Alat Limestone aquifer and the Khobar aquifer, both of which are part of the so-called Dammam Aquifer System. Groundwater in Bahrain is of poor quality when compared with the national water quality standards, and has always been at risk due to overexploitation of the already limited groundwater resources. Roughly, the best groundwater quality ranges between 3,000 and 4,800 mg/L.

The selected core parameters for groundwater body are: electrical conductivity (EC), nitrate, and acidity (pH). Recommended progressive monitoring parameters for groundwater body includes, among others, temperature, hardness, major anions, major cations, orthophosphate, nitrite, ammonia nitrogen, arsenic, fluoride, and heavy metals.

Indicator 6.3.2 calls for the monitoring of water quality status and percentage changes over time at the suggested water bodies. Fig. 5 shows the changes in EC and TDS values in the Alat Limestone aquifer, together with the EC percentage changes over time for the period 2006–2016. Between 2006 and 2009, EC values significantly increased from 7,457 µmohs/cm in 2006 to 9,159 µmohs/cm in 2009, but then substantially decreased to 7,055 µmohs/cm in 2016. Though still very high, this translates into an improvement of 23%. Over the same period, pH values (not shown in the figure) demonstrated minor inconsistency with slight variations outside the normal range being observed during the last 2 years.

In order to qualify a water body as having "good" water quality, countries need to define threshold target values for the respective core parameters for the water bodies as a whole or each water body separately (UN-Water, 2017b). For reporting on indicator 6.3.2, a country-specific EC target value for the Alat Limestone aquifer is set at 4,800 µmohs/cm (Fig. 5). This is merely a historical target value based on the aquifer average EC content during the 1960s. Despite the improvement witnessed on this parameter, it appears that progress during the last 17 years is insufficient to meet this target value by 2030. This is true unless a drastic improvement in the aquifer water quality has been reached. It is imperative, however, to frequently refine this target value throughout the 2030 Agenda time-frame.

Nitrate is not monitored as part of the routine groundwater monitoring programme, and historical data on this parameter are scant. Limited data have shown that Alat groundwater has a nitrate range of between 2.8 and 6 mg/L

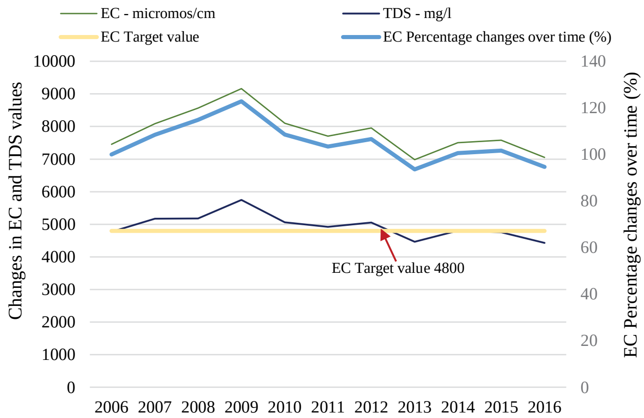

Fig. 5. Changes in the EC and TDS values in the Alat Limestone aquifer and percentage changes in the EC values over time 2000–2016, together with the EC target value.

(Al-Noaimi, 2004). Nitrate pollution normally arises from agricultural activities. Bahrain is not an agricultural country and groundwater is not likely to be used for drinking any longer (only in emergency cases); hence, a nitrate baseline value of 10 mg/L may be considered reasonable. Alternatively, the international guideline value (WHO, 2004) might be adequate to monitor progress on this parameter. Geological considerations and historical groundwater quality data indicate that noticeable changes in the pH values are unlikely to occur. As a result, the WHO guideline value of 6.5–9.5 could be adopted for this core parameter as a target value.

Groundwater in Bahrain suffers from continuous salinity degradation essentially caused by the saltwater intrusion. Hence, parameters such as sodium, chloride, and magnesium are necessary to assess the degree and extent of this phenomenon. Fortunately, these progressive monitoring parameters are generally part of the existing national monitoring programme. Between 2006 and 2016, their concentrations generally exhibited decreasing trends, driven by the notable improvement in the TDS levels. For instance, from 2008 to 2016, sodium and chloride contents in the Alat groundwater, respectively, decreased from 1,777 to 1,286 mg/L, and from 3,239 to 2,682 mg/L.

Fig. 6 shows the changes in EC and TDS values in the Khobar aquifer, along with the percentage changes in the EC values over time during 2006–2016. EC values vary from a maximum of 11,672 µmohs/cm in 2006 to a minimum of 8,531 µmohs/cm in 2015. Khobar's EC values decreased by about 22% between 2006 and 2016 – marking a percentage improvement almost equivalent to that reported for the Alat. The figure indicates that the trends of EC and TDS have almost identical patterns as those of the Alat Limestone aquifer unit (Fig. 5), confirming that the two aquifer units are in hydraulic connection and they are more or less behaving as one unit.

Historical evidence from the 1960s shows an average Khobar EC value close to 4,500 µmohs/cm (Fig. 6), this historical value is designated as the target value on track to meet target 6.3. According to Al-Noaimi (2004), nitrate contents in the Khobar aquifer ranged from 1.2 to 11.5 mg/L. With the

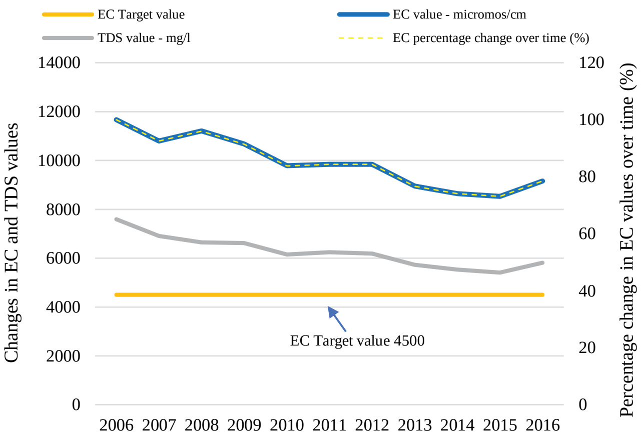

Fig. 6. Changes in the EC and TDS values in the Khobar aquifer and percentage changes in the EC values over time 2000–2016, together with the EC target value.

limited opportunities for sensible agricultural development, a target value of 20 mg/L appeared to be reasonable for this parameter over the SDGs schedule.

It follows from the foregoing discussion that progress on the issue of ambient quality of the groundwater body is simply lagging behind. EC average values of 9,919 and 7,831 μmohs/cm for the Khobar and Alat aquifer units, respectively, in the years 2006–2016 are possibly pointing out important gaps in the data point distribution, which needs to be seriously addressed. This suggests that there are still many monitoring challenges ahead, embracing the urgent need for improving the national groundwater quality monitoring programme in terms of spatial coverage of data points and frequency of measurements, as national capacity increases to support regular monitoring and reporting.

3.4. Target 6.4 water use and scarcity

By 2030, substantially increase water use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity. This target aims to ensure that there is sufficient water for the people, the economy and the environment, by reducing water withdrawals and increasing water use efficiency across all sectors of society (UN-Water, 2018).

Target 6.4 is strongly related to targets 6.1, 6.2, 6.3, and, more importantly, to target 6.5. It is assessed using two global indicators: Indicator 6.4.1 which focusses specifically on the change of water use efficiency over time in the various economic activities, and Indicator 6.4.2, which intends to address and alleviate levels of water stress. These indicators are interlinked to provide a full picture of target 6.4 regarding the relation between water use efficiency and water scarcity.

3.4.1. Indicator 6.4.1 change in water use efficiency over time

This indicator is concerned with the component substantially increase water use efficiency across all sectors. Sectors of the economy for reporting on this indicator are delineated according to the ISIC Rev. 4 coding referred to earlier. The indicator is defined as the change in gross value added in a given sector divided by the volume of water used by this sector, expressed in US$/m^3 (FAO, 2017a). This means that the indicator addresses the economic component of target 6.4 by assessing the impact of economic growth on water use. However, it differs from the concept of water productivity in which it does not consider the productivity of the water used in a given economic activity as an input to production, or even better, the marginal productivity of the extra dose; instead this indicator shows the level of decoupling of economic growth from water use, or the increase of value added produced by the economy in relation to the increase in water use (FAO, 2017a).

When time series data are available, this indicator monitors the trend of change in water use efficiency over time as related to the economy value added. For global monitoring, mathematical equations were developed to allow for the computation of water use efficiencies and for providing some economic information (FAO, 2017a; FAO, 2017b). The SEEA – Water (UN-DESA, 2012) terminologies, concepts, and recommendations on consumption-based statistics are adopted for components explanation and calculation of these equations.

Following ISIC Rev. 4 industrial standards, economic sectors are defined as: agriculture including livestock and aquaculture and excluding fishing and forestry; industry comprising manufacturing, mining and quarrying, construction, and energy; and services sector. Water use efficiency is computed separately for each sector, and total water use efficiency is then computed as the sum of the three sectors weighted by their proportionate use from total water use. The computing formulas of each sector, including component descriptions, are described in FAO (2017a) and FAO (2017b).

The main interpretation rationale for this indicator is the comparison between water use efficiency and the economic growth of the country; the indicator should at least follow the same trend of the economic growth in order to be acceptable (FAO, 2017b). This means that if the water use efficiency is growing more than the economy value added, the indicator is on the right track of progress. The opposite may suggest that progress is not on the right path, and that policy interventions may be required to reverse the trend and remedy the situation.

3.4.1.1. Change in water use efficiency in the agriculture sector

Agriculture water use efficiency may be defined as the irrigated agriculture value added divided by the volume of water withdrawn by the agriculture sector, including livestock and aquaculture and excluding forestry and fishing, expressed in US$/m^3. Although it uses more than 70% of the already limited groundwater resources, and about 90% of the available treated sewage effluent, agriculture in Bahrain is in a poor condition and has a limited potential for improvement. In 2016, for example, the contribution of agriculture (excluding forestry and fishing) to the gross domestic product (GDP) was limited to only 0.20%.

Our data have shown that the lowest value of agriculture water use efficiency was 0.26 US$/m^3 in 2000, while the highest value was 0.53 US$/m^3 in 2016; the average being

0.39 US$/m^3. This positive trend can easily be explained by the widespread adoption of protected agriculture and hydroponic systems which tend to save large amount of irrigation water; the abandonment of many agricultural lands during the two decades might also be contributed. Given the current pattern of agricultural development, an increase in water use efficiency in agriculture is expected to persist over the coming years. Although these results appear to be encouraging, they have to be interpreted with care, taking into consideration the poor condition of the agriculture sector in the country and its trivial value added to the economy.

Fig. 7 relates the percentage changes in water use efficiency in agriculture and agriculture gross value added for the period 2001–2016. The figure shows that the change in water use efficiency is outpacing the growth in the agriculture value added, with only slight inconsistencies, suggesting relatively good performance. On average, between 2001 and 2016, the agriculture sector grew by only 2.2%, while the percentage change in water use efficiency in agriculture recorded a 5% increase.

3.4.1.2. Change in water use efficiency in industry

Water use efficiency in industry is defined as the gross industrial value added per unit of industrial water withdrawn, expressed in US$/m^3. Water withdrawn for industry includes water used for manufacturing, energy, mining and quarrying, and construction activities.

In general, the trend in water use efficiency in industry revealed a wide range from 585.9 US$/m^3 in 2000 to 853.8 US$/m^3 in 2016, with an average efficiency of 716.8 US$/m^3. A rather erratic progress has been observed up to 2011. For example, it rose by about 28% between 2004 and 2006, or from 663.04 to 846.7 US$/m^3 in absolute values, but then dropped between 2007 and 2012 from 653.9 to 585.9 US$/m^3, or by 10%. After 2013, considerable progress was attained increasing from 648.3 to 853.8 US$/m^3 in 2016. This corresponds to an increase of 32%.

The graph in Fig. 8 shows that, on average, from 2001 to 2016, the percentage change in water use efficiency in industry was found to be 1.5%, while the industry value added grew on average by 2.7%. This indicates that the industrial value added was generally growing more than the sector water use efficiency. The exceptions to this tendency were evident in the years 2005 to 2006 and 2014 to 2016. Surprisingly enough, during the periods mentioned, the change in water use efficiency in industry experienced several sharp rises and falls. Such a behaviour is difficult to explain given the limited data to hand regarding the overall economic development and water use characteristics in industry.

3.4.1.3. Change in water use efficiency in services

The services sector covers a wide range of economic activities (ISIC 36–39) and (ISIC 45 – 99). Water use efficiency in services is defined as the services value added divided by the volume of water withdrawn for distribution by the water collection, treatment, and supply industry, expressed in US$/m^3 (FAO, 2017a). This suggests that data on water use efficiency in this sector are to be collected from different sources, and perhaps require further disaggregation as conceptually dictated by SEEA-Water. For this reason, computation of water use efficiency in services requires careful attention.

The emerging trend in water use efficiency in services reveals a significant increase from 42.5 US$/m^3 in 2001 to 64.3 US$/m^3 in 2007. This matches an increase of almost 52%. From 2008 until 2011, a slight decrease of 4% was documented. Subsequently, it increased to 64.8 US$/m^3 in 2016 compared with the 2011 figure of 56.8 US$/m^3. This equates to an increase of 14%. The average water use efficiency in services was found to be 56.02 US$/m^3; the highest and lowest efficiencies being 64.83 and 42.50 US$/m^3, reported for the years 2016 and 2001, respectively.

The relationship between the change in water use efficiency in services and the gross services value added is illustrated in Fig. 9. It shows that while services gross value added is increasing, water use efficiency is decreasing. In the years 2001 – 2016, the average growth in water use efficiency in services was 2.6%, against an average growth of 7.1% in services gross value added, indicating that this sector is the weakest element, with a low absolute value of efficiency.

It is interesting to note, however, that the two trends have comparable profiles with evident erratic progress. Both components increased from 2001 to 2004, then decreased

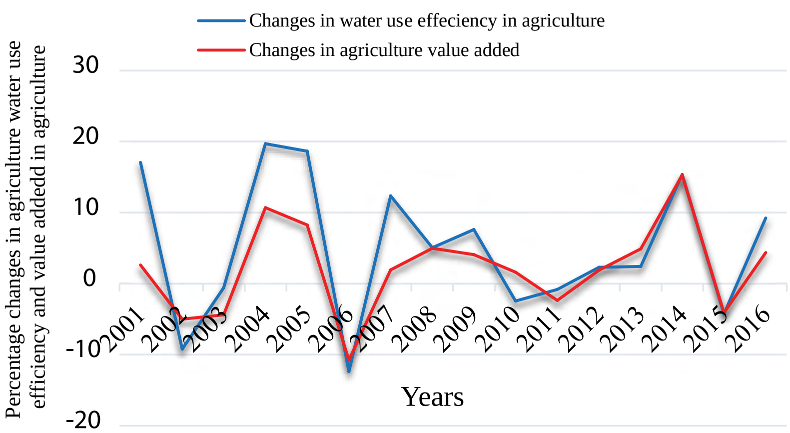

Fig. 7. Percentage changes in agriculture water use efficiency and value added in agriculture 2001–2016 (In percentage).

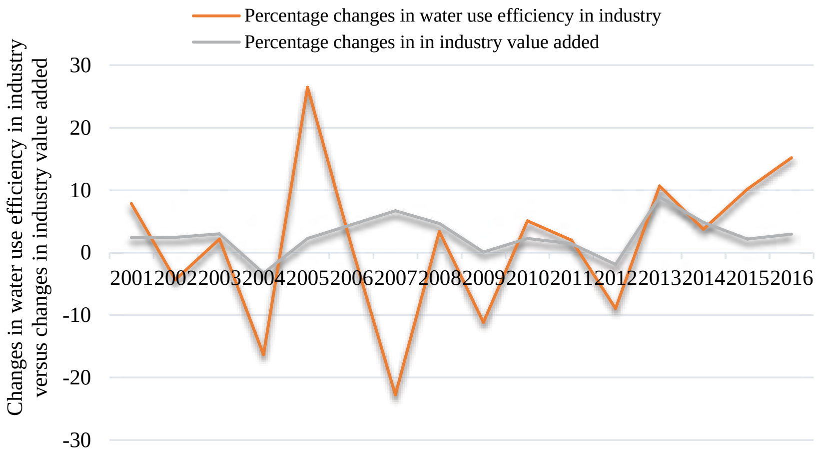

Fig. 8. Percentage changes in the water use efficiency in industry and industry value added 2001–2016 (In percentages).

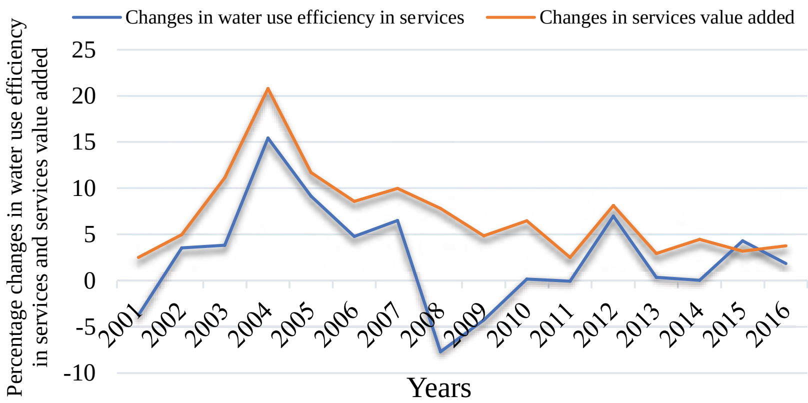

Fig. 9. Percentage changes in services water use efficiency and services value added 2001–2016 (In percentage).

from 2005 to 2009. The trend from 2010 onward witnessed another cycle of rise and fall. The substantial and quite sharp fall in the degree of water use efficiency between 2005 and 2009 may be partially explained by the increase in the water supply, most likely as a result of the commissioning of more desalination plants. In part, the complex structure coupled with the intermingling with respect to the water use in this sector of the economy may have contributed to this performance.

3.4.1.4. Change in total water use efficiency

As mentioned earlier, total water use efficiency is computed as the sum of the three major sectors, weighted according to the proportion of water withdrawn by each sector over the total withdrawal, expressed in US$/m^3 (FAO, 2017b). It means that the percentage share withdrawal of each economic sector from total withdrawal is crucial in computing this indicator.

The highest water use efficiency value was 77.26 US$/m^3 in 2016, while the lowest was reported in 2000 at 46.07 US$/m^3, suggesting a very positive progress. In detail, total water use efficiency significantly rose from 46.07 US$/m^3 in 2000 to 69.97 US$/m^3 in 2007; this corresponds to an increase of nearly 52%. Between 2009 and 2012, water use efficiency virtually remained unchanged, but has gradually risen again from 2013 onward.

On average, water use efficiency is 63.34 US$/m^3. Globally, preliminary data show that water use efficiency accounts for 15 US$/m^3, with country values ranging from about 2 to 1,000 US$/m^3 (UN-Water, 2018). It should be noted, however, that the global assessment might hide some details.

It was found that the positive and negative trend values in the change in water use efficiency virtually coincide with those of the change in water use efficiency in services, confirming the supremacy of this sector on total water use (67% in 2016). Examples of these performances may be perceived between 2004–2005 and 2008–2009. High water use efficiency values were reported for the years 2004 and 2005, 15% and 9%, respectively.

Fig. 10 compares the percentage change in water use efficiency and the percentage change in GDP growth from 2000 to 2016. It shows that, during the period 2000–2016, the percentage change in water use efficiency recorded an average value of 3.4% against a GDP average percentage growth of 4.8%, meaning that more water is proportionally needed by the growing economy. This could lead to the conclusion that water use efficiency in Bahrain remains an important

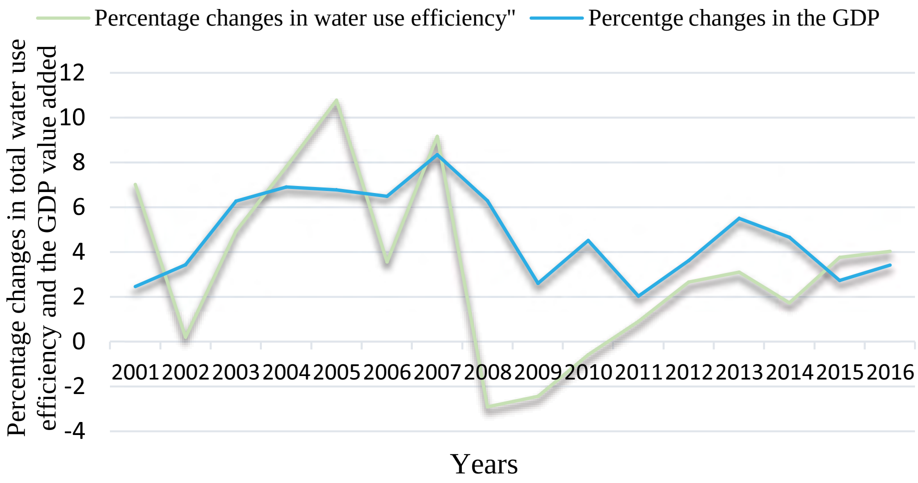

Fig. 10. Percentage changes in the water use efficiency and the GDP 2001–2016 (in percentage).

challenge and places more pressure on the available water resources, despite the fact that recent years demonstrate a few encouraging signs.

Although these percentage changes appeared to be anomalous, a similar picture is evident for all the economic sectors. A possible explanation for this anomaly could be the surge of additional water supply. From the water management perspective, this trend is worthy of closer analysis.

Fig. 11 shows the decoupling relationships between the percentage changes in water use efficiencies and values added in the three major economic sectors and percentage changes in the total water use efficiency and the GDP over time for the years 2000–2016. It can be seen that the obtained results coincide with our detailed separate analyses for each economic sector and the economy as a whole, possibly indicating limited effects of the external factors.

3.4.2. Indicator 6.4.2 level of water stress: freshwater withdrawal in percentage of available freshwater resources

This indicator measures the degree of pressure placed on the available freshwater resources in a country; thereby the extent of challenge on the sustainability of these resources. The level of water stress may be defined as the ratio between total freshwater withdrawn by all major sectors and the total available freshwater resources, after having taken into account environmental flow requirements (EFRs), expressed in percentages (Un-Water, 2017c).

Building on the MDGs indicator 7.5 on water stress, which is equivalent to the SDG indicator 6.4.2, three levels of water stress were considered as thresholds: low stress: 0–25%, high stress: 25%–70%, very high stress: >70% (Navarro, 2018). The world's average water stress stands at almost 13%, although

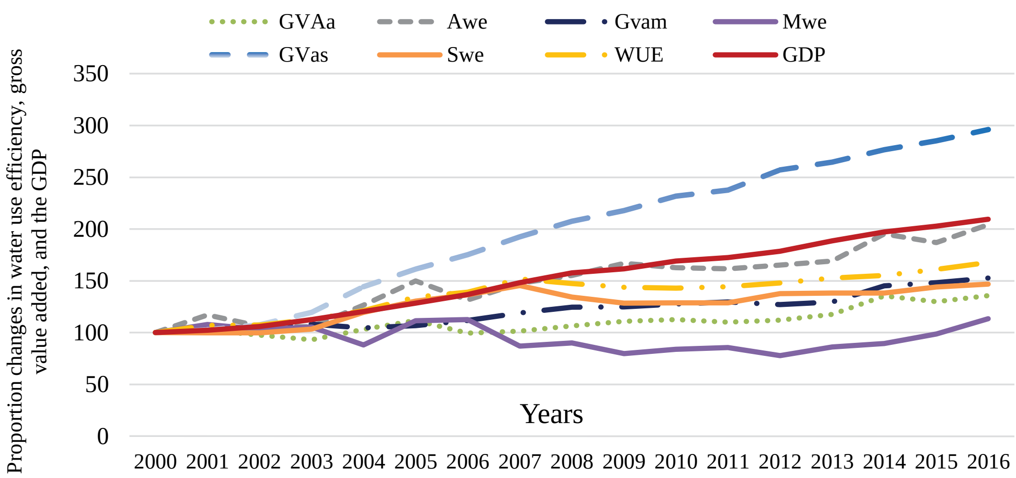

Fig. 11. Proportion changes in water use efficiencies, gross values added in the major economic sectors and total water use and the GDP 2000–2016 (In percentage).

Notes:

GVAa = agriculture value added, Awe = water use efficiency in agriculture, Gvam = industry value added, Mwe = water use efficiency in industry, GVas = value added in services, Swe = water use efficiency in services, WUE = water use efficiency, and GDP = Gross domestic product.

Values added are at constant prices.

evidently, there are significant differences among world regions, a fact that a global assessment hides (FAO, 2018).

In water scarce countries, such as Bahrain, progress on this indicator is expected to be insufficient always, even though some countries have exerted significant efforts to improve their water management policies. Countries are, however, encouraged to identify their own threshold values depending on several factors; among which are level of development, population density, climatic conditions, etc.

Bahrain depends primarily on very limited groundwater resources as the only renewable natural resources to meet its water demand. Currently, demand for freshwater is largely being met from desalinated water and treated sewage effluents. Data required for calculating indicator 6.4.2 are already captured in the computation of indicator 6.4.1, as the two indicators are interlinked to address water use efficiency and water scarcity. Sufficient historical time series data are available on the total withdrawal from both the renewable and non-renewable groundwater resources.

Time series data on renewable freshwater resources are, however, scant. Previous estimates have shown that the external renewable water resources are about 112 Mm^3 (Al-Noaimi, 1993). This represents the average annual inflow from Saudi Arabia mainland. The same study has estimated the internal renewable water resources at about 0.270 Mm^3/year. Therefore, the total renewable freshwater resources may be taken at 112.3 Mm^3/year. Unfortunately, this represents the most recent recharge estimate made available for our analysis and was, therefore, assumed to be constant over the monitoring period. The EFRs component was excluded from our calculations on the reasoning that it is not applicable to the Bahrain situation.

Level of water stress is monitored over the period 2000 to 2016, as shown in Fig. 12. It revealed water stress ranging from a minimum of 138% in 2016 to a maximum of 234% in 2000; the average being 179%. It can be seen that, although appreciable improvement has been attained over the reference period, thanks to the supply increase from non-traditional water resources, Bahrain is a seriously water stressed country.

Because of the quality constrains related to the non-renewable groundwater resources (only available for use after desalination), a country-specific national indicator for the global indicator 6.4.2 was created as shown in Fig. 13, with only freshwater withdrawn from the renewable groundwater resources being considered. Though still high at 96% in 2016, water stress declined remarkably from a peak of 195% in 2000. Progress from 2001 to 2009 witnessed a substantial decrease from 174% to 100%. This corresponds to a water stress decline of 74%. From 2010 until 2013, water stress increased by 20%. The indicator then developed a positive direction over the next 3 years.

3.5. Target 6.5 water resources management

By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate. Implementing a holistic IWRM approach will provide institutional structures and multi-stakeholder processes to balance the development and use of water resources for people, for sustainable economic growth and for supporting vital ecosystem services (UN-Water, 2018). Target 6.5 highlights the great importance of sound development, management and use of water resources, including transboundary cooperation over water resources in solving water resources problems. Therefore, the target is not only essential for SDG 6 alone but also all SDGs.

The global Indicators 6.5.1 Degree of IWRM implementation, and 6.5.2 Proportion of transboundary basin area with an operational arrangement for water cooperation

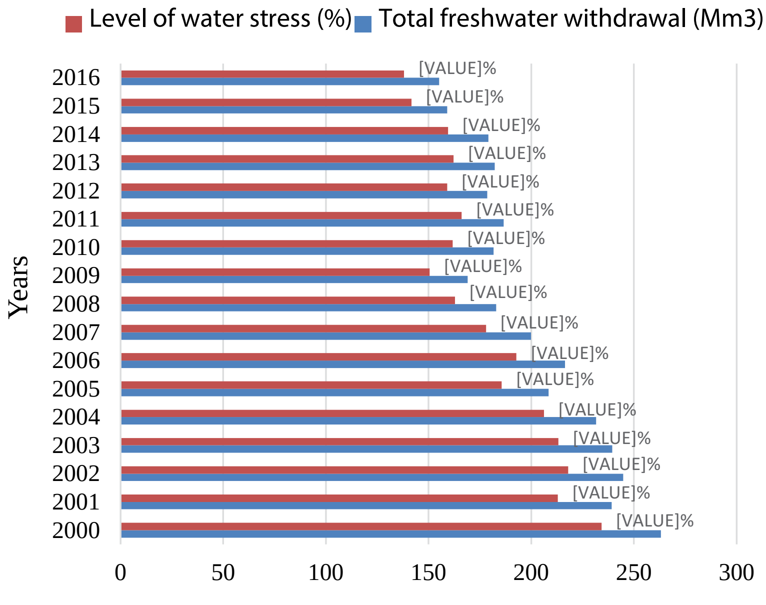

Fig. 12. Indicator 6.4.2 Level of water stress (Global indicator).
Notes:
EFRs were not considered in our calculations.
Low stress: 0%–25%, High stress: 25%–70%, Very high stress: >70%.

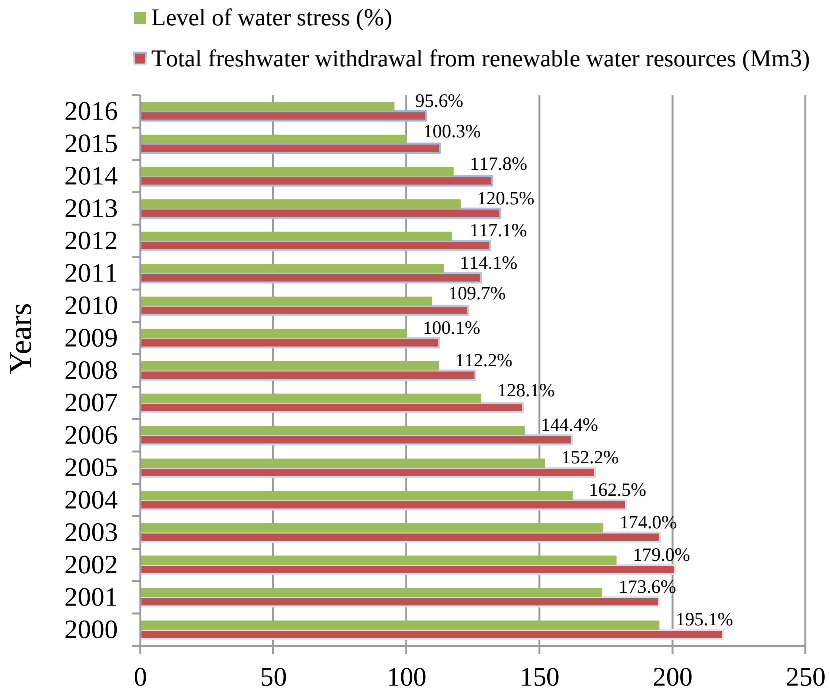

Fig. 13. Level of water stress (national indicator).
Notes:
EFRs were not considered in our calculations.
Low stress: 0%–25%, High stress: 25%–70%, Very high stress: >70%.

are proposed to track progress towards target 6.5. The two indicators complement each other in the way that they combine to address the IWRM implementation at all levels.

3.5.1. Indicator 6.5.1 Degree of water resources management implementation (0–100)

This indicator intends to measure the degree of IWRM implementation in different stages of development and implementation, expressed in percentages. It reflects the extent to which IWRM is implemented as scores between 0 and 100. Zero "0" percentage score indicates IWRM not implemented and "100" corresponds to IWRM being fully implemented.

Globally, progress on this indicator is monitored through a self-assessed country survey questionnaire (UNSD/UNEP Questionnaire) structured in four sections: (1) enabling environment, (2) institutions and participation, (3) management instruments, and (4) financing. Each of these sections contains two sub-sections; the first covering the national level and the second covering the all levels, which includes sub-national, basin/aquifer and transboundary levels as appropriate (UNEP, 2017). The questions for all sections are then averaged to compute the overall score for the indicator. The questionnaire also provides reasoning and justifications for the scores for each question to help in qualification of scores, enable better understanding of the scores, and to assist in identifying areas of good progress and those which hinder implementation of IWRM.

Bahrain has contributed to the 2017/2018 UNSD/UNEP IWRM questionnaire, with questions completed are only those related to national and aquifer elements of IWRM implementation as other levels are not applicable to the Bahrain situation. The country section scores and average score are presented in Table 6. The table shows that Bahrain reported medium to low levels of IWRM implementation (40%), with scores ranging from 28% to 48%. The lowest level of implementation (28%) was reported for the enabling environment, while the highest (48%) was for institutions and participation, which was also a medium-low degree of implementation. It also reported having a medium to low score, about 43%, for management instruments. The country scored 40%, or medium-low level of implementation for financing.

In 2017/2018, the global average degree of implementation of IWRM was 48%, corresponding to medium – low, but with great variations among countries (UN-Water, 2018). As can be seen, Bahrain reported a limited to modest progress with an average indicator value of nearly 40%; this is within a close reach of the global average. This indicates that elements of IWRM are generally institutionalised and implementation is underway. This progress, however, could have been much lower prior to the re-creation of the water resources council and the formulation of the national water strategy (under way), respectively.

According to UNEP-DHI and UN-Water (2018), countries with medium low implementation and below, are unlikely to reach the global target of "very high" implementation. This means that, although good progress has been made in some aspects of IWRM, significant efforts are needed to enhance the element of IWRM implementation and promote cooperation and coordinated actions in all aspects related to management and development of water resources.

Table 6
Indicator 6.5.1 Degree of integrated water resources management implementation (0–100)

Section	Definition	Average score
1. Enabling environment	Creating the conditions that help to support the implementation of IWRM, which includes the most typical policy, legal and strategic planning tools for IWRM.	28.0
2. Institution and Participation	The range and roles of political, social, economic and administrative institutions and other stakeholder groups that help to support the implementation of IWRM.	48.3
3. Management Instruments	The tools and activities that enable decision-makers and users to make rational and informed choices between alternative actions.	42.5
4. Financing	Budgeting and financing made available and used for water resources development and management from various sources.	40.0
Indicator 6.5.1 Degree of integrated water resources management implementation (0–100)		39.7

Future efforts need to be focussed on the establishment of a favourable enabling environment that helps to support IWRM implementation, including enhancing of the national legal, institutional, administrative frameworks, and promoting water policies and strategic planning tools. Allocating sufficient financial resources for water supply and sanitation infrastructures and water resources management should also be given a higher priority. The establishment of the IWRM implementation process and coordination mechanism for future monitoring of progress on indicator 6.5.1 is also imperative.

3.5.2. Indicator 6.5.2 Proportion of transboundary basin area with an operational arrangement for water cooperation

This indicator measures and monitors transboundary water cooperation covered by an operational arrangement, and is expressed in percentage share of the transboundary surface areas. The indicator defines the term "operational arrangement" as any sort of treaty, convention, agreement or other formal arrangement that meets established criteria. It also stresses the importance of transboundary cooperation to implement IWRM of shared water resources, and closely integrates with indicator 6.5.1 to provide full coverage of elements of IWRM implementation.

The Dammam Aquifer System is delineated as a shared aquifer between Bahrain and the Kingdom of Saudi Arabia, yet the two countries have not entered into formal transboundary operational arrangements for the development and management of this aquifer system. The UNSD/UNEP Questionnaire referred to earlier contains questions on transboundary water cooperation. Bahrain gave an indicator value of (0), or a very low level of IWRM implementation to Question (1.2.c) of Section I "Enabling Environment" of the survey questionnaire, regarding arrangements for transboundary water management in most important aquifers, signifying that development in this aspect was not started and not progressing (Table 7). It also reported, "not applicable" to Question (2.2.d) of Section II "Institution and Participation" on gender-specific objectives and plans at transboundary level. This was also the case with Question (2.2.e) of the same section, addressing the availability of an organisational framework for transboundary water management for most important aquifers.

In Section VI of the questionnaire "Financing", Bahrain reported "not applicable" on Question (4.2.c) on financing for transboundary cooperation on the reasoning that frameworks for transboundary water management do not exist. Limited data and information sharing, however, exist through some regional mechanisms (i.e., Gulf Cooperation Council committees), mutual groundwater studies, and on an ad-hoc or informal basis. This was clearly reflected on the answer to Question (3.2.d) of Section III "Management Instruments" on transboundary data and information sharing between countries, where a low to medium low (30) IWRM implementation value was reported.

3.6. Target 6.6 water-related ecosystems

By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers, and lakes. Freshwater aquatic ecosystems are the world's most biologically diverse environment and provide many products and services on which human well-being depends (UN-Water, 2018). Target 6.6 seeks to halt the degradation and destruction of water-related ecosystems such as vegetated wetlands, rivers, lakes, reservoirs and groundwater as well as those occurring in mountains and forests, which play a special role in storing freshwater and maintaining water quality.

Therefore, the global ambition of this target is to protect and restore these ecosystems; as the loss of water-related ecosystems can lead to increasing water insecurity (Dickens, et al., 2017). Global progress towards target 6.6 is monitored through the global indicator 6.6.1.

3.6.1. Indicator 6.6.1 Change in the extent of water-related ecosystems over time

This indicator is a measure of change in the extent of water-related ecosystems over time, expressed in % change/year. Indicator 6.6.1 seeks to provide data and information on the spatial extent of these ecosystems to enable management and protection of water-related ecosystems, so that

Table 7
Summary results of questions in the UNSD/UNEP Questionnaire related to Indicator 6.5.2 Proportion of transboundary basin area with an operational arrangement for water cooperation

Section	Sub-question	Question	Score
Enabling environment	1.2.c Presence of arrangements for transboundary water management in most important basin/aquifer	1.2	(0) Very low
Institution and participation	2.2.d Gender-specific objectives and plans at transboundary levels	2.2	Not applicable
Institution and participation	2.2.e Presence of organisational framework for transboundary water management for most important basins/aquifers	2.2	Not applicable
Management instruments	3.2.d Transboundary data and information sharing between countries	3.2	(30) Low-medium low
Financing	4.2.c Financing for transboundary cooperation	4.2	Not applicable

ecosystem services, especially those related to water and sanitation, continue to be available to society (UN-Water, 2017d). Considering the complex nature of these ecosystems in terms of diversity, indicator 6.6.1 is divided into four sub-indicators to enable describing the aspects of each ecosystem and to assist with implementation of monitoring procedures for target 6.6 at a global level. The sub-indicators describe the spatial extent of ecosystems (sub-indicator 6.6.1a), the quantity of water contained within these ecosystems (6.6.1b), the quality of water in ecosystems (6.6.1c), and the state/health of ecosystems (6.6.1d) (Dickens, et al., 2017; UN-Water, 2017d).

Indicator 6.6.1 is closely related to indicator 6.3.2 on monitoring ambient water quality as the two indicators are combined to address the aspects of ecosystems management in qualitative (6.3.2 and 6.6.1c) and quantitative/health (6.6.1a, 6.6.1b, and 6.6.1d) terms. The two indicators, in turn, are interlinked with SDG 13 on climate change and SDG 15 on terrestrial ecosystems.

For global monitoring and reporting on target 6.6, change in the extent of ecosystems over time is assessed against a reference condition, before which ecosystems were assumed to be in a natural condition. Regarding benchmarking, these are categorised into five stages conditions: unmodified natural, largely natural, moderately modified, largely modified, and seriously modified. For further details on this categorisation in terms of percentage change equivalents, refer to UN-Water (2017d).

Groundwater ecosystem is the only ecosystem category that is applicable to the Bahrain situation. Vegetated wetlands at Tubli Bay Preserved Area, including Sanad, contain saltwater but receive large amounts of treated sewage effluent. Whether this ecosystem is included in this indicator or not remains to be answered.

Storage in groundwater aquifers is normally estimated from numerical modelling taking into consideration the areal extent of aquifers, their saturated thickness, transmissivity and storage coefficient. For SDG 6 indicator 6.6.1, however, change in volume of groundwater stored in these aquifers is difficult to quantify. In this situation, changes in groundwater volume may, however, be inferred from changes in groundwater levels.

The quantity of water in groundwater aquifer ecosystems was assessed using data provided by the related line ministry, including historical records on groundwater levels. In addition, groundwater levels data are made available from various documents, including consultant reports, groundwater studies, and academic and journal papers.

In order to satisfy the SDG 6 monitoring and reporting requirements, changes in groundwater level and percentage changes over time in the Alat Limestone and Khobar aquifers were monitored and assessed for time series data covering the period 2000 to 2016, as shown in Figs. 14 and 15, respectively. The figures also present target values against which future progress will be gauged. It is important to mention here that the proposed target values are merely baseline references, which need to be constantly evaluated and improved as SDG 6 monitoring continues and more data become available.

Fig. 14 shows that, between 2000 and 2010, the Alat water level dropped from 0.07 m in 2000 to –1.01 m in 2010, a significant drop of 1.08 m. By the end of 2014, it rose to 0.01 m, or a recovery of slightly more than 1.0 m. Although it declined again by 0.13 m in 2016, the general trend reveal a positive sign over time. The percentage changes in the Alat water level over time range from around –1,500% to about 230%.

The natural "reference" condition for the Dammam Aquifer System is that of 1924 when the system was in a steady-state condition. Ideally, for SDG reporting, this natural condition is difficult to attain. Therefore, an indicator target value of 1.7 m was established for the Alat aquifer based on the historical reference condition criterion. This virtually represents the average water level during the 1990s (Al-Noaimi, 1993); analysis of data prior to the 1990s produced unreliable results. It can be seen that the observed rate of progress appears to be insufficient to meet the proposed target value before the target deadline of 2030.

From Fig. 15, the Khobar aquifer has an almost similar pattern as the water level in the Alat aquifer, with the water

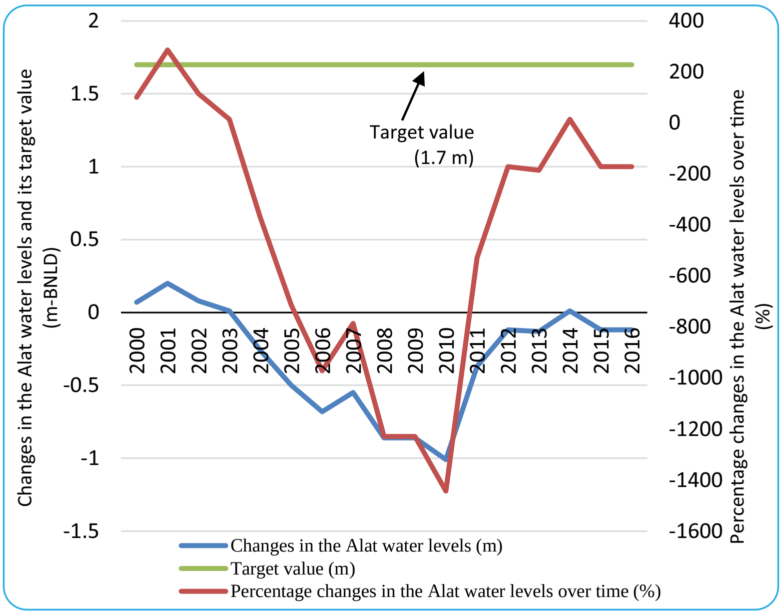

Fig. 14. Hydrograph for the changes and percentage changes over time in the Alat Limestone aquifer water levels 2000–2016, together with the aquifer target value.
Note: BNLD = National Level Datum.

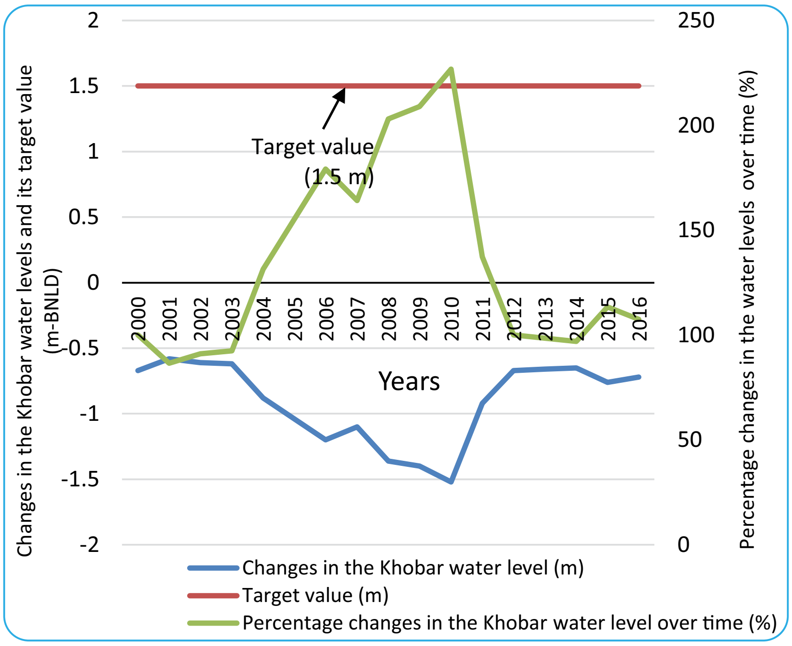

Fig. 15. Hydrograph for the changes and percentage changes over time in the Khobar aquifer water levels 2000–2016, together with the aquifer target value.
Note: BNLD = National Level Datum.

level in the latter aquifer generally exceeding that of the former by almost 0.5 m. The percentage changes in the Khobar water level over time range from a minimum of about 80% to a maximum of around 230%. A target value of 1.5 m was established for the Khobar aquifer, which is also a historical reference value set based on the calculated average water level observed during the 1990s (Al-Noaimi, 1993). Again, the observed trend indicates that the progress achieved is insufficient to meet this value.

3.7. SDG 6 means of implementation targets

The means of implementation targets may be defined as a set of coherence policies and measures, finance, capacity building, technologies, innovations, trade, level of stakeholder participation, and robust national data collection systems that are required to be mobilised in order to support the implementation of the water and sanitation goal. SDG 6 comprises two means of implementation targets: target 6.a on cooperation and capacity building, and target 6.b on stakeholder participation. These targets are closely integrated with SDG 17 targets, which address the means of implementation of all SDGs goals, and are supported by two additional global indicators to report on their progress. In the following paragraphs, the means of implementation targets and their global indicators will be discussed.

3.8. Target 6.a international cooperation and capacity building

By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination water efficiency, wastewater treatment, recycling and reuse technologies. Expanded international cooperation and capacity building support are vital to accelerate progress on achieving SDGs targets. This target is being measured by indicator 6.a.1, which focuses specifically on the, external financial and capacity building support for developing countries in water and sanitation.

3.8.1. Indicator 6.a.1 Amount of water- and sanitation-related official development assistance that is part of a government-coordinated spending plan

The amount of water- and sanitation-related official development assistance that is part of a government coordinated spending plan is expressed here as the proportion of total water and sanitation-related Official Development Assistance (ODA) disbursements that are included in the government budget (UNSD, 2017). A low indicator value indicates that international aids on water and sanitation are not appropriately aligned with government plans for water and sanitation, while a high value would suggest that these aids are aligned with the government spending on this sector. In quantitative financial terms, ODA is used here as a "proxy" for international cooperation and capacity development support.

As mentioned, the indicator focusses on the international financial support directed to the developing countries. Given its socio-economic status and high GDP per capita level, Bahrain do not receive overseas development assistance directly from international donors. Therefore, this indicator may be not applicable to the Bahrain situation. However, in 2011, the Gulf Cooperation Council (GCC) endorsed the so-called "Gulf Development Programme" – a 10-year regional development plan aimed at financially supporting the Kingdom of Bahrain and Sultanate of Oman to promote economic and infrastructure development.

Concerning Bahrain, a major amount of this financial assistance is directed to water and sanitation projects and constitutes part of the government coordinated spending plan on water supply, wastewater and sanitation, and water resources management. The available data on these flows are not sufficient to assess and monitor this target. On the other hand, the question of whether these amounts are included in indicator 6.a.1 or not is still open for debate.

3.9. Target 6.b stakeholder participation

Support and strengthen the participation of local communities in improving water and sanitation management. Stakeholder participation in all aspects related to water and sanitation services is essential to ensure the sustainability of these services. Participation implies provision of mechanisms to enable affected individuals and communities to contribute meaningfully to decisions related to water and sanitation planning and management (UN-Water, 2018). Target 6.b is monitored by indicator 6.b.1, which addresses the need for the effective participation of local communities and other stakeholders on matters associated with water and sanitation.

3.9.1. Indicator 6.b.1 Proportion of local administrative units with established and operational policies and procedures for participation of local communities in water and sanitation management

Indicator 6.b.1 is proposed to evaluate target 6.b. It measures the proportion of local administrative units having established policies and procedures for the participation of local communities in water and sanitation management. A low proportionate value of this indicator would suggest that participation of these communities in water planning and management is marginal; the opposite would indicate high participation of local communities. This indicator is strongly interlinked with indicator 6.1.1 on drinking water, indicator 6.2.1 on sanitation services and, more importantly, with indicator 6.5.1 on the implementation of IWRM.

Owing to the political, geographical, and social environments dominant in Bahrain, public and stakeholder participation play a minimal role in water planning and management. To a certain degree, this indicator is built on the data collected for the status of IWRM reporting in SDG target 6.5. On the answer to Question 2.1.c, of the 2017/2018 IWRM questionnaire, regarding public participation in water resources policy, planning and management at national level, Bahrain reported medium low (40), meaning that government authorities only occasionally request information, experience, and the opinions of stakeholders.

In the same section "Institution and Participation", the answer to Question 2.1.d on the business participation on water resources development, management and use at national level, was zero (0) or very low, which indicates that there is no communication between government and business about water resources development, management, and use. Finally, Question 2.2.b of the same section, also addressing public participation in water resources, was considered not applicable to the Bahrain situation.

4. Conclusions and recommendations

The 2030 Agenda for sustainable development is an ambitious, aspirational, and indivisible in nature global development plan of action that aims to transform our world drastically. Water and sanitation are at the core of sustainable development. Therefore, water is evident as a cross-sectoral issue that affects the achievement of all the other 16 SDGs. In this paper, progress towards achieving SDG 6 targets in the Kingdom of Bahrain was assessed and monitored using a trend analysis approach for time series data covering the period from 2000 to 2016. This research has provided a realistic baseline and sound methodology for monitoring and reporting on SDG 6 targets. The major findings, key challenges, and recommendations of this research are as follows:

- It becomes evident that natural water scarcity, high population growth rates, accelerated socio-economic development, non-efficient water use, shortages in financial outlays, and the lack of adequate technical and institutional capacities are the crucial factors hindering or decelerating progress on achieving SDG 6 targets.
- The monitoring results have shown that progress on achieving SDG 6 targets varies significantly.
- Bahrain has fully achieved the targets of increasing the coverage of population who have access to safely managed drinking water and sanitation services, and halving the proportion of untreated wastewater, well ahead of the SDGs deadlines.
- In contrast, progress achieved in targets related to the protection and restoring of water-related ecosystems, reducing water pollution, and increasing recycling and safe reuse are considerably lagging behind at various degrees of implementation.
- Evidence shows that disposing of large quantities of secondary treated effluents of somewhat inferior quality to the marine environment has resulted in severe environmental problems. Although efforts are assumed to be already under way to substantially upgrade the TWPCC, there exists a need at this stage to establish an efficient wastewater reuse programme to coordinate and optimise safe wastewater reuse and sludge management, and to reduce wastewater discharge into the environment. Moreover, some gaps remain to be addressed with regard to the status of water quality monitoring programmes and laboratory infrastructures, including the nonexistence of an independent quality regulator and/or a surveillance agency.
- Also noteworthy is the importance of enhancing the national capacity about data collection and analyses, and analytical capabilities. Greater efforts are needed to improve laboratory infrastructures and quality assurance measures. More efforts are also needed to establish effective intersectoral coordination on issues related to water quality monitoring and analyses of data. Building on the existing positive changes in the groundwater quality is also imperative.
- Our monitoring efforts indicate that progress towards attaining the targets associated with water use efficiency and water scarcity are falling short. Trends in water use efficiency reveal that the economy is growing more than the water use efficiency, indicating low efficiency and that more water is proportionally needed for economic growth. Unexpectedly, the agriculture sector demonstrates remarkable progress, while the services sector shows the weakest performance. This means that greater efforts are necessary to improve water use efficiency in the various economic sectors.
- In spite of the water supply augmentation during the last three decades, Bahrain is still a seriously stressed country. Reducing the level of water stress should remain a priority over the SDG targeted time-reference.
- An important finding is that, despite the progress made in enhancing the enabling environment for water resources planning and management, implementation of IWRM is still facing enormous challenges. Much work remains to be done in the strengthening of the technical and institutional capacities and enhancement of the legal and policy instruments. Additional investments and provision of sufficient financial resources are also needed to accelerate progress in all aspects of SDG 6.
- Stakeholder involvement in water resources planning and management is significantly falling short. Further efforts are necessary to ensure effective stakeholder participation in various issues of water management.
- Finally, and most importantly, although a large amount of water data and related statistics were made available for our analyses through the BWRDB that assist in the establishment of a baseline for monitoring progress on SDG 6, strengthening of the national statistical capacity and creation of a harmonised data collection system should be deemed necessary to fill data gaps and solve discrepancies; thereby allowing for more effective progressive monitoring. In this context, the incorporation of census data and household surveys (monitoring at consumer level) may be considered to supplement the available data and to facilitate micro-analysis that might improve the monitoring capability.

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Pursuing Water Security within the context of the 2030 Agenda for Sustainable Development

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The Arab States are among the most water scarce in the world with nearly 362 million people in the Arab region under water scarcity to absolute scarcity conditions. The freshwater scarcity situation in the Arab region is aggravated by several factors such as dependency on shared water resources, occupation and conflict, climate change, water pollution, aging water systems, inefficient use of water and high population growth rates. Constructing a conceptual framework for moving towards achieving water security in the Arab region requires first putting people at the center of water issues and second a solid understanding of the main systemic conditions that hamper its achievement.

A conceptual framework for moving towards achieving water security in the Arab region is presented by ESCWA. It considers the regional systemic conditions of water stress and scarcity, shared water and climate change that hinder the achievement of water security. This is done through a sustainable development lens where water is critical and central to the three dimensions of sustainable development, economic, social and environmental dimensions. This is combined with a human rights-based approach to examine water security implications at all scales including at the community and household level in order to ensure that water security in the Arab region is fully grounded in efforts to ensure that no one is left behind. It does so in view of an enabling environment based on a set of means of implementation addressing systemic conditions at various scales.

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UN Environment's Freshwater Strategy 2017–2021: Tackling Global Water Quality Challenges

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When healthy and functional, freshwater ecosystems provide key ecosystem services that include water storage and purification, climate and water regulation, natural hazard regulation and a variety of other provisioning, regulating, cultural and supporting services. Freshwater bodies provide critical life support not only for humans and all human activity – essential for daily drinking and food production needs but also for energy and industrial processes. Freshwater ecosystems also provide habitats for 10% of all living species – 80% of which have disappeared since 1970, thus making them one of the most critically endangered forms of ecosystems on Earth.

Poor land and water management, degradation of water-related ecosystems, and the loss of their critical services, is a growing concern worldwide with an important role to be played by the UN Environment, embedded in the 2030 Agenda for Sustainable Development and its Sustainable Development Goals (SDGs) and forming the core of UN Environment's Global Strategy for Freshwater 2017–2021. The mandate and urgency for UN Environment to take a lead in specific areas relating to freshwater ecosystems including water quality, water ecosystem protection and restoration, and water resources management, was explicitly reinforced at the 3rd UN Environment Assembly in December 2017 in a comprehensive resolution towards the protection and restoration of water-related ecosystems from pollution and other threats.

It is estimated that the world has already lost at least 60% of its natural water bodies since wide-scale development began in 1900, and that one-third to one-seventh of rivers in developing countries face severe pathogenic and organic pollution, including from a lack of safely managed wastewater and from run-off from land-based activities. Growing water stress in many parts of the world, as well as drought and desertification, is a further serious concern which the World Economic Forum among has identified as one of the most serious threats facing our current and future societies and businesses. Robust and abundant evidence also exists that freshwater resources are particularly vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems. More erratic precipitation and climatic patterns, including both drought and flood, are expected to be the result. The integrated management of water resources to ensure the sustainability of freshwater ecosystems and their services is therefore of utmost importance given future trends of population growth, development, and climate change.

The core of UN Environment's Freshwater Strategy 2017–2021: tackling global water quality challenges (corresponding to SDG indicator 6.3.2), protecting and restoring freshwater ecosystems (SDG 6.6.1), advancing integrated water resources management (IWRM) approaches (SDG 6.5.1), and addressing water-related conflict and disasters in support of peaceful and resilient societies (SDGs 11, 13 and 16). The strategy provides actionable guidance to support countries' implementation of sustainable freshwater management practices globally. Achievement of these targets is essential for implementing the entirety of SDG 6 dedicated to water and sanitation, in addition to other SDGs closely linked to freshwater such as those on water-related disasters and climate change, food and energy security and terrestrial and marine ecosystems, and peaceful and inclusive societies, among many others.

Along these lines, UN Environment provides global leadership in four strategic areas:

- Meeting the global water quality challenge (SDG target 6.3): The importance of reversing water quality degradation in the world's freshwater systems is recognized by governments, businesses and communities and steps are taken to improve ambient freshwater quality and reduce the impact of discharge of untreated wastewater into water bodies;
- Protecting and restoring freshwater ecosystems (SDG target 6.6): Services provided by ecosystems are recognized and valued as part of sustainable development and the benefits are shared equitably;
- Advancing the Integrated Water Resources Management approach (SDG target 6.5): Integrated Water Resources Management (IWRM) underpins the coordinated development and management of water, land and related resources to maximise economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems1; and
- Promoting resilience and addressing the environmental aspects of water-related disasters and conflict (SDG targets 11.5 and 16.1): The capability to mitigate and adapt to current and future water-related hazards and risks facing ecosystem functions and human communities is strengthened and embedded into existing environmental planning and management systems.

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Interlinkages between SDG6 and the SDGs: a regional perspective

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Many Arab states have started developing plans and policy settings for the implementation of the SDGs within their national development strategies. Water has a centrality in achieving the 2030 Agenda because of its importance to each of the four dimensions that cut across all SDGs (society, economy, environment and governance). The development and implementation of effective national strategies necessitates to inform policy makers on the importance of water for the achievement of the SDGs. Informing policy makers will help to maximize synergies and address trade-offs between SDG 6 and other SDGs.

First, the interlinkages between SDG 6 (Clean water and sanitation) and the other SDGs will be explored. The presentation will discuss how SDG 6 connects and contributes to implementing the SDGs for review by HLPF in 2019: SDG 4 (Quality education), SDG 8 (Decent work and economic growth), SDG 10 (Reduced inequalities), SDG 13 (Climate action), SDG 16 (Peace, justice and strong institutions) and SDG 17 (Partnerships for the Goals). Regional challenges, water dependency levels and policy recommendations will be presented to promote discussions on effective water use in implementing the SDGs. Second, the presentation will discuss how the quantitative water, energy and food (WEF) nexus approach is helping to achieve the SDGs by ensuring coherent and integrated SDGs achievement policy settings.

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Session 10

Climate Change and Water Resources

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Water security and climate change

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The term water security appears to have emerged at the 2nd World Water Forum in 2000. Shortly thereafter, water security achieved further prominence when it was identified, conceptualized and operationalized by the international water community. At present, water security is generally perceived as one of the main objectives of water resources management. As water security is a rather new concept, definitions of the term are evolving. Reviewing key definitions of the term, as introduced by international agencies, academic researchers and practitioners, suggests that water security refers to the "the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water related risks to people, environments and economies". Water security can be thought of as the adaptive capacity expressing the status of water management, both to enhance its productive potential and to mitigate its destructive potential.

Water security is not only about having enough water. Water security goes beyond water scarcity to take into account not only availability of water resource but also the productive and protective actions to secure water. Water security has three key dimensions: social equity, environmental sustainability, and economic efficiency. Water security comprises complex and interconnected challenges and highlights water's importance for achieving a wider sense of security, sustainability, development and human well-being. Water security is, therefore, also about mitigating water-related risks, such as floods and droughts, addressing conflicts that arise from disputes over shared water resources, and resolving tensions among the various stakeholders who compete for a limited resource. Water security is addressed through two main approaches. One is a developmental approach that seeks to improve water security over time through a combination of policies, reforms, and investment projects. The second is a risk-based approach, which seeks to manage risks and reduce vulnerability to water-related disasters. However, the two approaches are complementary, and need to be pursued simultaneously and in a balanced manner. Addressing water security, therefore, requires interdisciplinary collaboration across sectors, communities and political borders.

A water-secure world harnesses the productive power of water and minimizes its destructive force. It is a world where every person has enough safe, affordable, clean water to lead a healthy and productive life. It is a world where communities are protected from water-related disasters. Water security promotes environmental protection as well as social justice, and addresses the consequences of poor water management. There is now growing international consensus for increasing water security in a sustainable manner and for building more resilient and robust water systems. However, challenges to increase water security are rooted in political, economic, social and environmental issues specific to each country.

Improving water security requires understanding and managing for a changing and unpredictable climate. Climate change will bring about severe economic, social and environmental effects, which require both mitigation and adaptation. The Intergovernmental Panel on Climate Change (IPCC) alerted the global community to the great vulnerability of freshwater resources as a result of climate change. The major impact of climate change will be on the water cycle, and water is the main way through which the impacts of climate change will be manifested around the world. Climate change inevitably will ultimately result in changes in the timing of delivery, availability, distribution and quality of water resources. These shifts severely impact lives and livelihoods. Decreased water supplies mean more human suffering and increased risk of instability, violent conflict and migration. In addition, climate change will result in increased uncertainties, stress and potential for conflicts in water management. These changes are expected to produce threats to water security. Such threats are likely to be amplified by the related uncertainties. Hence, climate change is likely to increase the complexity and costs of ensuring water security.

The combination of hydrological variability and extremes, pertinent to climate change, is at the heart of the challenge of achieving basic water security. The water security challenge will, therefore, be aggravated by climate change and it will require significant adaptation. Achieving and sustaining water security against climate change is the immediate challenge of adaptation. Hence, the anticipated negative impacts of climate change on the functions and uses

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of water and on the associated risks to water security call for an adaptive management process. Resilience and adaptive capacity will become key attributes in the process and the relevance of security will simultaneously become greater.

The keynote speech discusses the concept of water security in the context of climate change with specific emphasis on Arab Region. Threats that climate change poses to water security will be examined. Giving more effort to measure water security and understand the climate change nexus is recommended. Since the context that informs water security is constantly changing, the need to adapt is clear. In the light of these, adaptation challenges to account for the risks posed by climate change to water security will be explored, along with the need for adaptive management as a possible solution.

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Modeling the impacts of climate change on water resources in Mediterranean and Atlantic hydraulic basins of Morocco

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Extended Abstract

This research work investigates the climate change variability and its impact on water resources in hydraulic basins located in both Mediterranean and Atlantic fronts of Morocco, using climate and hydrological modeling. Several climate parameters and their projections in the future have been analyzed to assess climate changes, including wet and dry periods with focus on intensity and frequency. Furthermore, modeling of the impact of this climate change on water resources based on climate scenarios is also studied to evaluate water balance components in the basin/aquifer, in addition to drawdown lowering, water table depletion and seawater intrusion extents into the coastal aquifer.

The Ghis-Nekkor plain, located in the north of Morocco, is a vulnerable area for climate changes, due to its influence by the Mediterranean front to the north and its strong urbanization. In fact, a reduction in precipitation and increase of temperature due to climate change will affect the severity of drought in the plain. In this study, the influence of the decrease of precipitation (about 18%) and increase in average temperature (0.5°C) on future drought conditions is assessed by the SPI index. This SPI is basically calculated for the period (1963–2013) at two-time scales (6 and 12 months), then it is used to assess future drought events in the study area under the Representative Concentrations Pathways (RCP 4.5) climate change scenario. The projected change in precipitation for the period (2020–2070) was simulated by the Regional Climate Model (RCM) Hirham5 from the Cordex Project. The results indicated that the Ghis-Nekkor plain experienced a dry period from 1980 to 1987. For the period 2040–2070, the drought severity and duration will increase under the RCP 4.5 scenario with 19% of severe dry. The rate predicted for the drought condition is about 12%, which represents the double compared with the reference period (1965–2013). The analysis of drought intensity showed that the study area is more prone to both moderate and severe droughts but less prone to extreme drought.

The Oum Er-Rbia hydraulic basin, located in the mid-west part of morocco (Atlas and Atlantic front), is one of the largest watersheds in the country (4,800 km²). Its strategic importance with economic activities and the rapid demographic change make it vulnerable to any fluid imbalance, especially climate change. Hence, the assessment of drought is crucial for many aspects notably water sectors. Thus, the objective of the present study is the estimation of the regional characteristics of drought, frequency and duration using the SPI index.

The results show that during these last 40 years, the Oum Er-Rbia basin experienced dry periods from 1980 to 1987, from 1991 to 1995, from 1997 to 2002 and from 2006 to 2008, and their intensity varies from moderate to severe. They are remarkably composed of three, four and five consecutive dry years. Finally, based on the obtained results from the SPI mapping that the moderate and severe droughts occurred in the North East of the study area, characterized by topographic and geological conditions that are not in favorable conditions as for water storage for long time. The results

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show also a relatively high frequency and large spatial extent of drought in the basin. During these periods, surface water and groundwater resources suffered from significant deficits, such as reduced water storage in dam reservoirs and groundwater table depletion in several aquifers.

Generally, the Oum Er-Rbia basin was affected by 53% of dry periods. The most dominant type of droughts is moderate (38%), while 15% is of severe droughts, and took place especially in North East of the study area. We can conclude that, based on the SPI values and their mapping, the Oum E-rRbia basin is highly vulnerable to drought for which the duration and intensity vary considerably. Drought is, therefore, a recurrent phenomenon but difficult to predict over time for its mitigation. When it occurs, it has negative impact on water resources with less water storage causing water scarcity in several areas of the catchment. However, the results obtained from this study is of great importance for water resources management in the Oum Er-Rbia basin, as it will assist the regional water managers for water resources planning, protection and rational management. Further research work in the catchment is going on to assess the impact of climate change on water resources using climate modeling projections.

The Rmel-O. Ogbane is unconfined coastal aquifer situated near Larache city in the north of Morocco and is a part of the main sub-Atlantic coastal aquifers. The aquifer supplies good quality groundwater that is easily accessible. This favorable situation has increased pumping, and caused environmental problems, such as water table decline and saltwater intrusion. Moreover, the future precipitation decline is due to the impacts of CC and causes longer and more frequent droughts and less groundwater recharge, which directly affect the groundwater level. An integrated approach is developed for linking climate models and groundwater models to investigate future impacts of climate change on groundwater resources. Projected temperature and precipitation values are obtained, respectively, from (RACMO22T and HIRHAM5) Regional Climate Models (RCMs) under Representative Concentration Pathways (RCP) 4.5 scenario. Those projections show an increase in temperature of about 0.45°C and a reduction in precipitation of 16.7% for the period 2016–2040. Based on these results, the input parameters for the groundwater model are calculated, such as evapotranspiration and aquifer recharge, in addition to sea level rise variation, which rises up from ~6.45 cm by 2017 to ~21.3 cm by 2040. The simulation results show that groundwater extraction is the predominant driver of seawater intrusion in the study area. The aquifer area will be contaminated in the NW sector of the coastal part, where the toe interface will reach 5.8 km inland and will be intruded with high salinity concentrations ranging from 15 to 25 g/L by 2040. Beyond these zones, the contamination of the aquifer is limited, but the drawdowns remain significant in some sectors of the study area. Hence, implementation of efficient strategies by decision makers for groundwater development and management in this coastal aquifer are necessary to protect freshwater aquifers against seawater intrusion and groundwater overexploitation.

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Climate change impacts on the agricultural sector in the Arab region

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The Arab region is one of the most water scarce regions in the world with more than 80% of its surface covered by deserts. Climate change projections for the Arab region are predicting a significant rainfall decrease and an increase of temperatures, which will lead to profound, non-linear effects on productivity. In this region as well as in different parts of the world, agriculture is one of the most vulnerable of all human activities to weather and climate variability. Any change in temperature, precipitation, soil moisture, carbon dioxide levels, and disease and pests (themselves largely climate-dependent) will have negative impacts on agricultural production in the region.

The IPCC Special report on Global Warming of 1.5°C stated, "Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C. Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate (high confidence)" and that some regions have already crossed the warming threshold of 1.5°C. The Arab region is one of the areas where temperature has already increased by more than 1.5°C above pre-industrial levels. It emerges also as one of the hotspots for worsening extreme heat, drought and aridity conditions under climate change.

The agricultural sector in the Arab region, of which 70% is rain-fed, is highly exposed to changing climatic conditions. Impacts will be high in a 2°C world, as the annual water discharge for example, already critically low, is projected to drop by another 15%–45% (75% in a 4°C world) and unusual heat extremes projected to affect about one-third of the land area with likely consequences for local food production. The climate conditions projected in the future under different scenarios are unfavorable to grow staple crops to ensure food for a projected increased population that may double by 2070 in the Arab region.

Key messages:

- Human activities have already caused approximately 1.0°C of global warming above pre-industrial levels.
- Temperature in the Arab region has already increased by more than 1.5°C and, as consequence of this regional warming, many sectors including agriculture have already been impacted negatively.
- Future increase in temperature and decrease in rainfall in the Arab region is expected to shorten the growing season and to decrease production of some staple crops including winter wheat and barley.
- Extreme events such as extreme heat and drought are also expected to have negative impacts on food production which will exacerbate the region's vulnerability and its dependence on import to secure food for a growing population.

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Impact of climate change on raw and untreated wastewater use for agriculture, especially in arid regions

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Climate change is one of the major challenges of our time that pose unprecedented stress to the environment and threats to human health. The global impacts of climate change are vast, spanning from extreme weather events to changes in patterns and distribution of infectious diseases. Lack of rainfall associated with higher temperatures has a direct influence on agricultural production. This is compounded by a growing population forecasted to expand further with increasing needs for food and water. All this has led to the increasing use of wastewater worldwide. In this review, we more specifically discuss the use of untreated wastewater in agriculture in the Middle East and North Africa (MENA) countries, the most arid region in the world. This presents challenges for agriculture with respect to water availability and increasing wastewater use in agri-food chain. This in turn exerts pressures on the safety of food raised from such irrigated crops. Current practices in the MENA region indicate that ineffective water resource management, lack of water quality policies, and slow-paced wastewater management strategies continue to contribute to a decline in water resources and an increased unplanned use of black and gray water in agriculture. Radical actions are needed in the region to improve water and wastewater management to adapt to these impacts. In this regard, the 2006 WHO guidelines for the use of wastewater contain recommendations for the most effective solutions. They provide a step-by-step guide for series of appropriate health protection measures for microbial reduction targets of 6 log units for viral, bacterial, and protozoan pathogens, but these need to be combined with new varieties of crops that are drought and pest resistant. More research into economic local treatment procedures for wastewater in the region is warranted.

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Water Science and Technology Association (WSTA)

Introduction

The Water Sciences and Technology Association (WSTA) was formed as a result of individual efforts of some of those concerned with water affairs in the Gulf Cooperation Council (GCC) Countries with an objective mainly to encourage and promote interest in water sciences and strengthen scientific ties among water professionals, encourage scientific research, training programs, and the development of local capabilities in the different fields of water sciences and technology.

The Government of Bahrain consented to register the Association in Bahrain, and the Association was formally founded in September 1987, to be the first scientific association in the field of water sciences and technology in the Arabian Gulf region. WSTA is a non-government organization and its membership is open to all water professionals in the GCC, water-related national and international organizations, educational institutes, consultants, and companies.

Activities and Achievements

A. Conferences

WSTA has organized a series of conferences under the title **Gulf Water Conference**:

1st October 10–13, 1992, Dubai. UAE Water and Development in the Gulf Region. Challenges of the Nineties

2nd November 5–9, 1994, Bahrain. Water in the Gulf. Towards an Integrated Management

3rd March 8–13, 1997 Muscat, Oman. Towards Efficient Utilization of Water Resources the Gulf

4th February 13–19, 1999 Bahrain. Water in the Gulf. Challenges in the 21st Century

5th March 24–28, 2001 Doha, Qatar. Water Security in the Gulf

6th March 8–12, 2003 Riyadh, Saudi Arabia. Water in the GCC. Towards Sustainable Development

7th November 19–23, 2005 Kuwait. Water in the GCC. Towards an Integrated Water Resources Management

8th March 3–6, 2008, Bahrain. Water in the GCC Towards an Optimal Planning Economic Perspective

9th March 22–25, 2010, Muscat, Oman. Water Sustainability in the GCC Countries. The need for a Socio-Economic and Environmental Definition

10th April 22–24, 2012, Doha, Qatar. Water in the GCC. Water-Energy-Food Nexus

11th October 20–22, 2014, Muscat, Oman. Water in the GCC States. Towards an Efficient Management

12th March 28–30, 2017, Bahrain. Water in the GCC States. Towards an Integrated Strategy

13th March 12–14, 2019, Kuwait. Water in the GCC: Challenges and Innovative Solutions

B. Symposia and Workshops

WSTA organized many symposia and training workshops:

October 1996, Kuwait. Symposium on Water Supply Fluoridation

March 8, 1998, Bahrain. Future of Desalination in the GCC Countries Workshop

The following workshops on the subject of The Future of Desalination Research WSTA organized in co-operation with the European Desalination Society (EDS)

1st September 8–11, 2002, L'Aquila, Italy. Operation and Maintenance: Performance Problems Workshop

2nd August 24–27, 2003, Amsterdam, Holland

3rd December 1–2, 2004, Bahrain. Capacity Building Workshop

On 3–4 April 2013, Al-Ain, UAE Environmental Impact Assessment workshop was held in collaboration with UAE University.

On 20–22 April 2015, Bahrain, WSTA organised a training course on Water Footprint Assessments for GCC and Arab Countries in collaboration with AWARENET, Arabian Gulf University and MENA NWC.

Moreover, WSTA conducted many training workshops, either during its conferences or separately. The Association recently held a workshop and training course on the "Quality of Irrigation Water in Oman" for a group of workers in the field of agriculture in April 2018, in cooperation with the Ministry of Agriculture and Fisheries in the Sultanate.

C. Affiliations

The Association is affiliated with a number of Regional and International NGO's and Institutions addressing the global water issues, most notably the European Desalination Society EDS. International Desalination Association IDA, Arab Countries Water Utilities Association ACWUA and Oman Water Society OWS. In addition, WSTA has established strong ties with many UN organizations (UNESCO, ESCWA, UNDP, UNEP, FAO and many more) working in the water sector to enforce its position as a pioneer in addressing the importance of conserving water and protecting water resources in the Gulf Region.

WSTA Board of Directors

For further information, please visit the WSTA website at: www.wstagcc.org

KISR
معهد الكويت للأبحاث العلمية
KUWAIT INSTITUTE FOR SCIENTIFIC RESEARCH

Kuwait Institute for Scientific Research

KISR is a pioneering, independent, national institute of scientific excellence. It was established in 1967 by Japan's Arabian Oil Company Limited, in partial fulfillment of its obligations under an oil concession agreement with the government of the State of Kuwait. KISR's initial role was dedicated to developing three fields of national importance: petroleum, desert agriculture, and marine biology. Since then, KISR's role and responsibilities have expanded greatly to include the advancement of national industry and the undertaking of studies to address key challenges, such as the preservation of the environment, sustainable management of Kuwait's natural resources, responsible management of water and energy, and development of innovative methods of agriculture.

KISR was restructured by an Amiri decree issued in 1973, under which it became directly responsible, via its Board of Trustees, to the Council of Ministers. The main objectives of the institute, as specified in the decree, were to carry out applied scientific research. In 1981, KISR's status was further reviewed, and its role reconfirmed in the development of scientific research and technology in the country. In addition, the law broadened the mission and entrusted the institute with undertaking research and scientific and technological consultations for both the governmental and the private sectors in Kuwait, the Arabian Gulf region and the Arab world, and encouraged collaboration with international institutes.

KISR's approach to meeting challenges is distinguished by a culture of openness, a commitment to our clients, and an integrated, cross-disciplinary approach. KISR routinely embarks on strategic partnerships with other regional and international institutes, agencies, and academic bodies, allowing an exchange of knowledge and expertise. Today, KISR is home to over 580 researchers and engineers and over 100 laboratories, housed at 9 locations, with growth expected through the implementation of a new strategic plan. KISR conducts scientific research and performs technological consultations, often in partnership with other regional and international institutions, for governmental and industrial clients in Kuwait, the Gulf region, and the rest of the world. These partnerships, driven by a philosophy of collaboration that runs deep within our culture, help build up our knowledge base, and facilitate the free flow of information, data, and expertise.

At KISR, we take pride not only in our scientific achievements, but our diversity as well. We are a melting pot of cultures, ideas, and disciplines, all dedicated to one common goal: putting science in action.

Vision

By 2030, KISR will be acknowledged internationally as the region's most respected science, technology, and innovation (STI) and knowledge gateway, and recognized as a driving force for sustainable economic prosperity and enhanced quality of life.

Mission

KISR leads and partners internationally to develop, deploy, and exploit the best science, technology, knowledge, and innovation for public and private sector clients, for the benefit of Kuwait and other countries facing similar challenges and opportunities.

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