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14th Gulf Water Conference

Water in the GCC... Towards Economic Efficiency and Financial Sustainability

13th - 15th FEBRUARY, 2022 | HILTON HOTEL, RIYADH

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Publisher / Editor-in-Chief: Miriam Balaban

Publishing Team: Naomi Balaban, Galina Bitler, Suzanne Trauffer

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Volume 263, July 2022

Desalination Publications

International Science Services

ISSN 1944-3994 (print)
ISSN 1944-3986 (online)

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Preface

The GCC countries are situated in one of the most water scarce regions of the world and have one of the lowest per capita share of freshwater resources globally, with values much below the threshold of absolute water scarcity of 500 m^3/year. In the last few decades, the GCC countries have witnessed an accelerated socio-economic, agricultural, and industrial development growth, which was associated with substantial increase in water demands. To provide these water demands, the GCC countries have primarily focused their efforts on the development and supply augmentation aspects of water management, manifested by development of groundwater, installation of desalination plants, expansion in the reuse of treated wastewater, in addition to dams construction.

To meet increasing domestic water demands, the GCC countries have resorted heavily to desalination. Currently, almost all of the municipal water supply systems rely on desalination in the majority of the GCC countries. However, desalination is associated with substantial financial cost and are energy-intensive affecting both the economies and the environment of the GCC countries. In addition to the challenges of meeting the rapid growth of municipal water demands, rates of per capita domestic water consumption in many GCC countries are considered excessive and are ranked among the highest in the world. This is attributed mainly to the provision of high quality domestic water supply service coupled with very heavy blanket non-targeted subsidies, which gives the consumers the false impression of water abundancy.

To fulfil the requirements of agricultural water demands, the GCC countries have relied on groundwater resources and to a lesser extent on treated municipal wastewater. A major concern is that the majority of groundwater resources in the region are non-renewable and are being extensively mined and rapidly depleting. Furthermore, renewable groundwater resources are being over-exploited beyond their replenishment rates leading to quality degradation due to saltwater intrusion. The loss of groundwater resources assets will have dire consequences on the GCC countries in terms of the loss of a long-term strategic water supply and the cost of the replacement water. Groundwater excessive withdrawal is attributed to many factors, the most important is poor irrigation practices with irrigation efficiencies ranked among the lowest in the world. Some of the reasons for such practices is inadequate monitoring of groundwater abstraction and absence of charges for groundwater withdrawal, providing no incentive for water conservation.

Notably, to meet the ever-increasing demand for water, the GCC countries have adopted a supply-side management approach for securing water supplies. This has forced the countries, increasingly, into more expensive and costly investments in water supply sources and infrastructure. The heavy financial, economic and rising environmental costs associated with such approach cannot be over-emphasized. Clearly, such approach cannot be a long-term solution to water scarcity in the GCC countries, and a new conceptual approach in managing the countries' limited and costly water resources will be required. The GCC countries will need to shift their emphasis from ensuring "**sustainability of supply**" to ensuring "**sustainability of consumption**", while achieving economic efficiency and financial sustainability as core objectives.

To achieve such shift, there are basically three types of policy instruments that can be implemented: structural & operational (e.g., metering, retrofitting water saving devices, flow control, recycling,), sociopolitical (e.g., education and awareness, building codes, appliances labeling,), and economic (incentives and disincentives). In this regard, economic policies instruments are more effective in achieving economic efficiency and financial sustainability and can complement and reinforce the use of the other two policy instruments.

In general, economic instruments involve the use of prices and charges to provide incentives to water users to utilize water efficiently and rationally. The purpose of water pricing policies is three-fold: 1) cost reflectivity (signal to users the true scarcity value of water and the cost of service provision as an incentive for more efficient water use); 2) environmental and resource protection (encouraging conservation and efficient use and recognizing environmental co-benefits); and 3) cost recovery (generation of revenues for the efficient operation of the present system, its maintenance, modernization and future expansion). A properly designed water pricing policy will direct subsidies towards guaranteeing water as human rights and that pricing is set proportional to volume of usage with heavy water users paying the most to achieve social equity.

On the other hand, one of the main problems threatening the sustainability of the water services in the GCC countries is the low cost recovery. Although water supply utilities in the GCC countries are considered among the top-ranked service providers in the world, the existing very high rates of subsidies result in very low cost recovery percentages. Moreover, unlike the water supply utilities, the wastewater sector in the majority of the GCC countries has literally zero cost recovery due to the absence of wastewater tariff for collection, treatment, and reuse. This creates a heavy financial burden on the countries fiscal budget, and holds the sector captive to government allocations, which are susceptible to oil-prices volatility, eventually influencing the general water services performance.

One of the measures that have been taken towards reducing the cost and alleviating the financial burden of water services is privatization. The majority of the GCC countries have moved to privatizing production where many desalination plants are built as independent water and power projects (IWPP), with desalinated water purchased by the government through a long-term plan. Still, the municipal water sector can benefit from the many advantages privatization can offer in the whole water supply chain, which has not been adequately investigated in the region yet.

The WSTA 14th Gulf Water Conference is advocating for a paradigm shift in the management of water resources in the GCC countries to move from the current emphasis on supply sustainability approach to a consumption sustainability approach, with its core objectives of economic efficiency of water uses and financial sustainability of water services. Moreover, the conference deliberations and results will be the GCC countries contribution to the selected UN Water topic for 2021 "Valuing Water" and for 2022 "Groundwater: making the invisible visible".

The WSTA 14th Gulf Water Conference is organized in the Kingdom of Saudi Arabia in collaboration with the Saudi Ministry of Environment, Water and Agriculture. 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) and the Saline Water Conversion Corporation (SWCC). The conference is supported and endorsed by the active UN organizations in the region of UNESCO Cairo Office, UN-ESCWA, and FAO; and the international and regional organizations of IWMI, ICBA, IDA, AGU, OWS, 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 Fourteenth 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.

Furthermore, we would like to express our thanks to the *Desalination and Water Treatment* Journal Editor, Miriam Balaban for giving us the opportunity to publish selected papers presented at the conference.

Prof. Waleed K Al-Zubari,
Chairperson
Conference Scientific Committee

Conference Objectives

Reviewing current policies and strategies related to economic efficiency and financial sustainability in the water sector in the GCC countries.
Informing policy and decision-making on the impacts of the use of economic instruments to achieve sustainable water consumption patterns in the GCC countries.
Identifying challenges and opportunities in implementing economic instruments to achieve sustainable water consumption under the prevailing socio-economic, environmental, cultural, and political conditions in the GCC countries.
Exchanging experiences and best practice case studies in the GCC countries and other countries in the region on achieving economic efficiency and financial sustainability in the water sector.

Conference Recommendations

On Achieving Water Sector Economic Efficiency and Financial Sustainability

1. To achieve high levels of security and sustainability of the water sector, the GCC countries need to shift their focus from ensuring the "**sustainability of supply**", which is currently prevailing in most of the water sectors in the GCC countries, to ensuring "**sustainability of consumption**", which can be achieved by moving towards the approach of "demand management, efficiency, and conservation". In this regard, economic tools (incentives and disincentives) represent the most effective tools for such transformation and to achieve economic efficiency and financial sustainability compared to the socio-political and structural-operational tools, and they can complement and reinforce them.
2. To incentivize the private sector to participate in the provision and management of water services, that is, in the entire water supply chain, which is expected to contribute to reducing the costs of water services and management and raising the levels of cost recovery, thus contributing to the financial sustainability of the water sector. However, this must be under a high-level and independent regulatory and supervisory system; experiences of some GCC countries in this field and the lessons learned to be disseminated.

On Desalination

3. Desalination represents the main source of drinking/domestic water, and its sustainability is an essential foundation for water security in the GCC countries. Therefore, there is an absolute necessity to enhance the joint GCC efforts to localize the desalination industry and increase its added value to their economies, including joint investment and manufacturing of spare parts and consumables, and coordinating research and education and training programs at the level of the GCC and Arab countries.
4. Intensifying research efforts in the field of reducing financial, economic costs and environmental costs of desalination, investment opportunities in desalination reject, and developing unified key indicators for the performance and operation of desalination plants and the desalination sector as a whole in the GCC countries.

On Surface Water and Groundwater

5. Improving groundwater reserves through managed aquifer recharge (MAR) various schemes (Aquifer Storage and Recovery, Aquifer-Storage-Transfer-Recovery, Soil Aquifer Treatment, rainfall harvesting), while taking into account health and environmental risks when using treated wastewater and the purpose for which it is stored, in order to assist in efforts to rehabilitate aquifers and to provide a strategic reserve of groundwater for emergency conditions, or for other uses such as meeting the requirements of the agricultural sector.
6. Regulating the use of groundwater basins through enacting and implementing comprehensive legislation that reaffirms the state ownership of groundwater and considers well owners as water users, establishing an appropriate institutional mechanism for stakeholder participation, and implementing economic stimulus tools by imposing appropriate tariffs on groundwater use on the basis of its economic value in order to provide a price-signaling mechanism and to raise awareness of the value of groundwater to aid groundwater rehabilitation efforts.
7. Maximizing surface water utilization through the development and implementation of rain and flood water harvesting programs to mitigate and take advantage of extreme events caused by climate change.

On Municipal Wastewater

8. Increasing wastewater collection rates, raising treatment levels, and maximizing reuse rates in the appropriate sectors through integrated strategies and plans for its reuse, developing required health and environmental risk management plans for the treated wastewater reuse, and motivating the private sector to use this renewable source through appropriate economic incentives.
9. Support research and development efforts related to maximizing wastewater utilization in areas other than irrigation, such as waste-to-energy programs and the beneficial use of sludge in the fertilizer industry.

10. Ensure the separation of medical wastewater (i.e., those generated from medical institutions, such as dispensaries, hospitals and medical complexes) from domestic wastewater, as well as educating the public not to dispose pharmaceutical wastes into domestic sewage systems (as well as chemicals), to reduce the possibility of transferring pharmaceutical substances, hormones and other medical substance into treated wastewater when reused.
11. Conduct research on the possibility of the transfer of emerging substances and compounds such as pharmaceuticals, hormones, heavy metals to plants when reusing treated wastewater in the final product in the long run.

On Municipal Water Management

12. Achieving best practices and international standards for drinking water supply and sanitation utilities in the GCC countries, which include customer satisfaction, service quality, capacity development and leadership programs, rationalization of operation and resilience, financial sustainability, infrastructure stability, and environmental commitment.
13. Management of non-revenue water levels in accordance with best international best practices and benchmarks to enhance the efficiency of municipal water supply and reduce its costs to contribute to enhancing the financial sustainability of municipal water supply utilities.

On Agricultural Water Management

14. Raising irrigation efficiency through the use of modern farming and irrigation systems and techniques and adopting smart farming systems and selecting drought- and salt-tolerant crops appropriate for the region.
15. Supporting research and development efforts to enhance water productivity and water efficiency in the agricultural sector, and integrating drylands-desert farming curricula into academic and vocational programs with the aim of reducing overall water consumption in the agricultural sector.
16. Providing farmers with incentives and appropriate training to adopt modern farming systems, and support their participation in the decision-making process, with the aim of raising their awareness and facilitating the implementation of administrative procedures.

On Industrial Water Management

17. Increasing water use efficiency and demand management in the oil and industrial sector, and enforcing industrial wastewater treatment and reuse programs through the enactment of appropriate legislation.
18. Ensuring that industrial wastewater is not discharged into the municipal wastewater collection networks by formulating and enacting necessary legislation as well as in the general land use planning and zoning.

On Addressing Climate Change Impacts

19. Inviting and encouraging governments, research institutions and researchers to benefit from the technical outputs of the project of the "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 formulate Adaptation plans.

On Management of Water Information and Decision Support Systems

20. Effective planning and management of water resources and making effective and sound decisions depends mainly on the availability of reliable water data and information for all major components of the water management system, including water sources, water users, water infrastructure, water quality, and system characteristics, spatially and temporally. Therefore there is an absolute necessity to establish a comprehensive national, or basin-wide, water management information system (MIS) to be used in the monitoring and modeling process and is linked to the decision-making and planning process.
21. To take advantage of the rapid developments in modern technologies in all aspects of hydroinformatics, such as data collection from on-site and remote sensors, cloud analytics and artificial intelligence, interactive dashboards and advanced access platforms, which are providing a new world of data and analytics open in the public domain. The GCC countries should take advantage of these developments to modernize all aspects of the water information data value chain - from data to information to knowledge - to generate insights to support decision making at all levels for planning and day-to-day operations.

The conference authorizes the Board of Directors of the Water Science and Technology Association (WSTA) to submit these recommendations to the Secretariat General of the Cooperation Council for the Arab States of the Gulf (GCC SG) for presentation at the Water Ministerial Committee meetings and to follow up on their implementation progress. The conference also requests WSTA to circulate these recommendations to relevant regional and national organizations and water-related forums, and to the Arab regional preparatory meeting for the comprehensive mid-term review of the International Decade of Action on Water for Sustainable Development (2018–2028).

Desalination and Water Treatment
www.deswater.com

263 (2022) xi–xii
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doi:10.5004/dwt.2022.28827

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Volume 263

Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2022.28193

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Hybrid desalination technologies for sustainable water-energy nexus: innovation in integrated membrane module development

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ABSTRACT

Global water scarcity is an imminent problem caused by the increasing water demand arising from population and economic growth. Against this background, technologies for water resource management and treatment have been developed steadily to meet the water demand targets. However, further advances are necessary for securing environmental and economic sustainability. The management of saline water and wastewater is one of the focus areas to tackle the problems of water scarcity and sustainability in the context of water desalination.

Hybrid desalination is one of the most practical and efficient technologies that can afford environmental and economic sustainability. Hybridization of multiple processes maximizes the advantages of individual technologies and minimizes their drawbacks. The overall research on desalination and research on hybrid desalination, in particular, increased by a compound annual growth rate of 16.6% and 21.8%, respectively, from 2011 to 2020. Meanwhile, in 2020, 10.7% of scientific articles and reviews dealt with hybrid technologies. Moreover, the advances in hybrid technology are not limited to academic research; they have been widely implemented in the desalination industry. Reverse osmosis–multistage flash (RO-MSF) hybrid technology has been adopted for the largest desalination plant in the world, with a total water production of 1,036,000 m^3/d in Ras Al-Khair, Saudi Arabia.

The synergetic impacts of hybridization have various benefits depending on the desalination processes selected. In an RO-MSF system, the hybridization leads to additional water production with higher water recovery compared to a standalone RO system. Improvement in energy efficiency is another advantage of hybrid technologies as observed in the case of membrane distillation–adsorption (MD-AD) hybrid system. However, the challenges of hybrid desalination technologies are the complexity of process design, optimization, and operations. In this paper, the case of a forward osmosis–membrane distillation (FO-MD) hybrid system is presented to identify the challenges and potential solutions for hybrid desalination technologies.

An FO process is driven by the osmotic pressure difference between two streams and produces water across a hydrophilic polymeric membrane. By using a saline solution, known as the draw solution, freshwater may be recovered from a targeted feed solution stream with relatively lower salinity. MD is a thermal membrane process that makes use of the difference in vapor pressure between hot and cold streams to transport water vapor across the membrane to a cold permeate solution. These two membrane processes (FO and MD) are selected to treat the produced water, which is a by-product in the oil and gas industry; produced water has extremely high salinity and complex organic composition and hence is one of the most challenging wastewater streams for water treatment. Since FO and MD employ two different energy potentials (i.e., osmotic and thermal energies, respectively), hybridization allows maximizing the use of available energy in target streams (i.e., produced water). To solve the challenge of complexity of hybridization, a novel integrated membrane module was developed for an FO-MD hybrid system.

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

To evaluate the performance of the FO-MD hybrid system for produced water treatment, synthetic produced water streams were prepared according to water quality references from a conventional oil and gas production facility. Separate FO and MD experiments were conducted to study the membrane-fouling phenomena of different produced water qualities. In addition, the FO-MD hybrid system is operated with varied combinations of produced water streams for sustainability evaluation. The experimental results demonstrate the great potential of the FO-MD hybrid system for sustainable produced water treatment. Long-term operation of the hybrid system and experiments with real produced water samples are necessary for scaling up and optimizing the technology.

Investigating the water–energy nexus related to the desalination technologies integrated with renewable energy is one approach to broaden the applications of hybrid desalination technologies. Such a study will emphasize the advantages of hybridization despite the complex challenges. The benefits of hybrid technologies in terms of greater water production, higher recovery, and cleaner water quality will be synergized with less energy consumption by their integration with renewable energy. Meanwhile, artificial intelligence (AI)-based process design, optimization, and control will be an important tool to address the complexity of hybrid desalination technologies and will provide a comprehensive understanding of the challenges, for which the conventional experimental and theoretical studies are still limited. AI algorithms, such as machine learning and artificial neural network algorithms, are the leading approaches to the advancement of AI-assisted smart desalination.

Keywords: Hybrid desalination; Water-energy nexus; Reverse osmosis–multistage flash; Forward osmosis–membrane distillation

Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2022.28194

263 (2022) 3–8
July

Levelized cost analysis for desalination using renewable energy in GCC

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Received 28 February 2022; Accepted 12 April 2022

ABSTRACT

Seawater desalination plants are considered the main source of fresh water in most of the GCC countries. Desalination is an energy-intensive process, where energy price represents more than 44% of the cost of desalinated water. Almost all commercial desalination plants rely on fossil fuel to secure the energy requirements either in thermal or electrical form. GCC countries are gifted with consistent and predictable solar energy that can be used to power the desalination processes and to improve their sustainability and to reduce their environmental impacts. Solar energy can be harvested using photovoltaics (PV) panels or different forms of concentrated solar power. In this paper, the energy cost in the form of levelized cost of energy (LCOE) was calculated for a PV solar energy generation plant and hence, the levelized cost of water (LCOW) for a reverse osmosis reference desalination plant in the six GCC countries had been estimated and compared. System Advisor Model (SAM) is a comprehensive renewable energy analysis software developed by the National Renewable Energy Laboratory and is used in this work. SAM relies on the metrological weather data for the evaluation of solar energy. The included financial model within SAM was used to estimate the LCOE and the Power Purchase Agreement price. A reference reverse osmosis desalination plant of a capacity of 400,000 m^3/d (88 MIGD) has been used in this study. The power consumption of the plant is estimated as 76 MW at 4.56 kWh/m^3. A photovoltaic power plant of capacity 76 MW was designed and the LCOE produced by this pant was estimated. The LCOE was different according to the PV plant location in GCC countries. The obtained LCOE is used to estimate the LCOW produced by this plant using Desalination Economic Evaluation Program software. The LCOE for the studied locations ranged from 8.46 to 9.11 ¢/kWh (1.0 USD $ = 100 ¢), and the LCOW ranged from 103.0 to 105.0 ¢/m^3, compared to 10.737 ¢/kWh and 110.1 ¢/m^3 for the conventional combined cycle power plant.

Keywords: Levelized cost of energy (LCOE); Levelized cost of water (LCOW); Desalination processes; Renewable energy; Solar desalination; System Advisor Model (SAM); Desalination Economic Evaluation Program (DEEP)

1. Introduction

Renewable energy can play a vital role in desalination. Renewable technologies suited to desalination include solar thermal, solar photovoltaics, wind, and geothermal energy [1,2]. Solar technologies based on solar heat concentration, notably concentrating solar power, produce a large amount of heat and is suited to thermal desalination. Photovoltaic (PV) and wind electricity are often combined with membrane desalination units (reverse osmosis, electrodialysis). As electricity storage is still a challenge, combining power generation and water desalination can be a cost-effective storage option when generation exceeds demand.

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

Renewable energy-based desalination provides a sustainable way for freshwater production. In the past decade, the cost of renewable desalination was higher than that of conventional desalination based on fossil fuels for energy input [1,2]. However, solar desalination is expected to become economically attractive as renewable technologies' costs continue to decline, and the prices of fossil fuels continue to increase. Using locally available renewable energy resources for desalination is likely to be a cost-effective solution, particularly in remote regions, with low population density and inadequate infrastructure for fresh water and electricity transmission and distribution [3].

2. Methodology

The key factor for utilizing renewable energy sources in desalination is the overall cost of freshwater production. The levelized cost of water (LCOW) represents the average cost for water production over the project life. The energy cost is presented by the levelized cost of energy (LCOE) and is used in the calculation of the energy cost in water. In this work, a reference desalination plant was selected for this investigation, as shown in Table 1. This plant was mainly operated using combined cycle power plants (CCPP). The LCOW of this plant is first evaluated based on the energy produced by CCPP. The required power for this desalination plant was estimated and then provided by a renewable energy power plant (REPP). The LCOE of these REPP was evaluated based on the latest cost of renewable energy equipment. The LCOE of the REPP is then used to estimate the LCOW based on renewable energy. Renewable energy sources are particularly site-dependent, and for this reason, the study includes an investigation of REPP in different GCC countries; Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, the United Arab Emirates, for comparison, Fig. 1.

The power needed for this desalination plant was estimated using the average specific energy consumption according to the technology type and plant capacity, among other parameters. The Desalination Economic Evaluation Program (DEEP) 5.13 software [5,6] was used to estimate the power and the LCOW based on the CCPP. DEEP estimates the LCOE of the combined cycle and uses this value to evaluate the LCOW. The combined gas-steam cycle was used with oil as the fuel. However, the LCOE using REPP is calculated and plugged into DEEP to evaluate the LCOW using renewable energy. System Advisor Model (SAM) software [7–9] was used to evaluate the LCOE of the REPP. SAM uses design DNI value from the weather data file along with other design parameter values to determine the nominal capacities of the solar field and other components in the system. The design DNI is different from the hourly DNI values in the weather file. The design DNI is used to calculate the nameplate capacities. For the reference reverse osmosis

Table 1
Reference desalination plants [4]

	Shuaiba-4
Status	Construction
Location	Shuaiba, Saudi Arabia
Location type	Land-based
Technology	Reverse osmosis
No. of passes	Two-pass
Pretreatment	Dual media filtration
No. of units	
Max. brine temp.	Atm. temp.
Feedwater type	Seawater
Capacity	400,000 m^3/d
Online date	2020
Award date	2017
User category	Municipalities
Est. EPC cost	SAR 1,600,000,000
Est. project cost	

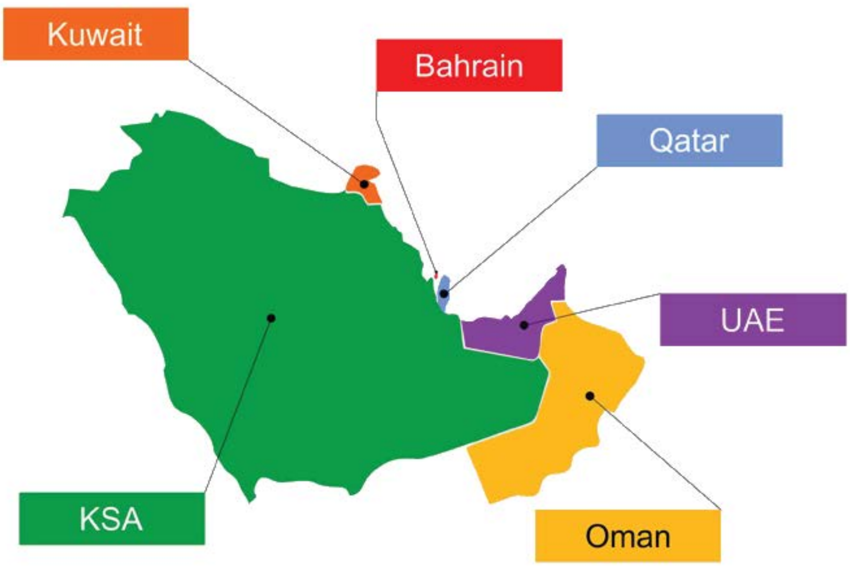

Fig. 1. GCC countries.

desalination plant, the required electric power is 76 MW. A photovoltaic power plant (PVPP) of capacity 76 MW was designed, and the LCOE is evaluated using SAM software as explained above.

3. Photovoltaic power plant economics

A 76 MW, net output capacity PVPP was designed using SAM 2020.11.29 software. The design steps started with choosing the PVPP location and specifying the weather data file. In this study, we downloaded the required weather data files from OneBuilding [10]. Details presented here are for PVPP using weather data obtained from Kuwait International Airport. The next step in the design procedure was to select the PV module and inverter. SunPower SPR-E19-310-COM PV panels were selected for this plant. The module's nominal efficiency was 19%, and the maximum DC power produced based on the reference conditions of 1,000 W/m² and PV cell temperature of 25°C was 310 W_{dc}. Other specifications of the module, along with the characteristics curve, are shown in Fig. 2.

A Power Electronics FS0450PU inverter was selected for this system; specifications and characteristics of the inverter is shown in Fig. 3. The next step was to size the system based on the needed capacity. SAM provides two methods for sizing the system, and we chose the automated estimation of the system configuration method.

For the case of Kuwait International Airport data, the following system sizing results were obtained from SAM.

Nameplate DC capacity: 91,198 kW_{dc}
Total AC capacity: 76,050 kW_{ac}
Total inverter DC capacity: 78,826 kW_{dc}
Number of modules: 294,048
Number of strings: 24,504
Total module area: 479,592 m²
String V_{oc} at reference conditions (V): 772.8
String V_{mp} at reference conditions (V): 656.4

The next step was to estimate the system cost. The cost of the modules and inverters, along with the balance of system (BOS) equipment, are evaluated from ATB [11], and supplied into SAM, Fig. 4. The total direct capital cost was 78,522,072 $.

The indirect capital cost includes the permitting and environmental studies, engineering, and development overhead

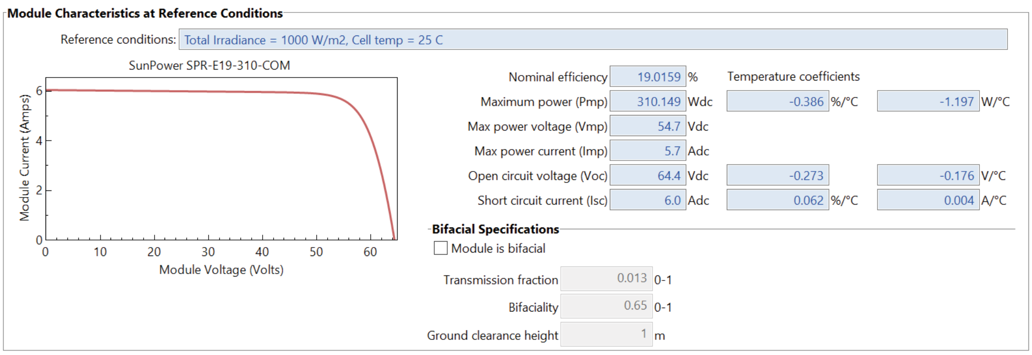

Fig. 2. SunPower PV module characteristics.

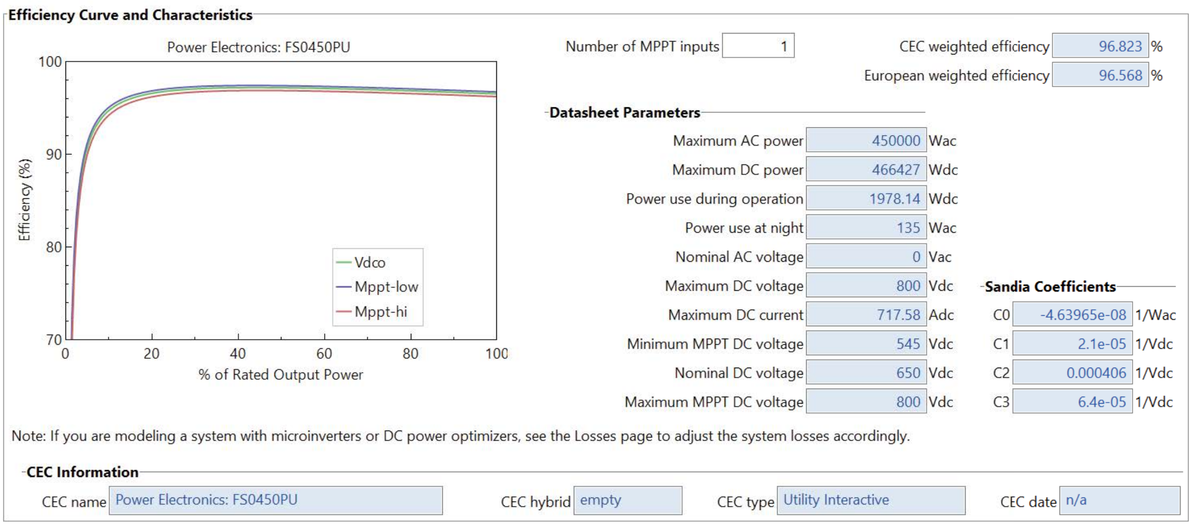

Fig. 3. Power electronics inverter characteristics.

along with the land cost, as shown in Fig. 5. It is worth mentioning that the sales tax is omitted in this study as it is not applied in many GCC countries.

For the PVPP in Kuwait, the total indirect cost was estimated to be 15,503,777 $, which results in a total installation cost equal to 94,025,848 $, and the cost per kW of the capacity was 1,133.0 $/kW. The project was financed by a loan for 60% of the cost of the total installed capacity, with an inflation rate of 2.5%/y and discount rate of 10%/y, project lifetime of 25 y, and no taxes. The LCOE of this plant was estimated at 9.045 ¢/kWh. For the private sector to be involved in these projects, the electricity was usually sold to the national grid authority according to a Power Purchase Agreement (PPA) price. For an internal rate of return (IRR) of 11% at the 20th year, the PPA was estimated to 9.102 ¢/kWh. This was the value that has been used in the evaluation of the LCOW using DEEP software. Table 2 shows a summary of the results obtained by SAM for the PVPP in different locations in GCC countries.

In Table 2, the real levelized cost is a constant dollar, inflation-adjusted value, while the nominal LCOE is a current dollar value, the same definition for the real and nominal PPA prices is applied [7]. LCOE is the total value of energy costs divided by the total energy generated. For the evaluation of the LCOW, the nominal PPA prices were used. The net present value (NPV) in Table 2 represents the time value of money and a discount rate for the cash flows, while the IRR is the discount rate that causes the NPV of electricity investments to become zero [12].

The values of the nominal PPA prices from Table 2 were used to calculate the LCOW using DEEP software, Table 3. For the conventional CCPP, the LCOE were estimated at 10.737 ¢/kWh, which was resulted in an LCOW of 1.1014 $/m^3, which was higher than all the values in Table 3.

Kuwait International Airport was not the optimum location for a PVPP. Two further sites in Kuwait were also studied for choosing better location; results are shown in Table 4. The LCOW for the three sites in Kuwait were also shown in Table 4. The Salmi site showed minimum freshwater cost. It is worth mentioning that, the Kuwait Institute for Scientific Research (KISR) built the first renewable energy park in Kuwait in Shagaya, near Salmi.

4. Conclusions

Renewable energy is a sustainable source for supplying energy for desalination. Like most renewable power generation technologies, PV systems are capital intensive but have no fuel costs. The LCOE for the studied locations ranged from 8.46 to 9.11 ¢/kWh, and the LCOW ranged from

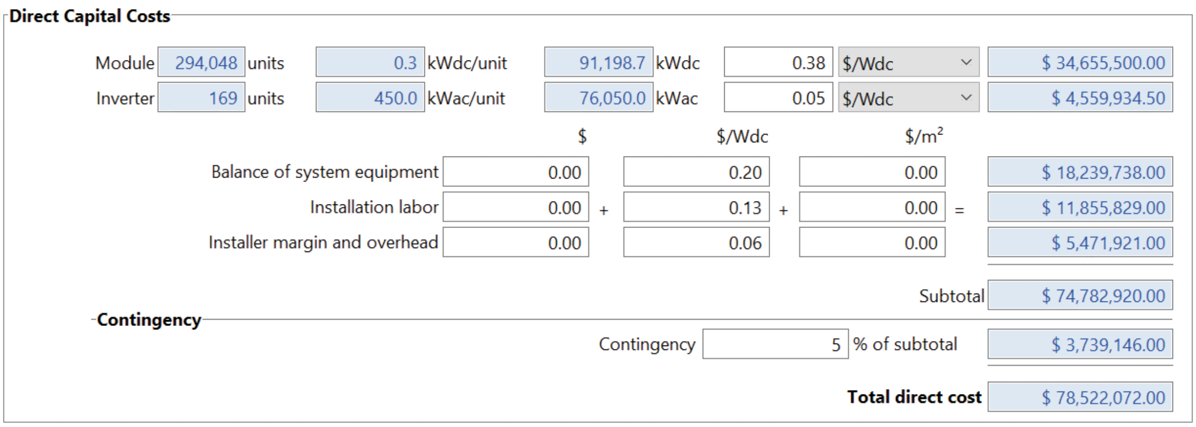

Fig. 4. Direct capital cost of PVPP in Kuwait.

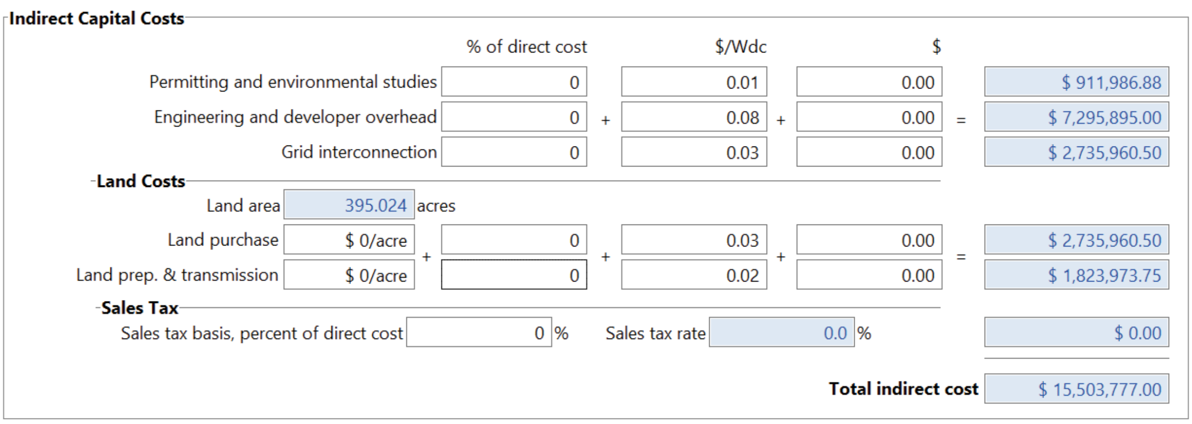

Fig. 5. Indirect capital cost of the PVPP in Kuwait.

Table 2
PVPP analysis results in GCC countries

Country	BHR	KWT	OMN	QAT	SAU	ARE
Location	Bahrain Intl Ap	Kuwait Intl Ap	Muscat Intl Ap	Doha Intl Ap	Riyadh Khalid Intl Ap	Abu Dhabi Intl Ap
Annual energy, GWh/y	173.040	169.449	170.985	175.046	173.154	176.449
Annual energy yield, kWh/kW	1,897.401	1,858.018	1,874.861	1,919.395	1,898.641	1,934.775
Capacity factor	21.660	21.210	21.403	21.911	21.674	22.086
Performance ratio, %	0.781	0.770	0.769	0.770	0.765	0.769
No of modules	294,048	294,048	294,048	294,048	294,048	294,048
No of inverters	169	169	169	169	169	169
Installation cost, $	103,343,968	103,342,432	103,346,832	103,345,840	103,343,800	103,345,784
Installation cost, $/kW	1,133	1,133	1,133	1,133	1,133	1,133
Size of debt, $	79,833,544	79,833,256	79,833,752	79,833,696	79,833,536	79,833,672
Size of equity, $	23,510,428	23,509,178	23,513,082	23,512,144	23,510,264	23,512,112
PPA price (year 1), ¢/kWh	8.354	8.529	8.459	8.261	8.348	8.195
PPA price (nominal), ¢/kWh	8.915	9.102	9.027	8.816	8.909	8.746
PPA price (real), ¢/kWh	7.353	7.507	7.445	7.271	7.348	7.213
LCOE (nominal), ¢/kWh	8.860	9.045	8.971	8.762	8.854	8.692
LCOE (real), ¢/kWh	7.307	7.460	7.399	7.226	7.302	7.169
Project NPV, $	690,553	691,413	689,471	689,799	690,597	689,875
NPV for PPA revenue, $	111,404,128	111,401,488	111,408,680	111,407,336	111,403,976	111,407,200
IRR target year	20	20	20	20	20	20
IRR in target year, %	11.00	11.00	11.00	11.00	11.00	11.00
IRR at end of project, %	13.07	13.07	13.07	13.07	13.07	13.07

Table 3
LCOW produced in different GCC countries

Country	BHR	KWT	OMN	QAT	SAU	ARE
Location	Bahrain Intl Ap	Kuwait Intl Ap	Muscat Intl Ap	Doha Intl Ap	Khalid Intl Ap	Abu Dhabi Intl Ap
PPA nom, ¢/kWh	8.915	9.102	9.027	8.816	8.909	8.746
LCOW, $/m^3	1.0427	1.0488	1.0463	1.0395	1.0427	1.0373

1.03 to1.05 $/m^3, compared to 10.737 ¢/kWh and 1.101 $/m^3 for the conventional CCPP.

The three key drivers of the LCOE of PVPP are:

- The capital and the installation costs of PV modules and BOS ($/W);
- The average annual electricity yield (kWh per kW); functions of the local solar radiation and the solar cells' technical performance;
- The finance cost of the PV system.

While desalination processes are still costly, declining renewable energy technology deployment costs are expected to bring the desalination cost down in the coming years, which is of particular interest to remote regions and

Table 4
PVPP and LCOW in three different locations in Kuwait

Country	KWT	KWT	KWT
Location	Kuwait Intl Ap	Failaka Island	Salmi
Annual energy, GWh/y	169.449	176.081	182.421
Annual energy yield, kWh/kW	1,858.018	1,930.740	2,000.264
Capacity factor	21.210	22.040	22.834
Performance ratio, %	0.770	0.778	0.779
No of modules	294,048	294,048	294,048
No of inverters	169	169	169
Installation cost, $	103,342,432	103,342,944	103,341,784
Installation cost, $/kW	1,133	1,133	1,133
Size of debt, $	79,833,256	79,833,456	79,833,280
Size of equity, $	23,509,178	23,509,488	23,508,502
PPA price (year 1), ¢/kWh	8.529	8.208	7.921
PPA price (nominal), ¢/kWh	9.102	8.760	8.454
PPA price (real), ¢/kWh	7.507	7.225	6.972
LCOE (nominal), ¢/kWh	9.045	8.706	8.401
LCOE (real), ¢/kWh	7.460	7.180	6.929
Project NPV, $	691,413	690,915	691,561
NPV for PPA revenue, $	111,401,488	111,402,888	111,400,896
IRR target year	20	20	20
IRR in target year, %	11.00	11.00	11.00
IRR at end of Project, %	13.07	13.07	13.07
LCOW, $/m^3	1.0488	1.0379	1.0279

islands with small populations and for areas of inadequate infrastructure for freshwater and electricity transmission and distribution.

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Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2022.28195

263 (2022) 9–14
July

Prospect of utilization of solar energy in SWCC existing multi-effect desalination satellite plants

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Received 28 February 2022; Accepted 12 April 2022

ABSTRACT

The shortage of drinking water source limits the socio-economic development of many areas of the world. Saudi Arabia has very limited resources in fresh water source and around 40%–50% of portable water in Saudi Arabia is produced by desalination technology which depends on using fossil energy. As the high cost of water and electricity production reflects depleting oil resources of the country which is non-renewable, solar energy would be a good alternative since Saudi Arabia has abundant free solar energy. This study investigates the feasibility of using concentrated solar power system (CSP) for thermal desalination. The study is conducted for CSP coupled with multi-effect desalination with thermal vapor compressor existed in western province Saudi Arabia in five locations with various DNI, for two cases, without storage and with 16 h storage. The total saving from coupling solar collectors to all five plants shows around 20.45 million $/y. Using of solar energy can reduce carbon dioxide emission to the environment by 420 thousand ton/y for all selected plants.

Keywords: Multi-effect desalination with thermal vapor compressor; Solar; Desalination; Cost of water (LCOW)

1. Introduction

Freshwater demand is persistently increasing as populations around the world keep growing and as existing freshwater reserves keep declining due to high consumption and pollution [1]. The worldwide capacity of desalination using renewable energy is less than 1% of that of conventional desalination due to high capital and maintenance costs associated with using renewable energy. Therefore, further techno economic evaluations are needed and are important steps to select the promising configuration before construction phase.

97% of the earth's water is available is salty water in the oceans and sea while only3% remained is fresh water. About 70% of the fresh water is frozen in the earth poles and the other 30% is ground water rivers, which used for drinking water [2]. Therefore this limited resources of fresh water is not enough to fulfill human requirement as drinking, industrial and agriculture use. Desalination can play an important solution of the scarcity of fresh water. Two main techniques are used in desalination: by evaporation or by using of a semi-permeable membrane to separate fresh water from a concentrate. Historically, seawater desalination has been the most expensive way to produce drinking water at the commercial scale because of the high capital and energy costs [3]. Fuel cost is major component of water unit cost almost 40%–50% of the water total cost. Many research works have been conducted to reduce the fuel cost by increasing efficiency and change fuel sources.

Solar energy considered as attractive source of renewable clean energy, which does not contribute to global warming. Attention has been directed towards improving

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

the conversion efficiency of solar energy systems. However, desalination technologies are highly intense power consumption industry. Optimization of coupling between desalination and solar system is highly attractive to enhance the economics of desalination which have reliable and renewable source of energy. Solar desalination is in particular attractive and promising in high solar radiation intensity countries such as KSA and Gulf countries in general. There are essentially two widely known methods to combine solar and desalination systems. The solar collection sub-system is used either to collect heat using solar collectors and supply it via a heat exchanger to a thermal desalination process or convert heat to electricity using photovoltaic cells to drive pressure driven technology; membrane desalination process (reverse osmosis).

2. Materials and methods

This project will focus on analyzing the operation data of the existing multi-effect desalination (MED) units located in red sea coast of Saudi Arabia, based on solar radiation data Fig. 1 shows the solar intensity in the kingdom and plants locations.

A techno-economic analysis was conducted based on mass and energy balances for the main components of the solar desalination system and cost estimation giving the total cost of water.

The selected locations solar data is shown in Table 1 [5].

Multi-effect desalination with thermal vapor compressor (MED-TVC) desalination plants have different production capacity varied from (8,000–18,000 m^3/d) and different performance ratio (8–10) detail heat and mass balance was carried out based on actual operational data to estimate the required energy to drive the unit all over the year. Estimation of required solar field was estimated using System Advisor Model (SAM) developed by the National Renewable Energy Laboratory (NREL) USA. An economic model developed and implemented on Excel tool by DTRI thermal team was used to evaluate the cost of water. Considering different thermal storage time (0 and 16 h storage).

2.1. Research objectives

The principal objective of the project is to conduct a feasibility study on the utilization of solar energy in thermal desalination plants in Saudi Arabia. The specific objectives can be expressed as:

To develop the appropriate design, configuration and operating conditions of solar assisted thermal desalination systems located in the Western Coast of Saudi Arabia.

To conduct technical and cost studies of the solar desalination system with and without storage for a 1-year period.

To evaluate the economic benefits of such integration.

2.2. Research methodology

The methodology of this project can be described as shown in Fig. 2.

SAM which is developed at the National Renewable Energy Laboratory (NREL), usually used to simulate solar field assisted power plants that simulate the concentrated solar power system (CSP) system by using solar data however, the solar field and related output would be extracted from SAM used as input to the generated in house excel file to calculate the specific water production cost. The procedure of calculation is shown in Fig. 2.

Table 1
Solar radiation at different location

Location	Radiation, kWh/m²/d
Al-Wajih	2,450
Umluj	2,300
Rabigh	1,900
Al-Qunfuthah	1,600
Frasan	1,485

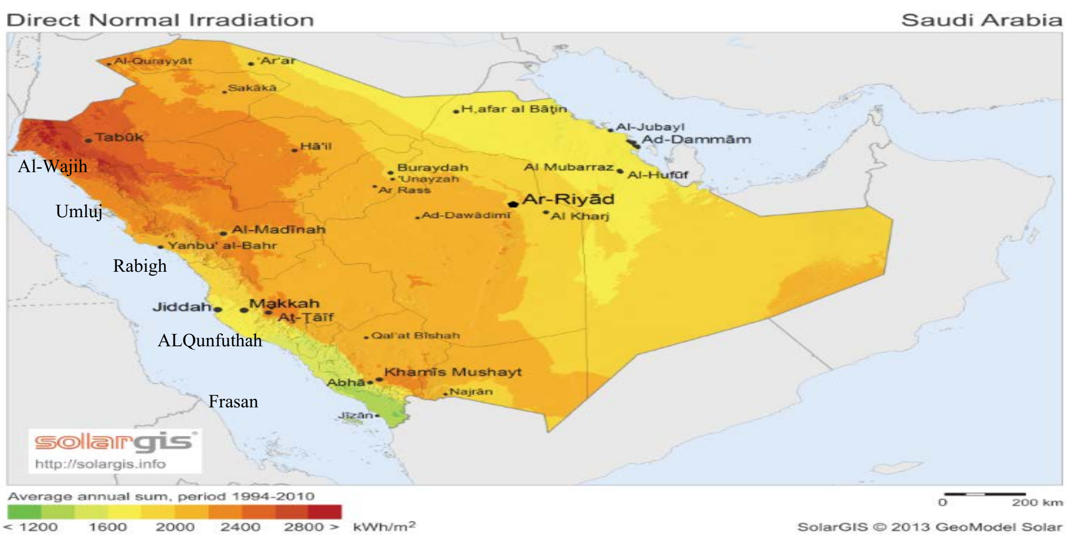

Fig. 1. Solar radiation in Saudi Arabia.

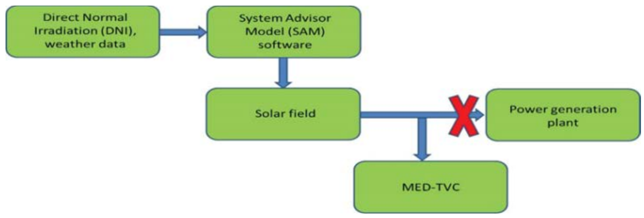

Fig. 2. Simplified diagram for the project methodology.

Table 2
Existed MED-TVC plants criteria

	Production (m^3/d)	PR	Availability
Al-Wajih	8,400	8.4	98
Umluj	12,100	9	97
Rabigh	17,600	9.4	98
Al-Qunfuthah	7,600	10	95
Frasan	7,400	7.9	98

The analysis is based on the conservation of mass and energy principles with technical specifications of the various components of the combined plant. Up to date prices for the various systems and fuels needed in the economic analysis is considered in order to have reliable results. Theoretical models based on the first law of thermodynamic for solar collector assisted MED-TVC will be developed. The solar collector will be simulated and designed by using SAM.

Several scenarios characterized by various configurations of solar collectors and desalination technologies and options on the use of storage system shall be considered and analyzed in the study. The comprehensive study will cover the following configurations:

Hybrid system Linear Fresnel assisted MED-TVC with back up fossil fuel.

Hybrid system Linear Fresnel assisted MED-TVC with thermal storage 16 h.

The proposed system can be described as in Fig. 3, which shown the hybridization of the solar system (power source) and the steam transformer which is used to produce the steam which drive the MED-TVC plant.

2.3. Mathematical model

An Excel program is used to evaluate the cost of water; it is linked between MED-TVC model and CSP model. Thermal energy required to operate MED-TVC plant calculated as in Eq. (1).

$$Q_s = \frac{\text{DT}}{\text{PR}} \times \left(H_{si} - H_{so}\right) \quad (1)$$

Then by using (SAM) the solar field area calculated based on required energy, form solar field area CAPEX of solar field calculated based on the values in Table 3. Then contingency and engineering, procurement and construction management cost (EPC) are added to the capital cost as percentage of total cost as 7% contingency and 11% EPC cost. The capital cost of solar system are calculated from following equations.

Table 3
Capital cost for CSP system based to SAM program

	LFR (steam HTF)	LFR (molten salt HTF)
Site improvement	20 $/m^2$	20 $/m^2$
Solar field	150 $/m^2$	150 $/m^2$
HTF system	33 $/m^2$	47 $/m^2$
Storage	32 $/kWht	32 $/kWht

Table 4
Operation cost of solar field [8]

	LFR
Operation cost of solar field	11.2 $/m^2$
Operation cost of storage	70 $/MWh/y

The capital cost of MED-TVC can be calculated as unit cost equal 1,542 $/m^3$/d [6], and operation cost of MED-TVC equal 0.18 $/m^3$/d including pumping cost [7]. Table 4 used to calculate the OPEX of solar field.

Back up fossil fuel calculated from the balance energy required as number of barrels, then multiply by the oil price from 10 to 100 $/bbl to calculate specific fuel cost $/m^3$.

Cost of water calculated from all previse information and calculation by the following method:

Find total capital investment by summation of all capital cost of integrated system

$$\text{Total CAPEX} = \text{CAPEX of solar} + \text{CAPEX of MED} + \text{CAPEX of boiler} \quad (2)$$

The LCOW calculated by using the following equation which depend of economic methods [9].

$$\text{LCOW} = \frac{\text{CRF} \times \text{CAPEX} + \text{OPEX} + \text{Backup fuel cost}}{\text{Water production}} \quad (3)$$

where (CRF) the capital recovery factor is generally used to find out the uniform annual amount 'CAPEX' of a uniform series from the known present worth at a given interest rate '*i*' per interest period (n) [10].

$$\text{CRF} = \left(\frac{z(1+z)^n}{(1+z)^n - 1}\right) + k \quad (4)$$

where z is discount rate assumed as 0.05; n is amortization period per year assumed 20 y; k is yearly insurance assumed 0.01.

3. Results and discussion

A techno economic analysis was performed for MED-TVC desalination plant based on average plant production, performance ratio and availability extracted from actual data. Fig. 5 shows the variation of water cost with oil price for each plant simulated as operated 8 h by using Linear Fresnel and the rest of the day by back up fossil fuel. Then compared with conventional plant operated by fossil fuel only, which presented as dotted line in the figure this would give a clear criterion for the economic benefits via different oil prices.

As expected, the best economic benefits are obtained when the solar radiation is high with high performance MED. Frasan was found as the worst unit for coupling solar with MED-TVC desalination unit that since it has low DNI and low performance (efficiency) plant. On the other hand, Umluj was found to be the best option for such configuration. Detail analysis is shown in Figs. 5 and 6 for different storages. However, all the plants are economically feasible almost at oil price of 25 $/bbl, except for Frasan plant, which is feasible at 45 $/bbl, which present the worst case.

Table 5 summarizes the main results at international oil price (60 $/bbl). It shows the feasibility, water cost and saving for each plant when coupled with LFR without storage.

Fig. 6 shows variation of water cost with oil price for individual plants simulated as operated 24 h by using LFR. MED-TVC plant, using of LFR for 16 h shows water cost stability at high oil price is more economically feasible than conventional MED-TVC and LFR assisted MED-TVC without storage. Additionally, in this case the plant performance is more effective and the breakeven cost starts at 30 $/bbl for the best performing plant Umluj and shows a breakeven point of around 50 $/bbl for worst plant, which is Frasan.

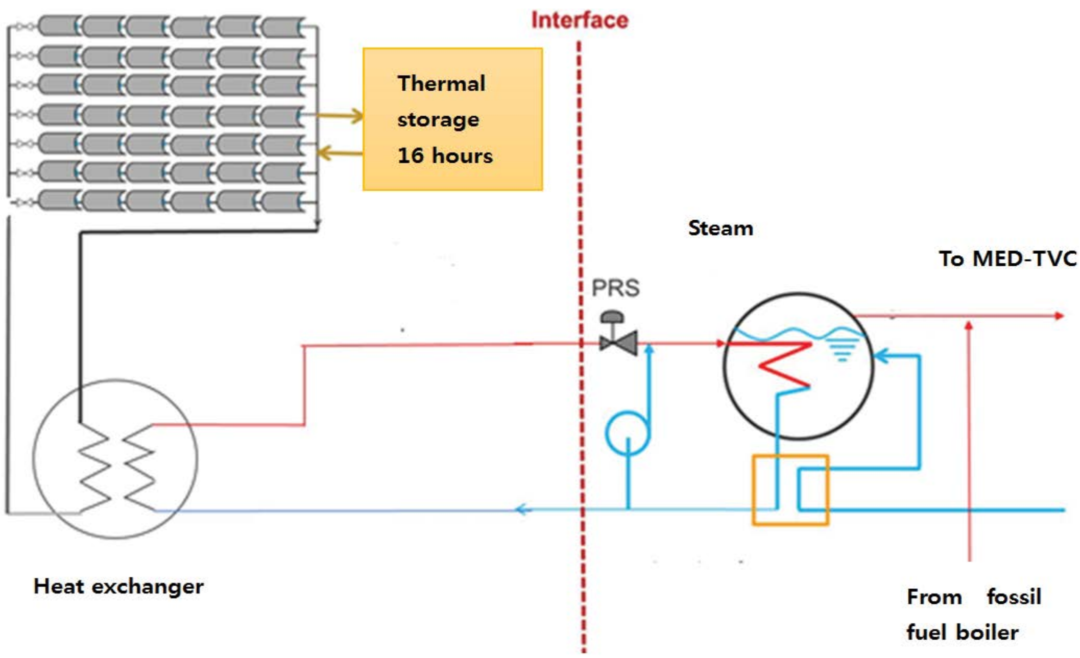

Fig. 3. Configuration of CSP coupled with MED-TVC.

Table 5
Simulation results for case LFR-MED-TVC without storage

@Oil price 60 $/bbl. CSP + MED-TVC (0 h storage)	Conventional MED-TVC	Al-Wajih	Umluj	Rabigh	Al-Qunfuthah	Frasan
Unit production, $/m^3$	3.48	2.81	2.82	2.79	2.73	3.33
Gain output ratio, kg product/kg/steam	9	8.4	9	9.4	10	7.9
TBT	65	65	65	65	65	65
Motive steam pressure	8	8	8	8	8	8
Solar field area	0	49,305	65,741	106,829	54,362	57,523
Solar operational hours	0	8	8	8	8	8
Plant production	9,000	8,400	12,100	17,600	7,600	7,400
Amortization period year	25	25	25	25	25	25
Operation cost (MED + CSP), $/m^2$	0.27	0.45	0.44	0.45	0.51	0.49
Carbon dioxide reduction, T/Y	0	27	34	53	21	25
Total saving million, $/Y	0	2	2.9	4.4	2.08	0.41

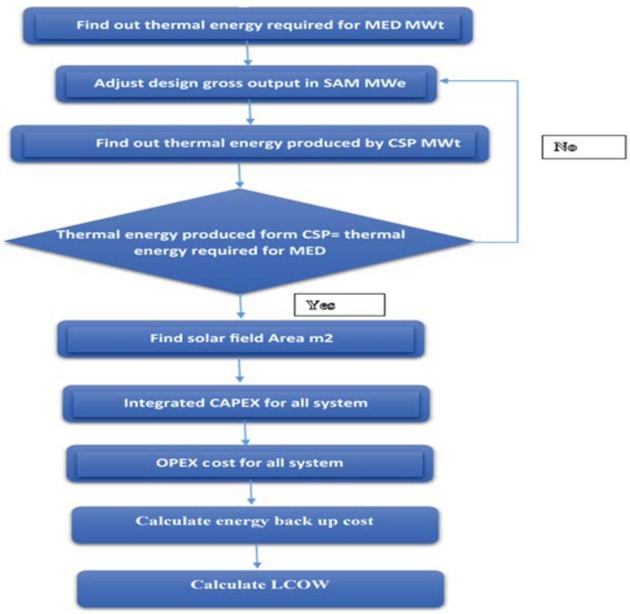

Fig. 4. Description of the general calculation procedure of project.

The cost of water and saving in \$/y is shown to be better when using 16 h storage comparing to LFR without storage.

4. Conclusions

A techno economic analysis of combination between CSP and MED-TVC was carried out for five existed MED-TVC plants located at western region of Saudi Arabia (Al-Wajih, Umluj, Rabigh, Al-Qunfuthah and Frasan). Energy consumption of MED-TVC calculated by the information from each plant based on plant capacity, performance ratio, Temperatures and pressures. Based on energy requirement, simulation was conducted to couple these plants with Linear Fresnel collector to provide a thermal energy required to run such units. SAM was used to simulate leaner Fresnel with different thermal storage capacity (0 and 16 h storage) and the coupled systems were simulated by using Excel program. All cases were compared with conventional MED-TVC (running by fossil fuel) as a reference to find out the breakeven cost with different fossil fuel price. The main issue in these plants is fuel consumption which is too high (14.3 kW/m^3).

Using of LFR coupled with MED-TVC is feasible average of breakeven cost for all plants is 25 \$/bbl. for zero-hour

Table 6
Simulation results for case LFR-MED-TVC with 16 h storage

@Oil price 60 \$/bbl. CSP + MED-TVC (16 h storage)	Conventional MED-TVC	Al-Wajih	Umluj	Rabigh	Al-Qunfuthah	Frasan
Unit production, \$/m^3	3.48	2.41	2.1	2.35	2.6	2.97
Gain output ratio, kg product/kg/steam	9	8.4	9	9.4	10	7.9
TBT	65	65	65	65	65	65
Motive steam pressure	8	8	8	8	8	8
Solar field area	0	158,021	195,645	3461,41	173,256	195,645
Solar operational hours	0	24	24	24	24	24
Plant production	9,000	8,400	12,100	17,600	7,600	7,400
Amortization period year	25	25	25	25	25	25
Operation cost (MED + CSP), \$/m^2	0.27	0.86	0.77	0.88	0.98	1.09
Carbon dioxide reduction, T/Y	0	70	93	136	54	67
Total saving million, \$/Y	0	3.3	6.09	7.25	2.44	1.37

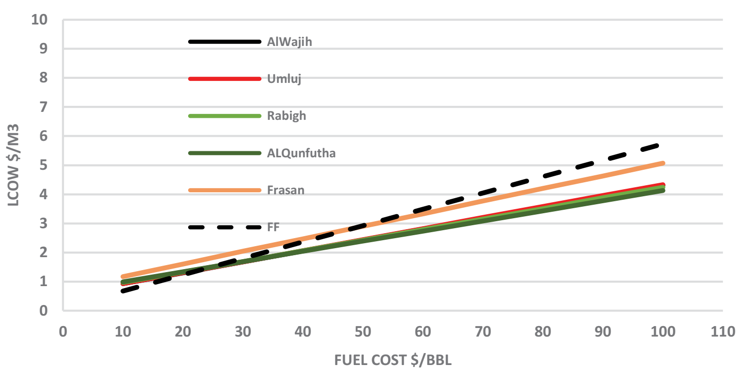

Fig. 5. Variation of water cost without storage.

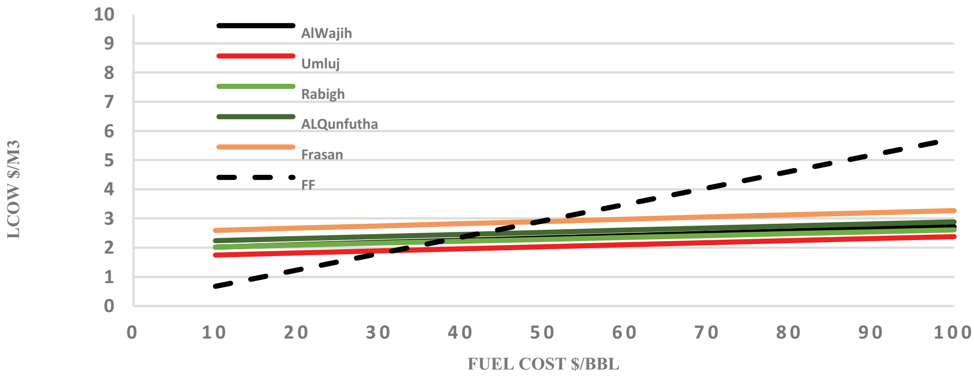

Fig. 6. Water cost vs. oil price 16 h storage.

storage case except Frasan plant at 50 $/bbl. For 16 h storage the difference appear in breakeven cost between each plants. The lower breakeven cost was shown in Umluj plant where higher performance ratio and very high DNI breakeven cost of 32 $/bbl compared to Frasan which has low performance and low DNI and shows the higher breakeven cost 50 $/bbl. The results also show that using of 16 h storage is more feasible than other cases when the LCOW calculated based on unsubsidized fuel cost (60 $/bbl), and using zero-hour storage is more feasible when fuel cost from 25 to 40 $/bbl. According to the results including fuel transportation cost the using of 16 h storage is more feasible than other cases in all fuel cost from 35 to 100 $/bbl and the total saving from coupling solar collectors to all five plants shows around 20.45 million $/y. Also, the main side effect of using fossil fuel is pollution and the results show that using solar energy can reduce carbon dioxide emission to the environment by 420 thousands ton/y for all selected plants.

Next step would be a validation test for different solar collector and to select the most efficient and cost effective scheme to be coupled with actual plant in selected SWCC plant. The project is in progress. Such technology, coupled with high efficient thermal MED would be a breakthrough in thermal desalination.

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Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2022.28198

263 (2022) 15–24
July

Toward developing key performance indicators for desalination processes

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Received 28 February 2022; Accepted 12 April 2022

ABSTRACT

Key performance indicator (KPI) is a discipline that involves articulating what an organization is trying to accomplish and afterward identifying the most meaningful and useful indicators of success. KPI is a key part of a strategic management system. Noteworthy KPIs provide information into whether strategies are working, and programs, objectives and goals are accomplished. In this work, KPIs principles will be reviewed. Then the strategic objectives and goals for operating desalination plants in effective manner will be utilized to develop viable strategic plan, set initiatives and programs to achieve certain objectives and goals in the field of water desalination. Operational performance measures will be used to identify the applicable and appropriate KPIs. KPIs for water desalination plants are convenient tools in assisting to manage practical operation of the plants.

Keywords: Performance; Metrics; Key performance indicators; Performance indicators; Strategic plan; Water strategic plans; Desalination

1. Introduction

Key performance indicators (KPI) focus on the aspects of organizational performance that are the most critical for the current and future success of the organization [1]. KPI can be defined as a measurable value that is used to demonstrate how effectively strategic goals or objectives are achieved.

According to the Intrafocus Guide, a key performance indicator may be counted, compared and provided evidence that an objective is being attained over a specified time [2]. These key words are explained in the Intrafocus Guide as follows [2];

Counted: This may seem a little trite, however, counted means that a quantity can be assigned. Examples of quantity are number, percentage or currency. It does not mean a percentage achievement. One of the most frequent mistakes in setting KPIs is to create a project and assess its success through how much work has been done. Just because a project has been completed does not mean it has been a success. Success is dependent on the outcome not the activity.

Compared: A number or value may be interesting, but it only becomes useful when it is compared to what is optimal, acceptable or unacceptable. Every KPI must have a comparator or benchmark. Using an industry benchmark gives an objective quality to the comparator, objectivity is not required, but it is desirable.

Evidence: The evidence will fall out by 'counting' and 'comparing' correctly. It is important to strive for a measure that will be observed in the same way by all stakeholders. The evidence should be clear and have specific meaning.

Objective: A KPI only has significance if it is contributing to an objective. If there is no objective, why is it being measured in the first place? This does not mean we should ignore all operational measures; they still need to be in place – but even operational measures should ultimately contribute to an objective.

Specified time: Everything is time bound; progress towards meeting an objective and therefore a strategy must be measured over a specified period.

Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

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The term indicator must comprise some basic requirements, such as [3]:

- indicators should represent targets effectively,
- they should be simple and easy to interpret,
- they should be able to indicate time trends,
- they should "respond" to changes within or outside the organization,
- the relevant data collection and data processing should be easy,
- they should be updated easily and quickly.

KPIs provide the most important performance information that enables organizations or their stakeholders to understand whether the organization is on track toward its stated objectives or not [4]. In addition, KPIs serve to reduce the complex nature of organizational performance to a small, manageable number of key indicators that provide evidence that can in turn assist decision making and ultimately improve performance.

KPIs should enable the organization to identify the criteria against which it can measure its performance against each strategic priority, which match up to the organization's long-term objectives. KPIs will determine the extent to which the strategies have been achieved. KPIs are measures that provide some feedback on performance. They should be related to the strategies and could include quality, quantity and time components. Other benefits of having KPIs are as follows [5]:

- Serve as a communication tool to keep individuals within an organization up to date with the group's progress or performance.
- Provide a self-explainable snapshot of the performance against the set objectives.
- Encourage and establish responsibility and accountability.
- Support the organization strategic goals.
- Constitute a transparent tool to view and communicate the organization performance at all levels.
- Objectively measure individuals and business units' contributions.
- Unite or align individuals and teams towards a common goal.
- Highlight opportunities for improvement and strengths.
- Encourage competitively and initiative.
- Promote consistency, continuity, and continuous improvement.
- Can enable an organization to gain a competitive advantage when they are set wisely.

Successful KPIs rely on effective objectives and goals. Objectives and goals need to be SMART to be effective. SMART stands for specific, measurable, achievable, relevant, and time-bound, such as:

- Specific (simple, sensible, significant).
- Measurable (meaningful, motivating).
- Achievable (agreed, attainable).
- Relevant (reasonable, realistic, and resourced, results-based).
- Time bound (time-based, time limited, time/cost limited, timely, time-sensitive).

In this regards, KPI serves as a convenient tool in assisting to manage practical operation of the desalination plants. So operational performance measures will be used to identify the applicable and appropriate KPIs for water desalination plants. This will be performed after the development of viable strategic plan based on setting initiatives and programs to achieve certain objectives and goals in the field of water desalination.

2. Development of strategic plan

The basic aim of strategic planning is to establish definitively the nature and character of an organization and the sector that it represents and to manage its future development [6]. Within the strategic planning process, goals, priorities and strategies are established and the measures needed to evaluate the success of these goals are defined. So a strategic plan represents an integrated set of strategic goals and operational objectives and activities needed to achieve a desired result (often defined as an organization's "mission" or "vision") [6].

The characteristics of strategic planning may be defined as follows [6].

It considers the environment in which an institution operates: strategic planning relies largely on the results of an external analysis of the environment in which an organization operates and which the organization has very little influence over. Different environmental factors, such as demographic trends, the macroeconomic situation, political trends, social tendencies, etc., may have a decisive impact on the organization's results.

Provides a mid-term framework for the organization's operations: The strategic plan is, amongst other things, developed in order to maintain the continuity and consistency of an organization's activities. This leads to the development of a plan with the longest possible timeframe. At the same time, constant changes within the environment require flexibility, whereas long-term planning reduces the precision of a plan. Thus, three to 5 y represents a good option for a strategic plan timeframe.

It is a dynamic process: Due to the fact that the environment is ever changing and that it is very difficult to forecast future events, planning is a continuous process. Consequently, adjustment of the plan to new circumstances within the environment has to be done on an annual basis.

It is the basis for the allocation of resources: The strategic planning process has to be integrated within the budgetary planning process in order for a plan to be feasible. In this way, the final allocation of resources reflects the selected priorities that contribute to the development of the sector for which it is responsible.

The major difference between strategic planning and long-range planning is in emphasis [7]. Long-range planning is generally considered to mean the development of a plan of action to accomplish a goal or set of goals over a period of several years. Table 1 illustrates the differences between strategic planning and conventional long-range plan.

Strategic planning allows an organization to become as successful as it possibly can be. It serves as a roadmap to the organization's future. A well-developed strategic plan should contain the basic information necessary to begin the formulation of an integrated performance measurement system as shown in Table 2 [8].

The quality of a strategic plan depends on the mode used to organize the strategic planning process within the organization [6]. Some of the key elements of such a process are [6]:

- presence of strong leadership and vision amongst the organization's management,
- an approach that presumes high levels of participation and consultation with a wide range of employees within the organization and with external stakeholders that are part of the strategic process,
- a specifically developed approach that uses best practice examples, but adjusted to correspond to the specific needs of the organization and the resources that it has at its disposal,
- collection of hard evidence used to inform the process of establishing strategic goals,
- a realistic assessment of resources and available human capacity,
- review of a wide range of views and priorities prior to taking decisions with the aim of reaching consensus,
- new ideas and continuity that ensure that the strategic plan, as well as the strategic planning process, is regularly analyzed and revised.

Table 1
Strategic planning vs. conventional long-range plan

Strategic planning	Conventional planning
External focus	Internal focus by the Chief Procurement Officer (CPO)
Process oriented a stream decisions by the Chief Executive Officer (CEO)	Product oriented, for example, the approved master plan
Dynamic and change oriented	Emphasizes stability
Innovation and creativity	Relies on tried and tested
Vision of the future that guides decision-making	Blueprint for the future that is to be carried out

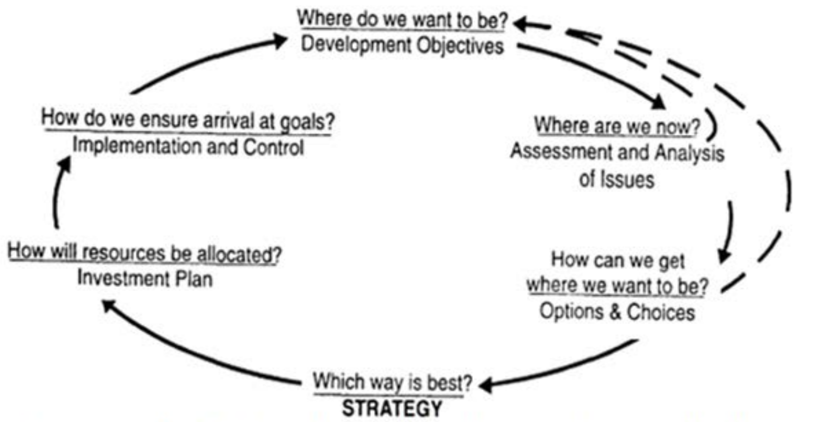
Sources: M. Meredith, R.G. Cope, O.T. Lenning, Differentiating Bona Fide Strategic Planning from Other Planning, U.S. Department of Education, Washington, DC, ERIC, ED 287 329, 1987.

Table 2
Strategic plan elements and performance measurement attributes [8]

Strategic plan elements	Performance measurement attributes
Strategic goal	Articulates the enduring mission or "end state" desired
Objective	Describes the strategic activities that are required to accomplish the goal
Strategy	Defines strategic (long-term) requirements that link to objectives. Typically contain dates, basis of measurement, and performance aspirations (targets)
Tactical plans	Identifies the short-term requirements that link to strategy. Typically contain cost, time, milestone, quality, or safety attributes as well as performance targets

Table 3
Process used to define strategic goals and programs

Steps	Actions
Setting strategic issues	- Setting strategic (priority) issues.
	- Consolidating a list of strategic issues.
Establishing strategic goals	- One strategic goal to be determined for each of the strategic issues.
	- To analyze each of the strategic goals against SMART criteria.
	- Development of a final strategic goals list (up to 3–5 goals max.).
Establishing strategic programs	- To establish a list of programs/activities needed to realize the goal.
	- To determine carriers and deadlines/dates of implementation for each of the programs/activities.
Determining priorities	- Determining prioritization criteria.
	- Sorting programs/activities in accordance with the criteria established.
	- Determining of the final programs/activities list according to priorities.



Source: A Guide to the Formulation of Water Resources Strategy, Edited by Guy Le Moigne, Ashok Subramanian, Mei Xie and Sandra Giltner, World Bank Technical Paper Number 263, 1994.

Fig. 1. The strategic planning cycle.

The strategic planning process steps are outlined in Table 3. SWOT (Strengths, Weaknesses Opportunities, Threats) is used to assess the strengths, weaknesses, opportunities, and threats that are strategically important to the organization. SWOT may be included in the strategic plan but as supporting documentation.

Fig. 1 illustrates an overall strategic planning cycle. Development objectives and key policies provide the platform from which to launch an assessment and analysis of issues. The examination of major issues and the evaluation of options may reflect back on development objectives, as illustrated by the dotted lines in Fig. 1.

3. Desalination issues emphasized in the Saudi National water plans

An early "Assessment and Strategic Plan" of the water sector was carried by Ministry of Economy and Planning in 2010 in collaboration with GTZ International Services/ Dornier Consulting. The Ministry of Water and Electricity (MOWE)[1] issued in 2014 a draft of the National Water Strategy 2014 (NWS 2014) with technical assistance provided by The World Bank [9]. The NWS 2014 has developed a guideline about water portfolio management till 2030 including all water use (agriculture, industry and municipal). MOWE works on the preparation of the strategy for some decade. The following are general directives from the Saudi Arabia's Five Year Development Plans[2] regarding the development of National Water Strategy which were proposed by MOWE.

- The Sixth National Water Plan (1415–1420, 1995–2000): Preparation of the National Water Strategy during the Sixth Development Plan to achieve optimal utilization of water and conservation of its sources.
- The Eight National Water Plan (1425–1430, 2005–2010): Completion of the preparation of the Eight National Water Plan.
- The Ninth National Water Plan (1430–1435, 2010–2015): The plan ensures the completion of National Water Strategy that involves spatial database compilation, water usages statistics, and mechanism and procedures for implementation. The Ninth Plan will also enhance implementation efficiency of water policies, focusing on the demand side of water management, along with supporting and developing water-saving technologies.
- The Tenth National Water Plan (1435–1440, 2015–2020): accelerate the approval of the National Water Strategy and implementation of its comprehensive plan.

Eventually, the National Water Strategy of 2014 was not officially approved. The following is an extract from the National Water Strategy of 2014 regarding desalination issues [9].

[1]The Ministry of Water and Electricity (MOWE) is a former Saudi ministry that was responsible for supervising water and electricity in Saudi Arabia. The Ministry of Environment, Water and Agriculture (MEWA) was established by virtue of the Royal Decree number (A/133), dated 30/07/1437 AH (May 8, 2016), upon which the "Ministry of Water and Electricity (MOWE)" was abolished, and the name of the Ministry of Agriculture (MOA) was changed to the Ministry of Environment, Water and Agriculture (MEWA), and transfer the tasks and responsibilities related to the environment and water activities to it.

[2]Saudi Arabia used five-year development plans to report on achievements, statistics, and present the goals and objectives of the Kingdom for the proceeding five years. Saudi Arabia has pursued ten successive five-year development plans (1970–1975 to 2015–2020). In 2016, "Saudi Vision 2030" was launched, providing an ambitious blueprint to restructure the Saudi economy, lessening its dependence on oil and creating more socioeconomic opportunities. More details are included in the National Transformation Program 2020 (NTP) and the Fiscal Balance Program 2020 (FBP), both also launched in 2016.

- The trade-off between groundwater use and reliance on desalination

  Desalination is seen as a viable alternative to securing water for towns and cities to the extent that nowadays more than 60% of the water supply comes from desalination plants. But as population and economic growth continue on a fast track, it would be unreasonable to assume that all the growth in municipal and industrial water demand will have to be absorbed by new investments in desalination plants.

  First MOWE needs to introduce strong water demand management measures (metering, realistic pricing, reduction of distribution losses) to curve down demand before embarking in a systematic desalination plant build-up. Second, the desalination option should be considered as part of a wide range of supply options during the integrated planning process with due consideration to the optimization of technical, economical and environmental aspects.

  Desalination may prove to be the best new supply option for high-valued uses of water in coastal regions where efforts to maximize efficiency are being made and where absolute supply constraints are severe. For inland supply at long distances from the desalination site it is imperative to consider the cost structure for fresh or brackish groundwater produced, treated, and supplied locally. In brief, only after an accurate assessment of the local hydrological and economical conditions has been drawn up is it possible to develop a well-considered action plan for the development of additional desalination capacities.
- Optimizing desalination as a source
- Each desalination project will be fully assessed on a case-by-case basis

  Given the high cost of desalination water, it will be used as a strategic water supply alternative as appropriate. Since each desalination project is unique and depends on project-specific conditions and considerations, each project will be evaluated on a case-by-case basis, with transparency and public participation throughout the planning, design and evaluation processes. An EIA will be conducted for all desalination facilities, and mitigation plans will be put in place to minimize and mitigate unavoidable environmental impacts. Projects will have to ensure equitable access to benefits from desalination and avoid disproportionate impacts particularly to vulnerable communities. This rigorous evaluation of projects and the associated disclosure and participation aspects and EIAs will ensure optimization of benefits (and minimization of costs) to society and the environment.
- Desalinated water will be assessed within a balanced supply package

  Desalination has high financial and environmental costs, and the energy cost is rising. Utilities will, therefore, consider all alternatives before opting for new desalination sources, based on studies of benefits, costs and environmental impacts for desalination compared to other water supply alternatives available to that area. Energy needs to be realistically priced in these studies. The water supply plan will provide, wherever possible, for transfer of part of groundwater saved in irrigation to municipal uses. Wherever possible, further renewable resources will be mobilized. However, in most cases (save some areas in the Shield) renewable water resources are a minor source, unlikely to figure largely in the water supply plans.
- The Kingdom will further develop its global leadership in renewable energy-desalination

  Saudi Arabia can become a leader in renewable energy (RE) desalination technologies and will therefore continue its strategic support to R&D in desalination processes, in the use of RE for desalination, and in mitigation of desalination-related environmental impacts. Saudi Arabia will develop knowledge management for desalination, disseminating monitoring results on desalination and creating a database and repository for storing and disseminating information. All desalination investment will seek to leverage new technologies for desalination and RE. The Kingdom will also benefit from its global leadership in desalination as well as strong capacity already existing at Saline Water Conversion Corporation (SWCC) by building industries around the technologies. Given the rising costs of energy, Saudi Arabia will conduct studies of the renewable energy-desalination nexus to evaluate the optimal technologies for desalination and renewable energy. Joint efforts being made by the King Abdullah City for Atomic and Renewable Energy (KACARE), King Abdulaziz City for Science and Technology (KACST) in collaboration with the IBM in Al-Khafji (to use concentrated PV for desalination) will continue.
- The Kingdom will take the lead in managing regional environmental impacts of desalination

  The Kingdom will assume the leading role for developing a coordination mechanism with other countries that are also tapping into the same shared water bodies in order to maintain the health of the shared-water ecosystem. In this context, the Kingdom will build on existing initiatives at the GCC level in terms of development and adoption of a common regulatory framework to ensure environmental sustainability of shared water bodies. It is also very important to include in this effort other countries that are outside the GCC but share water bodies with the Kingdom.
- Utilities will progressively move to paying the full cost of desalination water

  Desalinated water is a critical component of the Kingdom's water supply portfolio but use still has to reflect its high cost and environmental impacts. Saudi Arabia will progressively move to full cost pricing of desalination to create the incentives for efficient water sourcing, reducing fiscal outlays and promoting private sector participation in desalination investments.

The Saudi Arabia National Water Strategy 2030 was prepared by Booz Allen Hamilton. The Saudi National Water Strategy 2030 aims to work towards addressing all the key challenges, leveraging previous and on-going studies, and reform the water and wastewater sector to ensure sustainable development of the kingdom's water resources while providing affordable high-quality services [10]. The National Water Strategy 2030 is composed of a vision, strategic objectives, programs, and associated initiatives.

The sector's vision statement cites: "A sustainable water sector, safeguarding the natural resources and the environment of the Kingdom and providing cost-effective supply and high-quality services," as the central goals. This vision statement can be further detailed into five strategic objectives, as follows:

(1) ***Ensure*** continuous access to adequate quantities of safe water, under normal operations and during emergency situations.
(2) ***Enhance*** water demand management across all uses.
(3) ***Deliver*** cost-effective and high-quality water and wastewater services, accounting for affordability.
(4) ***Safeguard*** and optimize the use of water resources, while preserving the local environment for the highest benefit of the Saudi society in this generation and the future.
(5) ***Ensure*** water sector competitiveness and positive contribution to the national economy through promoting effective governance, private sector participation, localization of capabilities and innovation.

The following are review of Program 2 titled "Water Resource Management" and Program 7 titled "Desalination Sector Institutional Reform" which focused on Saudi desalination.

- *Program 2:* Water Resource Management.
  Initiative 10: Development of Sustainable Desalination.
  Initiative to develop desalination capacity following an assessment of local hydrological and economic conditions, while improving costs, energy efficiency and environment footprint and also accounting for the expansion in renewable energy.

  Key Activities:
- Develop a roadmap for clean energy desalination for the Kingdom (clean energy supply for desalination, energy efficiency system integration, research and development (R&D), outreach, action plan etc.),
- Integrate findings with master plans,
- Leverage new and efficient technologies for all new desalination investments and refurbishment of existing desalination plants,
- Undertake pilot studies in collaboration with SWCC R&D and academic institutions to assess techno-economic feasibility of desalination using renewable energy, and,
- Undertake studies to assess the environmental impact of desalination and implement necessary measures to mitigate impact on the environment.

  Key performance indicators:
- Renewable energy share of desalination fuel supply mix. (%); and,
- Energy consumption (kWh/m^3/100 m).
- ***Implementation Risks:***
  - Renewable energy technologies remain relatively costly compared to conventional fuel,
  - Delay in obtaining financing for investing in sustainable technologies, and,
  - Shift in government policy inhibiting development of sustainable technologies.
- *Program 7:* Desalination Sector Institutional Reform
  This program was developed as part of the SWCC privatization strategy. It entails the restructuring and transformation of SWCC to achieve its revised mandate. The program will be sponsored by SWCC and will include two initiatives.

  Initiative 1: Commercialization and TRANSCO Setup.
  Initiative 2: Preparation for Production Privatization.

Unified Water Strategy (UWS) for the Gulf Cooperation Council of Arab Member States for the Years 2015–2035 was developed in response to the directives of their Majesties and Highnesses the leaders of the Gulf Cooperation Council (GCC) at their 31st session of the Supreme Council of the Cooperation Council for the Arab Gulf States in Abu Dhabi on 6–7 December 2010. The scope of work of the unified water strategy had two main elements [11]:

- To develop a comprehensive and unified water strategy for the GCC countries for the next 20 y.
- To establish an office of strategic management in the GCC countries to implement, update the unified water strategy.

The vision and mission statements of the GCC UWS are formulated as follows:

Vision: By 2035 the GCC countries have established sustainable, efficient, equitable, and secure water resources management systems contributing to their sustainable socioeconomic development.

Mission: To align GCC states' national water strategies and master plans with a unified GCC water management strategy that foster joint initiatives and strengthen the capacities of each country in achieving a rational, integrated, efficient, and sustainable management of their water resources.

The GCC UWS is founded on five strategic themes; development and sustainability of water resources, efficient and equitable water resources utilization, enhanced municipal water supply security, effective water governance and awareness and economic efficiency and financial sustainability. Each theme contains one or more strategic objective (SO). The following is an overview of theme 1 titled "Development and Sustainability of Water Resources" and its associated Strategic Objectives (SO) as well as the proposed policies and programs [11].

Theme 1: Development and Sustainability of Water Resources

Strategic Objective-1: To Acquire Technology Development and Manufacturing of Desalination and Water Treatment Plants and Diversification of Energy Resources.

Collectively, the GCC countries have the highest concentration of desalination capacity worldwide and possess over 40% of the world's desalination capacity, with desalinated water representing the main source of their drinking water supply. This percentage is expected to increase in the future. However, the added value of desalination to the economies of the GCC countries is limited.

Hence, acquiring/owing, and localizing desalination technology in the region becomes an imperative strategic objective to ensure desalination sustainability and security to support national economy. Moreover, meeting escalating municipal water demands by the expansion of desalination has been associated with enormous financial, economic and environmental costs. In particular, the currently adopted thermal desalination technology is energy-intensive, claiming with alarming rates a sizable portion of energy resources and threatening the main source of income of the GCC countries. Therefore, implementing energy efficiency programs and diversifying energy resources in desalination, as well as the whole water sector, would enhance the sustainability of desalination and would help mitigate its associated environmental impacts.

The GCC countries have set targets for renewable energy share in their energy mix. These targets need to be implemented with priority in desalination and the whole water sector since they represent a major energy consumer in the GCC. Meanwhile, to address concerns about carbon emissions, GCC governments need to link any future expansion in desalination capacity to investments in abundantly available renewable sources of energy. In this regard, there are a number of major initiatives in the region towards solar desalination (e.g., KACST in Saudi Arabia and MASDAR in UAE). Other GCC countries should be encouraged to join these initiatives. Special attention should be paid to renewable and environmentally safe energy sources, of which the most important is solar, which can have enormous potential as the GCC countries are located within the "sun belt" of the world.

Policies and programs

SO1.1 Establishing joint GCC desalination and water treatment industry.
SO1.1.1 Joint GCC investment in establishing/owning desalination and treatment industries.

SO1.2 Establishing an advanced joint GCC R&D base in desalination and water treatment.
SO1.2.1 Create joint GCC advanced research programs in desalination and water treatment.

SO1.3 Developing professional and technical capacity in desalination and water treatment in the GCC countries.

SO1.3.1 Establish a unified GCC training programs that offers technical & vocational training in desalination and water treatment aspects as a major specialization in the GCC countries.

SO1.3.2 Set-up extensive educational specialization in desalination and water treatment at the graduate and undergraduate levels.

SO1.4 Diversifying energy sources in the water sector.

SO1.4.1 Develop plans for the use of renewable energy in the water sector in each GCC country.

SO1.5 Mitigating the impacts of desalination and water treatment practices on the environment.

SO1.5.1 Develop a comprehensive environmental legislation related to desalination and water treatment and provide enforcement and compliance mechanism.

SO1.6 Enhancing energy efficiency in desalination sector and the whole water sector.

SO1.6.1 Implement energy efficiency programs in desalination sector and the whole water sector.

The Saline Water Conversion Corporation (SWCC) is a Saudi Government Corporation responsible for the desalination of seawater producing electric power and supplying various regions in Saudi Arabia with desalinated water. SWCC was established by royal decree dated 20/08/1394 (07/09/1974) as an independent government corporation. The following is an overview of SWCC main objectives, vision mission and strategic goals [12].

SWCC main objectives

The corporation aims at consolidating the natural water resource in various regions and cities of the Kingdom where there are severe freshwater shortages, through the process of desalination.

The corporation is also habilitated to produce electric power as a by-product depending on economic and technical needs.

This is carried out in accordance with a comprehensive plan devised by the corporation and approved by the Council of Ministers.

The desalination of water, in addition to the production of electricity, represents the most important objectives of the development plans envisaged by the corporation. One of the main strategic goals for the implementation of these plans is to build a number of desalination plants, along with support facilities in regions suffering from shortages of fresh water supplies, based on the outcomes of technical feasibility studies.

SWCC vision

Leadership and excellence in sea water desalination and power production.

To excel and be the pioneer in the seawater desalination industry and electricity production.

SWCC mission

To meet the needs of our customers by providing them with desalinated seawater with effectiveness and credibility, at the lowest cost possible and with the highest economic returns, motivating and investing effectively in human resources, developing the desalination industry, contributing to social and economic development while complying with safety and environmental standards.

SWCC strategic goals

1. *Customer Service:* satisfy the needs of our clients by supplying them with desalinated seawater and

electricity and deliver reliable services with the highest quality.
2. *Financial sustainability:* achieve the highest economic return by increasing revenues and reducing cost.
3. *Operational effectiveness:* ensure quality and efficiency in terms of production and operations.
4. *Human resources:* develop, motivate, and build national competencies within a work environment characterized by fairness, teamwork, responsibility and loyalty.
5. *Economic development:* contribute effectively in developing and indigenizing know how in the field of desalination.
6. *Safety and security:* comply with the best practices of safety and security.
7. *Environmental sustainability:* comply with environmental rules and regulations.

5. Development of desalination KPIs

Almasri and Almurabti [13] recommended the following key performance indicators to assess the performance of the desalination plants:

- Availability factor
- Capacity factor (CF)
- Recovery ratio
- Reliability
- Thermal efficiency
- Product quality
- Unit product cost

They mentioned that objective of the assessment work is to measure how efficient and economic a plant is in meeting its objective in producing the design quantity and quality of water [13].

The performance of a given desalination plant is a measure of its efficiency for producing water. It is a measure of how efficient and economical the plant is in meeting its objective in producing the design quantity and quality of water by using specific indicators. However, there are no standard indicators for evaluating desalination plants performance.

The Saline Water Conversion Corporation (SWCC) performance was reviewed on Electricity and Cogeneration Regulatory Authority (ECRA) report titled "Regulating, Evaluating and Monitoring the Overall Performance of SWCC – Seawater Desalination Industry Review and Baseline of SWCC Performance Report", July 2015 [14]. SWCC is recognized for its strong technical capabilities in desalination given the scale and breadth of its operations, experience of its staff, and track record in meeting supply targets.

Within ECRA report the technical evaluation of SWCC plants was conducted by Black & Veatch. The evaluation is based on an on-site assessment of desalination plants in four locations – Jeddah, Shoaibah, Jubail and Khobar – and a review of gathered data. Table 4 lists the adopted desalination key performance indicators (KPIs).

Indeed, these indicators and criteria offer practical measures for the evaluation of the efficient operation of desalination plants.

Vision 2030 in Saudi Arabia and the National Transformation Program (NTP) call for the following key objectives for the water sector which associated with some initiatives like the ones listed [15]:

Key objectives:
- Promoting sustainable water supply sources and improving service coverage.
- Reducing excessive water consumption.

Table 4
Desalination KPIs overview

Criteria	Overview
Plant life	Commercial operation date and condition indicator.
Product quality	Quality parameters including turbidity, pH, hardness, total dissolved solids and chloride.
Plant availability	Percentage of time at which the plant is available for operation.
Production capacity	Plant's ability in meeting annual demand.
Gain output ratio (MSF)	Energy efficiency indicator.
Loss time injury frequency rate (safety)	Rate of occurrence of workplace incidents that result in lost time.
PM-CM ratio	Preventive Maintenance (PM) hours/Corrective Maintenance (CM) hours.
Non-fuel O&M costs	Costs/m^3 (manpower, chemicals, maintenance, spare parts etc.).
Environmental Legislation	Environmental preparedness, indicator.

Table 5
National Transformation Program (NTP) – Vision 2020 initiatives

Water resources	Ensure sustained water resources to all Saudi Arabia residents and visitors.
Increase SWCC Local Content	Elevate Saudi's capabilities and entrepreneurship in local manufacturing
SWCC privatization	Implement privatization strategy of swcc and enhance the operating model.
Enhance SWCC performance effectiveness	Ensure water safety and availability through enhancement of SWCC water production and cost reduction.

- Achieving customer satisfaction by providing high quality service and reducing waste.
- Reduce the sector dependence on state funding by taking steps toward privatization.
- Improving financial and operational efficiency.

Initiative examples:
- Increasing the capacity of strategic water storage.
- Increase the proportion of desalinated water produced by private operators.
- Reduce the waste of the water network.
- Expand the role of the water regulator.
- Attracting private sector participation across the water sector.
- Increase digital content to improve customer services.
- Reduce water service time.

These objectives face following main challenges facing water sector:

- Limited natural water resources.
- Elevated per-capita consumption.
- Rapid increase in population and unsustainable growth in water demand.
- High costs of water coupled with low tariffs making the sector unsustainable.
- Limited private sector participation in the kingdom's water sector.

Table 6
Key initiatives of SWCC's 2015 Transformation Program

Transformation pillars	Key initiatives
Strengthen our core business	Operational excellence Capital effectiveness
Transform our people engagement model	Human capital distinction Culture and values
Explore new and innovative frontiers	Value from intellectual property New business development
New operating model	Unbundling Integrated planning and control

Table 7
Operational excellence initiatives

Initiatives	Workstream objectives
Process and employee safety	Diagnose existing process and employee safety core practices maturity both at corporate level and within each of the four sites within scope, by focusing on: - Adopt a risk-based approach focusing on key risks areas; in particular, selecting sample areas as well as selected critical elements of the SMS based on experience in similar facilities. - Through a targeted review of core safety risks at both corporate and site level, help leadership team appreciate key risks areas and priorities to define a roadmap to develop mitigation plans and reduce overall operational risk.
Asset efficiency	Diagnose and define realistic asset efficiency target by focusing on water pumps and transmission systems, steam boilers, steam turbine and MSF, RO and MED desalinization process optimization with the objective to: - Reduce the operational expenditure induced by those assets by 20%, covering such as energy and power consumption, operational and maintenance costs, chemical costs, fuel cost. - Identify opportunities to improve capacity factor of desalination plant up to 93% and capacity factor of power generation up to 90%, and plant availability up to 97% and reduce the energy consumption by 10%.
Maintenance and reliability	Identify opportunities to optimize the overall expenditures related to fix and variable maintenance activities to improve asset availability up to 97% from reducing core assets downtime, by focusing on the following: - Maintenance and reliability organization structure, staffing and supervisory skillsets, work management process (planning, scheduling, work order management), material and spares management, reliability strategies, criticality ranking, preventive maintenance, task management, lubrication, problem elimination, material management, warehouse and inventory, kitting, information management (Computerized Maintenance Management System CMMS, equipment data, parts data, technical documentation).
CAPEX and contractor management	Diagnose existing capital efficiency to corporate level and Yanbu Sample and contractor management core practices and define realistic improvement efficiency target, by focusing on the following core dimensions: - Capital project/investment program effectiveness during business planning, front-end loading, design and construction, contractor management, namely contract performance, interface management, consumption patterns analysis and contractor performance evaluation. - Identify opportunities to optimize overall contractor spend, optimize capital expenditure for minor CAPEX investments, and optimize long term balance between capital expenditure and operational expenditure.
Culture and performance management	- Evaluate the overall corporate culture on each of the different sites and within core corporate functions by focusing on selected leadership team members thorough profiling and coaching, leveraging established practices around felt leadership models.

- Substantial investments required in the near future for new capacity to offset
- Planned decommissioning of existing desalination plants.

Table 5 lists major initiatives which will be executed through the National Transformation Program (NTP) of Water Sector in Saudi Arabia.

So to get in-line with these directions, SWCC is considering new corporate strategy which is under development and will focus on eight key initiatives along four transformation pillar. Table 6 display the recent SWCC corporate strategy [16].

SWCC has embarked on the following program to operational excellence initiatives which listed on Table 7 [16]:

- Full environmental compliances.
- Improve process safety and reliability.
- Reduce fuel and energy consumption.
- Improve desalination plants efficiency.
- Maximize the production.
- Reduce the cost SR/m^3.

6. Conclusions

Key performance indicator (KPI) is a metric which is one of the most important indicators of the current performance level of an individual, department and/or an organization in achieving goals. Key performance indicators (KPIs) are defined as a representation of a set of measures focusing on those aspects of organizational performance that are the most critical for the current and future success of the organization. KPIs are part of a strategic management system. They provide information into whether strategies are working, and programs, objectives and goals are accomplished. Often the strategic plan identifies goals, strategies, objectives and key performance indicators.

The principles KPI were reviewed in view of the strategic objectives and goals. The importance of the development of strategic plan was empathized. General overview of desalination issues which were indicated in various Saudi national water plans were highlighted. Eventually desalination KPIs were listed which include and not limited to: availability factor, capacity factor, recovery ratio, reliability, thermal efficiency, product quality and unit product cost.

In the development of KPIs for desalination processes, benchmarks and targets should be specified. Targets must be specific and time-bound. A target within the KPI identifies the achievement in relation to the final goal.

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Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28200

263 (2022) 25–31
July

Performance and cost analyses of hybrid diesel-photovoltaic powered small brackish water reverse osmosis system in Saudi Arabia

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Received 28 February 2022; Accepted 12 April 2022

ABSTRACT

The need for water is certainly very alarming in the Middle East and North Africa (MENA) region where water demand for domestic, agriculture, and industrial applications continue to increase, and on the other hand, water resources are increasingly becoming scarce (low precipitation and depletion of renewable groundwater). Inland desalination process in off-grid or remote areas contributes a significant portion to the water supply in Saudi Arabia. However, inland desalination systems have many challenges to be well implemented such as limited water distribution, water transmission cost from seawater desalination plants to the inland area. Many wells in Saudi Arabia have relatively high salinity water, which is not directly usable. This study aims to find the best hybrid diesel-photovoltaic powered reverse osmosis (RO) system to desalinate brackish water that has 6,000 ppm salinity for a remote area near Ummluj City in the Kingdom. Each RO system produces 202 m^3/d for two purposes: drinking and household purposes. A batch mode that operates 5 h/d is studied. The hybrid system composed of conventional and renewable energy systems driven brackish RO system are modelled using ROSA and HOMER software. Besides, the advantages of adding a pressure exchanger (PX) and a second-stage are investigated. Further, the effect of the fuel price on the cost of water production is analysed. It was found that adding a second storage tank for household applications with 1,000 ppm reduces the levelized cost of water by 11%. Furthermore, using a pressure exchanger leads to 26% reduction in the specific energy consumption (SEC) while adding a second-stage reduces the SEC by 22%. However, adding PX is economically feasible for fuel price higher than 40 USD/L.

Keywords: Solar energy; Fresh water; Optimization; Desalination; Batch mode; Remote areas

1. Introduction

The demand growth is more pronounced and rising in GCC, especially in KSA, with the desalination capacity share of 22% worldwide and 54% in GCC by the year 2017. In the year 2017, KSA has a total installed capacity of 8.3 million m^3/d with 48 operational plants and is expected to increase by up to 10.8 million m^3/d by 2030. Moreover, Saudi Arabia has an abundant solar resource with an average annual solar radiation of about 2,200 kWh/m^2. The global horizontal irradiance (GHI) varies throughout the Arabian Peninsula ranging between 3.7–7.9 and 4.1–7.5 kWh/m^2/d for the east and west coasts, respectively, while the central part receives 4.0–7.7 kWh/m^2/d KSA [1]. As a result, the kingdom of Saudi Arabia is set to target towards deployment of RE in general and solar photovoltaic (PV), in particular, to reach a planned capacity of 20 GW by 2023 and a long term plan to reach 40 GW by 2030 as stated by Renewable Energy Project Development Office. Further, the KSA government is looking for the

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

enhancement of efficiency and reducing the consumption of energy. Thus, the kingdom has to explore and develop sustainable production and supply of high quality freshwater by combining solar energy resources with the latest desalination technologies.

Inland desalination process in off-grid or remote areas contributes a significant portion to the water supply in Saudi Arabia. However, inland desalination systems have many challenges to be well implemented, such as limited water distribution water transmission cost from seawater desalination plants to the inland area. Inland desalination capacity in Saudi Arabia is over 3.600 million m^3/d, with more than 750 brackish water reverse osmosis plants (BWRO) in operation. Most of these plants use a diesel generator to meet the power requirement. Additional cost associated with fuel transportation increases the water production cost and energy consumption. As Saudi Arabia tries to reduce diesel consumption, deployment of renewable energy sources compatible with the desalination technologies is needed.

Several small and medium-scale renewable energy powered desalination plants have been installed worldwide. The reverse osmosis (RO) membrane desalination driven by solar PV energy is the most suitable combination of renewable energy and desalination as concluded by Karimi et al. [7]. Indeed 62% of global renewable energy installed capacity was used to power the reverse osmosis system in 2015 [2].

Alawaji et al. [3] built a PV-RO plant for a remote area in Saudi Arabia to desalinate brackish water for drinking purposes. The plant production was 15 m^3/d, where the PV size was 10 kW with a battery. Further work was conducted in 1996 by making two options: battery and battery-less [4]. They state that the performance of the plant was excellent, and the system was reliable. PV modules cost 42% of the total investment, while 31% for batteries and charge controllers. Another PV-RO setup evaluation was installed in Brazil in 2009. Riffel and Carvalho [5] compared two scenarios. In the first scenario, 2 PV modules were used to operate the RO pump and the module for the well pump. In the second scenario, all 3 modules are used for both loads. The study shows that the second scenario was the best. Elasaad et al. [6] evaluated a PV-RO setup in a remote area in Mexico, which was operating for 6 y. The setup desalinates well water with a 1 m^3/d production rate and 800 W power generation. The study shows that 1 m^3 of desalinated water costs USD9. Half of the capital cost was for the RO system, pre-treatment, and post-treatment, while 25% was for the PV modules and electronics. Regarding the operation expenditure (OPEX), 61.5% was for operation cost, and 9.23% for RO maintenance cost. The system is efficient and reliable. Recently, a comparative study between electrodialysis reversal (EDR) and RO systems integrated with PV modules was performed by Karimi et al. [7]. They concluded that for low salinity water, PV-EDR is more cost-efficient than PV-RO, while for high salinity water is the opposite.

2. Feasibility studies

PV-RO is technically effective solution to water shortage for off-grid or remote areas. However, the cost for water production via PV-RO is characterized by high volatility and vary substantially by location, water types, system demand, and plant size [8]. The water cost for typical reverse osmosis powered by PV reported in recent literature varies from 1.65 to 15.6 USD/m^3 [9,10]. A cost analysis of small PV powered brackish water reverse-osmosis with a battery system for Egypt desert conditions was conducted [11]. Even feed water characterised by low salinity (<2,000 ppm), the estimated cost of producing 1 m^3 of clean water is 3.73 USD.

Helal et al. [12] conducted a cost analysis of off-grid PV connected SWRO in the UAE. Three alternative power source cases are considered in this study: diesel generator, hybrid diesel-PV, and PV panels. The fresh water capacity for all the studied systems was 203/d. Simulated results showed that the specific water cost and specific energy consumption are USD7.64 and 7.74 kWh for the fully-diesel case, USD7.21 and 7.73 kWh for the hybrid case, and USD7.34 and 7.33 kWh for the fully-PV case.

Bilton and Kelley [13] developed a techno- economic approach based on optimization techniques to achieve the optimum lifetime cost of water production with respect to required water demand. The optimization variables considered in this study are the types of the power source (diesel generators, solar PV, wind and their combinations), design of RO, and water storage size. The developed methodology was used to design a RO system with a capacity of 10 m^3/d for three different locations (Honduras, Eritrea, and Australia). They concluded the cost-effective configuration to supply water is a function of wind speed, solar radiation, and fuel price. Other studies confirm the critical role of location in determining the feasibility of PV-RO system [9,12,13].

Based on the above literature, the water desalination through PV-RO is technically feasible. However, the cost of water production and power consumption are still relatively high, and vary substantially by location, water types, system demand, plant size, and local water transport cost [8,10]. A limited number of studies focusing on feasibility of PV-RO in the Saudi rural areas that suffer from clean water scarcity and high water cost, while Saudi Arabia has an abundant solar resource and large amounts of brackish waters.

The main objective of this study is to analyse the performance and cost of a hybrid diesel-PV powered RO system to desalinate brackish well water for a remote area in Saudi Arabia.

3. Mathematical model

3.1. Reverse osmosis modelling

A schematic of a reverse osmosis system in batch mode is depicted in Fig. 1. A second storage tank for household purposes with a salinity of 1,000 ppm. Excess cleaned water for drinking use is blended with the pre-treated water to reduce the total salinity to meet the required salinity for household applications. In addition, the studied system is included a pressure recovery (PX) converting the mechanical (in form of pressure) from high-pressure brine flow to low-pressure feed flow.

A simple model was developed to predict the flow, the pressure and the salinity of fresh water out of the membrane. The main equations for the RO process simulation and

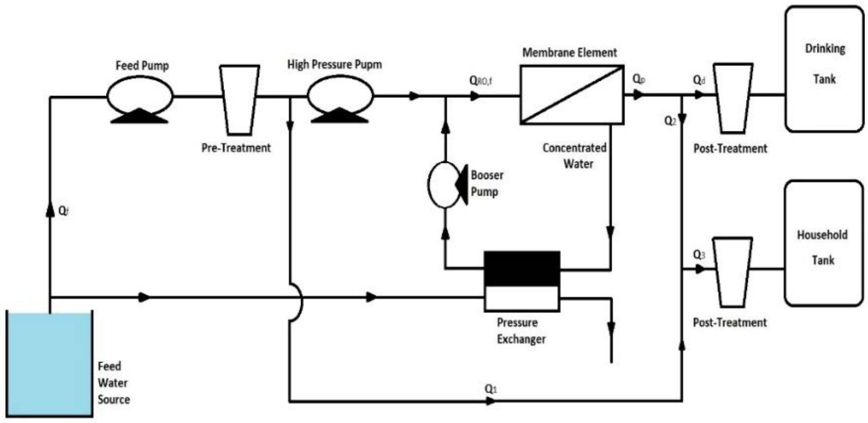

Fig. 1. Schematic diagram RO system with second storage tanks and PX.

design can be found in [8,14]. The developed model assisted reverse osmosis system analysis (ROSA) software is used to determine design parameters of the RO system (desalination, capacity, membrane pressure, and power required).

3.2. Energy source modelling with HOMER

The energy requirements for the RO system were determined based on water salinity and water depth. The energy sources considered in this study are provided by three sources: photovoltaic Panels, batteries, and diesel generator. For the PV-RO, it is assumed that the system will operate when solar energy is available. The average permeate flow rate during operation is calculated by dividing the daily RO production capacity in m^3/d by the number of daylight hours.

The rated power equation for photovoltaic panels is given by [15]:

$$P_{\text{PV-rated}} = \eta_{\text{PV}} A_{\text{PV}} G_{\text{STC}} \tag{1}$$

where $P_{\text{PV-rated}}$ is the rated power generated by the solar panel in W, A_{PV} is the panel area, η_{PV} is the panel efficiency and G_{STC} is the incident solar energy at the standard test condition. The solar module efficiency is affected by the ambient temperature. The actual PV power output from the solar PV operating under real weather conditions can be estimated using the following equation.

$$P_{\text{PV-output}} = P_{\text{PV-rated}} F_{\text{PV}} \left(\frac{G}{G_{\text{STC}}} \right) \left[1 + \alpha_p \left(T_{\text{cell}} - T_{\text{cell-STC}} \right) \right] \tag{2}$$

where $P_{\text{PV-output}}$ is the real power generated by the solar panel, G is the incident solar energy on the panel F_{PV} is the derating factor which account for the loss due to wiring, shading, snow and α_p is the cell temperature coefficient. T_{cell} and $T_{\text{cell-STC}}$ are the cell temperatures at real condition and standard test conditions, respectively.

To model the power system composed of PV, diesel generator and batteries, Hybrid Optimization Model for Electric Renewable software (HOMER) is used in this study. It is a tool for designing, analysing, and optimizing hybrid energy system configurations based on their technical and economic merits. For each simulated configuration, HOMER calculates its life-cycle cost including the capital, operating and maintenance costs and fuel and interest rate [15]. The schematic diagram of the hybrid system considered in this study is shown in Fig. 2.

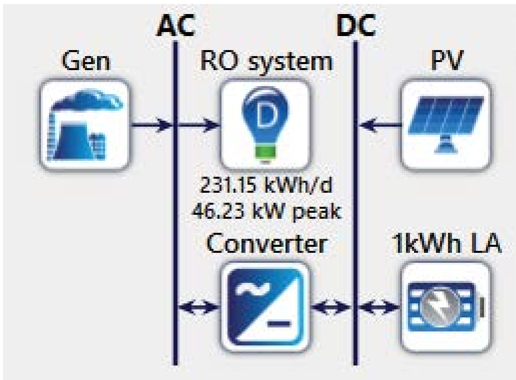

Fig. 2. Schematic diagram of the hybrid system.

3.3. Economic analysis

For an economic analysis of hybrid diesel-PV powered brackish water RO system, an excel program based on the annualized life-cycle method was developed to calculate the capital expenditure (CAPEX), operational and maintenance expenditure (OPEX) of all the components of the hybrid system. The levelized cost of water (LCOW), the levelized cost of energy (LCOE), the payback period was estimated by varying the price of fossil fuel. The total equivalent annul cost is the summation of the total equivalent annual cost of the power source (PV and diesel generator) and RO system. A detailed explication of the economic approach can be found in [8].

The LCOW is calculated using the following equation:

$$\text{LCOW} = \frac{\sum \text{CAPEX} \times \text{CRF} + \text{OPEX}}{365\tau \times Q_{\text{cap}}} \tag{3}$$

CAPEX is the total capital costs of all components of reverse osmosis system and the power system. CAPEX is converted into equivalent annual costs using the capital recovery factor (CRF) given by is given by:

$$\text{CRF} = \frac{z(1+z)^n}{(1+z)^n - 1} \tag{4}$$

where z is discount rate and n the amortization period.

The LCOE is the total annualised cost of the power system divided by the yearly electrical load served.

3.4. Input data and methodology

For predicting performance and cost analysis for hybrid diesel-PV powered well RO system; we used ROSA and HOMER simulations. The first step involves obtaining environment resources, water quality and capacity, and hybrid system configuration. Design parameters of RO system is then calculated using (ROSA). The second step consists in modelling and simulating ad optimizing the power energy system. Finally, economic analysis of the whole system is performed using the excel sheet program. The input data for of hybrid diesel-PV powered RO system used in this study are listed in Table 1.

4. Result and discussion

4.1. One stage RO simulation

Detailed economics related to the batch mode configuration of the optimized diesel-PV-RO were simulated using input data listed in Table 1. Table 2 shows the system configuration for different renewable energy fraction used to generate annual electricity and estimate annual CO_2 savings. With almost 51.6% renewable energy fraction, the system is estimated to generate annual energy of 81,869 kWh and save almost 31,591 kg of CO_2 annually. The LCOE and LCOW for various combinations of renewable energy fraction range between 0.12 to 0.18 USD/kWh and 0.8 to 0.9 USD/m^3, respectively as shown in Table 3. The optimal configuration was obtained using a diesel generator only, because of the low price of fossil fuel of 0.13 USD/L. With increasing renewable energy penetration, the costs associated with renewable energy components also increase resulting in a substantial rise in total equivalent annual cost for the hybrid system. For the value of RE penetration higher than 30%, the cost function decreases. The second optimal configuration after the diesel-only configuration is another combination of PV with 90.8% (99.3 kW) penetration with a 47 kW generator and 1 kWh battery connected to a 46.9 kW converter. This is because, at high renewable energy fraction, the number of

Table 1
Main input parameters for diesel-PV-RO analysis

Component	Parameters	Value
RO system	Recovery ratio (one-stage)	50%
	Capital cost of RO system	163,000 USD
	Capital cost of PX	72,000 USD
	O&M of RO	10,500USD
	HPP replacement (15 y)	23,700 USD
	Pump efficiency [8]	80%
	ERD efficiency (PX) [16]	96.7%
	Pre-treatment and post treatment power required	15% HPP power
Flat plate PV	PV cost for capacity <1 kW	2,500 USD/kW
	PV cost for capacity <10 kW	2,000 USD/kW
	PV cost for capacity <100 kW	1,500 USD/kW
	Efficiency [17]	17%
	Temperature coefficient [17]	–0.45%/oC
Lead acid battery	Nominal capacity [17]	1 kWh
	Capital cost [17]	300 USD
	Life time [17]	5 y
	Discount rate	5%
Diesel generator	Lower heating value [17]	43.2 MJ/kg
	Carbon content (%) [17]	88%
	Capital cost [17]	500 USD/kW
	Life time [17]	15,000 USD
	O&M [17]	0.03 USD/h
	Initial fuel price	0.13 USD
	Fuel transportation	325 USD/y

Table 2
Overall optimization results

Renewable fraction (%)	PV (kW)	Gen (kW)	Battery (kWh)	Converter (kW)	Excess electricity (kWh/y)	Percentage of excess electricity	CO_2 emission (kg/y)	CO_2 saving (kg/y)
100%	141	0	0	49	146,893	62%	–	63,380
91%	99.3	47	1	46.9	85,816	50%	6,012	57,368
81%	91.6	47	1	46.9	81,484	48%	12,472	50,908
73%	87	47	4	46.6	81,267	48%	17,927	45,453
63%	80.9	47	17	47.9	79,778	48%	24,290	39,090
52%	76.3	47	5	51.6	81,869	49%	31,789	31,591
43%	72	47	13	48	82,473	49%	37,491	25,889
33%	66.9	47	17	48.8	83,026	49%	44,293	19,087
22%	54	47	21	49.6	71,240	46%	51,574	11,806
13%	38	47	1	19.8	51,759	38%	51,221	12,159
0%	0	47	0	0	0	0%	63,380	0

Table 3
Detailed cost results for batch mode option 2 with ERD

PV penetration	An_{total} (USD)	LCOW (USD/m^3)	LCOE (USD/kWh)	Energy cost percentage	RO cost percentage
100%	44,159	0.90	0.18	65%	35%
91%	42,164	0.86	0.16	68%	32%
81%	42,195	0.86	0.16	68%	32%
73%	42,980	0.87	0.17	67%	33%
63%	44,306	0.90	0.19	65%	35%
52%	44,132	0.90	0.18	65%	35%
43%	45,445	0.92	0.2	63%	37%
33%	46,326	0.94	0.21	62%	38%
22%	46,450	0.94	0.21	62%	38%
13%	43,807	0.89	0.18	65%	35%
0%	39,193	0.80	0.12	73%	27%

batteries has been reduced; only one battery is considered for RE fraction higher than 81%.

Fig. 3 shows the LCOW variation with renewable energy penetration. The LCOW is slightly higher when using renewable energy power to drive the RO system due to the high cost associated with the renewable. As the power cost has a high share contribution to the total cost of water production, LCOW and LCOE have the same variation with renewable energy fraction. The same optimal configuration containing a 47 kW generator and 1 kWh battery connected to a 46.9 kW converter is obtained for LCOW and LCOE.

4.2. *Effect of number of stage and ERD*

Fig. 4 depicts the variation of LCOW with RE power penetration for one and two-stage RO system with and without ERD system. Adding a stage would indeed increase the recovery ratio of the RO system and reduce the LCOW of the hybrid diesel-PV powered RO. The two-stage RO configuration includes two trains of pressure vessels allowing for maximum recovery of permeate which positively affects the energy consumed. The recovery ratio is increased from 50% to 65% for one-stage and two-stage RO systems, respectively, leading to 22% reduction in the specific energy consumption. As a result, the two-stage RO system has the lowest total cost of water compared with one stage configuration. Besides, using a pressure exchanger as an energy recovery device in this mode is not cost-effective due to the initial high investment of the energy recovery system (PX).

4.3. *Effect of fuel price*

Sensitivity analysis is performed to study the effect of fuel prices on the cost of water production as shown in Fig. 5. It is clear that the fuel price has a great impact on the cost of water production. LCOW linearly increases with the increase of the fuel price. Besides, for the three studied configurations (Batch, batch with PX and batch with two stages), the lowest LCOW was found at low fuel price. Fig. 5 shows that the use of PX as ERD becomes economically feasible when the diesel price increases to USD 0.4/L which can be considered as the breakeven point between batch and batch with PX configuration. As the fuel price increases, its cost-sharing in the total cost of water production increases also until reaching the breakeven point at USD 40/L. it is concluded that the two-stage RO system

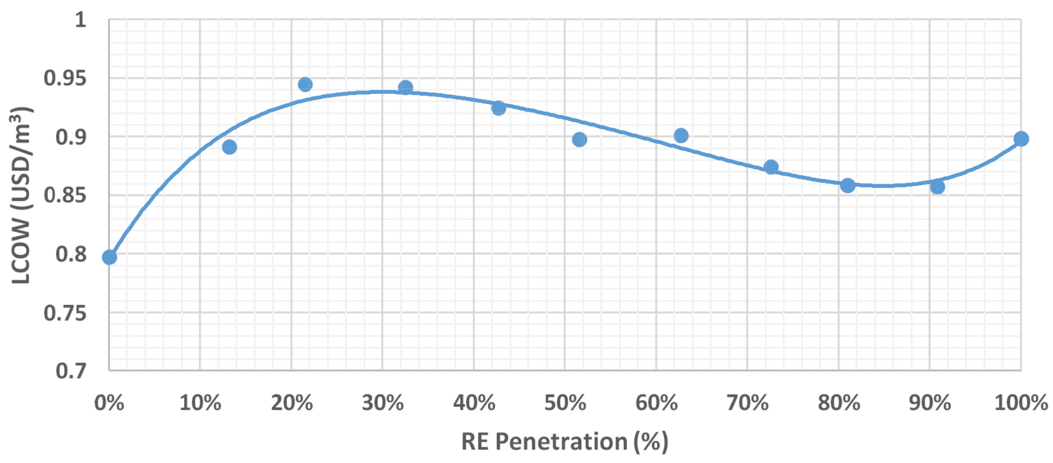

Fig. 3. Levelized cost of water variation with RE penetration.

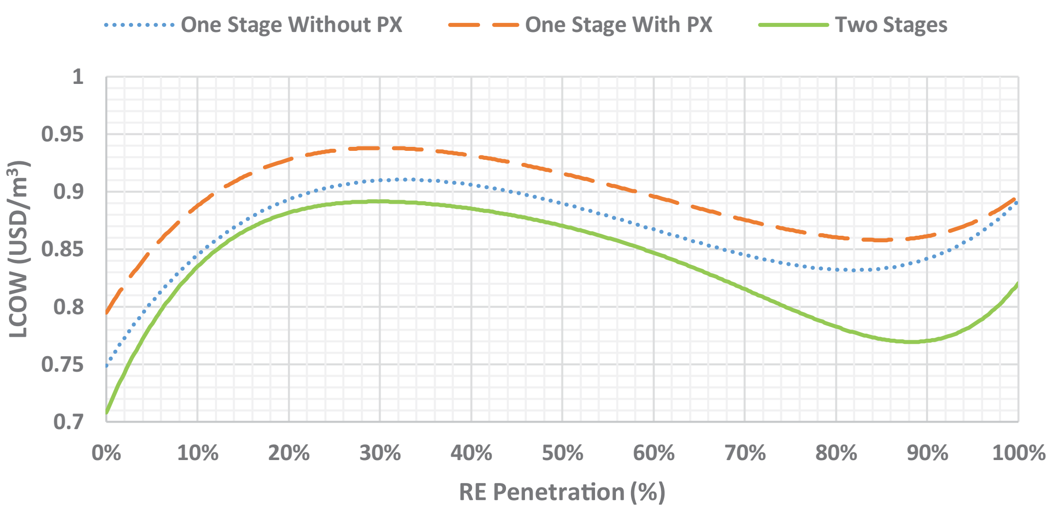

Fig. 4. LCOW vs. RE penetration for batch mode cases.

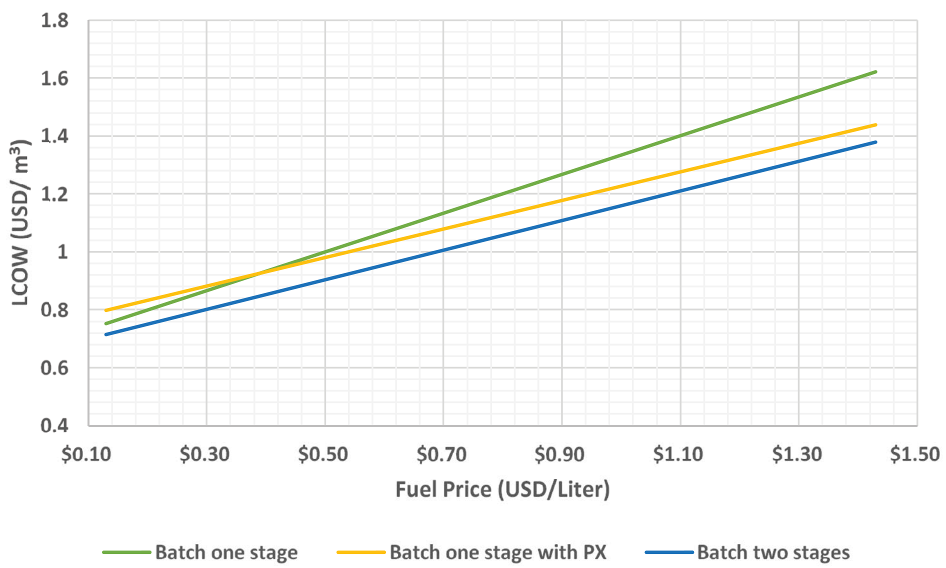

Fig. 5. LCOW for different fuel price at diesel powered RO system.

has the lowest total cost of water independent of fuel price variation.

5. Conclusion

Performance and cost analyses of hybrid diesel-PV powered brackish water RO system for supplying fresh water to a small rural community in KSA was studied. It was found that the power cost has a high share contribution to the total cost of water production with about 65%. The simulated results showed that LCOE and LCOW for different combinations of renewable energy system with RO system range between 0.12–0.18 USD/kWh and 0.8–0.9 USD/m^3. Further, it is concluded that the two-stage RO configuration positively affects the recovery ration leading to leading to 22% reduction in the specific energy consumption compared with one-stage system. For the integration of pressure exchanger (PX), it is demonstrated that it is cost effective solution for the diesel prices higher than 40 USD/L. At lower fuel prices (<40 USD/L), it is not cost-effective due to the high initial investment of the pressure exchanger.

The obtained results will be very valuable to identify the cost effective and technical efficient systems for best hybrid diesel-PV powered reverse osmosis (RO) systems for different rural areas in KSA. Thus, this proposed study would lead to the acceleration of Solar PV distribution in the inland desalination market and the reduction of fossil fuel use in KSA as well as ensure sustainable use of water resources.

Acknowledgements

The authors would like to acknowledge the resources provided by the Interdisciplinary Research Center for Renewable Energy and Power Systems at King Fahd University of Petroleum & Minerals.

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Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28202

263 (2022) 32–34
July

Sustainable desalination: how to produce sufficient water towards the future, while protecting the marine environment

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EXTENDED ABSTRACT

The population in the Middle East Gulf area is growing and with that the water demand. In a region with very little rainfall and almost no rivers, this presents a challenge. Over the past decades, groundwater has been used as a water supply for drinking water as well as agriculture, but in many places, the groundwater reserves have been depleted. Towards the future, the dependency on seawater desalination will become larger and some areas will completely depend on this source of produced water.

The total amount of desalination plants and their capacity has risen exponentially over the last few decades (Fig. 1), whereas the current production of desalinated water from reverse osmosis accounts for approximately 69% (~66 million m^3/d) of the global volume of desalinated water (~95 million m^3/d; [1]).

A clear trend from thermal desalination technologies (MSF, MED) to seawater reverse osmosis (SWRO) can be observed, globally and in the Middle East Gulf region specifically. This shift in technology also results in a trend in the market to decouple energy from water production. Power and desalination plants were commonly co-located in the past due to the use of thermal energy from the power production process for thermal desalination. However, an RO plant only uses electricity and can therefore be decoupled from the powerplant, both technically and economically.

The main difference between the different desalination technologies in relation to the marine environment is the type and amount of brine effluent these technologies produce. Thermal desalination typically has a larger brine flow (often with elevated temperature and slightly elevated salinity of about 10%). SWRO effluent typically has no elevated temperature, but strongly elevated salinity (of about 50% or more), but the discharge rate is much less. The SWRO effluent thus provides a smaller, denser effluent plume that could result in high salinity levels near the bed, if not properly diluted by the outfall (e.g., by a diffuser).

For sustainable desalination, it is important to be able to predict the effects on the environment of the discharged brine effluent when designing new desalination plants or planning plant capacity around the Gulf. Questions about this environmental impact play on different spatial and temporal scales and should be considered accordingly with suitable models and methodologies. Close to the desalination brine outfall, near field effects play an important role in the initial mixing of the effluent. Near field mixing models, like CORMIX and CFD are required to compute these non-hydrostatic effects accurately. However, these models use a simplified geometry and ambient flow conditions, relevant close to the outfall (typically about 100 m). Further away from the outfall, a far field model like Delft3D is required to predict the outfall plume dispersion and possible effects on the environment in more detail and to ensure a good, compliant outfall design. On an even larger scale, the combined effects of the desalination industry (i.e., multiple plants) should be considered, for example, on a Gulf-wide scale. Here, also the longer-term natural effects like evaporation, large-scale circulations and climate change effects play a role. Large-scale models, like the open Gulf Community Model (Fig. 2), are available to investigate and study long-term scenarios as input to a sustainable national desalination strategy.

Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

Here also important questions currently play in the Gulf region that are still subject to research: Does climate change have a larger impact on the Gulf's salinity or does the increasing desalination capacity have a larger impact? Our research shows that closer to desalination plants, an increase in capacity shows a larger impact and that in areas without brine discharges, climate change has the larger impact. On a Gulf-scale, differences average out more, but regional differences can be expected, as well as possible changes in circulations that could increase salinity and its variability in some regions, but also reduce salinity on average slightly in other areas. Knowledge from such research could also inform a sustainable desalination strategy and be downscaled to plant level again.

Back to the current market dynamics for desalination plants. It is a point of attention that independent water plants (built and operated by a consortium of partners for decades) are still granted the project at the lowest metre cube water price, rather than the most sustainable design and operation. It is a challenge, but also opportunity, for water companies to put projects on the market that demand the highest levels of sustainability (in conjunction with different stakeholders like environment agencies, local communities, looking at employment etc.) in addition to an economic preference. Steps are being made in the right direction and many innovations are being developed and tested that can promote this further, like sustainable outfall designs.

An example of such sustainable outfall designs could be an outfall that can double as an artificial reef. The impacts of brine discharges on the marine environment may not be as high as thought before according to our and Australian research, although it still needs careful consideration. Outfalls are often observed as covered with marine life, as being a hard substrate for life to settle on (Fig. 3). Outfalls (and intakes) could also be designed specifically with this (additional) function in mind [2].

Furthermore, not all sites around the World are equal and it is important to adopt site-specific and ecologically relevant criteria for a desalination brine outfall. Often mixing zone criteria are adopted from other parts in the world, with different ecosystems that could be either harmful to local ecosystems or be overly restrictive. Research is needed and useful to develop more relevant criteria that could be adopted by regulators and increase the sustainability of desalination in relation to the marine environment, while ensuring sufficient water for everyone in the future.

Keywords: Sustainable desalination; Seawater; Environment

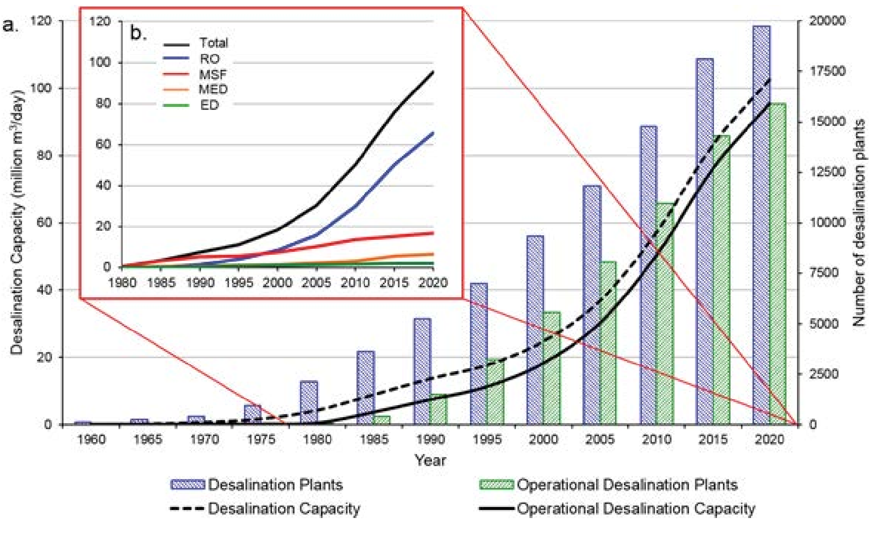

Fig. 1. Trends in global desalination by (a) number and capacity of total and operational desalination facilities and (b) operational capacity by desalination technology (Jones et al. [1]).

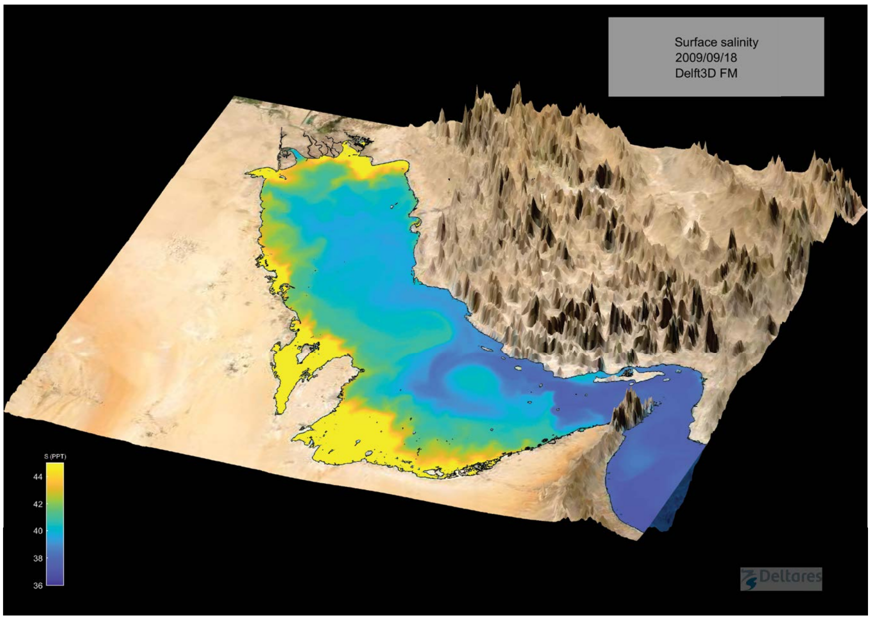

Fig. 2. Gulf-scale numerical modelling of the seawater salinity with the Delft3D-FM Gulf Community Model (https://www.agmcommunity.org/).

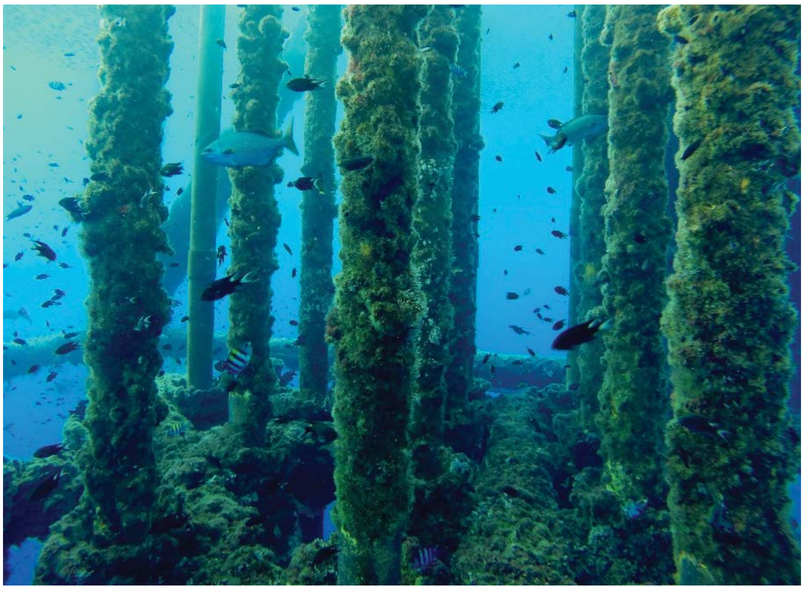

Fig. 3. Example of underwater structures functioning as habitats.

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Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2022.28203

263 (2022) 35–44
July

Characterization of the water mass dynamic changes surrounding a seawater reverse osmosis desalination plant on the east coast of the Kingdom of Bahrain

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Received 28 February 2022; Accepted 14 April 2022

ABSTRACT

Desalination in the Gulf Cooperation Council countries is essential in the provision of drinking water supply and in achieving the targets of the UN Sustainable Development Goals (SDGs), particularly SDG6.1 aiming at achieving access for all to safe drinking water. On the other hand, desalination process is associated with several environmental externalities that have adverse impacts on the coastal and marine environments. The aim of this research is to assess the dynamic changes of the water mass quality parameters resulting from a seawater reverse osmosis (SWRO) desalination plant located on the east coast of Bahrain, in relation to the tide cycle on seasonal basis. The evaluation is based on the spatial differences in water temperature and salinity in the surrounding areas of the plant outlet within about 2.5 km^2. Water samples were collected at 42 locations for both surface and bottom waters over high and low tide cycle during winter and summer. The results revealed an extreme elevation in temperature (>38°C) and hypersaline waters (>55‰) at locations nearby the discharge outlet as well as at bottom waters of depths >3 m in both seasons with exceptional levels in summer particularly during high tide cycle. Thermocline and halocline formations were noticeably occurred particularly during high tide in both seasons due to vertical differences in temperature (>3°C) and salinity (>1‰) at several locations associated with depths more than 3 m. The thermocline and halocline formations indicate the path by which the thermal and hypersaline water mass fluxed by the desalination plant sinking out towards the open water. The impacts of Al-Dur SWRO desalination need to be minimized to maintain the seagrass habitat around the coast to support the marine biodiversity, particularly the megafauna endangered species associated with seagrass, (dugongs, green turtles and dolphins) and other finfish and shellfish species.

Keywords: Environmental Impacts, Temperature, Salinity, Tide Cycle, Thermocline, Halocline, Al-Dur

1. Introduction

The Gulf Cooperation Council (GCC) countries are situated in an arid to semi-arid area and are characterized by high temperatures, low rainfall, and limited freshwater resources. In the past decades, these countries have experienced unprecedented social and economic development associated with rapid demographic and urbanization growth. To meet the water requirements for the rapidly expanding population under natural water scarcity, the GCC counties have relied essentially on desalination. This has been made possible by the availability of financial and energy resources the GCC countries possess. However, in addition to its financial and economic costs, desalination has several environmental externalities, which are manifested in its gaseous effluent, represented by greenhouse gasses emissions (CO_2, NOxs, SOxs, …), and liquid effluent, represented by the high concentration reject, or brines, of the desalination process, and in the case of thermal technology, thermal brine.

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability. 13–15 February 2022, Riyadh, Saudi Arabia

The production of desalination plants in the Arabian Gulf has increased from 0.04 million m^3/d in 1970 [1] to more than 21 million m^3/d in 2018 [2], which equivalent over 20% of total global [3]. The highest number of desalination plants and largest desalination capacity worldwide is found in the Arabian Gulf area; between 2000 to 2010 more than 64% of the world's total production capacity were reported in this region. Without exception, during the last three decades, desalination capacity in the GCC countries has increased substantially. This trend is expected to continue in the coming decades [4]. Desalination water production is supposed to increase from about 8,000 Mm^3/y to about 41,000 Mm^3/y by 2050 [5] and to 80,000 Mm^3 [6].

The Kingdom of Bahrain, like the rest of the GCC countries, have embarked on desalination projects to meet the municipal water requirement of rapidly increasing population and urbanization since the 1975, when it launched its first desalination plant in Sitra, Sitra MSF, located at the eastern coast of Bahrain island. This was followed by five desalination plants, all located on the eastern coastline of Bahrain: 1 MSF representing Al-Hidd, 2 MED including Al-Hidd and Alba, and 2 RO at Ras Abu Jarjur and Al-Dur [7]. Al-Dur desalination plant, the focus of this study, is designed to produce 220,000 m^3/d and was developed on a build-own-operate project (BOO) project basis, consisting of a combined power plant and a RO desalination plant.

While the socio-economic benefits of desalination plants and its key role in achieving sustainable development, particularly SDG6.1 concerned with the provision of safe drinking water supply to all population [8], the associated negative impacts related to desalination plants operation as a land-based source of pollution to the marine environment are of a major concern [9]. Namely, the main environmental concern is the impacts of the desalination brine discharge to the marine environment. The discharged brine water probably includes additional chemical pollutants, which possibly affect the chemical properties of both water and sediment quality.

The magnitude of this impact depends on the characteristics of the desalination plant and its reject brine. The rejected brine is characterized by extreme salinity, and in the case of thermal desalination it is also associated by extreme temperature. Thermal desalination plants usually discharge a temperature of 5°C–10°C above ambient seawater temperature [10]. Mann and Lazier [11] revealed that the highest temperature value in the surrounding area of the brine discharge is found very close to the mouth of the outfall diffuser. Abdul-Wahab [12] investigated the relationship between the temperature of seawater and the distance from the discharge site. The difference of temperature changes in the ocean water and the surrounding area of the discharge brine showed considerable fluctuation with a significant range from 10°C to almost 40°C, while the general ocean's temperature varies between 10°C to just under 25°C [13].

The discharged brine represents a desalination externality that has a negative impact on the surrounding marine environment due to its influencing changes of the surrounding area's physical properties, such as salinity, temperature, and density and the remains of chemical additives or corrosion products [14]. With continuous desalination brine discharge into the ambient seawater, a localized hypersaline water, termed halocline, will be created [15]. In the case of thermal technologies, a localized high temperature zone will also be created (thermocline). The extent of the halocline and thermocline will depend on many parameters related to the desalination plant and the surrounding marine environment. These include desalination plant size, technology (i.e., thermal or membrane), and age [16]; the surrounding marine environment characteristics, such as depth, currents, morphology, and many other parameters.

Desalination plants in the Gulf typically use nearshore surface water intakes. Therefore, the potential impacts of impingement and entrainment were explored through a simple volume calculation that compared the predicted volume of water passing through desalination plants on an annual basis with the total volume of water in the Gulf between the shore and the 10 m depth contour [6]. The effect of desalination is based on a mixture of experimental, field and modelling studies to identify the physiochemical, biological and ecological impacts, which vary depending on location, type and capacity of desalination plant. The release of discharge plumes, particularly into confined water bodies, or areas where topography constrains hydrodynamic dispersal, potentially lead to an extreme concentration of brines that would be rapidly dispersed on an open coastline [17]. Similarly, the impact of intakes and outfall based on both configuration and design [18], and on the type and amount of water preconditioning chemicals used in each desalination plant [19].

An important first step to mitigate the impacts of the brine of an existing desalination plant on the coastal and marine environment is to characterize the extent of the created halocline and thermocline, if any, and their dynamic changes over seasons as well as over tide cycle. These characterizations are essential input to design the mitigation plan to reduce the impact of brine on the marine environment.

2. Materials and methods

2.1. Study area

The present study is conducted on the Al-Dur coast, east of Bahrain within the vicinity of the Al-Dur power and desalination plant (Fig. 1). The Al-Dur reverse osmosis desalination plant is located on the southeast 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 for drinking water and electricity in Bahrain as well. The plant was developed as a build-own-operate project (BOO) engaged in the private sector.

The tidal regime circulation along the Bahrain coasts is diurnal twice a day with a depth range between 0–7 m. The water intake at 1.5 km and the pip supplemented by two subsurface intake filters each consisted of four units. Total of 20 barrier fishing traps (locally known as Hadrah) are distributed along the Al-Dur coast. Further, fishing activities practiced by drift nets and wire metal traps (locally known as Gargoor).

2.2. Sampling

The monitoring sites have been positioned using Global Positioning System (GPS) of Trimble type into a network form located in the vicinity of the discharge path within a grid area represented in Fig. 2. The measurements were carried out during winter (February) and summer (August) 2017. The *in situ* measurements of temperature and salinity were conducted using Pro DSS multi-meter probe. The measurements in winter (27th February 2017) covered 36 monitoring locations during high tide and 42 monitoring locations during low tide. In summer (6th August 2017), a total of 40 monitoring locations has been selected during the high tide and 41 monitoring locations during the low tide.

3. Results

3.1. Water temperature

A seasonal variation found between winter and summer temperatures. The measurements in winter were ranged between 17.0°C and 21.8°C; however, in summer were varied between 35.4°C and 38.8°C. The minimum, maximum and average are presented in Table 1. The results showed that no differences observed between the surface and bottom in both seasons indicating well thermal mixing. However, the temperature during the low tide seems to be warmer than high tide.

Relatively, the temperature was differed on a spatial basis following to distance from desalination plant outlet. The maximum values found at stations closest to the outlet, those associated with depth less than 1m at which the range was 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 are with an average of 18.5°C in winter and 36.5°C in summer.

Slight variations could be noticed between temperatures during high tide and low tide cycle in summer (Fig. 3), however, no real variations observed in winter

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

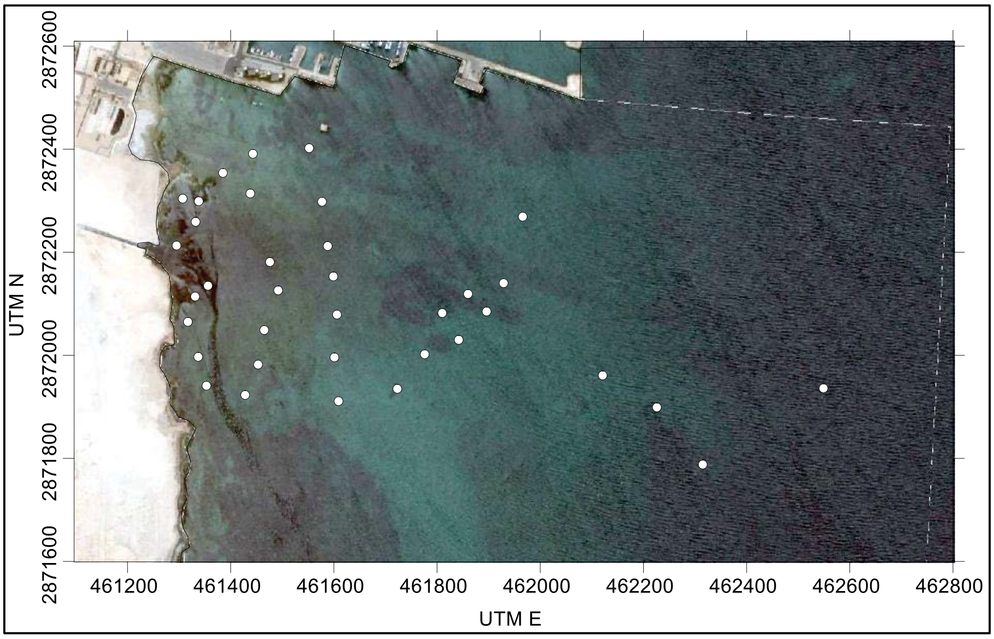

Fig. 2. Grid area of *in situ* water quality parameters.

Table 1
Surface and bottom water temperature during high and low tide cycle in summer and winter

Temperature	Summer				Winter			
	High tide		Low tide		High tide		Low tide	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
Min.	35.1	35.2	36.6	36.7	17.3	17.4	18.3	18.5
Max.	38.8	38.7	40.4	40.3	21.5	21.3	23.1	23.3
Average	36.5	36.5	37.9	37.9	18.3	18.6	19.5	20.1

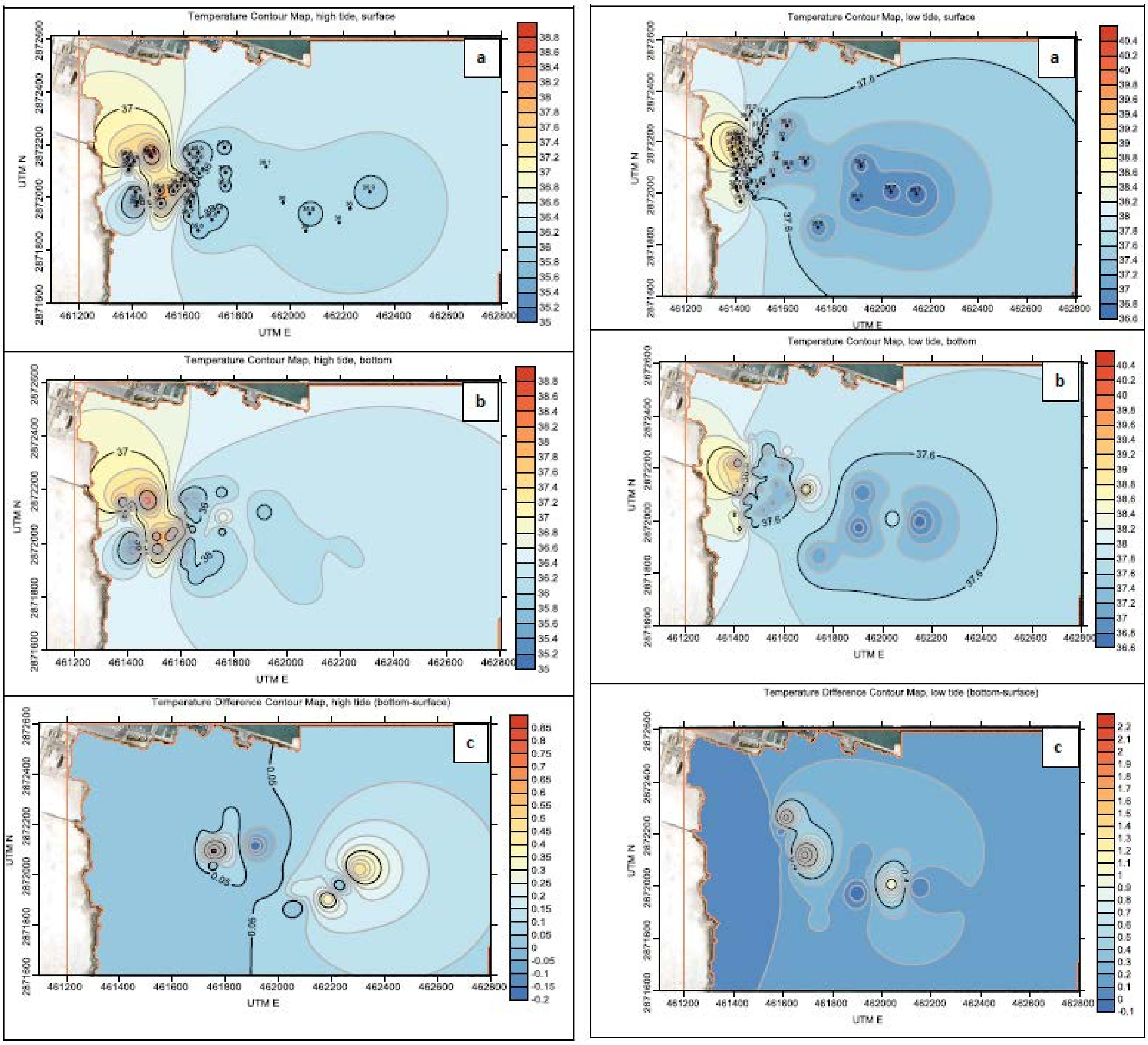

Fig. 3. Water temperature during high (left) and low (right) tide cycle in summer (a) surface, (b) bottom and (c) difference between surface and bottom.

(Fig. 4). A considerable thermocline was observed in winter where the bottom layers characterized by higher temperature mostly at stations characterized by depth more than 3–4 m. The other sampling locations exhibited marginal fluctuations on a vertical basis between surface and bottom layers mostly with less than 2°C (Fig. 5). In summer the water column seems to be thermally well mixed.

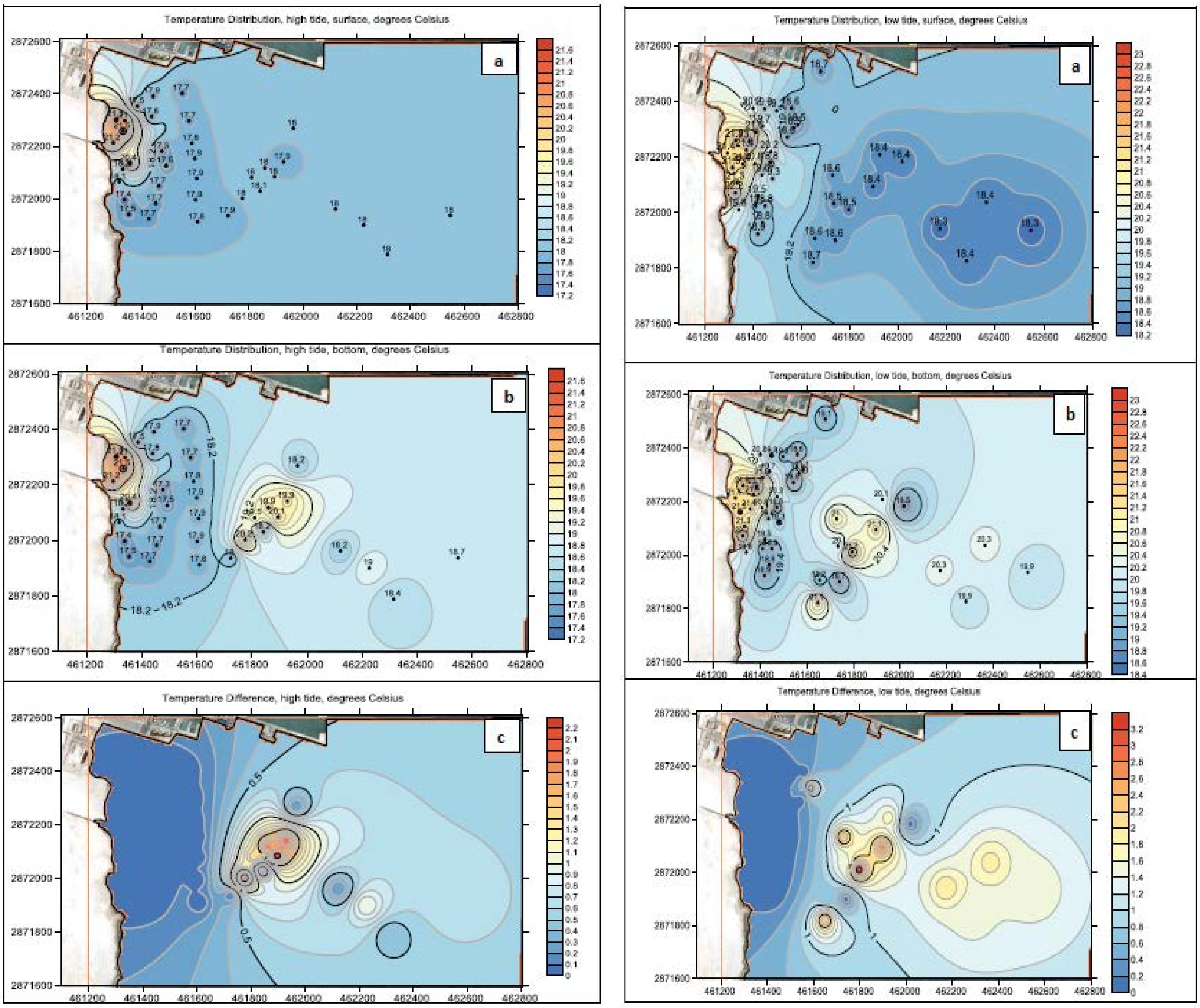

Fig. 4. Water temperature during high (left) and low (right) tide cycle in winter (a) surface, (b) bottom and (c) difference between surface and bottom.

The spatial variation of temperature considering the tide cycle in summer showed a heterogeneity distribution during the high tide at which three contours were formed characterized by different temperatures. However, during the low tide the water mass was spatially more homogenized within the outlet vicinity. In winter, different pattern has been observed indicating thermal stratification as visible contours were occurred representing high temperature at bottom in comparison with surface specifically at depths 3–5 m.

3.2. Salinity

The salinity levels throughout the study area were varied between 44‰ to 59‰ in summer 42‰ and 60‰ in winter (Figs. 6 and 7). The results presented in Table 2 revealed that no real differences on seasonal basis were observed between summer and winter measurements. The salinity levels at bottom are relatively higher than surface with a slight tendence to high concentration during low tide cycle.

Spatially, the salinity showed clear variations based on a distance from the desalination outlet during summer and winter (Figs. 6 and 7). Extreme salinity levels (58‰–60‰) were found at stations located nearest to the outlet at depth less than 1m. However, the salinity levels at other locations were ranged between 42‰ to 49‰.

The salinity levels during the high tide cycle found to be slightly higher than relevant ones during the low tide cycle. Halocline (salinity stratification with a difference >1‰) was observed at all sampling locations except stations located nearby the outlet associated with shallow depths (<1 m). Stations located at depth 3–4 m were found to be the most saline stratified where the difference was >5‰ during the high tide and >10‰ during the low tide (Fig. 8). The vertical differences in salinity in summer were slightly lower than those that occurred in winter.

Three to four main salinity contours could be observed during the high tide in summer indicating a clear variation on a spatial basis, however, the water mass seems to be more homogenized during the low tide where the water mass

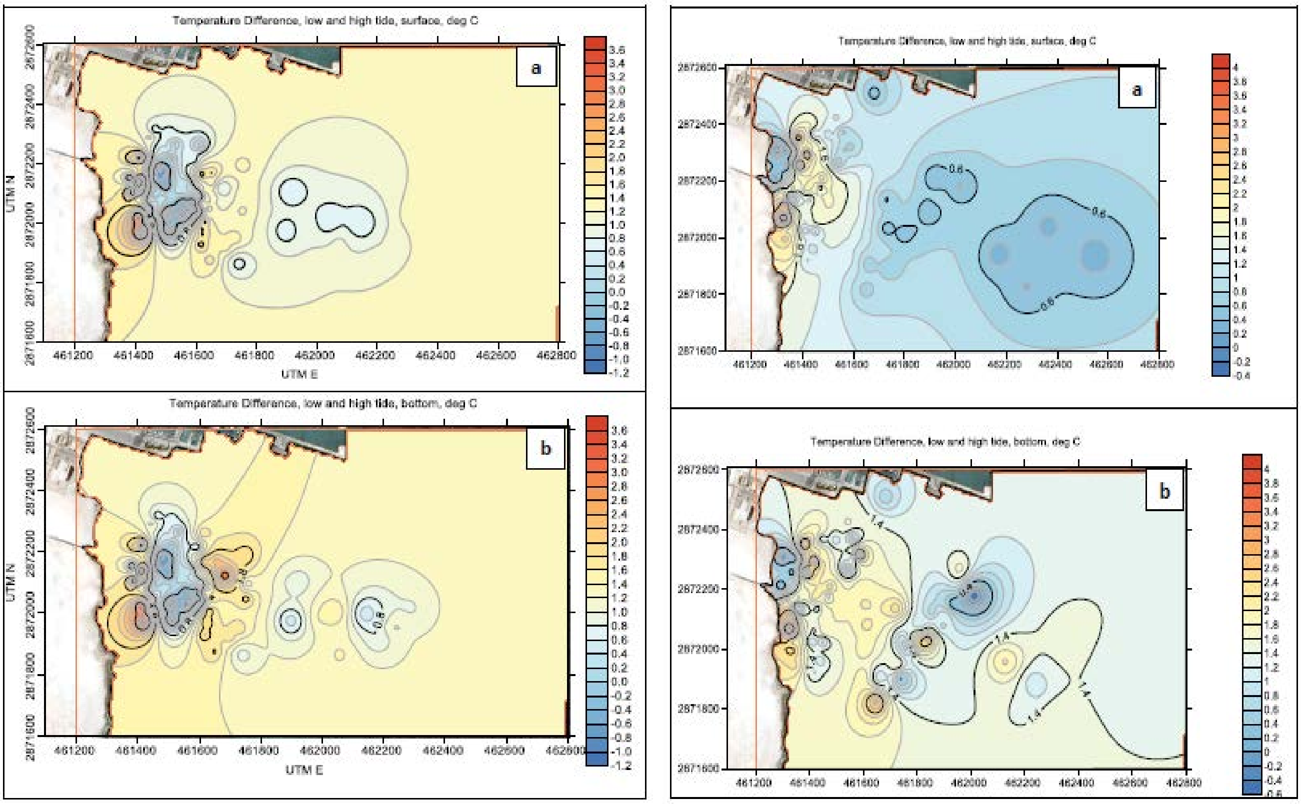

Fig. 5. Water temperature differences between high and low tide cycle of surface and bottom waters in summer (left) and winter (right).

well-mixed throughout the outlet area. The trend of salinity gradient was different in winter where a noticeable difference was obtained throughout the water column among the monitoring locations, particularly at stations associated with depths 5–6 m in which obvious halocline was observed. In general, the vertical distribution of salinity was more stratified in comparison with temperature during summer and winter.

4. Discussion

There is visible effect and impact due to the release of the brine water from Al-Dur desalination to the local water around the outlet of the desalination discharge. At the area facing the outfall high increase of water temperature extended to different distances following to tide cycle on a daily periodical basis as well as seasonal basis identified throughout the monitoring locations. The predicted scenarios in the Sitra desalination plant study showed that there is temporal variation in temperature during winter and summer as obtained by Saleh [20]. Similar findings indicated in the present study on the Al-Dur desalination plant. Palmer [21] proposed enforcement of national guidelines and standards for the brine discharge to minimize the environmental impacts. The Arabian Gulf is a highly stressed area due to the desalination activities and increasing capacity for providing fresh water. In addition to the environmental impacts expected to occur from climate change [5].

Al-Dur plant is one of the RO desalination plants in Bahrain. The trend of the desalination technology over the last 15 y indicated that the RO technology is expected to be the most common in the future capacity. However, although this technology type RO does not directly generate heated brine, the RO process will generate warm water typically discharged to the sea by the power stations, due to the associated energy production required unless very large-scale renewable energy sources are deployed [22].

The results on salinity gradient revealed that the effect of the brine water release is relatively high near the area of the outlet. The effect varied with the distance between 500–800 m from the discharge point. Such increase is continued through the whole period of investigation due to the continuous disposal of the brine water to the sea area. Since there is no standard for the salinity gradient in the Kingdom of Bahrain, a comparison made with the quality standard set by the Kuwait environment public authority for the release of cooling water to the sea area. The comparison has indicated that the salinity concentrations at most of the sampling locations were higher than effluent discharge standards with a mean ranging between 2.5‰–9.0‰. The effect of high salinity concentration may potentially reflect on benthic species composition indicated by [23]. Salinity can play a significant role in the growth and size of aquatic life and marine species disturbance mostly the migratory species as for common commercial fish species such as silver Pomfret and his shad that Kuwait environment

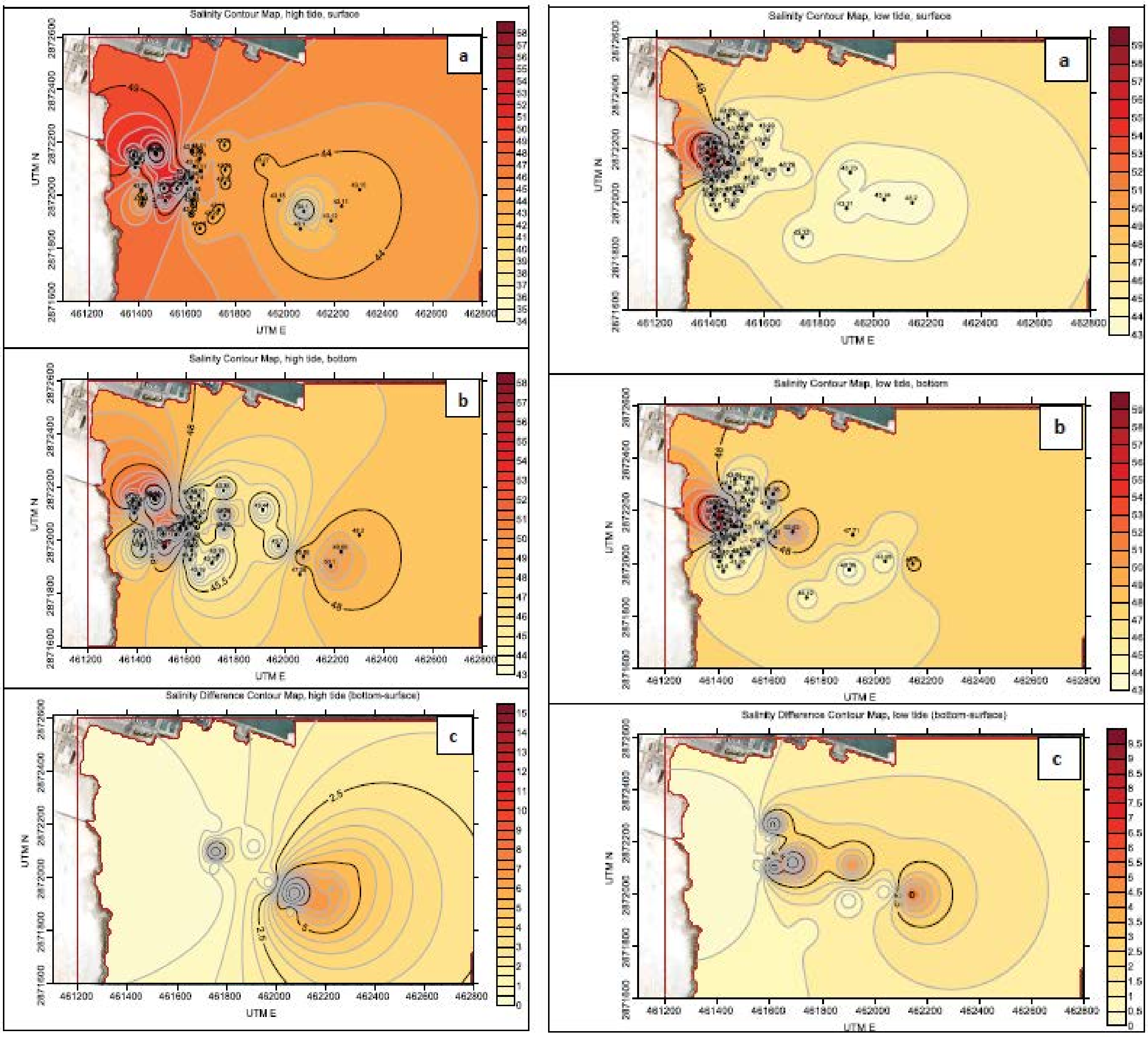

Fig. 6. Salinity gradient during high (left) and low (right) tide cycle in summer (a) surface, (b) bottom and (c) difference between surface and bottom.

is part of their migration cycle. The optimum seawater salinity (35‰), which may increase up to 70‰ characterize low water quality for marine living biodiversity [24]. In terms of physical scale of impacts, salinity increases >2‰ are rarely observed beyond a 400 m radius of outfalls [25] although may extend to several km's in some cases [26]. Studies concerning with the environmental impacts of seawater desalination suggest that impacts typically occur over spatially limited areas close to desalination plants [17,25,27], including the Arabian Gulf [28].

Al-Dur desalination plant is located adjacent to the seagrass habitat that extends from the east of Bahrain across Fasht al-Adam to Hawar Islands. Thermal tolerance of the seagrass beds in the Arabian Gulf showed that seagrass growth is reduced above 37°C, and temperatures above 40°C for an extended period are considered lethal limit [29], suggesting that discharge areas are likely inhospitable environments for seagrasses during summer. Some EIA reports suggest that at salinities greater than 58‰ affect the seagrass growth in the Arabian Gulf, while at salinities of more than 67‰, a location is not suitable for any seagrass species [29]. The present study indicated extreme salinity levels within the outlet vicinity with a tendence of high concentration at bottom, which may potentially affect the seagrass growth associated with Al-Dur coastal area. Al-Osaimi et al. [30] found that the infauna species in Al-Dur coast is considerably affected by salinity where the lowest species diversity was associated with locations characterized by high salinity difference between surface and bottom salinity.

In general, the water mass within the outlet vicinity showed a relative homogeneity throughout the water column during the low tide cycle compared with the high tide cycle where the temperature and salinity showed more stratified formation.

A pre-treatment process needs to be implemented for brine waters before its direct discharge to mitigate its impacts on physical, chemical and biological properties around the vicinity extent and buffer zone. It suggested to

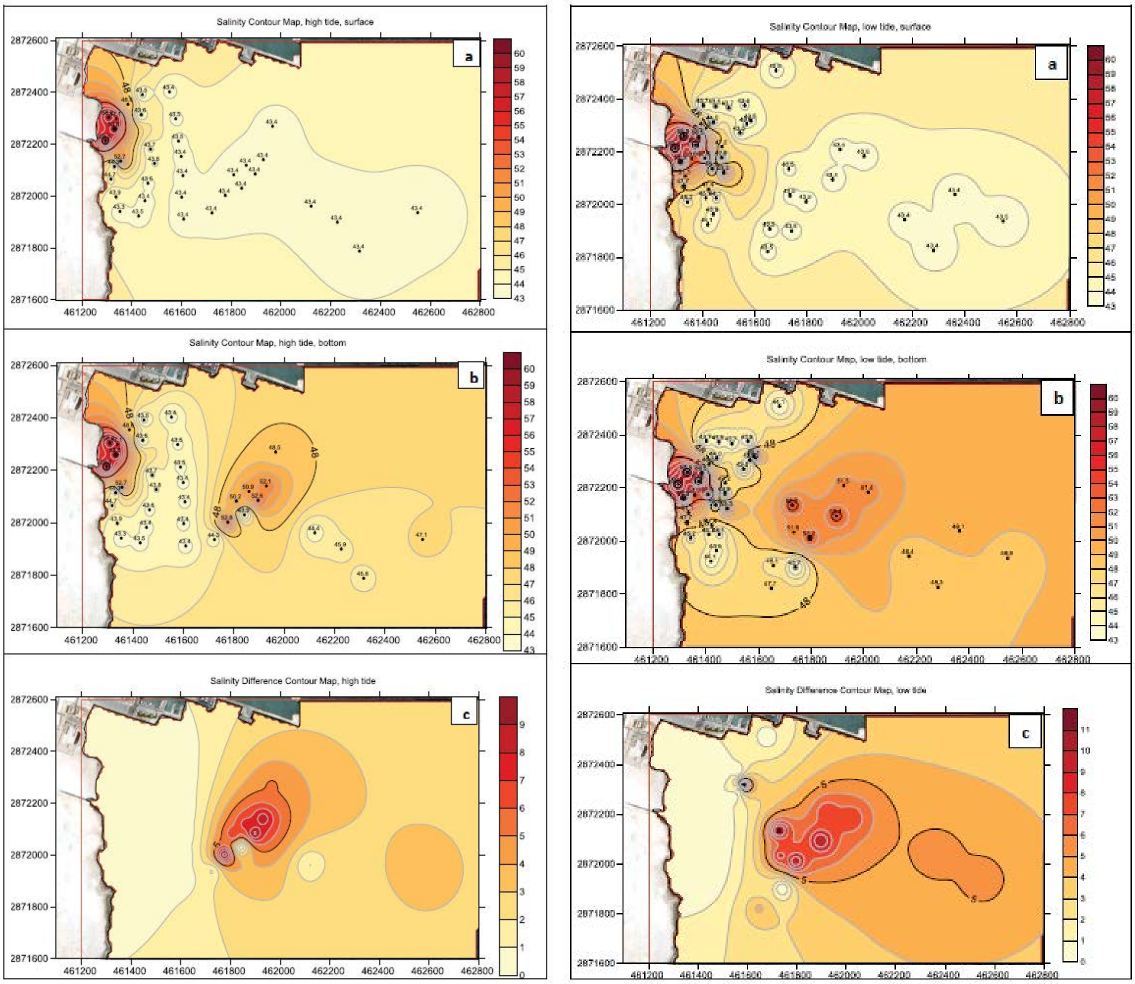

Fig. 7. Salinity gradient during high (left) and low (right) tide cycle in winter (a) surface, (b) bottom and (c) difference between surface and bottom.

Table 2
Surface and bottom salinity levels during high and low tide cycle in summer and winter

Salinity	Summer				Winter			
	High tide		Low tide		High tide		Low tide	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
Min.	34.1	43.2	42.6	42.8	43.3	43.4	43.4	43.6
Max.	58.2	58.3	58.7	58.9	59.3	59.5	60.0	60.0
Average	46.7	47.8	46.9	47.8	45.6	47.3	46.9	49.2

pass the discharged waters through a long channel before releasing to the coastal environment or extend the discharge pipe to deep water by diffuser lines. That promotes better mixing of the brine and seawater where the high current will improve the mixing process of the outlet. Moreover, it is of great importance to establish regional standards for the brine discharge from the desalination plant in the GCC countries.

An agreement was signed in March 2019 for Al-Dur 2 IWPP, an independent water and power project occupies an area of approximately 192,500 m^2 immediately south of the existing Al-Dur1 IWPP plant. The new plant shall be developed to generate 1,500MW of Power based on Combined Cycle Gas Turbine (CCGT) technology and produce 50MIGD of water through same technology seawater reverse osmosis (SWRO) of Al-Dur1. The plant is expected to be fully operational by the second quarter of 2022. Usually, during the planning of new plants, the intake system as well as the outfall system is carefully chosen to maintain water quality for plant operation and to minimize the potential impacts

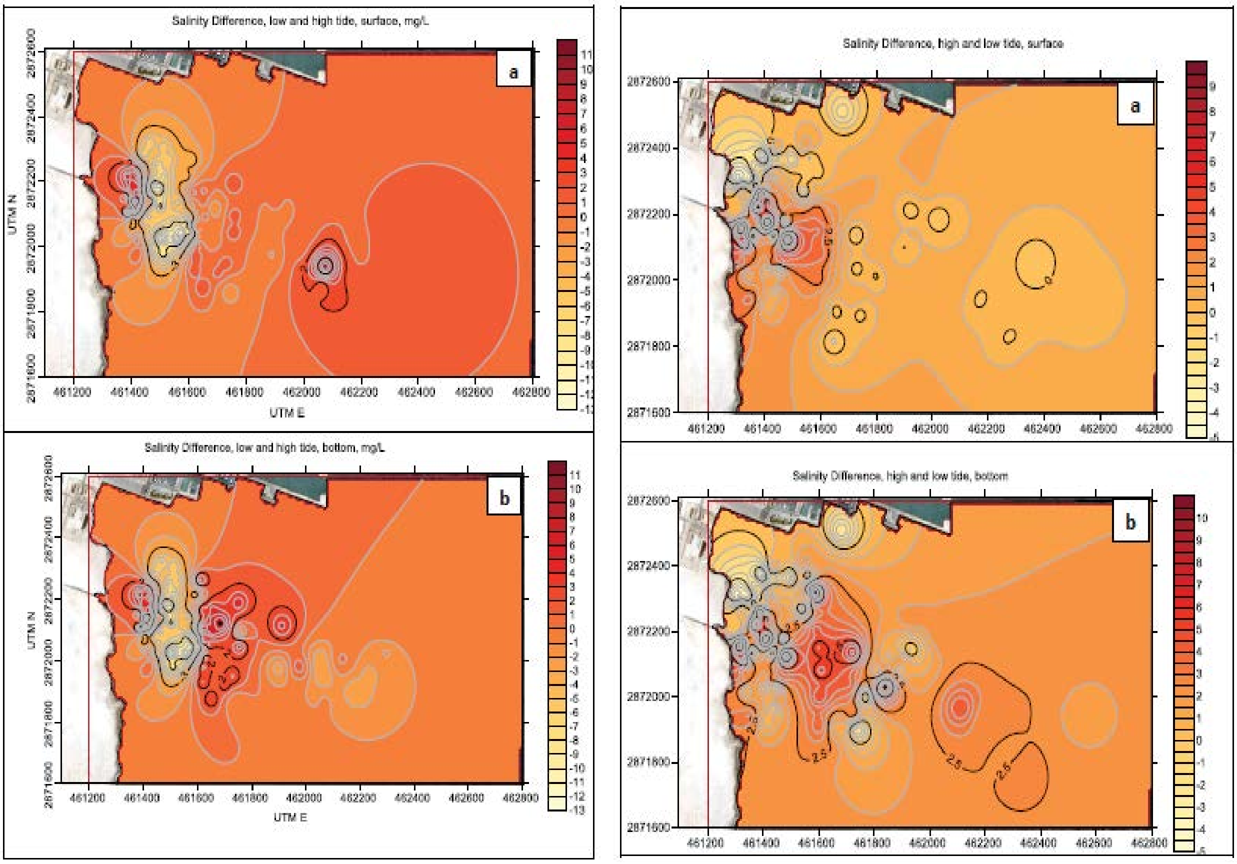

Fig. 8. Salinity difference between the high and low tide cycle of surface and bottom waters in summer (left) and winter (right).

of the discharged effluent on the surrounding marine area as well as the impact on the plant intake area. Therefore, Al-Dur coast will be vulnerable to further thermal pollution associated with hypersaline discharge. The extent of the additional impacts will be generated by the new plant need to be identified specifically for seagrass beds and benthic species associated with such habitat.

5. Conclusions

As a result of the lack of sufficient natural freshwater resources, the Kingdom of Bahrain depends heavily on desalination plants to provide sustainable needs for drinking freshwater. Consequently, utilization of seawater through desalination represents a coastal process activity in Bahrain. However, desalination plants could have several impacts on the surrounding marine environment. The impact's extent was varied concerning dynamic changes based on physical and chemical features considering the tide cycle associated with residual chemicals used in the pre-treatment process.

Analysis of available information regarding future scenarios of desalination capacity development and the impacts of desalination indicate that by 2050, desalination acting in combination with climate change, could have significant adverse impacts on the marine environment. There are several regulatory mechanisms that can be applied to control water demand and desalination activity, and these are tied in with technological development and practical reality. In terms of demand for water, regulation can be applied to control or limit water use or place demands on sectors to maximize water use efficiency.

The desalination outputs located adjacent to critical vulnerable habitats, for instance seagrass beds, may potentially impact the species diversity and ecosystem's function. In the southeast coast of Bahrain, the impacts will be complicated by further outlet of a new desalination plant (Al-Dur2) will be in place adjacent to the current one (Al-Dur1). On the other hand, the short-term observations, usually associated with monitoring program around power stations or desalination plants will not provide the opportunity to find out the impact trend on long-term scale for either temperature or salinity behaviour. Consequently, the current monitoring program implemented by the Supreme Council for Environment on seasonal basis needs to cover further monitoring locations representing the vicinity of each desalination plant. Moreover, a hydrodynamic modelling is required to assess the extent impact could be dispersed in relation to the seagrass beds.

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Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28205

263 (2022) 45–51
July

Evaluating the reuse and recycling options of end-of-life reverse osmosis membranes in Tajoura desalination plant

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Received 28 February 2022; Accepted 11 May 2022

ABSTRACT

Least-developed countries such as Libya face many challenges regarding their water supply due to the reduction in the groundwater, especially around the coastal region. This problem is likely to create challenges for drinking water supply and for agricultural activities. Desalination and wastewater treatment technologies could provide a solution to the problem. In Libya, around 5% of the installed desalination capacity is related on reverse osmosis (RO) membrane technology. Seawater desalination accounts for more than 40% of the total installed capacity of all RO plants. The Tajoura desalination plant is one of the oldest RO desalination plants established on the west coast of Libya. The plant has been under operation for three decades with little careful attention to its environmental impacts. Membranes used in the Tajoura plant had to be replaced when fouling effect is irreversible. The overall objective of the present paper is to estimate by thermogravimetric analysis and Fourier-transform infrared spectroscopic analysis the remaining potential value of end-of-life RO membranes for proposing alterative reuse options for used membranes. Number of reuse options for some membrane elements have been observed. Converting the fiberglass of the outer casing into small pieces or powder for other production is highly recommended, while polypropylene spacers provide potential opportunities for domestic and agricultural applications.

Keywords: Desalination technology; Environmental impacts; Chemical recycling; Energy recovery

1. Introduction

Water resources in arid and semi-arid regions like Libya are scarce. Groundwater is the main water source in Libya, supplying more than 98% of the water consumed [1]. Rainfall is the main source of groundwater recharge. According to Brika [2], the annual rainfall in Libya ranges from 100 to 600 mm in the northern areas. The rainfall average is less than 100 mm/y over about 93% of the Libyan's land surface [3,4].

Groundwater mainly from upper aquifer, is the main water source for domestic, industrial, and agricultural activities. The excessive groundwater exploitation due to the expansion in agriculture and the growth of population have contributed to a severe water crisis in Libya. Consequently, there is an urgent need to look for alternative water sources to meet people's needs and compensate for the reduction in groundwater. As far as researchers and experts are concerned, desalination of seawater could be a sustainable option to solve the problem of water scarcity in Libya, especially in the coastal populated cities, with growing increase in water demand and deterioration of groundwater availability quality. Given adequate attention by relevant authorities, seawater desalination plants

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

could become highly competitive in comparison to current water supplies such as man-made river project (MMRP).

According to data obtained from the formal water authorities, there are currently 21 operating desalination plants in Libya, with a total capacity of 525,680 m^3/d, while another 15 are in approval stages for constructing, with a total capacity of 1,695,000 m^3/d [2]. It is worth mentioning that the new approved desalination projects are adapting desalination using membrane technology (reverse osmosis process (RO)).

It has to be mentioned that the continuous growth in the use of desalination using membrane technology, creates a continuous build-up of the reverse osmosis membranes at the end of their life. Some sources indicate that the percentage of membrane replacement in reverse osmosis technology is about 10%–20% [5,6]. In general, the disposal of end-of-life RO membranes are dealt with according to the laws of each country, and unfortunately, these old membranes usually end up in landfills [7]. The current methods disposal of old membranes may result in significant negative environmental impacts. Therefore, to ensure sustainable and environmentally friendly use and disposal of old RO membranes, the construction of new desalination plants should be designed to take into account environmental considerations, including the process of safe disposal of end-of-life RO membranes. Moreover, old RO membranes should also be considered for potential reuse through recycling.

This study reviews the history of membranes usage in the Tajoura plant since its installation, specifically storage methods and the number of damaged membranes. Further, this paper proposes alternative options for reusing end-of-life membranes. The expected findings of this work will assist the people responsible for the plant and the operators to increase the life cycle of the membrane elements and safely disposal of old membranes. On the other hand, researchers, policy makers, environmentalists, and users are expected to learn lessons from the outcomes of this study for used in the design, installation and maintenance of future desalination plants using membrane technology.

1.1. Environmental regulations

Environmental impact assessment is a general and common technique used by industrialized countries, to preserve environment natural resources and to protect them [8].

In Libya, environmental impact assessment was established in July, 6th, 1982 under the name of Law No. 7 as a basic regulation on the protection of the environment, consists of 11 chapters divided into 75 articles, concerning all the environmental matters related to private and public projects.

Two years later further regulations were issued. These regulations included the establishment of the technical center for protecting environment, which was setup to focus on proposing, initiating plans, innovations that promotes the importance of the local environment as well as monitoring the conditions of ongoing construction projects and current operational private and public projects.

According to The Libyan Environmental General Authority (EGA) the environmental assessment adopted by Law No. 7 addresses the following aspects [9]:

- To all individuals and organizations, institutions and departments, companies and cooperatives and other entities, whether public or private, national or foreign make every effort to contribute to the reduction of pollution and through cooperation with the Technical Center for protecting environment and follow the instructions issued by it in this regard and adherence to implementation.
- The law expects that all stakeholders take into account environmental considerations when developing projects including housing, utilities, transportation, energy, industry, agriculture and other projects through the following schemes:
  - Prepare environmental impact studies for projects prior to construction and to provide these studies to the Technical Center for approval.
  - Consider the specifications and standards-based environmental standard in the design, implementation, operation, and maintenance of small and big projects.
  - Take preventive and remedial measure related to pollution as they may occur in the implementation and operation of the projects.
  - Write reports that demonstrate the environmental status of each project, and how the project conforms to environmental specification and standards.

Based on above-mentioned points, water desalination plants should be under the Law No 7 where an environmental impact assessment is mandatory. Nevertheless the Law No 7 is only the basic regulation for protecting the Libyan environment, other ministries such as agriculture, water resources, electricity and renewable energies should have further specific laws and regulations that protect the environment.

1.2. Specification and description of Tajoura RO desalination plant

The Tajoura seawater desalination plant, located approximately 25 km East of Tripoli, commenced operation in 1984. It is considered to be the first and the largest RO desalination plant in Libya. It has a designed capacity of 10,000 m^3/d. Due to the lack of consumers, the plant first started to operate at half of its capacity (5,000 m^3/d). The Tajoura reverse osmosis (RO) desalination plant was designed to be operated in two stages [10]: in the first stage, membrane modules with a 6-inch diameter were used, and sea water was used as raw water to be desalinated, while in the second stage, membrane modules with an 8-inch diameter were used. Water produced during the first stage was used as raw water in the second stage.

Ten years after the first operation of the Tajoura RO plant, new membranes (8-inches in diameter) were enhanced in order to desalinate sea water directly in only one stage. In this stage, 540 membrane modules were used in two rows.

Membranes used in the Tajoura RO plant used to be installed every 5–7 y. The estimated number of membrane modules in each period is 594 for each row (total rows = 4).

This number clearly shows that the total number of membrane modules changed in the first stage (6-inches in diameter) reached 1,188, while in the second stage (8-inches in diameter) 252 membrane modules were replaced by new ones. Fig. 1 shows membrane modules as currently used in the Tajoura desalination plant.

The lifespan of the Tajoura RO desalination plant is approaching its end, necessitating immediate action to dispose of the majority of the plant's systems (intake, high pressure pumps, membranes, and all the related equipment).

1.3. An overview of membranes used in Tajoura desalination plant

Old membranes in the Tajoura plant are replaced with new ones usually every 7 y. The number of membranes used and changed at the Tajoura desalination plant between 1984 and the end of this study is expected to be around 8,000 cells (membranes). Table 1 lists the membranes used and the specification for each membrane (supplied by the membrane manufacturer).

It has to be mentioned that recovery for membranes of 6-inch in the first stage reached 30%–33%, while for membranes of 8-inch in the second stage operated with a recovery of approximately 75%. Recovery for membranes of 8-inch during period from 2000–2013 reached 98%.

Fig. 1. Spiral wound membrane modules in the Tajoura desalination plant.

Based on data presented in Table 1 the total number of membranes that have been used is 8,136 units, divided into two stages (6,372 units in the first stage and 1,764 units in the second stage). Most of the membranes were 20 cm in diameter (8") and 1 m long. Consequently, a stock of used membranes has piled up over the years. These old membrane elements in stock are no longer appropriate for seawater desalination because they have lost their desalination properties (salts rejection lower than 99%) due to fouling, scaling, etc. These old membranes may constitute an environmental concern since they need to be disposed of in some way. Alternatively, it is suggested that these old unites mean an opportunity to recover some remaining value from the membranes if reused in another applications [11].

1.4. Present conditions of used membranes in the Tajoura desalination plant

Old membranes from the Tajoura RO desalination plant are currently being disposed of in landfills. These membranes may take a long time to reach their final destination, which is usually a land area packed with waste, due to the disposal and transport related issues.

When the membranes' lifespan has reached, the Tajoura plant's quality control department takes the appropriate and safe step by doing the essential analyses on the produced desalinated water. If the results of the analysis do not meet the Libyan Standards for drinking water, the plant's decision makers, in collaboration with the Tajoura Nuclear Research Center, must seriously consider replacing the used membranes with new ones. The plant unit supervisors will collect the old membranes and deposit them in containers brought particularly for this purpose, as shown in Fig. 2.

The container is locked for an unknown period, when the process of loading the old membranes is completed, as there is currently no safe way to discharge these old membranes. Workers and operators at the Tajoura plant indicate that the plant construction company has offered no recommendations on how to safely dispose of old membranes or repurpose them. Figs. 3a and b show some of the used membrane cells.

Table 1
Membranes used in the Tajoura RO desalination plant

Period	Membrane diameter	Number of units (elements)						Membrane model		Raw water source
		First stage				Second stage				
		R405	R406	R407	R408	R410	R411	First stage	Second stage	
1984–1989	6" + 8"	594	594	594	594	252	252	TFC 1501	TFC 8600	S.W*–Br.W**
1990–1991	6" + 8"	–	–	594	594	252	–	TFC 1501	TFC 8600	S.W–Br.W
1992–2000	6" + 8"	594	594	–	–	252	–	TFC 1501	TFC 8600	S.W–Br.W
2000–2005	8"	–	–	270	270	–	–	TFC 282255-360	–	S.W
2005–2013	8"	270	270	270	270	–	–	TFC 282255-360	–	S.W

*S.W is seawater;
**Br.W is brackish water.

Fig. 2. Old membranes as installed in a container.

It can be observed that the old membrane cells were placed randomly over each other. Old membrane cells are also found to be contaminated with deposits that could have a harmful impact on both the human body and the environment

2. Materials and methods

2.1. Old RO membranes

RO membrane under study is thin-film composite spiral wound membrane consists of two membrane sheets glued together and spirally wound around a perforated central tube through which the permeate (product water) exits the membrane element. The first membrane sheet, is made of thin-film composite polyamide material and has microscopic pores. This membrane sheet is supported by a second, thicker membrane sheet, which is made of higher-porosity polysulfone material (PSf). In addition, the membrane element structure contains a feed spacer, made of polypropylene (PP), a permeate spacer made of polyester, a permeate tube and end-caps made of acrylonitrile butadiene styrene (ABS), an outer casing made of fiberglass and the glued parts containing proprietary epoxy-like components. Having named the materials of each membrane component, the authors believe that the chemical analysis can further help to suggest options to repurpose each part of the old membrane in a way that would be acceptable for the environment.

Two experimental analyses were performed during the development of this study to determine the chemical composition and thermal stability of the membrane's primary components. Membrane components were separated and cut into small pieces, which were then sent to the lab. Fig. 4 shows the image of the membrane component samples analyzed in this study.

The membrane components shown in Fig. 4 were analyzed by thermogravimetric analysis (TGA) and some of them, due to some difficulties, were characterized by Fourier-transform infrared spectroscopy (FTIR).

3. Results and discussion

3.1. Combustion and carbonisation

Thermogravimetric analysis (TGA) is a thermal analysis technique that measures the weight, and hence the mass, of a sample as a function of temperature. TGA allows us to detect changes in the mass of a sample (gain or loss),

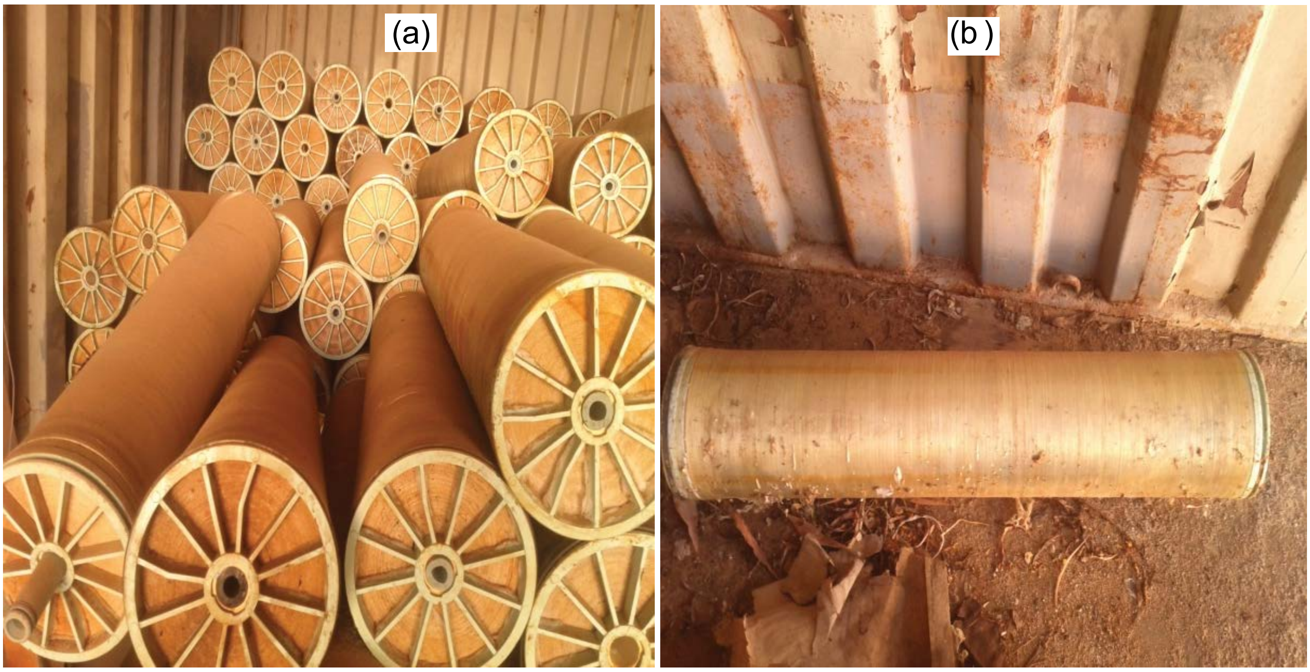

Fig. 3. (a and b) Old membrane cells.

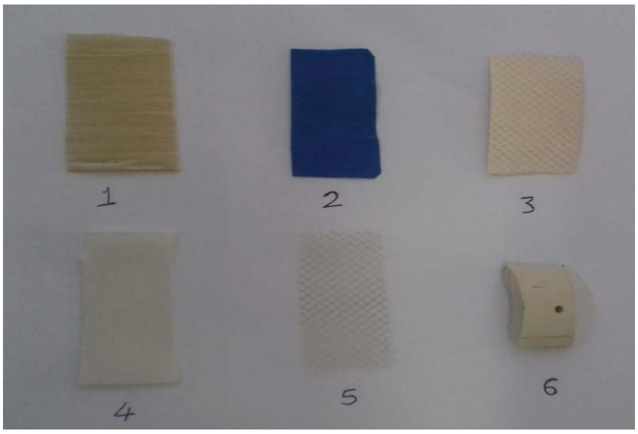

Fig. 4. Different membrane components that were tested in this study. From left to right: outer casing (1), glues (2), membrane sheet (3), permeate spacer (4), feed spacer (5), permeate tube (6).

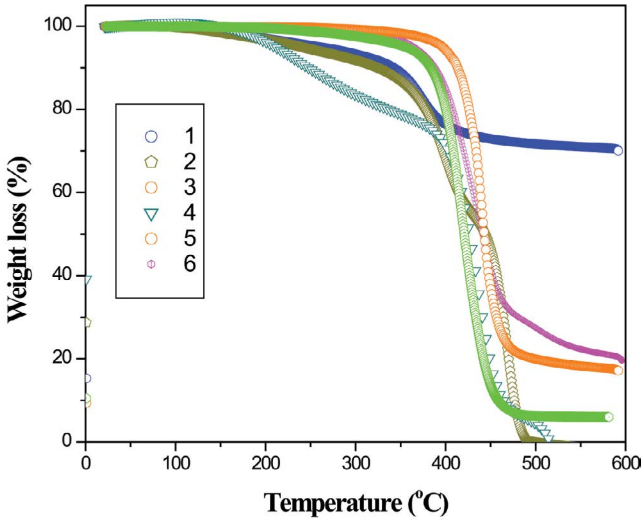

Fig. 5. Thermogravimetric analysis (TGA) of membrane element components.

evaluate stepwise changes in mass (usually as a percentage of the initial sample mass), and determine temperatures that characterize a step in the mass loss or mass gain curve.

TGA of membrane component samples was carried out using a HCT-5022 thermo-analyzer (Beijing Hengjun Instrument Company, China). Samples of 10–15 mg were degraded under nitrogen atmosphere (flow rate 50 mL/min) at a heating rate of 10°C/min. Fig. 5 shows the results of the thermogravimetric analyses of the membrane components. The figure shows that sample number 2 (glues) is the least thermally stable component, showing almost complete degradation around 480°C, while sample number 5 (feed spacer) is the second least thermally stable component as it is completely combusted at 520°C, followed by the permeate spacer (4) and permeate tube (6). The remaining membrane components including outer casing (1) and membrane sheet (3) are much more thermally stable as their curves decrease slowly towards a zero weight. In the case of the outer casing, which comprised mainly fiberglass, an inorganic residue of about 67 wt.% remains after TGA combustion.

Based on the thermogravimetric analysis, it is possible to thermally degrade the polymer components to carbon using thermal treatments [12]. Except for the fiberglass outer casing, all membrane element components are suitable for combustion and carbonisation treatment to convert the polymer components into an energy source [13].

Furthermore, old membrane elements that have proven to be thermally degraded, particularly feed spacer, can be used as a substitute for coke in electric arc furnaces used in the steel fabrication process. The use of polymeric waste in electric arc furnaces offers several advantages, such as increased furnace efficiency, reduced energy consumption, lower coke consumption as well as reduced volume of waste in landfills [14,15].

3.2. Chemical composition

Identification of the raw material of each component of the membrane is a key step in polymer recycling. The authors believe that it might be possible to suggest more recycling options of each membrane component individually. Based on this concept the Fourier transform infrared spectroscopic analysis (FTIR) was the only available technique to be used for identifying the polymer composition of the major membrane components.

FTIR spectra were recorded in the range 4,000–400 cm^{-1} with 2 cm^{-1} resolution on a Bruker Vector–22 Fourier transform spectrometer using the KBr pellet technique (1.0 mg of sample in 100.0 mg of KBr). The FTIR spectra analysis confirms that the feed spacer is comprised of polypropylene and the permeate spacer is made of polyester. The permeate tube and end caps are comprised of an amorphous material such as ABS. The FTIR spectroscopic analysis further showed that the outer casing is clearly made of fiberglass. The detailed polymer composition of the membrane components is illustrated in Table 2.

4. End-of-life reverse osmosis membranes options

In general, waste plastic disposal has not yet become a big environmental issue in Libya. Furthermore, there are few government regulations that govern waste management. As a result, the city of Tajoura, where the desalination plant is located, has a limited number of small companies that collect plastic waste. However, only a small percentage of these companies participate in the plastic waste recycling process. Local companies collect plastic waste, compact it, and sell it to other local companies/factories or export it overseas for further processing and manufacturing.

In order to evaluate the potential value of recycled polymer materials membrane components were separated and taken to one of the local companies. Membrane components were observed and examined carefully by the plastic waste recycling company's management team, and the following comment was made:

Currently, and due to the lack of investment, advanced equipment and expert personnel, the only membrane elements that could be recycled are the ones comprising a single polymer component such as the outer casing, feed

Table 2
Composition of typical membrane components as it is exacted from FTIR analysis

Membrane component	Composition
Outer casing	Fiberglass
Feed spacer	Polypropylene (PP)
Permeate spacer	Polyester
Membrane sheet (thin-film composite)	Aromatic polyamide
	Microporous polysulfone (PSf)
Permeate tube/end caps	Acrylonitrile butadiene styrene (ABS)
Glues	Epoxy resin
Rubber o-rings	Ethylene propylene diene monomer (EPDM)

Fig. 6. Permeate tube for irrigation.

Fig. 7. Frames with different sizes made for house's windows.

spacer and permeate spacer. Nevertheless, the local companies might not be able to recycle these components due to the lack of suitable separation technology equipment for such RO membrane cells.

Regarding alternative suggestions for the disposal and reuse of used RO membrane elements, the authors suggest the following:

- *Permeate tube*: an alternative reuse option is to connect a number of permeate tubes and use for irrigation (Fig. 6).
- Feed/permeate spacers for agricultural and domestic applications:
  - Feed spacer to prevent mosquitoes attack via house's windows (Fig. 7).
  - Permeate spacer as geotextile as reported in previous studies [13,16–18].
- Feed spacer is considered to be a single-polymer plastic that is clean and homogenous. Therefore, it has the ability to be directly recycled (mechanical recycling) and used as feed stock for the production of new products such as containers and packaging. This suggestion is in accordance with those stated in some previous investigations [15].
- Mechanical grinding can be done for some old RO membrane elements such as the outer casing, which is made of fiberglass. Grinding is the most obvious processing method used for recycling fiberglass. It leads to reducing material to small pieces or powder to be reused in other products. Grinding of fiberglass could provide a filler material or aggregate that could be used in concrete. Fiberglass powder could be used to make thermoforming molds or other structures. This suggestion is consistent with the recommendation of García et al. [19].
- RO membrane elements which comprise mixed plastic materials such as the membrane sheet can be used as an energy source. Gasification and pyrolysis are preferable processes to incineration because they produce fewer emissions [20–22].
- Another process, known as the remembrane project, was recently introduced with the goal of extending the lifecycle of membranes used in RO saltwater treatments by through an innovative technology to improve membrane recovery and reuse. The goal of such innovative technology is to reduce waste, lower costs, and increase overall desalination efficiency [23].

5. Conclusions and recommendations

The work reported in this paper represent a first attempt to assess the chances of reusing old RO membranes accumulated over the years at Tajoura RO desalination plant.

Amongst the results obtained, it was concluded that some membrane elements (the ones comprising a single polymer component) could be recycled and used effectively in other applications. Additionally, membrane elements that consist of mixed plastic materials such as the membrane sheet can be used as an energy source. By utilizing these alternative end-of-life option the volume of RO membranes sent to landfill will be reduced, eliminating the associated social and environmental costs.

Due to the lack of suitable separation technology equipment for such RO membrane cells, the authorized governmental authorities should make a huge effort to find potential international users for expired membranes. In this regard, particular attention must be given to the reuse, recycling and disposal of used RO membranes when establishing new desalination plants.

The local authorities and decision makers should take the initiative to invest partly or entirely in new, friendly desalination technology such as "the remembrane project".

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Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28206

263 (2022) 52–59
July

Assessment of freeze melting technology for brine concentration

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Received 28 February 2022; Accepted 26 April 2022

ABSTRACT

High saline waters are produced in large volumes in Kuwait from various industrial applications, including desalination and petroleum sectors. These types of waters as a waste have a significant impact on the surrounding environment, and some of which may pose a number of threats to human health. Freeze melting (FM) technology is considered a novel desalting process that can be further developed for innovative saline water desalination. This paper aimed at evaluating the viability and efficiency of FM process under static and dynamic influences for brine concentration. The dynamic crystallization process was investigated with three agitation systems, which are: a bubbling system, a mechanically stirred system, and an ultrasonic system. The results of dynamic crystallization process were compared to the results of the static crystallization process. The results of the experimental works showed that the most effective crystallization processes was the mechanically stirred agitation system followed by bubbling agitation process and the ultrasonic system using a single-stage of freeze crystallization. The promising results obtained, will lead to a future hybrid system of near zero liquid discharge that combine reverse osmosis and FM process to concentrate the volume of brine to the minimum level possible and simultaneously produce high quality product water, which will eventually lead to enhance the overall permeate water recovery of the integrated technologies.

Keywords: Freeze-melting process; Nucleation; Melt crystallization; Freezing desalination; Ice crystallization; Static freeze crystallization

1. Introduction

To date, intensive research activities on innovative nonconventional desalination technologies are continually being carried out by leading scientists in order to seek the most feasible and sustainable desalting process for brine concentration applications. Among a variety of innovative nonconventional desalination technologies, the freeze crystallization technology might be an economically and a technically feasible process for such an application. This process has a number of important advantages such as low energy requirement, low biological fouling challenges, very high separation factor, minimizes scaling and corrosion problems, low-cost materials can be used, absence of chemical pretreatment and chemical additives [1], low ecological impact [1–3]. Despite these advantages, all these processes are still in their infancy due to serious limitations and challenges [4]. To eliminate the limitations of handling and separating ice slurries in the conventional freezing desalination technologies, this paper will look at static solid layer freeze crystallization and various forms of dynamic solid layer freeze crystallization processes as alternative techniques to seawater desalination. This is due to the important advantages of solid layer freeze crystallization over the conventional freezing desalination technologies. According to Ulrich and Glade [5], the important advantages of solid layer crystallization technologies are (i) incrustation problems are avoided, as these incrustations represent the solid layer, which will eventually be separated, melted, and recovered as a final product water; (ii) easily controllable

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

crystal growth rates, due to the driving force being dependent on the temperature difference at the refrigerated surface area of the plate; (iii) a simplified separation process because of the absence of an ice slurry. Thus, complicated ice separation and washing equipment, usually used in conventional desalination through freezing processes and melt suspension crystallization technologies, is avoided.

The paper's main objective is to develop and demonstrate the viability of four different freeze melting (FM) processes, on a laboratory bench-scale, for brine desalination and concentration. The specific aims of this paper are to assess the viability of a static and three dynamic FM processes to concentrate brines; compare experimental data of the proposed FM technologies; and propose a conceptual design of pilot-scale system for desalting and concentrating high saline waters.

2. Experimental

2.1. Preparation of feed samples and physicochemical analysis

Since aqueous solutions of sodium chloride give results in the desalting process very close to process brines [6], salt concentrations of 7% by mass of NaCl salt were prepared, used, and examined as feed material in this experimental investigation. The physical and chemical analysis of the proposed water samples is tabulated in Table 1.

2.2. Experimental setup

Fig. 1 shows the equipment for the crystallization experiments using a static and agitated crystallization processes. The experimental setup for the static crystallization process comprises of a laboratory jacketed beaker with a capacity of 500 mL, refrigerated immersion cooler attached to the cooling coil, refrigerated thermostatic bath, circulator, and flexible tubing.

The experimental setup for the static and agitated crystallization processes are identical apart from the agitation system used. In the case of the mechanically stirred crystallization process, the setup consists of overhead stirrer assembly, which includes an overhead stirrer and stirring paddle. As for the experimental setup for the crystallization process using a bubbling system, an air pump assembly that includes an air pump with a ball type ceramic air-stone diffuser was utilized in this study. The experimental setup for the crystallization process using an ultrasonic radiation system was provided with the ultrasonic radiation assembly that consisted of an ultrasonic processor device and an ultrasonic probe.

Table 1
Physical and chemical analyses of feed samples

Feed	NaCl
Feed salinity (wt.%)	7.0
Electrical conductivity (mS/cm)	84.8
Volume (mL)	500
Freezing point (°C)	–4.8

2.3. Experimental procedure

The operating procedure is presented in Fig. 2. All experiments were conducted in batch mode. Referring to the simplified block diagram in Fig. 2, prior to conducting any experiment, the feed sample was prepared, and then the physiochemical analysis was performed on the feed sample. The jacketed beaker was filled with a constant mass of feed material, that is, 500 g. For all the experiments, the temperature of the heat transfer medium (HTM) was initially reduced via operation of the refrigerated immersion cooler. The circulator was manually turned on when the temperature of HTM reached the specified crystallization cooling rate. The operational cycle of precooling was started to lower the temperature of the jacketed beaker containing the feed sample. For all experiments using the agitated crystallization process, the agitator system used, such as; stirring paddle, airstone diffuser, or an ultrasonic probe, was dipped into the jacketed beaker. The agitation system was turned on prior to beginning the pre-cooling operation. The agitation rate was set at the predetermined value that remains constant for the duration of the experiment.

For all the experiments, once the temperature of the feed sample reached the freezing point of the feed, a seed ice crystal was added to achieve the nucleation of ice crystals,

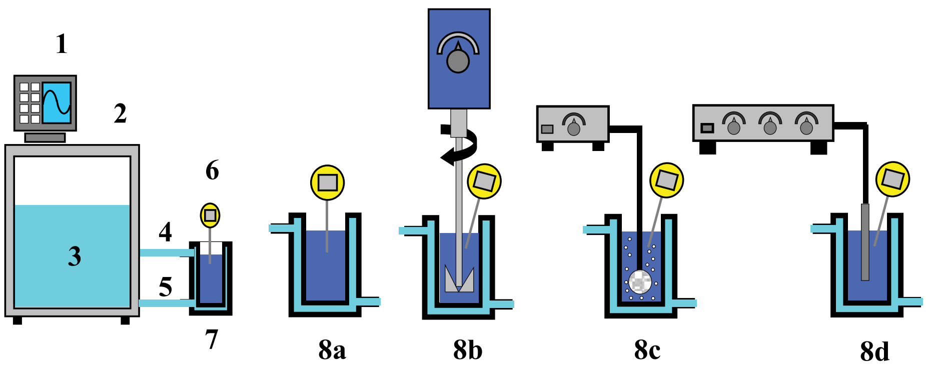

Fig. 1. Scheme of experimental setup. (1) Heating and cooling PID controller, (2) Heating and cooling bath thermostatic bath, (3) Heat transfer medium (HTM), (4 and 5) Inlet and outlet HTM flexible tubes, respectively, (6) Digital thermometer, (7) Jacketed beaker, (8a) Static crystallizer and agitated crystallizer using; (8b) Mechanical stirring, (8c) Air-pump, (8d) Ultrasonic device.

which was then gradually grew over the duration of the experiment. The ice crystals progressively crystallized on the refrigerated surfaces of the jacketed beaker perpendicularly outward to the surfaces leading to the formation on an evenly thin crystal coat on the refrigerated surface. After running the experiment for a predetermined time, the operation of the circulator was terminated, and simultaneously the residue (that is, brine) was drained and retained for further analysis, as shown in Fig. 2. After draining the brine from the system, the ice crystal layer was melted. Following sampling, physiochemical analyses was carried out on the residue and product water samples as per standard procedure.

3. Results and discussion

For all tests, Table 2 presents, concentrating and treating NaCl solution with a salt concentration of 7 wt.% using static crystallization process. The total time duration to reach the lowest temperature of crystallization was 70 min. In each test, the influencing parameter, that is, cooling rate was examined upon the performance indicators, including water recovery, permeate concentration, and salt rejection. These experiments were carried out in a feed stage process, that is, single freezing stage.

3.1. Static freeze crystallization process

In the first series of experiments, the potential of the static crystallization process was investigated for desalinating. Fig. 3 shows the experimental data on the salt concentration of feed of 7 wt.%. Results of the water recovery ratio and salt rejection ratio as a function of the cooling rate are shown in Fig. 3. It can be seen that at cooling rates of –0.004 and –0.061°C/min the water recovery is 24.52 and 44.70, respectively. Fig. 3 shows a dramatic decrease in water recovery ratio when the crystallization temperature was increased. This is due to the fact that growth rate of ice layer decreased as a result of increasing the crystallization temperature. For all experiments, the total time duration to reach the lowest temperature of crystallization was 70 min. The experiments were run for 5 min after attaining the lowest temperature. This trend observation has been demonstrated in earlier study conducted by Rich et al. [7], which was first thoroughly investigated by Burton et al. [8], and later reported by Wilson [9] and Rosenberger [10]. The trend of the graph was found more likely linear. The results indicate that the salinity of product water is very

Table 2
Investigated crystallization temperatures, cooling rates and crystallization time for static crystallization process

Feed concentration (wt.%)	7
Crystallization temperature (°C)	–6 to –10
Cooling rates (°C/min)	–0.004 to –0.061
Crystallization time (min)	70

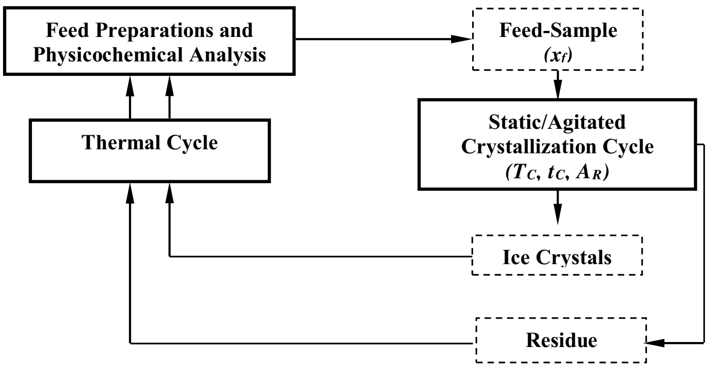

Fig. 2. Simplified block diagram of the experimental set-up. x_f is the feed concentration (wt.%), T_C is the temperature of crystallization process (°C), and t_C is the running time of crystallization process (minute), and A_R is the agitation rate.

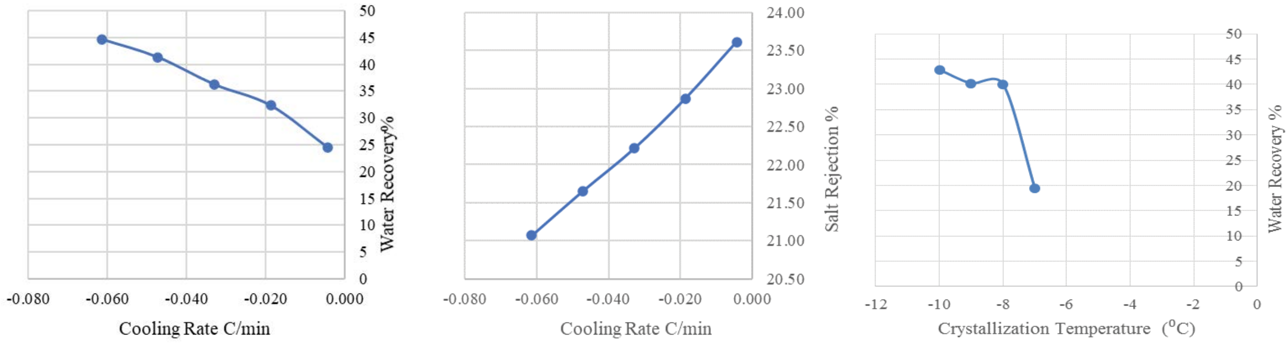

Fig. 3. Water recovery and salt rejection vs. cooling rate and water recovery vs. crystallization temperature at 70 min of crystallization time for 7 wt.% static crystallization.

sensitive to changes in cooling rate. The results proved that the slow crystal growth rates, dictated by increasing the cooling rate, are of great importance in improving the separation efficiency of the static crystallization process. According to Myerson [11], lower growth rate is leading to increasing diffusivity of the impurity and at the same time it is decreasing diffusion ice crystalline thickness. At cooling rates of –0.004, –0.019, –0.033, –0.047, and –0.061°C/min, the salt rejections are 23.61, 22.87, 22.21, 21.66 and 21.07, respectively. The trend of the graph of the salt rejection ratios (shown in Fig. 3) is more or less linear. This trend observation has been demonstrated in an earlier study conducted by Kim et al. [12], and this behavior can be noticed in all dynamic crystallization processes presented in Figs. 5–12.

In general, the water recovery ratio results were found to be inversely proportional to the crystallization cooling rate, whereas the salt rejection was found proportional to the cooling rate.

3.2. Dynamic crystallization process using ultrasonic process

In the second series of experiments, the potential of the dynamic crystallization process using ultrasonic process (UP) was investigated for desalinating, concentrating, and treating different concentrations of NaCl solution ranging from 7 wt.% as indicated in Table 2. The investigated amplitudes of UP were ranged from 20 up to 60%.

Fig. 4 shows the experimental results on feed concentration of 7 wt.% at cooling rates of –0.004 to –0.061°C/min at 80 min of crystallization time and 20%. Results of the water recovery ratio and salt rejection ratio as a function of the cooling rate are shown in Fig. 4. It can be seen that at cooling rates of –0.004 and –0.054°C/min, the water recovery ratio is 8.04% and 38.18%, respectively. At cooling rates of –0.015, –0.032, –0.048, and –0.065°C/min, the salt rejections are 3.17%, 9.77%, 14.43%, 15.94%, and 23.93%, respectively.

Fig. 5 shows the experimental results on feed concentration of 7 wt.% at cooling rates of –0.004 to –0.061°C/min at 80 min of crystallization time and 40%. Results of the water recovery ratio and salt rejection ratio as a function of the cooling rate are shown in Fig. 5. It can be seen that at cooling rates of –0.004 and –0.054°C/min, the water recovery ratio is 4.96% and 42.68%, respectively. For all cases (Figs. 5 and 6), similar to the static crystallization process, a decrease in water recovery ratio with the increase in crystallization temperature was observed due to the decreased growth rate of ice layer. At cooling rates of –0.015, –0.032, –0.048, and –0.065°C/min, the salt rejections are 9.03%, 11.63%, 12.20%, 13.39%, and 20.89%, respectively.

Fig. 6 shows the experimental results on feed concentration of 7 wt.% at cooling rates of –0.004 to –0.061°C/min

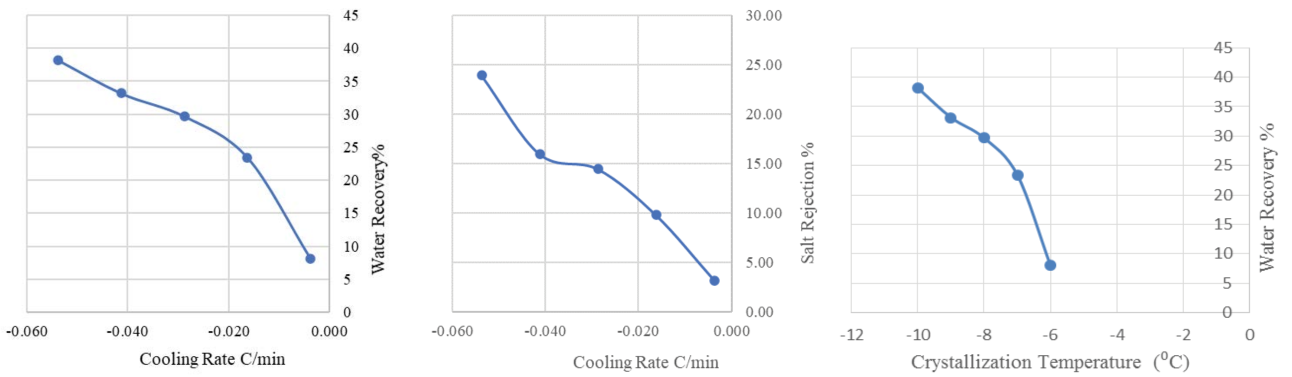

Fig. 4. Water recovery and salt rejection vs. cooling rate and water recovery vs. crystallization temperature at crystallization time of 80 min and amplitude of 20% for 7 wt.%.

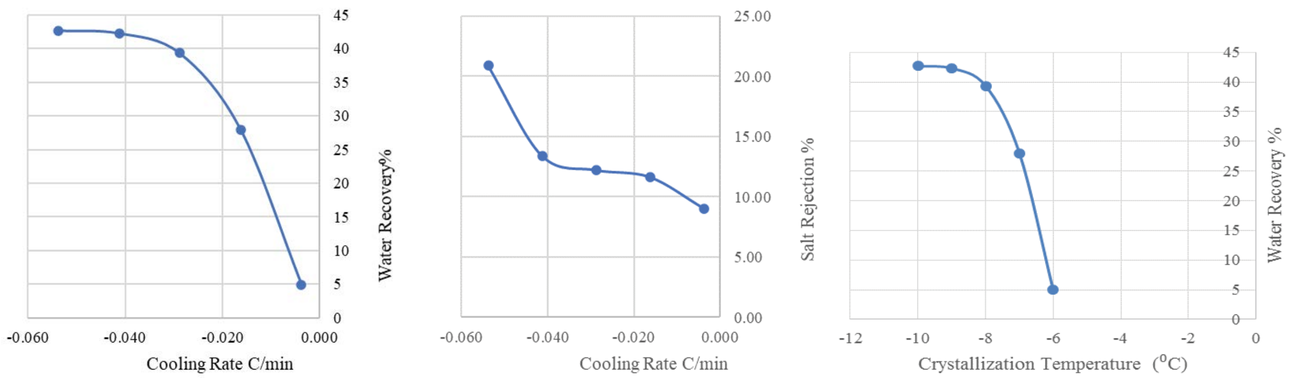

Fig. 5. Water recovery and salt rejection vs. cooling rate and water recovery vs. crystallization temperature at crystallization time of 80 min and amplitude of 40% for 7 wt.%.

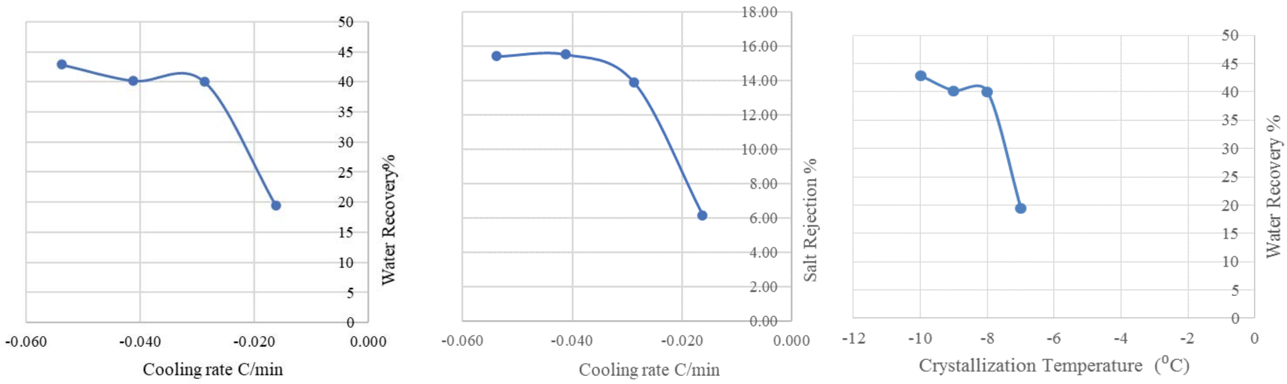

Fig. 6. Water recovery and salt rejection vs. cooling rate and water recovery vs. crystallization temperature at crystallization time of 80 min and amplitude of 60% for 7 wt.%.

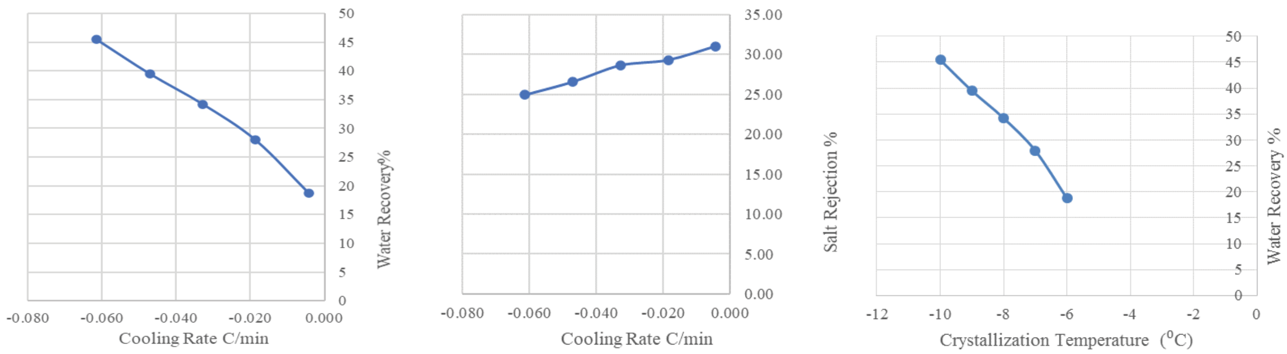

Fig. 7. Water recovery and salt rejection vs. cooling rate and water recovery vs. crystallization temperature at 70 min of crystallization time and flow rate of 10 L/min for 7 wt.%.

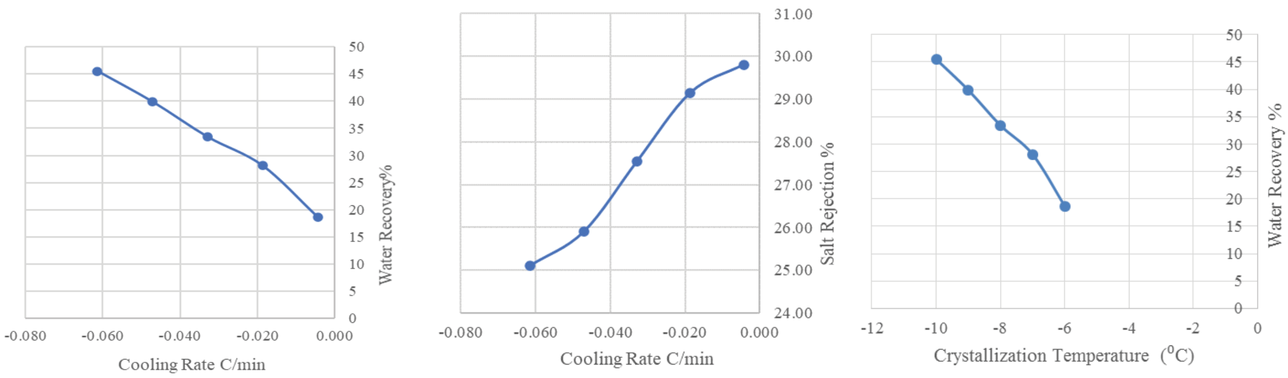

Fig. 8. Water recovery and salt rejection vs. cooling rate and water recovery vs. crystallization temperature at crystallization time of 70 min and flow rate of 20 L/min for 7 wt.%.

at 60 min of crystallization time and 60%. Results of the water recovery ratio and salt rejection ratio as a function of the cooling rate are shown in Fig. 6. It can be seen that at cooling rates of –0.016 and –0.054°C/min, the water recovery ratio is 19.48% and 42.90%, respectively. At cooling rates of –0.016, –0.029, –0.041, and –0.054°C/min, the salt rejections are 6.17%, 13.89%, 15.51%, and 15.40%, respectively.

3.3. Dynamic crystallization process using bubbling process (BP)

In the third series of experiments, the potential of the dynamic crystallization process using BP was investigated for desalinating, concentrating, and treating different concentration of NaCl solution ranging from 7 wt.% as indicated in Table 2. The investigated feed concentrations,

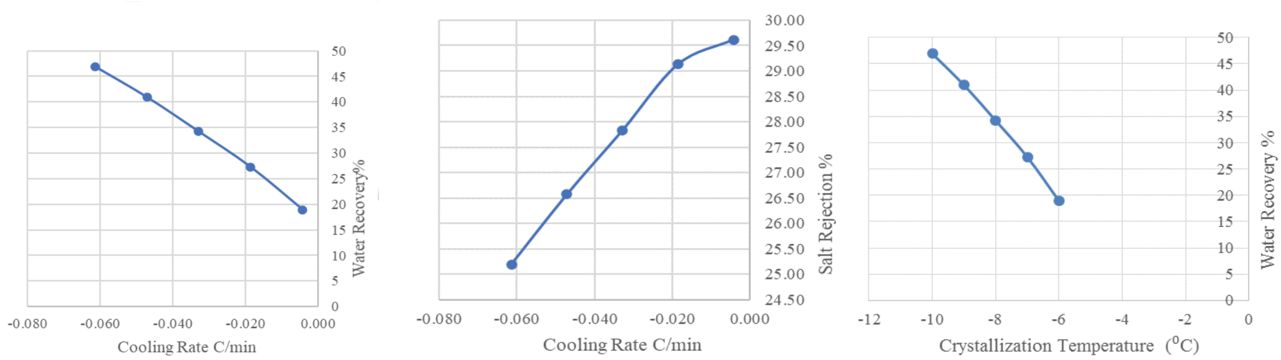

Fig. 9. Water recovery and salt rejection vs. cooling rate and water recovery vs. crystallization temperature at crystallization time of 70 min and flow rate of 30 L/min for 7 wt.%.

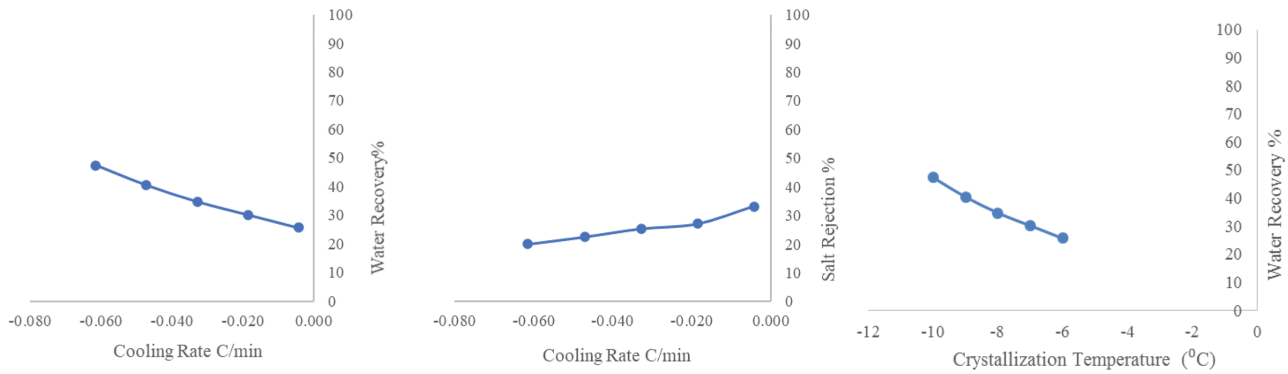

Fig. 10. Water recovery and salt rejection vs. cooling rate and water recovery vs. crystallization temperature at crystallization time of 70 min and stir rate of 200 rpm for 7 wt.%.

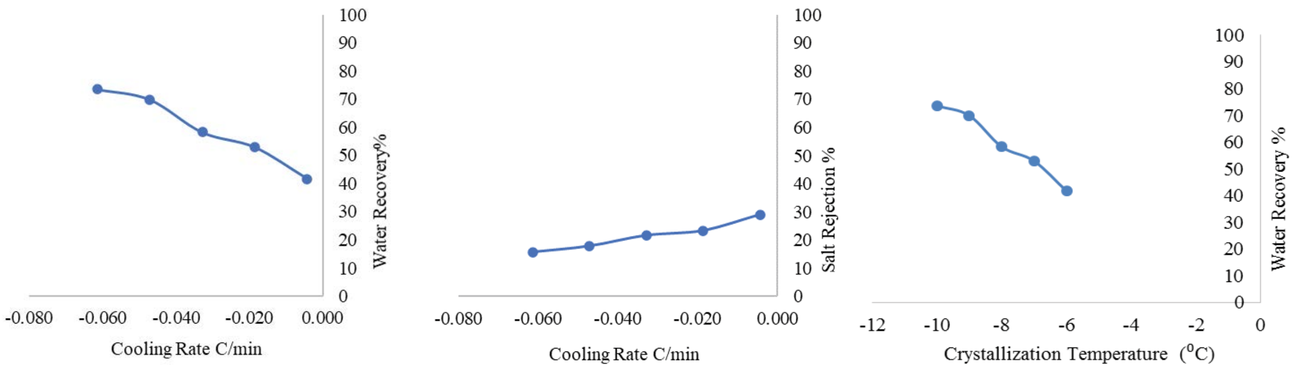

Fig. 11. Water recovery and salt rejection vs. cooling rate and water recovery vs. crystallization temperature at crystallization time of 70 min and stir rate of 400 rpm for 7 wt.%.

cooling rate, and crystallization time are as given previously for the first and second investigation. The investigated air pump flow rates ranged from 10 up to 30 L/min. In each experiment, the influences including: salt concentration, cooling rates and crystallization time were investigated upon concentration as well as the water recovery and salt rejection ratio. The predetermined values for the influences are shown in Table 2. All experiments were carried out in a feed stage process, that is, single freezing stage, without any post-treatment such as rinsing and/or sweating (i.e., partial melting).

Fig. 7 shows the experimental results on feed concentration of 7 wt.% at cooling rates of –0.004 to –0.061°C/min at 70 min of crystallization time and 10 L/min. Results of the water recovery ratio and salt rejection ratio as a function of the cooling rate are shown in Fig. 7. It can be seen that at cooling rates of –0.004 and –0.061°C/min, the water recovery ratio is 18.74% and 45.42%, respectively. At crystallization

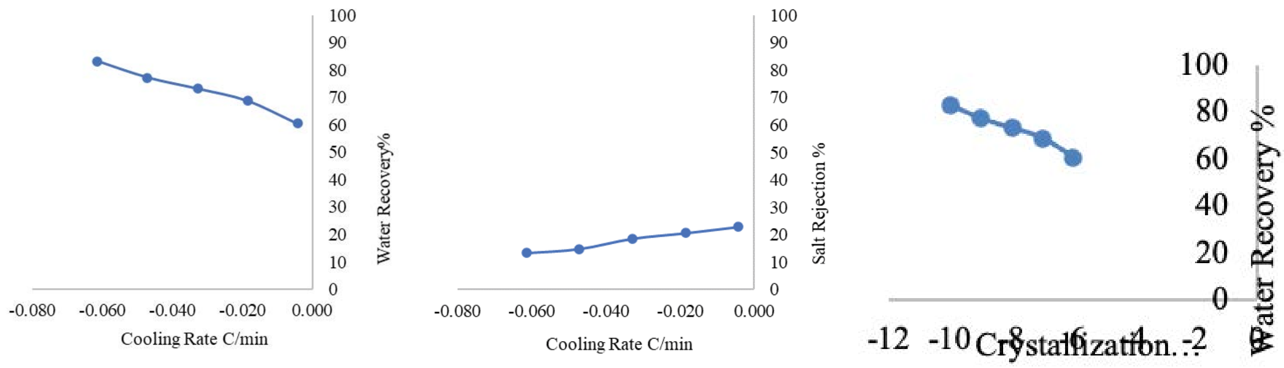

Fig. 12. Water recovery and salt rejection vs. cooling rate and water recovery vs. crystallization temperature at crystallization time of 70 min and stir rate of 600 rpm for 7 wt.%.

temperatures of cooling rates of –0.004, –0.019, –0.033, –0.047, and –0.061°C/min, the salt rejections are 31.04%, 29.30%, 28.63%, 26.56%, and 24.93%, respectively.

Fig. 8 shows the experimental results on feed concentration of 7 wt.% at cooling rates of –0.004 to –0.061°C/min at 70 min of crystallization time and 20 L/min. Results of the water recovery ratio and salt rejection ratio as a function of the cooling rate are shown in Fig. 8. It can be seen that at cooling rates of –0.004 and –0.061°C/min, the water recovery ratio is 18.68% and 45.48%, respectively. At cooling rates of –0.004, –0.019, –0.033, –0.047, and –0.061°C/min, the salt rejections are 29.80%, 29.14%, 27.54%, 25.90%, and 25.11%, respectively.

Fig. 9 shows the experimental results on feed concentration of 7 wt.% at cooling rates of –0.004 to –0.061°C/min at 70 min of crystallization time and 30 L/min. Results of the water recovery ratio and salt rejection ratio as a function of the cooling rate are shown in Fig. 9. It can be seen that at cooling rates of –0.004 and –0.061°C/min, the water recovery ratio is 18.94% and 46.90%, respectively. For all cases (Figs. 7–9), similar to the static and dynamic crystallization using UP process, a decrease in the water recovery ratio with the increase in crystallization temperature was observed due to the decreased growth rate of ice layer. At cooling rates of –0.004, –0.019, –0.033, –0.047, and –0.061°C/min, the salt rejections are 29.61%, 29.13%, 27.83%, 26.57%, and 25.20%, respectively.

3.4. Dynamic crystallization process using mechanically stirred system

In the fourth series of experiments, the potential of the dynamic crystallization process using mechanically stirred system was investigated for desalinating, concentrating, and treating different concentration of NaCl solution ranging from 7 wt.% as indicated in Table 2. The investigated feed concentrations, cooling rate, and crystallization time are as given previously for the first, second, and third investigation. The investigated stir rates ranged from 200 up to 600 rpm. In each experiment, the influences including: salt concentration, cooling rates and crystallization time were investigated upon concentration as well as the water recovery and salt rejection ratio. The predetermined values for the influences are shown in Table 2. All experiments were carried out in a feed stage process, that is, single freezing stage, without any post-treatment such as rinsing and/or sweating (i.e., partial melting).

Fig. 10 shows the experimental results on feed concentration of 7 wt.% at cooling rates of –0.004 to –0.061°C/min at 70 min crystallization time and stirring rate of 200 rpm. Results of the water recovery ratio and salt rejection ratio as a function of the cooling rate are shown in Fig. 10. It can be seen that at cooling rates of –0.004 and –0.061°C/min, the water recovery ratio is 25.68% and 47.32%, respectively. At cooling rates of –0.015, –0.032, –0.048, and –0.065°C/min, the salt rejections are 33.17%, 27.10%, 25.39%, 22.54%, and 20.04%, respectively.

Fig. 11 shows the experimental results on feed concentration of 7 wt.% at cooling rates of –0.004 to –0.061°C/min at 70 min crystallization time and stirring rate of 400 rpm. Results of the water recovery ratio and salt rejection ratio as a function of the cooling rate are shown in Fig. 11. It can be seen that at cooling rates of –0.004 and –0.061°C/min, the water recovery ratio is 41.70% and 73.58%, respectively. For all cases (Figs. 10–12), similar to the static and dynamic crystallization process using UP and BP, a decrease in water recovery ratio with the increase in crystallization temperature was observed due to the decreased growth rate of ice layer. At cooling rates of –0.015, –0.032, –0.048, and –0.065°C/min, the salt rejections are 29.01%, 23.31%, 21.61%, 17.81%, and 15.66%, respectively.

Fig. 12 shows the experimental results on feed concentration of 7 wt.% at cooling rates of –0.004 to –0.061°C/min at 70 min crystallization time and stirring rate of 600 rpm. Results of the water recovery ratio and salt rejection ratio as a function of the cooling rate are shown in Fig. 12. It can be seen that at cooling rates of –0.004 and –0.061°C/min, the water recovery ratio is 60.60% and 83.16%, respectively. At cooling rates of –0.015, –0.032, –0.048, and –0.065°C/min, the salt rejections are 22.86%, 20.60%, 18.57%, 14.83%, and 13.36%, respectively.

3.5. Conceptual design of pilot-scale system for desalting high saline waters

The performance data obtained from Fig. 11, and more specifically run number 10, the feed concentration was 7 wt.% tested at cooling rate and stir rate of –0.004 and

Table 3
Estimation of the annual rates of all water streams of the Kadhmah RO desalination, the freeze crystallization plant, and the combined plants, where (t/y) represents ton per year

Kadhmah RO plant			Freeze crystallization plant			Combined plant		
Feed[a]	Product[b]	Brine[c]	Feed	Product	Residue	Feed[a]	Product[b]	Residue
(t/y)	(t/y)	(t/y)	(t/y)	(t/y)	(t/y)	(t/y)	(t/y)	(t/y)
239.15	34.17	191.84	169.07	70.96	98.11	*168.19*	34.17	98.11

[a]The annual rate of the feed intake.
[b]The first-stage of the RO membrane assembly produces product water at 8 and 6.5 m^3/h of this is fed to the second-stage RO membrane assembly, while the remaining product water from the first-stage (i.e., 1.5 m^3/h which is equivalent to 13.14 t/y) is not used and drained.
[c]The first-stage of the RO membrane assembly produces rejected brine at 19.3 m^3/h, and this value was considered in Table 3.

400 rpm, respectively. Table 3 shows the estimated annual rates of all liquid streams of the combined water desalination plant including conventional reverse osmosis (RO) plant and freeze crystallization commercial plant. The results provided clear evidence that the proposed crystallization process, using a single freezing stage without use of a sweating process, was capable of producing a significant amount of seawater quality level from highly concentrated RO brine, whilst simultaneously minimizing the volume of the waste stream as far as possible.

4. Conclusions

The primary concern of this study was to seek the most feasible and applicable freezing desalination technologies that are potentially capable of desalting and/or concentrating the dissolved ionic content of liquid streams, especially those brines causing severe pollution. Therefore, various forms of melt crystallization processes, namely solid layer crystallization, were considered and experimentally investigated for such an application. These experimental studies were intended to evaluate and validate the separation performance of each treatment process. The overall experimental results showed that the freeze crystallization influenced by the stirring process was effective in concentrating high salinity feed, and more specifically feed with a total dissolved solids of 70,000 ppm, while producing saline water that could subsequently be easily desalted using any type of conventional desalination technology. As a result, the volumes of waste streams, such as RO brine, could be substantially reduced. For such an application, the experimental results were highly encouraging, and proved that the proposed technology was technically feasible and might be competitive with other available commercial brine concentration systems. The recommendation is for the crystallizer capacity to be increased to a suggested range of 50 to 100 L, taking into account that the investigated agitation system might be changed to higher agitation rates corresponding to the crystallizer's capacity. Detailed technical-economic analysis and studies are recommended to be taken into consideration in future research to estimate the actual power consumption of the investigated agitated crystallization process and compare the figures obtained to those for each crystallizer option.

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Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28223

263 (2022) 60–69
July

Produced water reuse enabling circularity in oil operations

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Received 28 February 2022; Accepted 27 April 2022

ABSTRACT

Saudi Aramco conducted comprehensive a field-testing program of produced water desalination technologies primarily targeted for produced water reuse as process/utility water and other industrial purposes with low total dissolved solids (TDS) (<1,000 mg/L). The main driver for the produced water re-use program was due to, firstly transition from linear model of economic growth, which is based on "take-make-dispose", which is not sustainable to circular economy model supporting "closing the loop" of recovering value from produced water considered waste stream and secondly the conservation of Saudi Arabia's precious non-renewable ground water resources which are currently used for crude washing in desalting across Saudi Aramco. The program will reuse produced water in its oil operations, with potential ground water savings up to several billion gallons annually post implementation and also enable circularity sustainably in its oil operations. The objectives of the program were to evaluate the produced water desalination with minimum 70% recovery factor as performance for two different configurations, that is, desalination of low salinity (TDS) produced water (<15,000 mg/L) and high salinity (TDS) produced water (<120,000 mg/L). A US patent 10,703,989 was also granted for the concept of produced water reuse. Produced water desalination testing was conducted at two different produced water streams in Arab Light crude oil at two different sites with gravities of 36–41 API, to determine the desalination performance and challenges with pre-treatment. Variation in feed conditions such as flow rate, temperature, inlet oil in water concentration and H_2S in water, recovery factor were introduced to establish operating envelopes for the produced water desalination systems. The performance of two field produced water desalination technologies was evaluated by determining the salinity (TDS) and oil in water concentration at different operating conditions. Prior to piloting the laboratory bench test were conducted at lab scale to characterize the performance of produced water. The lab test helped identify the challenges during pilot testing and demonstrated that produced water desalination for sustained flow conditions. This paper presents the key results of produced water re-use program along with two field tests as well as the path forward to deployment of these technologies to unlock the value for produced water as resource in circular economy. The implications of this program success extend beyond Saudi Aramco. By increasing produced water reuse in the oil and gas processing, more groundwater will be available for non-industrial applications in Saudi Arabia, which reduces reliance on seawater desalination.

Keywords: Produced water; Desalination; Sustainability; Produced water reuse; Circularity; Arab light

1. Introduction

Saudi Aramco has one of the largest integrated oil and gas supply chains in the world as shown in Fig. 1. The supply chain starts from onshore and offshore oil fields where the multiphase oil, gas and produced water is transported to oil processing facilities through pipelines. In oil processing facilities are also known as gas oil separation plants (GOSP) at Saudi Aramco, where crude oil is produced with

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

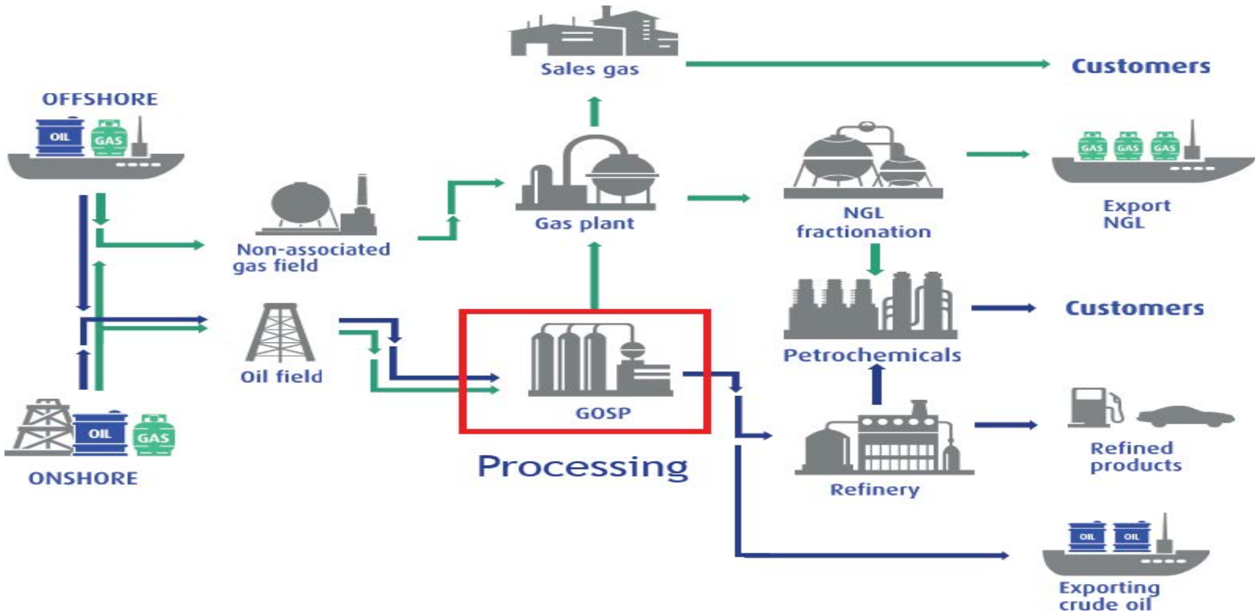

Fig. 1. Oil and gas supply chain at Saudi Aramco.

associated produced water and gas is processed to separate into three separate products – crude oil, gas and produced water. GOSPs are designed to meet each product quality specifications. The associated produced water is disposed to dedicated wells for removal and in some cases to wells for reservoir pressure maintenance. The associated gas is process to produce lean gas (methane) is sent to Master gas system for industrial needs such as desalination, power and feedstock to petrochemical plants. Natural gas liquids (NGL) recovered from gas plants are sent to NGL fractionation plants. The crude oil from GOSPs is either sent to terminals for export to global customers or to refineries for further processing into refined products.

In the crude supply chain, GOSPs are the heart of the process and represent large proportion of facilities (50+) at Saudi Aramco. There are 5 types of crude grades processed namely Arab Light, Arab extra light, Arab Super light, Arab Medium and Arab heavy. This paper will focus on Arab Light (36–41 API degree) processed at GOSPs which represents large proportion of the crude production.

2. Gas oil separation plant (GOSP)

The process scheme of the GOSP is shown in Fig. 2. In GOSPs, wild wet crude oil is routed through pipelines to production header which feeds the gravity separators. Gravity separators separate the crude, associated gas and water in three distinct phases with volume fractions of gas in liquids and vice versa. The separation is driven by stokes law and aided with oil field chemicals such as demulsifier. Wet gas is sent to the gas gathering system for processing. The two-phase oil and produced water is pumped through charge pumps to the wet crude handling (WCH) train which consists of two electrostatic vessels – dehydrator and desalter in series to meet the crude quality specs for un-stabilized crude to pipelines. Wash water and demulsifier are injected upstream of the mixing valve. Wash water used for crude desalting is obtained from natural aquifers. In electrostatic vessels, a high voltage electric field is generated between the electrode grids which coalesces the water droplets to drop to bottom for removal from the vessels. The crude is then pumped to crude stabiliser to further remove the light ends in the crude and meet H_2S specification in crude using steam reboilers. The crude oil is stabilised in the stabilizer column by removing H_2S and remaining gases using steam reboiler. The crude is then pumped by the crude export pumps to downstream facilities or stored in tanks for batching process.

The produced water separated in gravity separators/dehydrators/desalters and wash water used to “desalt” the crude oil are sent to produced water treatment equipment (API separator/WOSEP-water oil separator) to recover remaining oil in water before disposal to wells. The API separator is designed to treat produced water from with oil in water content from 1,000–2,500 to 50 ppm.

3. Water circularity and sustainability

Produced water is considered as waste product and is part of the current linear economy model of “take-make-dispose”. Produced water is injection after de-oiling into disposal reservoirs and not reused in any oil operations. In addition to this produced water disposal, wash water with low salinity (<1,500 mg/L) is obtained from non-renewable ground water aquifers for crude washing. This water once utilised in crude desalting is disposed along with the produced water as shown in Fig. 2. Given that most GOSPs in Saudi Aramco utilise precious non-renewable ground water resources which are currently used for crude washing. Saudi Aramco develop a plan in 2011 and committed to the conservation of Kingdom’s ground water resources. Corporate water conservation policy (CP-25) was developed which mandated a companywide drive to minimize groundwater use through optimizing water consumption, minimizing water losses, maximizing wastewater reuse and promoting the use of sustainable alternative to ground water [1,2]. The policy drove the development of ground water conservation program which eventually developed into the produced water re-use program.

4. Produced Water Reuse Program

The program aims to treatment produced water for reuse eliminating ground water utilization to promote water circularity and sustainability of oil operations. Produced Water Reuse program was developed on the principles of circular economy for water with the 3Rs – reduce, recycle and reuse in focus. This program will eventually conserve up to several billion gallons of non-renewable ground water currently used for crude desalting in Saudi Aramco GOSPs and Refineries. The program drove innovation to identify waste streams in oil operations and recycle them to be reused. The program mapped and identified two main waste stream as shown in Fig. 3. The desalter effluent stream with low salinity (<15,000 mg/L) after crude washing as ideal stream for de-oiling and desalination. The second stream identified was the API separator (Water Oil Separator) with higher salinity (<100,000 mg/L). These two streams were utilised by the in-house engineers to develop technology flow chart and screening of technologies for produced water reuse. The objective of the program was to determine treatment scheme with process equipment for implementation. The program was supported with bench scale verification

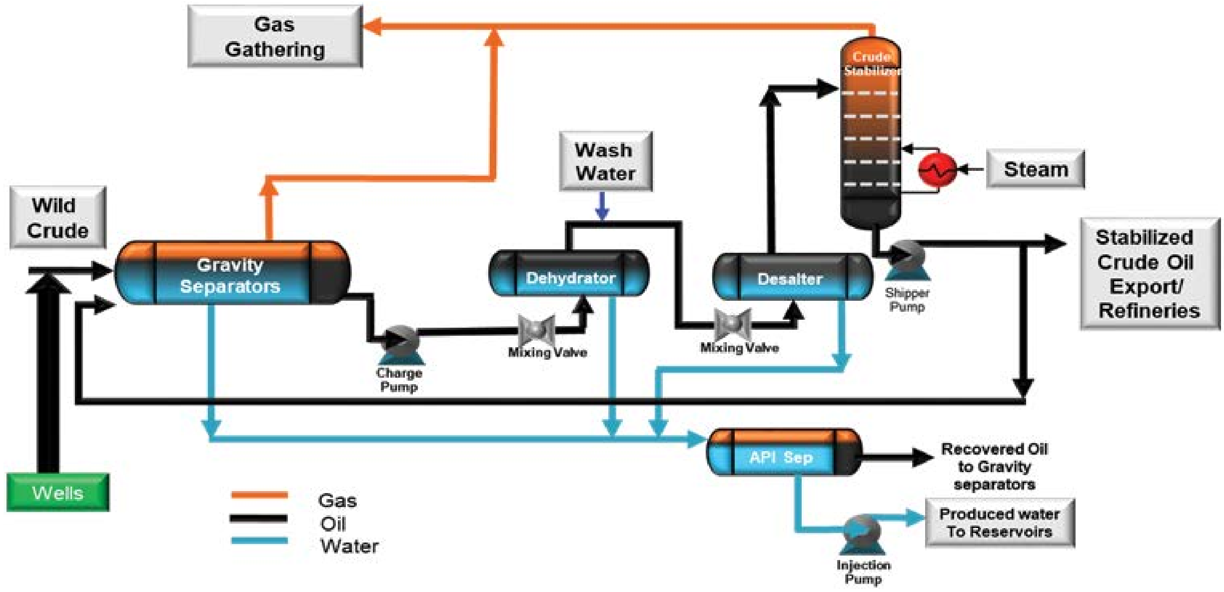

Fig. 2. Process scheme of gas oil separation plant (GOSP) at Saudi Aramco.

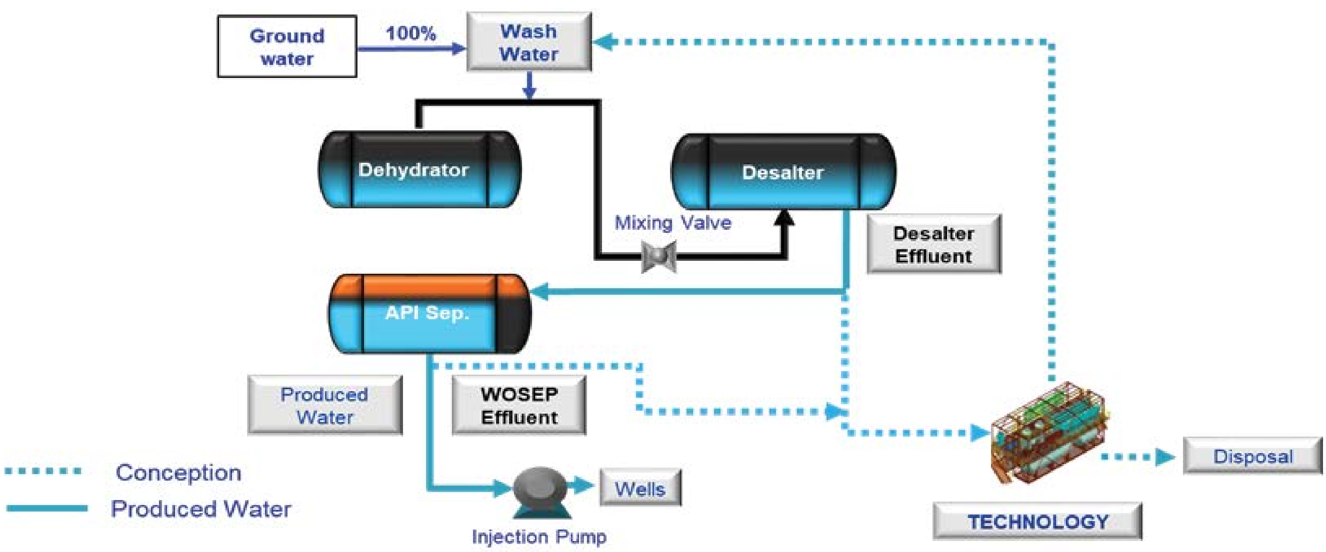

Fig. 3. Produced water reuse process schematic.

for produced water de-oiling and desalination. The program considered both summer and winter conditions and defined the limits for produced water desalination. Saudi Aramco was also recently granted US Patent Office No. 10,703,989 "Conserving fresh wash water usage in desalting crude oil" which is the guiding process for produced water reuse in oil operations.

5. Produced water desalination

The program identified several mature and emerging technologies to treat the two produced water streams – low salinity (<15,000 mg/L) and higher salinity (<120,000 mg/L). The technologies identified from literature survey were mapped on their sensitivity to oil in produced water and recovery factor. The technologies were evaluate to desalination produced water with minimum 70% recovery factor in terms of performance and along with energy and utility costs (chemicals) for desalination.

$$\text{Recovery Factor}(\%) = \frac{\text{Product flow}}{\text{Feed flow}} \times 100 \quad (1)$$

The technology selection was categorise based on technology readiness level (TRL): method of estimating technology maturity was developed by NASA in early 70s [5]. The use of TRLs as shown in Fig. 4 enables consistent, uniform, discussions of technical maturity across different types of technology. The TRL scale used in Saudi Aramco and utilised also by US DoD technology readiness assessment (TRA). Table 1 describes the different technology readiness levels from TRL 9 to TRL 1 adapted for technology deployment in produced water reuse program.

Table 2 lists all the technologies that were identifies by the program for pilot testing and deployment subject to entire lifecycle economic analysis with respect to net present value (NPV) The program also considered the reuse of membrane and other consumables with respect to circularity. Given the two waste streams low salinity (<15,000 mg/L) and higher salinity (<120,000 mg/L), the several technologies were shortlisted for de-oiling and desalination.

Based on the above technology maturity, the program develop a basic process scheme so that our produced water can be handled by any of the selected technologies. Fig. 5 is an example of the process scheme that contains two main sections: pre-treatment and desalination. Produced water desalination requires robust, reliable and compact equipment for use in existing brownfield applications both onshore and offshore. The performance testing is the recommended way to confirm the feasibility of produced water desalination technologies for produced water reuse and demonstrated that within given operating envelope the system can treat produced water stream with oil in water content of up to 400 ppm, reducing it down to 0 ppm level while reducing salinity which is our target specification. In addition, the issue of pre-treatment of sour water can be addressed by designing the de oiling system with H_2S strippers and packed beds for contaminants as BTEX and other organics. These sections are further explained with the objectives with respect to our produced water.

5.1. Pre-treatment

In this section is designed to condition the produced water feed to be processed by conventional desalination technologies. This subsection de-oiling removes the dissolved and dispersed oils with conventional technologies such as

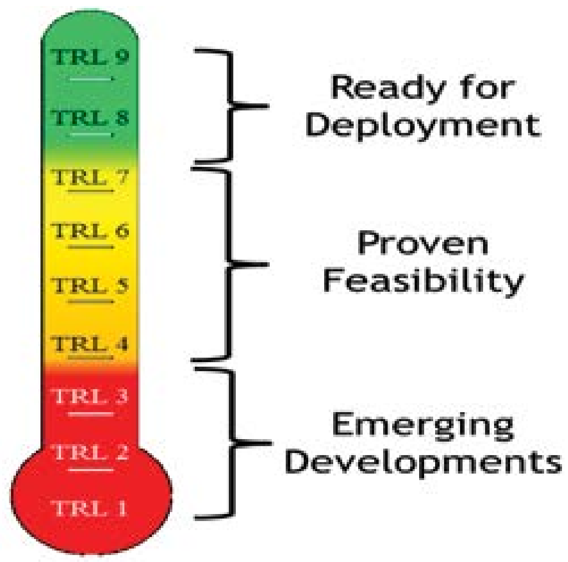

Fig. 4. Technology readiness level (TRL).

Table 1
Technology readiness level-maturity

TRL	Maturity level	Description
9	Ready for deployment	Proven technology with successful deployments in industry
8		Proven technology with demonstration in field conditions
7	Proven feasibility	Technology prototype in field conditions
6		Technology prototype in simulated field conditions at laboratories
5		Technology prototype validation in laboratories
4		Basic technology prototype testing
3	Emerging developments	Analytical and experimental concept
2		Technology concept formulation
1		Basic technology principles observed

hydrocyclone or induced gas flotation. The dispersed oil can also be removed using ultrafiltration membranes. H_2S is stripped from the produced water with chemicals and stripping column to prevent extensive scaling in the downstream process. The organic scavenger are used to reduce the total organic carbon content along with BTEX using packed beds.

5.2. Desalination

In this section, the produced water is subjected to desalination only and several technologies listed in Table 2 can be utilised to achieve the desired reduction in salinity. Each technology has it limitation dependent on the feed salinity expressed as total dissolved solids (TDS) in mg/L. Higher the salinity, greater would be the energy requirements to reduce the salinity and there have been advances in produced water treatment to reduce the OPEX for such treatment schemes.

6. Produced water feed quality and performance target

In this section, the produced water feed quality from both our case studies over last few years is listed with the defined target performance as shown in Table 3. This section will detail the complete geochemical analysis of the two produced water stream-low salinity (<15,000 mg/L) and high salinity (<120,000 mg/L). This will be basis used for the two pilot case studies conducted at Saudi Aramco. Tables 4 and 5 showcase the dissolved organics along with their geochemistry for low salinity (<15,000 mg/L) and high salinity (<120,000 mg/L) streams.

6.1. Case study 1: produced water low salinity desalination

The program shortlisted several GOSPs for the field testing based on the process scheme defined in Fig. 5. One technology supplier was shortlisted to provide and integrate all the components of the system for deployment. One of the largest onshore Saudi Aramco GOSPs located in Southern area was selected which processes 1,500 MBD of stabilised Arab Light (AL) crude oil with API 38. The GOSP is setup with five crude oil processing trains 300 MBD capacity besides gas trains, produced water treatme nt and injection pumps, utilities, crude storage tanks, crude shipping pumps and flare system. The GOSP processes wild wet crude oil and associated gas to separate them into stabilized crude oil and gas for transport through pipelines and injects their produced water to disposal reservoirs. The GOSP was also selected on account of centralised utilities (i.e., steam, N_2 gas and demineralised water) and lab support setup for field testing. The selected GOSP however posed a technical challenge of high temperature feed stream (160°F) as the crude oil desalting in this GOSP had crude preheating to break stable emulsions, unlike other GOSPs in Saudi Aramco. A high temperature desalination technology was required to avoid cooling water required during the field test phase. Fig. 6 is the process scheme at this GOSP with feed stream from the desalter effluent feeding the produced water reuse unit denoted in blue and the brine is sent to disposal pits.

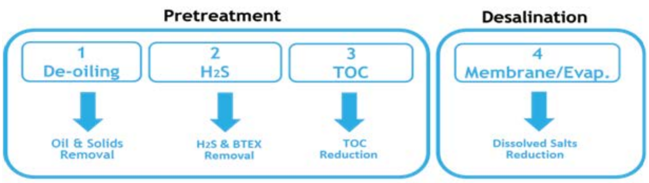

Fig. 5. Produced water reuse-pre-treatment (de-oiling) and desalination

Table 2
Produced water desalination technologies readiness level

Technology	Maturity	Salinity TDS (mg/L)	OIW limit	Oil removal requirement	Recovery factor %
Mechanical vapour compression	TRL 9	<150,000	No	N/A	70%–90%
Membranes	TRL 8	<100,000	Sensitive	Yes	70%–90%
Multiple effect distillation	TRL 8	<150,000	No	N/A	70%
Adsorption	TRL 9	<150,000	No	N/A	70%
Ion exchange	TRL 6	<1,000	Sensitive	Yes	<90%
Engineered wetlands	TRL 8	<15,000	N/A	N/A	Variable

Table 3
Produced water quality overview with target quality

Parameter	Case study 1 feed	Case study 2 feed	Performance target
Salinity: total dissolved solids (TDS), mg/L	10,962	94,157	<1,000
Oil in water, mg/L	10	1,000	<1
Total suspended solids (TSS), mg/L	202	263	<1
Temperature, °F	150	140	–
pH	7.7	7.4	6–7.5
Recovery factor, %	–	–	70

Table 4
Case study 1 feed water quality

Process parameters			
Process pressure, Psig			70
Process temperature, °F			90–150
H_2S content, ppm wt.			200–400
CO_2 content, ppm wt.			200
Basic parameters		**Cations**	
pH	7.7	Calcium (Ca), mg/L	641
Specific gravity	1.0289	Magnesium (Mg), mg/L	235
Total suspended solids TSS, mg/L	16.7	Sodium (Na), mg/L	2,400
Total dissolved solids TDS, mg/L	10,962	Potassium (K), mg/L	98.6
Bicarbonate alkalinity as $CaCO_3$, mg/L	202	Barium (Ba), mg/L	0.1
Bicarbonate HCO^{3-}, mg/L	186.7	Strontium (Sr), mg/L	8.9
Carbonate CO_3^{2-}, mg/L	19.7	**Anions**	
Total hardness as $CaCO_3$, mg/L	2,570	Chloride Cl^-, mg/L	5,330
Oil & grease, mg/L	28	Sulfate as SO_4^{2-}, mg/L	1,220
TOC, mg/L	12	Silica as SiO_2, mg/L	11.93
Total petroleum hydrocarbon (TPH)		**Volatile organic compounds – BTEX**	
$C_6 – C_9$ fraction, µg/L	34,800	Benzene, µg/L	27,200
$C_{10} – C_{14}$ fraction, µg/L	1,700	Ethylbenzene, µg/L	805
$C_{15} – C_{28}$ fraction, µg/L	1,820	Toluene, µg/L	4,720
$C_{29} – C_{36}$ fraction, µg/L	90	Meta and para-Xylene, µg/L	941
$C_{37} – C_{40}$ fraction, µg/L	<50	Ortho-xylene, µg/L	932
$C_{10} – C_{40}$ fraction, µg/L	3,610		
Volatile organic compounds – surrogates			
1,2-dichloroethane-d4, %	97.4	Toluence-D8, %	91.6
4-bromofluorobenzene, %	97.4		

The target for the unit was to produce water with salinity <1,000 mg/L [3,4].

Produced water reuse unit feed is defined in Tables 3 and 4 along with the performance target requirements. The process scheme in Fig. 7 was developed with the support of the technology and subject matter experts. The process scheme has several modules spread across pre-treatment and desalination which are briefly explained with their functions and individual performance. The field test was conducted for 3 months with continuous 24 × 7 operation with shutdowns to replace and test new membranes for ultrafiltration. Power was supplied by diesel generators and chemical used were caustic soda for pH adjustment, sulphuric acid to convert all sulphide ions to H_2S gas and anti-scalant for scale control.

Ultrafiltration (UF) membrane was the first module which was designed with inlet feed of 1,000–2,500 mg/L oil and 200 mg/L total suspended solids (TSS) and the outlet was <1 mg/L of oil and TSS. The module was able to achieve an average performance of 86% oil removal efficiency and 70% TSS removal efficiency. Ceramic membranes were used for UF module and both SiC and TiO_2 ceramic membranes were tested onsite and the regenerative performance of SiC membranes was better than TiO_2. H_2S Stripper module was able to strip the H_2S gas in sour feed and with injection of sulphuric acid upstream meet average performance of 1 ppm wt. while target was 0.2 ppm wt. as feed to reverse osmosis (RO) membranes. This was attributed to poor chemical management. The overall efficient was 99.5% and some volatile organic compounds such as BTEX were also reduced. The organic scavenger module selected was strong base anion resin which removes between 60%–80% of the dissolved organics. Polystyrenic resin was used due to greater reversible removal of organics on regeneration and can cope with higher levels of dissolved organics. They able to reduce the total organic carbon (TOC) from 12 mg/L down to 1 mg/L on average.

The next module was desalination, where high temperature reverse osmosis membranes were used. The RO module was designed with a recovery of 70%, (low TDS RO) permeate/product is produced. To achieve this recovery, the RO is designed as two stages RO unit with the configuration 2X–1X, that is two pressure vessels in the first stage, one pressure vessel in the second stage. Each pressure vessels contains 6 4-inch brackish water RO modules in series. The concentrate from the first stage is sent through

Table 5
Case study 2 feed water quality

Process parameters			
Process pressure, Psig			70
Process temperature, °F			90–140
H_2S content, ppm wt.			112
CO_2 content, ppm wt.			200
Basic parameters		**Cations**	
pH	7.4	Calcium (Ca), mg/L	10,000
Specific gravity	1.05396	Magnesium (Mg), mg/L	1,130
Electrical conductivity at 25°C, µs/cm	105,033	Sodium (Na), mg/L	39,000
Total suspended solids TSS, mg/L	265	Potassium (K), mg/L	1,335
Total dissolved solids TDS, mg/L	98,393	Barium (Ba), mg/L	1.8
Bicarbonate alkalinity as $CaCO_3$, mg/L	515	Strontium (Sr), mg/L	350
Bicarbonate HCO^{3-}, mg/L	628	**Anions**	
Carbonate CO_3^{2-}, mg/L	0	Chloride Cl^-, mg/L	45,331
Silica as SiO_2, mg/L	15	Sulfate as SO_4^{2-}, mg/L	618

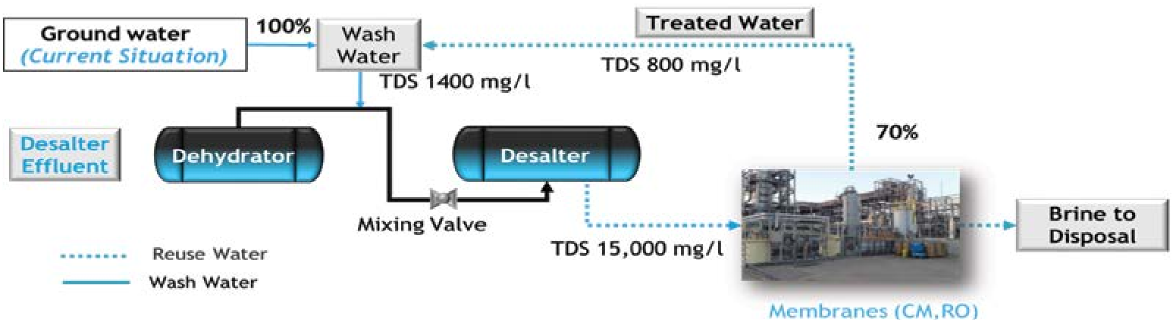

Fig. 6. Produced water desalination: membranes.

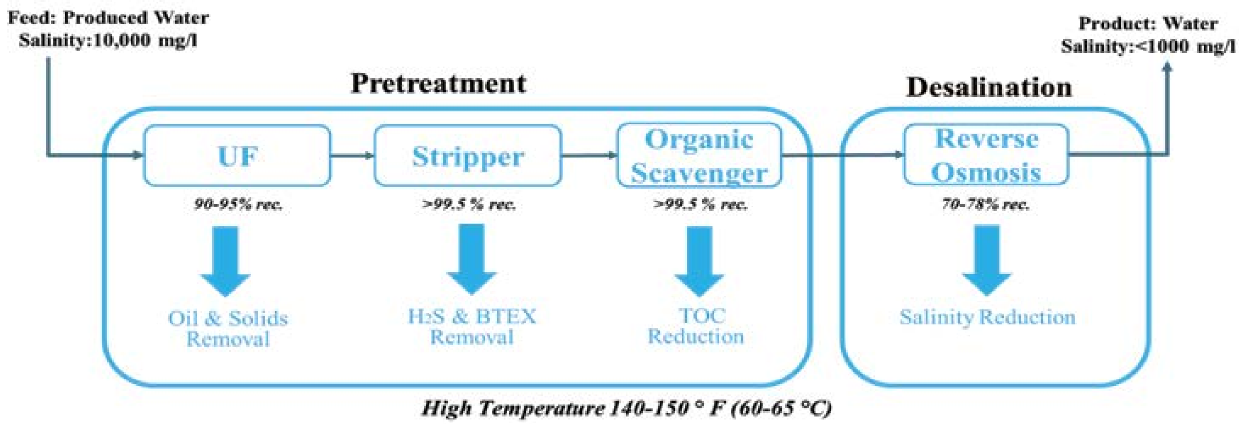

Fig. 7. Produced water desalination: membranes process scheme.

the second stage to maximize the recovery. The module was able to reduce the TDS inlet from 10,962 mg/L down to 800 mg/L average with target of TDS <1,000 mg/L.

The average recovery factor of 70% was achieved with this field testing with membranes and Fig. 8 is images of the field testing unit on site at the onshore GOSP with all the major equipment (RO membrane, H_2S stripper, organic scavenger (MPRA) shown along with feed and product.

6.2. Case study 2: produced water high salinity desalination

The program shortlisted several GOSPs for the field testing based on the process scheme defined in Fig. 5.

One technology supplier was shortlisted to provide and integrate all the components of the system for deployment. One of the onshore Saudi Aramco GOSPs located in Southern area was selected which processes 300 MBD of stabilised Arab Light (AL) crude oil with API 40. The GOSP processes wild wet crude oil and associated gas to separate them into stabilized crude oil & gas for transport through pipelines and injects their produced water to disposal reservoirs. The GOSP was also selected since it had the highest salinity produced water in the field and was located close to local laboratories for testing. Fig. 9 is the process scheme at this GOSP with feed stream from the water oil separator (WOSEP) effluent feeding the produced water reuse unit denoted in blue and the brine is sent to disposal pits. The target for the unit was to produce water with salinity <1,000 mg/L with feed of >100,000 mg/L.

Produced water reuse unit feed was defined in Tables 3 and 4 along with the performance target requirements. The process scheme in Fig. 10 was developed with support of the technology and subject matter experts. The process scheme has several modules spread across pre-treatment and desalination which are briefly explained with their functions and individual performance. The field test was conducted for 1 months with continuous 24 × 7 operation with shutdowns to clean heat exchangers. Power was supplied by diesel generators and chemical used were

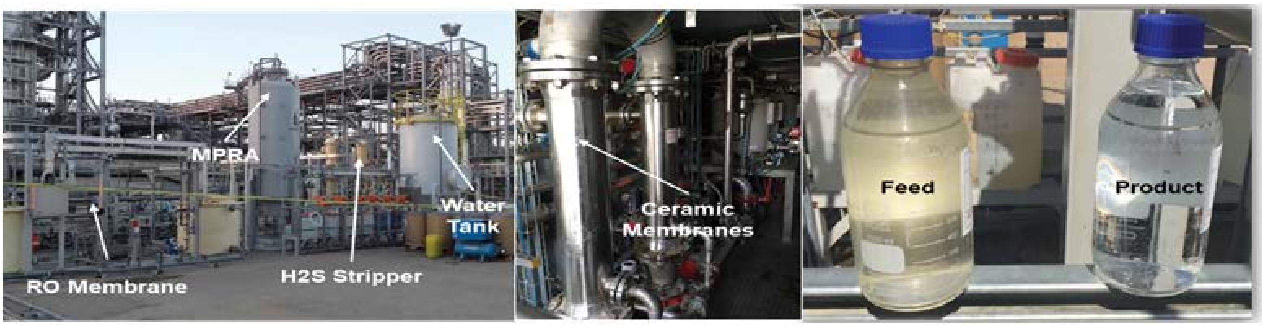

Fig. 8. Produced water desalination: membranes at field site.

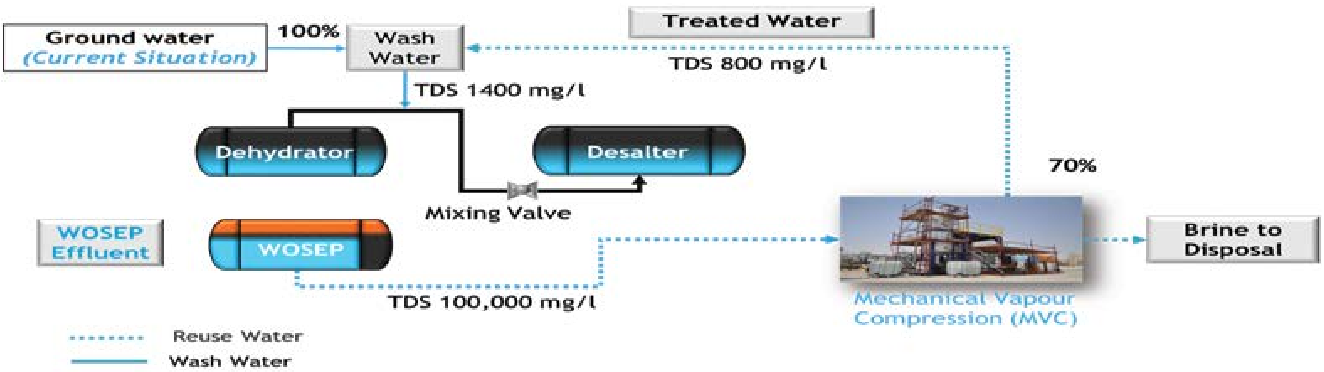

Fig. 9. Produced water desalination: high salinity (<150,000 mg/L).

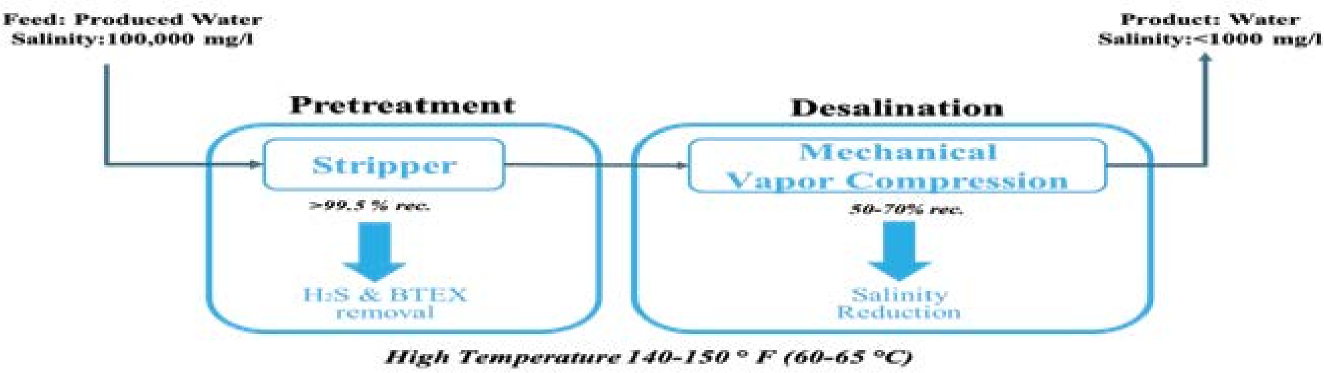

Fig. 10. Produced water desalination: mechanical vapour compression process schematic.

caustic soda for pH adjustment and anti-scalant for scale control.

Mechanical vapour compression (MVC) was selected for field testing technology after extensive review with technology suppliers to address the high salinity. In the pre-treatment module, stripper was used to remove the H_2S gas. Fig. 11 is the simplified operating principle for the MVC.

Produced water from WOSEP was routed to MVC unit and mixed with small volume of brine water at suction of circulation pump (CP). CP pumps brine water at high flow rate through primary heat exchanger in which brine is heated by compressed vapor flowing from rotary blower before it entered the flash vessel. At startup and during concentrate blow-down, an external heating from gas boiler is used as make up steam. Due to the low pressure, once the brine enters flash vessel, partial flash vapor is generated and sucked by the rotary blower and remaining water goes to bottom of vessel which is then circulated by the CP. Rotary blower compresses the generated vapor and increased its temperature. The compressed vapor is exchanging heat with circulated brine in primary plate heat exchanger and condensed as product. Cooling water is used to maintain the temperature of this product with salinity (<1,000 mg/L). The blow-down concentrate can be diluted with existing produced water and sent to the disposal well. The average recovery factor was 54% with variation between 45% and 70% vs. target of 70%. Fig. 12 shows the images of the field testing unit on site at the onshore GOSP with all the major equipment (flash vessel, distillate tank, compressors, pumps) shown along with feed, product and concentrate.

6.3. Case study summary: produced water desalination

The below Table 6 summaries the performance in terms of recovery factor, energy requirements and chemicals used in the two case studies.

6.4. Value opportunity: water circularity in oil operations

The program proved that technology was able to adeptly handle produced water with low (<15,000) and high salinity (<120,000 mg/L) levels and treat it to lower salinity (<1,000 mg/L) for reuse. The product water is of the ideal quality to use in Saudi Aramco's crude oil washing, well maintenance and drilling operations. This approach transitions from linear model of economic growth, which is based on "take-make-dispose", to circular economy model "closing the loop" of recovering value from produced water considered waste stream and also expedite the conservation of Saudi Arabia's precious non-renewable

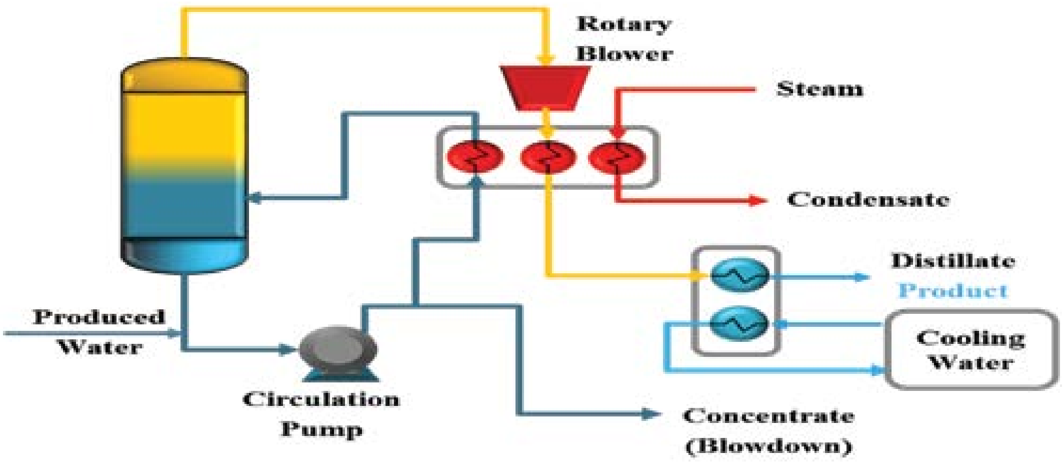

Fig. 11. Produced water desalination: mechanical vapour compression principle.

Fig. 12. Produced water desalination: mechanical vapour compression at field site.

Table 6
Produced water desalination comparison for salinities

Technology	Membranes (CM, RO)			Mechanical vapour compression (MVC)			
Feed salinity TDS (mg/L)	10,963	Recovery factor	70%	Feed salinity TDS (mg/L)	100,000	Recovery factor	54%
Unit capacity (m^3)	786	Concentrate (blow-down) m^3	235	Unit capacity (m^3)	786	Concentrate (blow-down) m^3	361
Energy, kWh/m^3	10			54			
Equipment	UF membranes H_2S stripper Oxygen scavenger RO membranes Pumps			H_2S stripper Rotatory blower Heat exchanger Flash vessel Chiller, pumps			
Chemicals	Caustic soda: 14 kg/d Sulphuric acid: 20 kg/d Anti-scalants: 5 ppmw Membrane replacement Every 7 years			Caustic soda: 14 kg/d Anti-scalants: 5 ppmw			

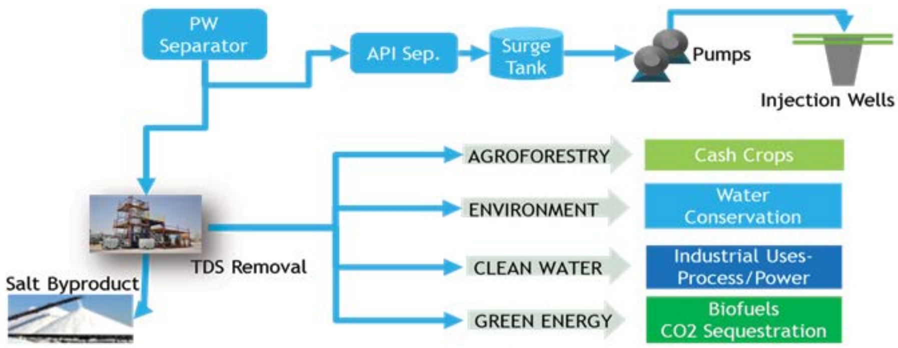

Fig. 13. Produced water reuse-water circularity.

ground water resources. The implications of this technology/program success extend beyond Saudi Aramco. As shown in Fig. 13 produced water reuse-water circularity, the water has applications across Saudi Aramco and Saudi Arabia. The water can be used in agroforestry for cash crops, from sustainability/environment point of view reduces reliance on ground water aquifers, clean water for industrial uses such as power and process water reducing reliance on sea water and finally water for use in the green energy program at Saudi Aramco to generate bio fuels and CO_2 sequestration.

Acknowledgement

The authors would like to thank Saudi Aramco for providing permission to present and publish this work. Also thank management of Process & Control Systems Department, Khurais Producing Department, South Ghawar Producing Department and Southern Area Oil Operation Technical Support Department for commitment to sustainability and circularity. Lastly thank my mentors Vilas S. Koleshwar, Saif F. Albluwi, Ejaz Khan from P&CSD and Hani Khalifa, Jesus Pinango, Ashiff Khan, Amro Abbasi in the field for their support in testing at GOSPs.

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Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28225

263 (2022) 70–77
July

Database for total petroleum hydrocarbon in industrial wastewater generated at Sabhan area in Kuwait

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Received 28 February 2022; Accepted 28 April 2022

ABSTRACT

A research study was carried out to collect data on the quality and quantity of petroleum and non-petroleum industrial wastewater from different sources in Kuwait over a period of 1 y as well as developing a database of such characteristics and attributes using geographic information system (GIS) technique. During the field visits, a specially designed field surveys were submitted to the owners of industrial facilities in three industrial areas in Kuwait, namely, Sabhan, Kuwait City, and Shuaiba industrial areas. In this study, wastewater samples were collected and analysed on monthly and biweekly basis from 14 non-petroleum factories of Sabhan industrial areas. This paper was targeting assessment of total petroleum hydrocarbon (TPH) in the raw wastewater for factories of Sabhan industrial area. The field wastewater data indicated presence slightly acid to slightly alkaline (4.9–10.8), reduced to oxidized environment (–410 mv–538 mv) and freshwater to brackish water (120–8,673 μS/cm). The laboratory results revealed that total petroleum hydrocarbon concentrations for wastewater of 14 factories ranged between 0.3 and 19 mg/L. The mean values of total petroleum hydrocarbon concentrations for wastewater of 14 factories were meeting the maximum limit (5 mg/L) set by KEPA for irrigation water purposes except those values of TPH (>5 mg/L) for three factories. The mean value of quantities of wastewater generated from 14 factories was found 55,894 m^3/week. The large quantities of raw wastewater generated from these factories can be used safely as irrigation water for landscaping and greenery with respect to total petroleum hydrocarbon concentrations.

Keywords: Sample collection; Laboratory results; Field survey; Non-petroleum and reduced

1. Introduction

Kuwait is one of the water-stressed countries of the world. The main source of water supply for municipal uses is the costly desalinated seawater. Groundwater supply in the country is depleting in an alarming rate. Living with the reality of the high cost of water production and scarcity of water resources other than the sea, Kuwait is in dire need of an integrated water resources management scheme that includes aspects of water conservation and reuse wherever possible. The foundation block of such a management scheme is a sound database of all potential sources of water supply, supply locations, use, after-use discharge, recycle potential, reuse, environmental impacts, and sustainability of the national resources and developmental systems. One of the major sectors involved in such a scheme is industrial (petroleum and non-petroleum) water use and wastewater generation, including areas of after-use discharges, wastewater quality at origins and discharge points, locations of discharge and/or reuse, and recycle potential. A basic and comprehensive database utilizing ArcGIS in this sector is presently lacking in the country. A comprehensive, centralized, well formatted and compiled data system on the type and quality of industrial wastewater produced with specifics of location, quality, provision of treatment and discharge and/or reuse in the country is presently missing. Accordingly, this study was initiated to collect data on the quality and quantity of petroleum and non-petroleum

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

1944-3994/1944-3986

industrial wastewater from different sources in Kuwait over a period of 1 y. Additionally, the study aims at developing a database on the above-mentioned attributes using geographic information system (GIS) technique. The study is a continuation of a previous project [1] that aimed at collecting data on the quality of wastewater streams from various sources in Kuwait and developing a state-wide database on the quality of wastewater generated at selected industrial sources in an attempt to develop a baseline information source of wastewater quality for the country. This paper aims is to evaluate the concentrations of different total petroleum hydrocarbon (TPH) in raw wastewater generated from 14 non-petroleum factories of Sabhan industrial area, to determine quantizes of wastewater generated and to draw distribution maps for total petroleum hydrocarbon concentration for wastewater generated from these factories using GIS technique.

2. Methodology

2.1. Survey of industries

In this study, a field survey was conducted during which a specially designed questionnaire was distributed among the targeted industries. It is worth mentioning that the industries in Kuwait are mainly distributed in three areas, namely Kuwait City, Sabhan, and Shuaiba industrial areas (Fig. 1). Shuaiba industrial area represents factories of petroleum wastewater origin, while the other sites (Kuwait City, Sabhan) represent factories of non-petroleum wastewater origin. The total number of factories in Sabhan industrial area is approximately 1,250. Total of 14 factories were selected in this study to determine the quality and quantity of wastewater from Sabhan industrial area. Fig. 2 represents location maps for these factories. Summary of the factory names, sampling codes along with coordinates are presented Table 1.

2.2. Industrial wastewater sampling and laboratory analysis

Based on the field surveys of the targeted industries, wastewater sampling and associated measurements was determined. The measurements and sampling started for all factories in mid-December 2018 on a monthly basis during the period between mid-December 2018 and end of April 2019, as instructed by the owners of factories, followed by biweekly sampling during June–July 2019. The samples were collected using bailers from wastewater collection points. Prior to sampling, wastewater field measurements, including, temperature, pH, electrical conductivity (EC), dissolved oxygen (DO), and oxidation–reduction potential (ORP), were carried out for all sites. The wastewater sampling plan was prepared along with the distribution of the collected samples to the concerned laboratories of KISR's Water Research Center (WRC). Wastewater parameters were analysed according to standard methods for the examination of water and wastewater [2]. In the data analysis section, the laboratory results of the wastewater samples were compared with local standards [3] for irrigation water standards.

2.3. Wastewater quantities

The quantities of freshwater consumption inside each plant measured near flow meter gage, and these data were collected from owners of the factories while the raw

Fig. 1. Location map of the study area.

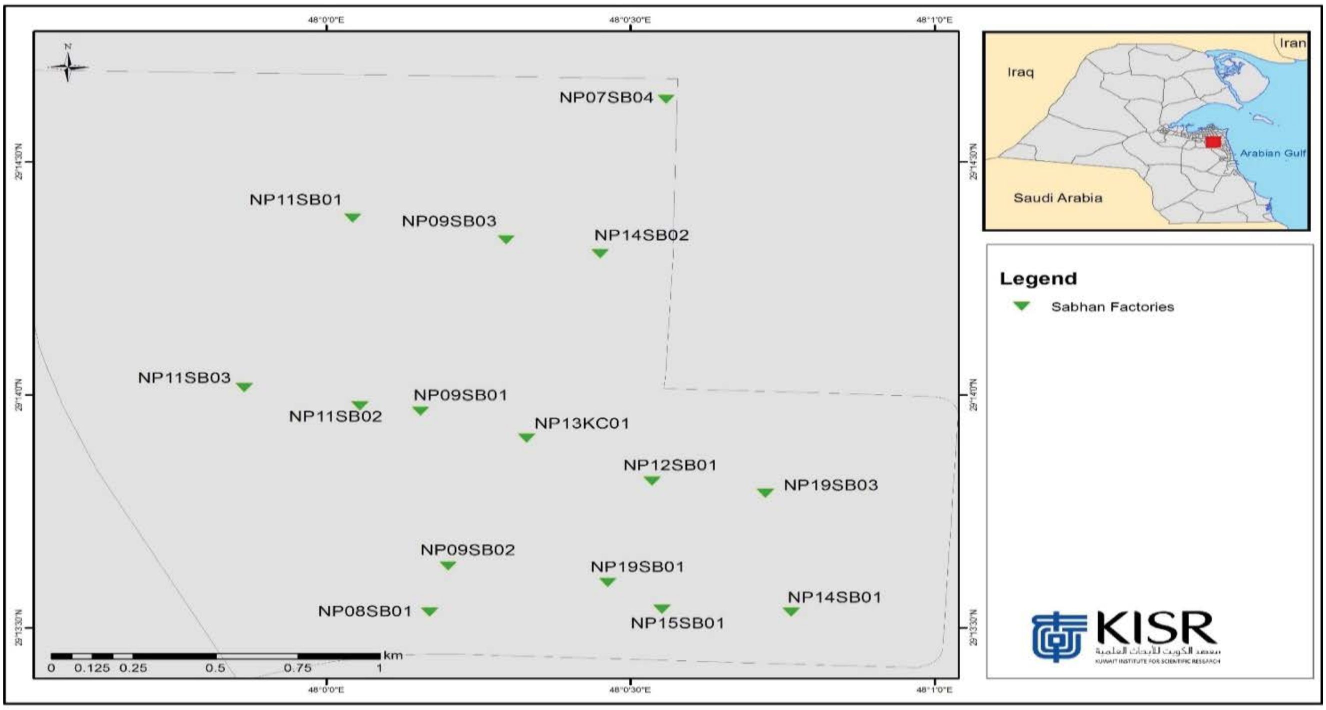

Fig. 2. Location map of selected factories at Sabhan industrial area.

Table 1
Summary of selected factories names, codes and coordinates at Sabhan industrial area

Serial No.	Factory/site name	Sample code	Factory/site coordinates (UTM)	
			North	East
1	Al-Yasra Company	NP07-SB04	29.2438987	48.0093041
2	Petra Food Manufacturing Company	NP08-SB01	29.2255592	48.0028326
3	Al Mejhem Global Group Company	NP09-SB01	29.2327471	48.0025814
4	Kuwait Flour Mills & Bakeries Company	NP09-SB02	29.2272129	48.0033348
5	Gulf Pastries Manufacturing Company	NP09-SB03	29.2388726	48.0049314
6	Refreshment Trading Company (Coca Cola)	NP11-SB01	29.2396461	48.0007190
7	United Beverage Company (Pepsi)	NP11-SB02	29.2329353	48.0009185
8	Al-Sayer Soft Drinks Factory (RC Cola)	NP11-SB03	29.2335895	47.9977508
9	Carton Industries Company	NP12-SB01	29.2302470	48.0089239
10	Gulf Insulating Material Plant Company-1	NP14-SB01	29.2255583	48.0127323
11	Gulf Insulating Material Plant Company-2	NP14-SB02	29.2383767	48.0075050
12	Kuwait Aluminum Extrusion Company	NP15-SB01	29.2256665	48.0091978
13	Al-Bahar Industries	NP19-SB01	29.2266184	48.0077132
14	Sabhan Factory	NP19-SB03	29.2298120	48.0120292

UTM – Universal Transverse Mercator

industrial wastewater was measured through calculating number of sewage takers (each tanker with capacity 5,000 gallons) discharged per week from each factory.

2.4. Preparation of database and data entry

To develop a site coding, the industries were first divided into two main groups: petroleum and non-petroleum industries. The abbreviations PT was used to indicate the petroleum group of industries while the abbreviation NP to indicate non-petroleum group of industries. Each of the two main groups of industries (PT and NP) was then subdivided into subgroups. A two-digit code was then assigned for each sub-group. Coordination of the industrial site studied were measured in Universal Transverse Mercator (UTM) system, North and East.

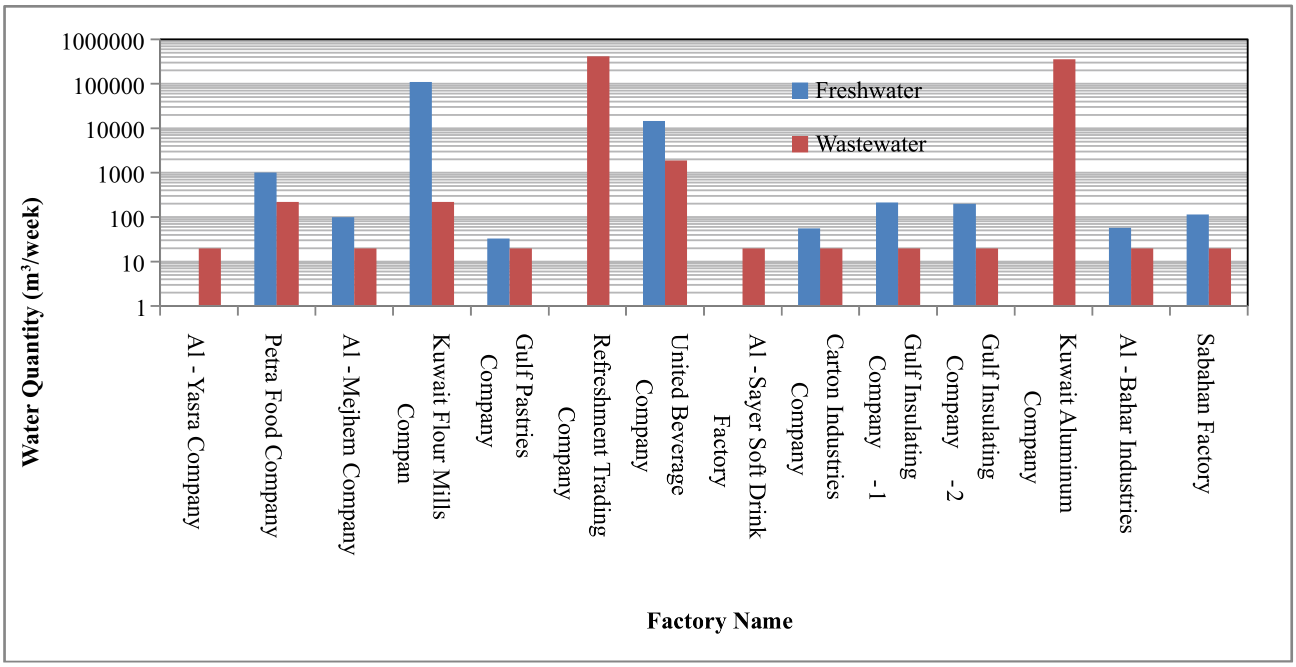

Fig. 3. Quantities of freshwater and wastewater for each factory of Sabhan industrial area.

Table 1 shows the codes and the UTM coordinates of the 14 industrial factories that agreed to participate in the study. Excel spread-sheet was prepared as a database in which values of field measurements (Temperature, DO, EC, ORP, and pH) and the wastewater quality parameters determined in the lab were regularly entered and updated. The Excel database was then converted into a GIS database, using ArcGIS software. From the GIS database, GIS maps for each wastewater quality parameter have been generated to help in analyzing the spatial distribution of the quality of the raw wastewater produced by the various factories.

3. Results and discussions

The quantities of freshwater consumption and wastewater generated from each industry are presented in Fig. 3. The maximum, mean and minimum values of freshwater consumption for 14 factories of Sabhan industrial areas were found to be 110,535; 9,073 and 33 m^3/week, respectively. The highest freshwater consumption was found with Kuwait Flour Mills Company. Total of 127,027 m^3/week of freshwater was consumed by 14 factories. On the other hand, the maximum, mean and minimum values of wastewater produced by 14 factories of Sabhan industrial areas were found to be 420,000, 55,894 and 20 m^3/week, respectively. The highest wastewater generated was found with Refreshment Trading Company. Total quantity of 782,520 m^3/week of raw wastewater was generated by 14 factories (Fig. 3).

The pH is field parameter provides information about of wastewater environment if it is acidic, neutral or alkaline media associated with certain dissolved gases in that media. Lower limit (6.5) and upper limit (8.5) were set for pH parameter of wastewater by Kuwait EPA for irrigation water purposes. The maximum, average and minimum values of wastewater pH for 14 factories of Sabhan area were plotted in Fig. 4. Except five factories (Al-Yasra, Al-Mejhem, Insulatine-2, Aluminum and Al-Bahar) where wastewater pH was found alkaline, the wastewater pH for the remaining factories represent acidic environment. The mean values of pH of wastewater for eight companies (Petra, Flour, Pastries, Coca Cola, Pepsi, RC Cola, Carton and Al-Bahar) do not meet either the lower or upper limits set by KEPA for irrigation water standard.

Electrical conductivity of wastewater was measured to estimate the salinity of wastewater (represented by TDS values) in the field. The minimum and maximum values of electrical conductivity of wastewater of 14 factories was found to be 174 and 8,673 μS/cm, respectively (Fig. 5). The average values of electrical conductivity (lower than 550 μS/cm) of wastewater for all factories categorized as freshwater type except the mean values of electric conductivity (3,156 μS/cm) of wastewater of Al-Bahar Company which characterized as brackish water type.

The oxidation–reduction potential values of the wastewater ranged between –410.0 and 538.0 mV for the 14 factories. The ORP values of the wastewater of total of eight factories indicated reduced environments while the ORP values (below 0.0 mV) for the wastewater of the remaining factories (Al-Yasra, Insulating-1, Insulating-2, Aluminum, Al-Bahar and Sabhan) indicated oxidized environments (above 0.0 mV) as shown in Fig. 6. The negative values of ORP values might be due to presence of number of reduced gases such as ammonia, methane, hydrogen sulfide and volatile organic compounds in the raw wastewater.

The dissolved oxygen (DO) values of the wastewater ranged between 0.0 and 8.6 mg/L for the 14 factories. The same eight factories with reduced ORP values of the wastewater had 0.0 mg/L DO while the DO values (below 0.0 mV) for the wastewater of the remaining indicated oxidized environments (above 0.0 mV) as shown in Fig. 7.

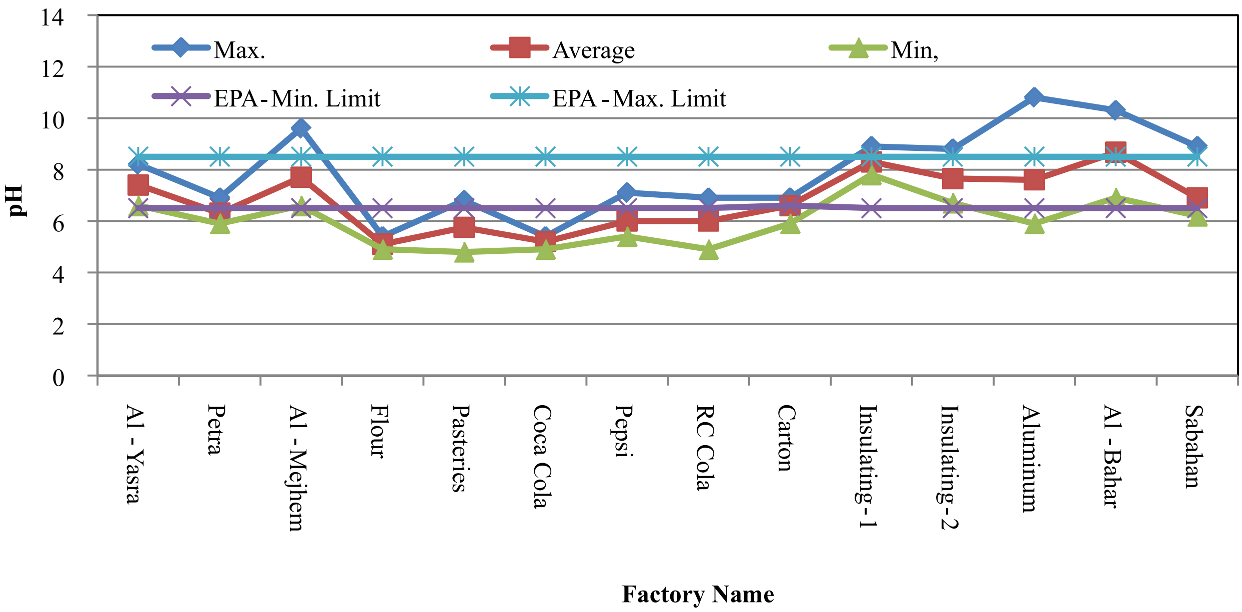

Fig. 4. Changes in pH values of wastewater for Sabhan factories.

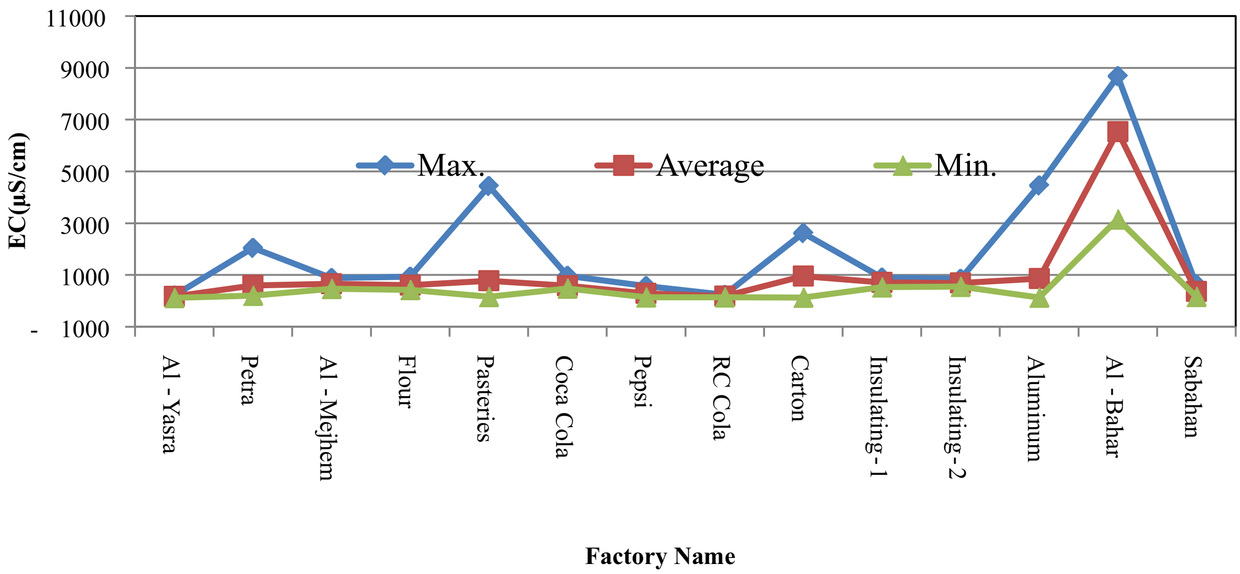

Fig. 5. Changes in electrical conductivity values of wastewater for Sabhan factories.

The mean values of DO of wastewater for six companies (Al-Yasra, Insulating-1, Insulating-2, Aluminum, Al-Bahar and Sabhan) do not meet the maximum limit set by KEPA for irrigation water standard.

The TPH value of 5 mg/L were set by KEPA as maximum limits for irrigation water. The total TPH values of the wastewater ranged between 0.3 and 19 mg/L for the 14 factories as shown in Fig. 8. All average values of total petroleum hydrocarbon concentration of the wastewater meet the maximum limit set by KEPA for irrigation water purposes except those values of TPH (>5 mg/L) for three factories (Flour, Pepsi and Sabhan) and this parameter should be treated. Distribution GIS maps were generated for TPH based on the data of GIS database using ArcGIS software as shown in Figs. 9–11. Sabhan area results were shown in top red square in Figs. 9–11.

Total of five factories (Al-Sayer soft drinks, Gulf Insulating Material Plant Co.-1, Gulf Insulating Material Plant Co.-2, Kuwait Aluminum Extrusion Company and Al-Bahar Industries Co.) used onsite treatment system in Sabhan industrial area. The water treatment system varied between pH control and ion exchange water

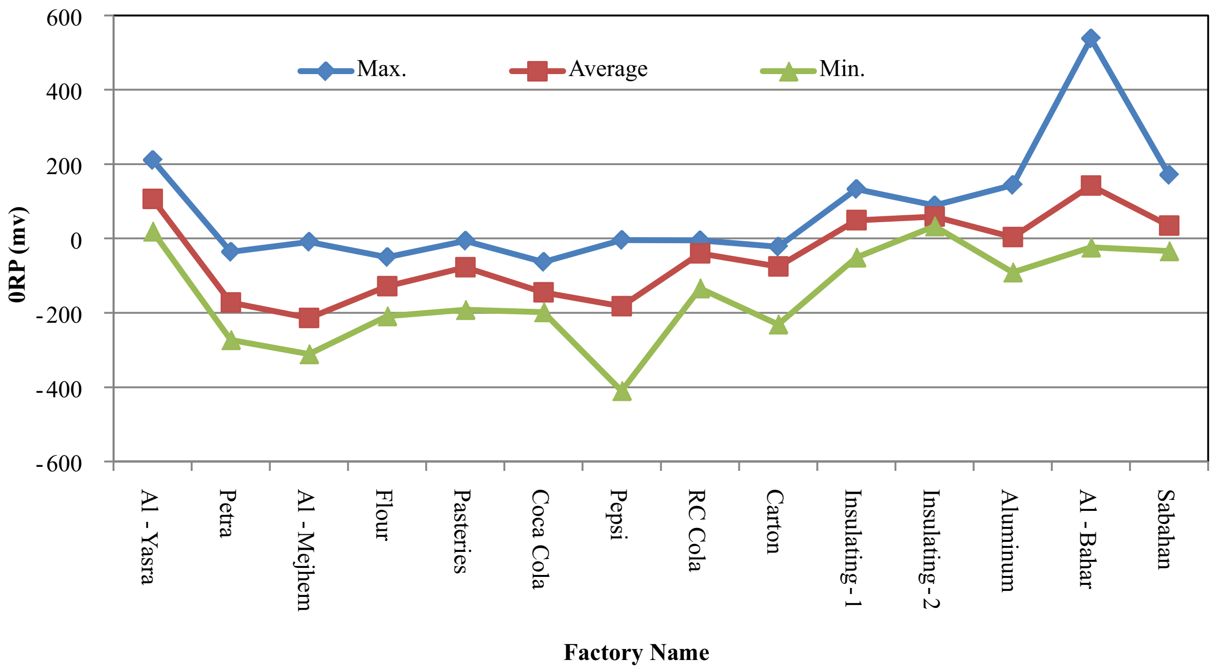

Fig. 6. Changes in oxidation–reduction potential values of wastewater for Sabhan factories.

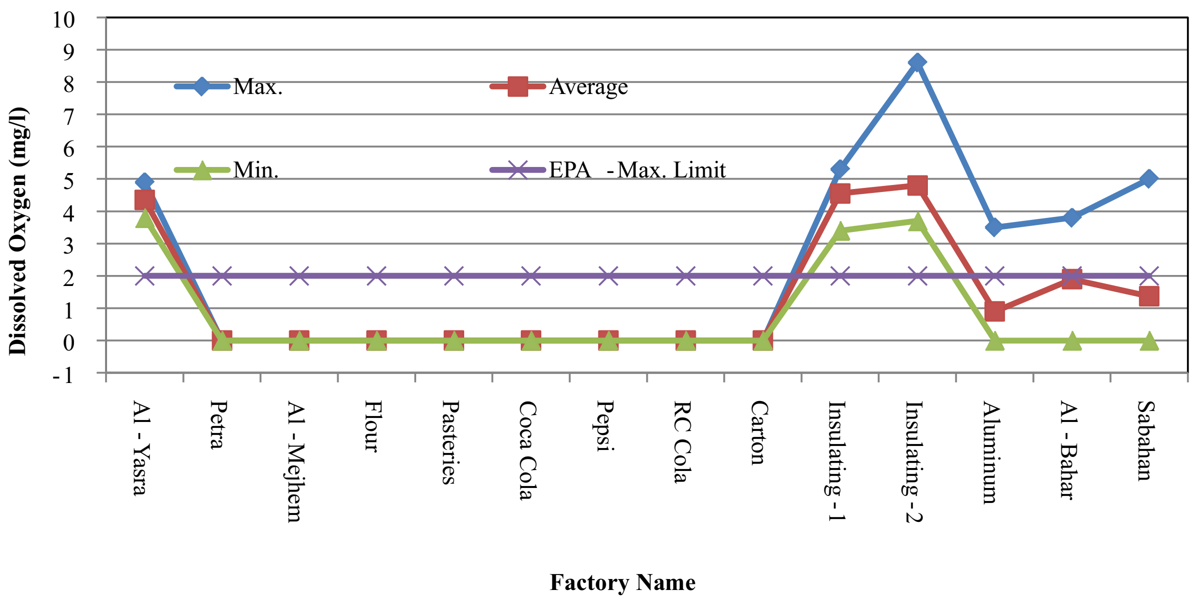

Fig. 7. Changes in dissolved oxygen values of wastewater for Sabhan factories.

treatment units. The remaining factories send the untreated wastewater to Wafra Industrial wastewater Treatment Plant (WIWWTP).

4. Conclusions

A field study was carried out to collect data on the quality and quantity of wastewater from 14 non-petroleum factories of Sabhan industrial area, and developing a database for the target industries using ArcGIS technique. Wastewater samples were collected and analysed for chemical parameters. The laboratory results of total petroleum hydrocarbon indicated that their concentrations in the raw wastewater are meeting KEPA irrigation water standards for landscaping and greenery except for those values of TPH (>5 mg/L) for three factories (Flour, Pepsi and Sabhan). Also, the obtained field data suggest that only a few industries use on-site wastewater treatment systems. Based on the field, laboratory and GIS results, following recommendations are forwarded:

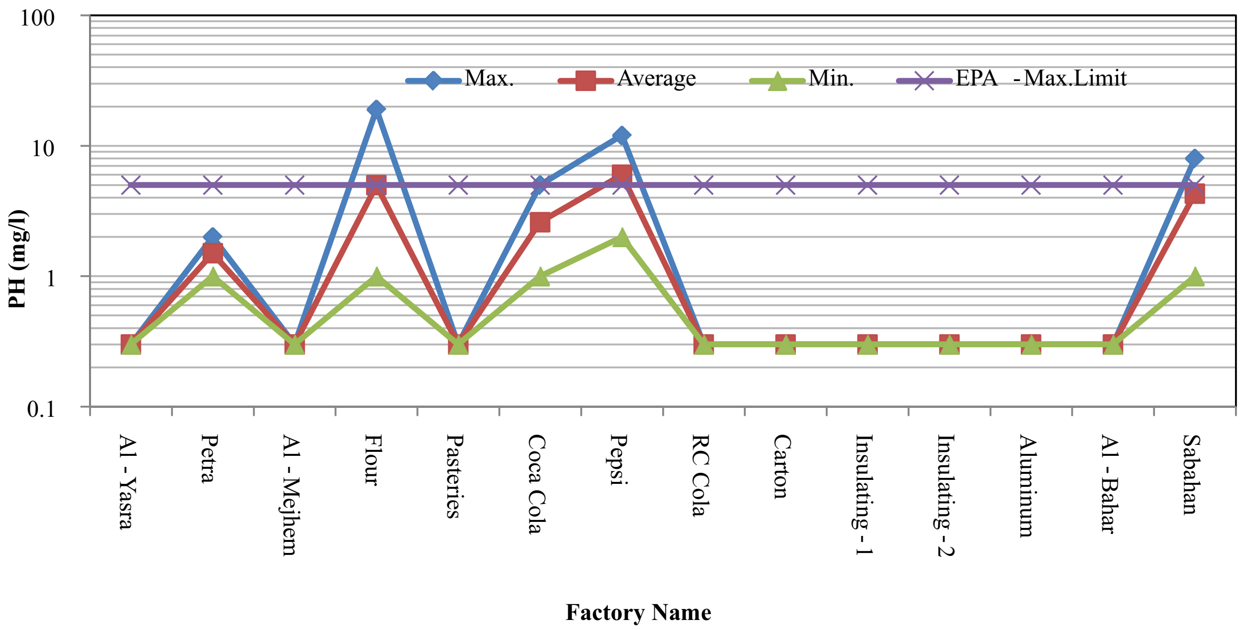

Fig. 8. Changes in TPH values of wastewater for Sabhan factories.

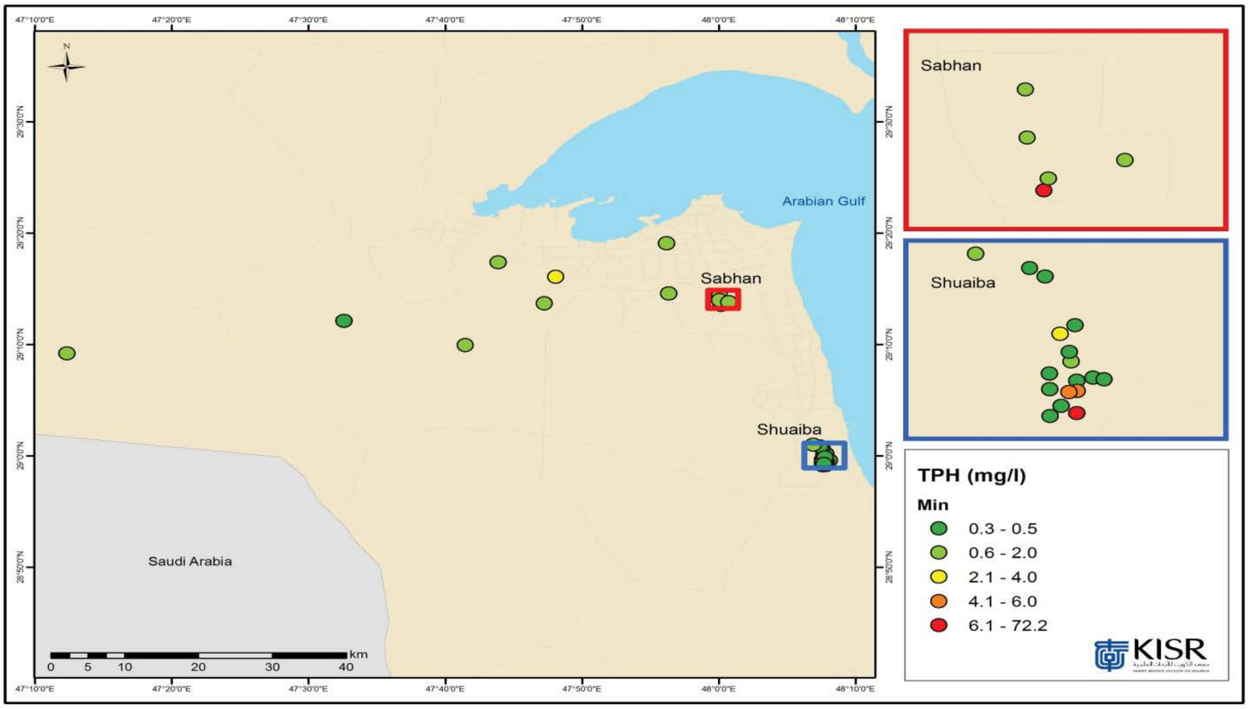

Fig. 9. Distribution map of minimum values of TPH (mg/L) in wastewater for various industries in Kuwait.

(1) Collection data regarding quantity and quality of industrial wastewater for petroleum and nonpetroleum sectors should be continue for long monitoring period and for all parameters.
(2) The development of industrial database should be updated every 2 y by Public Authority Industry (PAI).
(3) Onsite treatment systems should be installed to treat the industrial wastewater for group of industries of similar sources.

Acknowledgments

The authors are grateful to the Kuwait Foundation for the Advancement of Sciences (KFAS) for participating in funding the study. The unlimited support of KISR's management was pivotal in carrying out the study. Its permission to publish the paper is gratefully acknowledged. This paper was published under KISR Publication No. 17120.

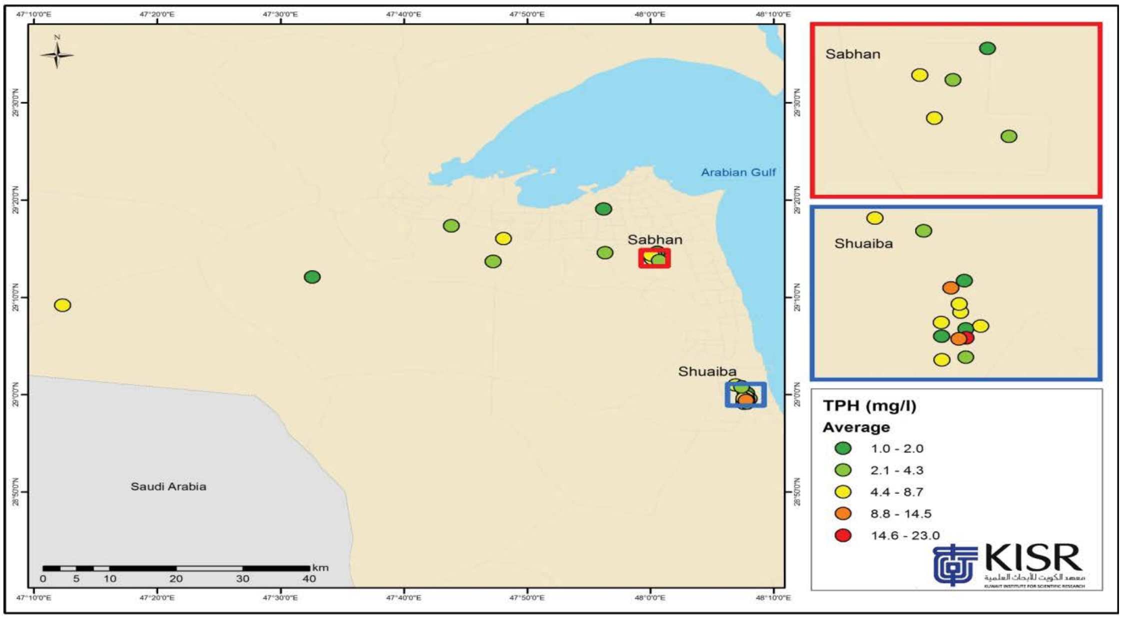

Fig. 10. Distribution map of average values of TPH (mg/L) in wastewater for various industries in Kuwait.

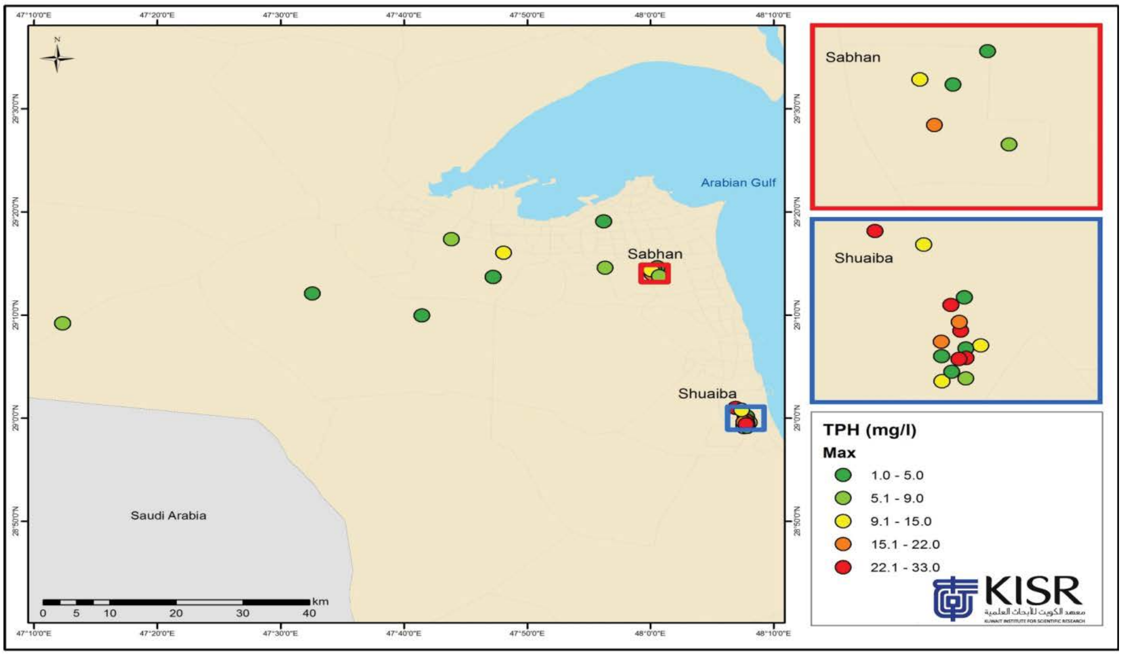

Fig. 11. Distribution map of maximum values of TPH (mg/L) in wastewater for various industries in Kuwait.

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Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2022.28208

263 (2022) 78–86
July

Cost-benefit analysis of the shift from traditional irrigation systems to modern irrigation methods by small farmers in Al-Ahsa and its role in the dissemination of modern irrigation techniques

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Received 28 February 2022; Accepted 26 April 2022

ABSTRACT

This study explores the feasibility of investing in modern irrigation methods for small farmers who rely on date palms as the main crop. The financial and cost-benefit analysis proves that the investment in such a method has the ability to recover all the costs at the end of the first year and then realize benefits. The feasibility was highest for the farmers who use irrigation water provided by the Saudi Irrigation Organization (SIO) compared to those who use their own private wells. The reduction in the electricity bill estimated at about 40% because of rationalizing the use of water constitutes an incentive for owners of private wells to switch to modern irrigation methods, and their benefits will be the highest in case they shut down their wells and use water provided by SIO. The study also tested the ability of small farmers to pay the irrigation water tariff expected to be applied in the future, and showed that the highest price a palm date farmer can pay is estimated at about 0.06 riyals/m^3 of water, which is an indication of their ability to respond if water tariff is imposed. And based on the amount of water that SIO provided to farmers during 2019, if the mentioned rate of water value is adopted as a tariff, the return for SIO is estimated at about 8–9 million riyals annually.

Keywords: Rationalizing the use of water; Cost-benefit analysis; Modern irrigation methods; Saudi Irrigation Organization; Ability to pay; Water tariff

1. Introduction

The agricultural sector is the largest water consuming sector in the Kingdom of Saudi Arabia in terms of size and growth rate, as it consumes more than 80% of total water demand and is growing at an annual rate of 7% (The National Water Strategy 2030). Considering the limited sources of groundwater and surface water, this exacerbates the problem of water scarcity and constitutes a major challenge facing the agricultural sector and the irrigation sector. To meet this challenge and achieve sustainable agricultural development, both the National Water Strategy and Saudi Irrigation Organization (SIO) strategy included ambitious initiatives to reduce the demand for agricultural water through the application of modern irrigation techniques, and the best practices of agriculture and irrigation, besides increasing the utilization of sustainable water sources such as renewable water (treated sewage effluent), dam water and rain harvesting. Although the high rates of development achieved by the agricultural sector during the last three decades, which was represented in achieving self-sufficiency in many important agricultural products, it faces major challenges, the most important of which is the low water use efficiency of the already scarce water sources, and its dependence on non-renewable groundwater resources, which reach a percentage of about 90% of the total water consumed in the sector (The National Water Strategy 2030). The average irrigation efficiency in Saudi Arabia over the past decade is estimated to be around

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

1944-3994/1944-3986

53%, although international best practices indicate the possibility of achieving efficiency ranging from 75% to 85% (The National Water Strategy 2030).

It is believed that the low water efficiency in the agricultural sector is due to the low rates of adoption of modern irrigation techniques and systems, especially in the irrigated areas that still use traditional irrigation systems with low efficiency, such as the regions of Jazan and Makkah. Fig. 1 shows the average prevalence rate of irrigation methods in the Kingdom, and its prevalence in the main regions.

In the case of Al-Ahsa project area, which is the focus of this study, the development of traditional irrigation methods began early by introducing enhanced surface irrigation methods that consume less water known as Bouaki, Tadwees and Circle irrigation to replace the traditional flood irrigation. In the Tadwees method, the land is divided into longitudinal slices, a slice is irrigated, and the adjacent slice is left without irrigation, and the young palm trees are planted in the middle of the irrigated slices (Fig. 2). In the Al-Bouaki method, land is backfilled around the mature palm trees to raise its level, irrigation water is given to the adjacent slides (Al-Bouaki – Fig. 3), and due to the length of the date palm tree roots, it can reach the water in the adjacent irrigated slides. In the circle irrigation method, irrigation is carried out in circular basins with diameters of up to 3 m, keeping 7 m space between any two basins, and the palm tree is inside the basin (Fig. 4).

With the establishment of the Water extension Department in 1,417 AH, the application of modern irrigation methods known as bubbler irrigation began (Fig. 5), and this was accompanied by awareness programs and incentives to encourage farmers to adopt modern irrigation methods, that included:

- SIO participates in the costs of introducing the modern irrigation system especially the network, storage basin and pump) in varying proportions according to the farm area.

Fig. 2. Tadwees method.

Fig. 3. Bawaki method.

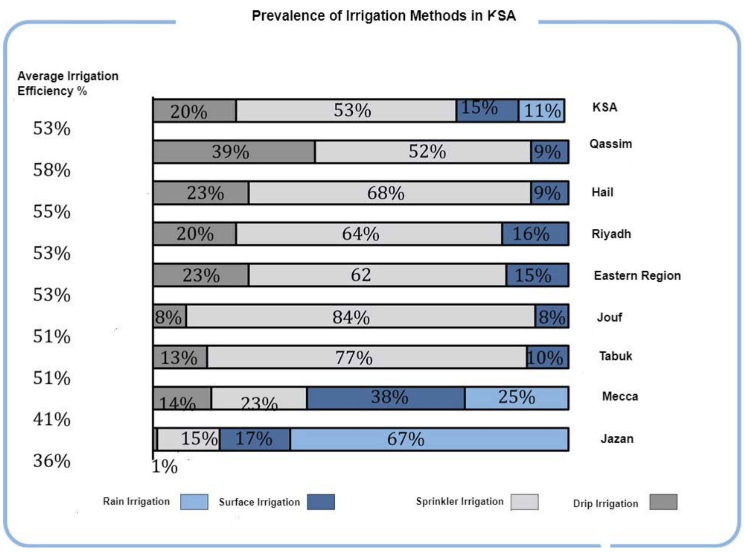

Fig. 1. Prevalence of irrigation methods in the main regions of KSA (*Source*: SIO Strategy 2018).

- Buying dates from farmers who implement modern irrigation methods at a higher price (5 riyals/kg instead of 3 riyals/kg for non-implementers).
- Shortening the irrigation period from 7 to 4 days, or from 14 to 7 days for farmers who switch to modern irrigation methods.

Accordingly, there has been steady progress in switching from the traditional irrigation system to modern irrigation systems. The number of farms that converted to modern irrigation until 2019 reached about 6381 farms with an area of 2018 ha, or 25% of the number of farms within the command area of the project. It is expected that the percentage of conversion to modern irrigation methods will increase steadily after the irrigation network with open channels was converted into a pressurized distribution network, which provides sufficient pressure at the entrance to the farm with a 3 bar, enabling the farmer to connect his field network without the need for a pump or a storage pond.

This study aims to:

- Highlight the feasibility of investing in the introduction of modern irrigation methods by farmers as an alternative to the traditional methods used.

Fig. 4. Circle method.

Fig. 5. Bubbler method.

- Test the ability of small palm tree farmers to pay in case of imposing a tariff for irrigation water, so that this would be a guiding indicator for SIO to plan and take decision regarding imposing irrigation water tariff.
- Assist SIO in its plans to implement an incentive system that promotes the application of modern irrigation techniques among small farmers, whether those who benefit from SIO's water sources or those who use their private wells for irrigation.

2. Literature survey

One of the most important challenges facing water resources in the Kingdom alongside the scarcity is the low efficiency of agricultural water use, especially in oases and old cultivation areas, where the prevailing irrigation methods are still the traditional surface irrigation methods, whose average efficiency is estimated at about 30% (the SIO strategy). To address this, studies indicated a trend towards introducing modern irrigation techniques and methods that lead to raising the efficiency of low surface field irrigation methods, in addition to achieving a significant reduction in consumption and cost of energy and labor. Table 1 shows the reduction in the cost of energy and labor by using modern irrigation techniques compared to using surface field irrigation methods in some Arab countries.

However, modernizing traditional field irrigation methods in the Arab countries faces some technical, economic and social obstacles and difficulties, the most important of which are: the weak water extension and management services, the high cost of introducing modern irrigation methods compared to traditional irrigation methods, and the weak agricultural yield for small farmers with a small area, which does not help Cost recovery; in addition to the scarcity of specialized research centers (The Arab Organization for Agricultural Development 1999). The study titled "Factors Affecting the Adoption of Modern Irrigation

Table 1
Energy and labor cost reduction in adopting modern irrigation methods compared to traditional surface methods

Country	Reduction in the cost of energy and labor by using modern irrigation methods compared to surface irrigation	
	Energy %	Labor %
Jordan	42.3	
Qatar	44.8	
Kuwait	78.9	90
Syria	42.0	70.3
UAE	41.9	50
Palestine	52.5	
Egypt	–	49.9
Yemen	–	33
Sultanate of Oman	–	97

Source: Adapted from a study evaluating the uses of modern irrigation techniques under Arab Agricultural conditions – The Arab Organization for Agricultural Development

Techniques in the Kingdom" (King Abdulaziz City for Science and Technology – General Administration of Grant Programs 03-641 – Project: A T) concluded that the high cost and difficulty of maintenance were the most important obstacles against the adoption of modern irrigation methods by farmers, and recommends implementing financing policies and support for the cost of modern irrigation network so that the farmer can adopt them.

In Tabuk region Al-Zaidi et al. [1] conducted a study to determine the relationship between some personal characteristics and socio-economic conditions of farmers and their attitudes towards using both traditional and modern irrigation methods, in addition to identifying the factors that affect farmers' attitudes towards using modern irrigation methods. Regarding the trends towards modern irrigation methods, it was found that about 28.3% of the total respondents/farmers have positive attitudes and about 71.7% have a neutral orientation. The results also reflected a significant and positive correlation for factors such as: age, area cultivated using traditional methods, land area, and farmers' attitude towards using traditional irrigation methods. In contrast to a significant inverse positive relationship between the number of family workers in agriculture, annual income, and farmers' attitudes towards using different irrigation methods. The study recommended carrying out large-scale awareness campaigns for farmers using various modern methods for water conservation.

In the Qassim region, AL-Subaiee et al. [2] conducted a study with the aim of determining the irrigation methods used by farmers and the obstacles that face the adoption of modern irrigation methods. The results of the study indicated that more than a third (38.3%) of farmers use the surface (flood) irrigation method, while about 31.2% of the farmers used the drip irrigation method. A significant and positive correlation was achieved between educational levels and the level of using modern irrigation methods. However, the age and years of experience of the farmers were negatively correlated with using modern irrigation methods, while the farm area was negatively correlated with the use of traditional irrigation methods. The study recommended launching extension education programs to enhance the rates of farmers' adoption of modern irrigation methods to conserve the limited water resources.

Lazaridou et al. [3] also conducted a study examining farmers' willingness to pay for the use of treated wastewater for irrigation in the Nestos region, Greece. This was done by applying the Contingent Valuation Method (CVM) to the results of a questionnaire that included 302 farmers. The results showed that farmers expressed a positive attitude towards the use of treated wastewater, as they were 64.2% willing to pay its cost, but they were willing to pay an average cash amount of 20.54 Euro/ha/y, which is much less than what they pay for fresh water, which is equivalent to only 12.7% of the cost of using fresh water. In addition, the analysis shows that the use of treated wastewater in agriculture is more acceptable to farmers who are aware of its environmental benefits.

Cost-benefit analysis (CBA) is generally considered a suitable decision-making mechanism and one of the tools used by policy makers to choose among several alternative investment opportunities, and it is a widely practiced technique for testing the financial viability of any project, that is, whether the investment to be made is profitable financially or not. In Mongolia, Baranchuluun et al. [4] used a cost-benefit analysis to assess the response of farmers to the trade-off between different irrigation systems including drip irrigation, sprinkler irrigation and surface irrigation (strip irrigation) for growing types of vegetables such as tomatoes, cabbage, radish, and potatoes by each of the mentioned irrigation methods. The results of the analysis showed that the drip irrigation method is the most effective and the best alternative for farms and saves water and labor compared to surface irrigation methods.

In Iraqi Kurdistan Zagonari [5] combined financial analysis, cost-benefit analysis, and social status to assess and determine the feasibility of the financial and social sustainability of the Shahrazour Irrigation Project. The results indicated that in case the price of the irrigation tariff imposed on farmers is between 0.32 and 0.57 US$ and that the interest rate of the loan paid by the farmer is less than 3%, the irrigation project can achieve financial feasibility at a rate of 13.6% for all reliable economic solutions and social sustainability at a rate of 35.8% of the proposed solutions.

Also Luhach et al. [6] used economic analysis to test the feasibility of investing in drip and sprinkler irrigation methods compared to traditional surface irrigation methods in Haryana, India, where a number of farms were selected that produce grapes and citrus, including 60 farms drip irrigated, 60 sprinkler irrigated and 60 surface irrigated. By estimating the construction and operating costs and production inputs, as well as calculating the returns, the net present value, the internal return rate and the benefits/costs ratio were calculated. The results indicated a higher value in both the drip and sprinkler irrigation methods compared to the surface irrigation method. Thus, drip irrigation and sprinkler irrigation are considered water-saving techniques with better economic feasibility than surface irrigation, and investment in them should be encouraged.

In the Punjab province of Pakistan (Amar Razzaq et al. [7]) carried out an economic analysis, measurement, and comparison of water productivity of modern and traditional irrigation systems using primary data collected from 120 farms where mango and wheat crops are grown. Economic analysis indicators were estimated for cost benefit ratio (BCR) and net present value (NPV). The results of the study showed that users of modern irrigation systems (sprinkler and drip irrigation) obtained higher total values of cost-benefit ratio and net present value, which indicates that adopting modern irrigation methods was an economically viable option. In addition, the water productivity of farms using modern irrigation methods was higher than that of traditional farms.

Regarding analyzing the farmers' willingness and their ability to pay the cost of irrigation water, Tabieh et al. [8] conducted a study to determine the farmers' ability to pay the cost of irrigation water in the Jordan River Valley. The Residual Imputation Approach was used to determine the real cost of irrigation water, where all production costs except the cost of water are deducted from the total return of the farm. The study also found that the profitability of water and, consequently, the value of irrigation water showed a high level of variance by location, type of crop, quality and source of irrigation water, planting season and irrigation technique used. For example, it was found that the profitability of surface water is the highest, followed by mixed water and then groundwater is the lowest. They also found that the average value of irrigation water was 0.51 JD/m^3 at the state level, and the highest value is for water used for irrigation of: vegetables under greenhouses, citrus crops, other fruit trees and field crops such as wheat, respectively. The results showed that the cost of irrigation water is equivalent to 1.1% of the total cost, which is considered low so that it does not encourage farmers to save water. The weighted average of farmers' maximum ability to pay for irrigation water in the Jordan Valley was estimated at 0.76 JD/m^3 of water (1 JD = 5.28 SAR).

3. Study area and data collected

This study was carried out in Al-Ahsa project, which is managed by SIO and located in the Eastern region of Saudi Arabia (Fig. 6). The necessary data for the study was collected after a comprehensive survey and inventory of the farms applying modern irrigation methods (bubbler irrigation). 100 farms were selected distributed over the ten irrigation zones that make up the entire project area, 90% of them benefit from the project's irrigation water and the rest from private wells. The farms were subjected to a questionnaire from September to December 2020, which included meetings with farmers to take data on the components of the irrigation network in terms of types and diameters of pipes, valves, drippers/emitters and their cost, storage tanks, pump, energy and fuel cost in the case of a private well, in addition to other production inputs such as service, fertilization and crop protection etc., as well as productivity and marketing data. Then the cost of introducing modern irrigation methods for certain farms is estimated.

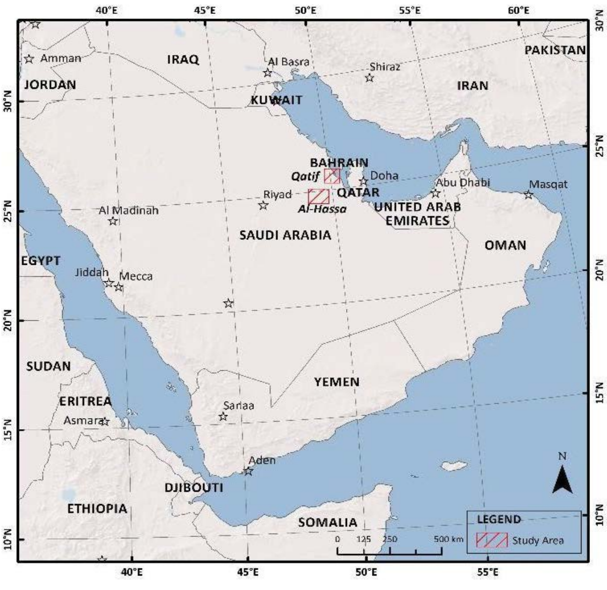

Fig. 6. Al-Ahsa project area.

Since the small farmers are the target segment of the study because it represents most of the farmers in the project, it was taken into account that the cost-benefit analysis and financial analysis are designed to suit this segment, and therefore, through statistical analysis, the average area representing the segment of small farmers was chosen at about 3 dunums (3,000 m^2). Then, Excel programs were used to calculate the cost and benefits (CBA) and make financial analysis. Cost-benefit analysis is widely used to test the financial viability of a project, that is, whether the investment to be made is financially rewarding and worth making or not [9]. A cash flow analysis was conducted for a period of 10 y to determine the payback period for the investment in modern irrigation methods.

Accordingly, the following indicators were estimated as a function of the feasibility of investing small farmers in modern irrigation techniques as an alternative to traditional irrigation methods for a farm irrigated from SIO water resource, and another irrigated from a private well.

A cost-benefit analysis model of a small palm tree farm was also carried out using the data of productivity, benefits and all costs incurred by the farmer during the production process, and then estimating the share of irrigation water from the total costs, thus sensing the extent of the farmer's ability to pay any tariff that could be imposed on irrigation water.

4. Results and discussion

Through the questionnaire data, which included 100 farms, the cost of introducing the modern irrigation system with the Bubblers system was estimated in those farms. The cost of introducing modern irrigation methods amounted to 8,150 riyals, including the irrigation network consisting of plastic pipes with diameters 3, 2 and 0.25-inch; In addition to a pond/tank of dimensions (1.5 m × 4 m × 5 m) and a pump capacity of 2.5–5 HP. Table 2 shows the cost details, bearing in mind that the cost drops to 2,100 riyals in the case of farms that irrigate from SIO project, taking advantage of the pressure available in the network (about 3 bar), and therefore do not need neither a pump nor a storage pond.

Accordingly, cost-benefit analysis and financial analysis were used for a period of 10 y in order to determine the feasibility of investing in the application of modern irrigation methods from the point of view of the simple farmer,

Parameter	Equation	Feasibility
Benefit-cost ratio, BCR	BCR = Total benefits/Total cost	If ratio >1 project feasible
Repayment period	Investment cost/yearly income	Shorter the repayment period, the more feasible the project
Residual imputation approach	Water cost = total revenue – cost of other inputs	Farmer/user ability to pay water tariff indicator

and to determine the recovery period for the cost of investment in modern irrigation methods for a farm with an area of 3 dunams irrigated from SIO project (with a pond and a pump) and another of the same area irrigated from a private well. Taking into consideration all the costs that the farmer will incur, including the annual maintenance costs and the replacement of the irrigation network and the pump. Table 3 shows the data and assumptions used in the financial analysis.

The results of the financial and cost/benefit analyses indicated that the investment of the farmer who irrigates from the project in introducing modern irrigation methods, which amounts to 8,150 riyals during the first year, will rise to 8,605 riyals as a result of annual maintenance costs, and in the 10th y the irrigation network and pump will be replaced. The analysis showed according to Table 4 the high feasibility of investing in the introduction of modern irrigation methods, as the farmer can recover the full cost of the investment at the end of the second year, with a cumulative value of 1,729 riyals, in the case of option (B) when the farmer sells his production at a price of 3 riyals/kg; The interest rises in the case of option (A) when the farmer sells his production at the incentive price of 5 riyals/kg, as he recovers the investment cost in the first year.

The results also showed the high feasibility of investing in the introduction of modern irrigation methods for the farmer who irrigates from a private well, as he recovers the investment cost at the end of the second year, in addition to saving about 40% of the electricity cost, estimated at about 1,500 riyals annually because of raising the irrigation efficiency from 50% to 90% after switching to modern irrigation (Table 5). But if he stops using the well and turns to benefit from the project's water, his benefits will be higher, as he will save the entire electricity consumption of 1,500 riyals annually. Also Table 5 shows that the reduction in the electricity consumption alone is not sufficient to recover the cost of investment in modern irrigation.

With regard to the analysis of farmers' willingness and ability to pay the cost of irrigation water (Table 6), a cost-benefit analysis was conducted, and the Residual Imputation Approach was used to determine the cost of irrigation water after deducting all production costs except for water cost from the total return of the farm and the difference represents the cost of water. Where the results showed that the value of water amounted to 0.06 riyals/m^3 (i.e., about 114 riyals/dunam/y) and is an indicator of the economic efficiency of water and an indication of the maximum capacity of the farmer to pay the irrigation water tariff [8]. In a report by MEWA, the Residual Imputation Approach was used to estimate the cost of treated wastewater produced by the National Water Company. The cost was determined for the sectors of agriculture, industry, municipalities and rest houses.

5. Recommendations

Given the high feasibility and benefits for farmers who invest in the application of modern irrigation methods, in addition to its contribution to reducing agricultural water consumption, it is recommended that SIO provides more incentives for small farmers and consider the possibility of bearing part of the cost of the irrigation network in addition to providing advice and technical support.

Activating programs with the Saudi Agricultural Development Fund to provide loans for farmers to be used in introducing modern irrigation methods.

Motivating the owners of private wells to apply modern irrigation methods by offering to provide them with

Table 2
Cost of bubbler irrigation system components

Area	Reservoir Cost		Pump Cost		Irrigation System Cost		Installation Cost		Total Cost		
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Av.
3 Dunam	4000	3000	2700	2400	1200	1000	1200	800	9100	7200	8150

The cost of farms irrigated by private wells that have a pump and tank = 8150 SAR/ Dunam
The cost of farms irrigated by Saudi Irrigation Organization that have a pump and tank = 8150 SAR/ Dunam
The cost of farms irrigated by Saudi Irrigation Organization that do not need neither a tank nor a pump = 2100 SAR/ Dunam

Table 3
Data and assumptions used in financial analysis

Number of date palm tree/ha	100 ha	–According to MEWA recommendations
Production	60 kg/tree	60 kg/tree taken as average
Water quantity/ha	19000 m^3/year	–SIO
Bubbler irrigation efficiency	90%	–SIO
Surface irrigation efficiency	50%	–SIO
Inflation rate	2.5%	–General Authority for Statistics
Subsidized price for dates	5 SAR/kg	–Dates factory
non-subsidized price for dates	3 SAR/kg	–questionnaire
Electricity cost(private well)	500 SAR/donum	–questionnaire

Table 4
Financial analysis to recover the investment cost of a farm with an area of 3 donums irrigated by SIO

Investment	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11
Cost of irrigation network											
Main and lateral pipes, bubblers	1,100										1,408
Cost of network installation	1,000										1,280
Cost of pond/tank	3,500										
Cost of pump	2,550										2,614
Cost of investment	8,150										5,302
Cost of annual maintenance											
Pump	255	261	268	275	281	289	296	303	311	318	326
Pond/Tank	35	36	37	38	39	40	41	42	43	44	45
Farm network	165	169	173	178	182	187	191	196	201	206	211
Total annual cost	8,605	466	478	490	502	515	528	541	554	568	5,884
Cumulative cost	8,605	9,071	9,549	10,039	10,542	11,056	11,584	12,125	12,679	13,248	19,132
Annual benefits											
Option a (5 SAR/kg)	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000
Option b (3 SAR/kg)	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400
Annual response											
Option a (5 SAR/kg)	395	8,534	8,522	8,510	8,498	8,485	8,472	8,459	8,446	8,432	3,116
Option b (3 SAR/kg	–3,205	4,934	4,922	4,910	4,898	4,885	4,872	4,859	4,846	4,832	–484
Cumulative annual response											
Option a (5 SAR/kg)	395	8,929	17,451	25,961	34,458	42,944	51,416	59,875	68,321	76,752	79,868
Option b (3 SAR/kg)	–3,205	1,729	6,651	11,561	16,458	21,344	26,216	31,075	35,921	40,752	40,268

Table 5
Financial analysis to recover the investment cost of a farm with an area of 3 donums irrigated by private well

Investment	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11
Cost of irrigation network											
Main and lateral pipes, bubblers	1,100										1,408
Cost of network installation	1,000					1,131					1,280
Cost of pond/tank	3,500										
Cost of pump	2,550										
Cost of investment	8,150					1,131					2,688
Cost of annual maintenance											
Pump	255	261	268	275	281	289	296	303	311	318	326
Pond/Tank	35	36	37	38	39	40	41	42	43	44	45
Farm network	165	169	173	178	182	187	191	196	201	206	211
Total annual cost	8,605	466	478	490	502	1,646	528	541	554	568	3,270
Cumulative cost	8,605	9,071	9,549	10,039	10,542	12,187	12,715	13,256	13,810	14,379	17,649
Annual benefits											
Reduction in electricity consumption SAR/year	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500
Option a (5 SAR/kg)	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000	9,000
Option b (3 SAR/kg)	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400
Annual response											
Reduction in electricity consumption SAR/year	–7,105	1,034	1,022	1,010	998	–146	972	959	946	932	–1,770
Option a (5 SAR/kg)	395	8,534	8,522	8,510	8,498	7,354	8,472	8,459	8,446	8,432	5,730
Option b (3 SAR/kg)	–3,205	4,934	4,922	4,910	4,898	3,754	4,872	4,859	4,846	4,832	2,130
Cumulative annual response											
Reduction in electricity consumption	–8,125	–7,091	–6,069	–5,059	–4,062	–4,207	–3,235	–2,276	–1,330	–399	–2,169
Option a (5 SAR/kg)	5,195	13,729	22,251	30,761	39,258	46,613	55,085	63,544	71,990	80,421	86,151
Option b (3 SAR/kg)	–325	4,609	9,531	14,441	19,338	23,093	27,965	32,824	37,670	42,501	44,631

Table 6
Calculation of the cost of irrigation water as an indicator of the farmer's ability to pay for water tariff

	Price/unit	Quantity/ton	Ton/ha	Total income (SAR)
Production	9.2	1.0	9.2	5,000
Production cost (SAR)				
Organic fertilizer (kg/ha)	8,000.0	869.6	0.3	260.9
Chemical fertilizer				
Urea (kg/ha)	100.0	10.9	1.6	17.4
DAB (kg/ha)	200.0	21.7	4.0	87.0
Pesticides (kg/ha)	7.0	0.8	120.0	91.3
Protection (palm insects, etc.)	2,500.0	271.7	217.4	217.4
Service (using machines)	10.0	1.1	140.0	152.2
Labour				
Cleaning (SAR)	2,000.0	217.4	217.4	217.4
Pollination (SAR)	1,000.0	108.7	108.7	108.7
Harvesting (SAR)	3,000.0	326.1	326.1	326.2
Crop containers (SAR)	2,200.0	239.1	239.1	239.1
Transport (SAR)	2,000.0	217.4	217.4	217.4
Zakat (SAR)	3,360.0	365.2	365.2	365.2
Land rent (SAR)	10,000.0	1,087.0	1,087.0	1,087.0
Total cost				3,387.0
Quantity of water used	19,000.0 m^3/ha	2,065.2 m^3/ton		
Assuming a 30% profit margin				
Total cost should not exceed 3,500 riyals (70% of 5,000)				
Total cost of producing a ton = 3,500–3,387 = 113 riyals				
Value of water should not exceed 0.06 riyals/m^3 (113/2,065.2 = 0.054 riyals/m^3)				

irrigation water from SIO, which is currently provided free of charge.

Given the importance of the irrigation water tariff in reducing water consumption in addition to its contribution to bearing part of the operating and maintenance costs and modernizing the infrastructure of irrigation projects, it is recommended to adopt and apply an appropriate tariff for irrigation water after conducting studies that take into account all the influencing factors such as water quality, type of crop and irrigation method as well as the socio-economic conditions of farmers.

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263 (2022) 87–97
July

Natural resources management in Southern Tunisia: sustainable exploitation and degradation issues of the oasis agro-systems

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Received 28 February 2022; Accepted 26 April 2022

ABSTRACT

In Southern Tunisia, as in the major part of agro-based countries under arid and semi-arid climate, the growing water dependent-economies, the increasing scarcity of freshwater resources amplified by the frequent dry climatic episodes and the continuous aquifer decompression define huge challenges for sustainable agricultural development. Multiple environmental issues have been observed related principally to natural resources degradation. Besides to the ecological value, the decreasing of agro-systems production has crucial social, economic and health repercussions. Thus, the present study aims the assessment of the sustainability of different natural resources in the oasis lands, the principal agro-system in southwestern Tunisia. The collected data from field investigations and farming surveys have been completed by analytical laboratory work and literature review. The obtained results indicate that groundwater resources are highly mineralized with doubtful to locally unsuitable quality to be used in irrigation according to the different calculated ionic indices (EC > 3,000 µs/cm; SAR from 6.7 to 9.5; TH between 48 and 69; PI from 46% to 58%) suggesting severe recommendations to be used especially for long term irrigation. The physico-chemical analyses of the soil samples highlight, furthermore, the progressive degradation of these agricultural lands characterized by high EC values above 3.6 and 5.8 mS/cm threatening the safe production of many crop yields. In addition to the difficult natural conditions, farming practices are the most influential factors governing the distribution of water quality related issues and soil hydrodynamic and physico-chemical proprieties. A comprehensive flexible adaptation management measures are required in the study area as the degradation issues have reached tolerance limits of different ecological systems and many irreversible alteration have been observed. These strategies should be evaluated as a shared task between the different parts relative to water consumption and agro-based activities

Keywords: Water quality; Irrigation; Oasis agro-systems; Soil degradation; Southern Tunisia

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

1. Introduction

Sustainable agricultural development relies on appropriate farming practices, a flexible adaptation to the unpredictable variability of weather conditions and an optimal exploitation of natural resources inhibiting overexploitation and degradation issues. However, on a large parts of the agro-based regions, and especially, in developing countries, the expansion of agricultural activities and the increasing dependency on agro-related products, and activities reveal great awareness about the decreasing productivity of these systems related principally to the progressive alteration of soil and water resources.

In Tunisia, the agriculture activities is the principal economic activity supporting social and economic pressure especially in the southern and southwestern provinces where the production of date palm, namely Deglet Nour variety, constitutes the principal source securing the livelihood of the local residents. In fact, in Tozeur and Kebili regions (SW Tunisia) the annual agricultural production of date is more than 260,000 tons representing more than 90% of the total agriculture production in the main oases of Southern Tunisia [1–3]. The total cultivated lands are about 54,000 ha of which 60% are devoted for the production of Deglet Nour variety [4] that has the highest value of quality all over the world according to Food and Agriculture Organization reports.

The growing agro-related investment, given the harsh climate conditions and the lack of perennial surface water (less than 15% of total surface water resources) [5], is challenged by quasi-perennial annual water deficit and frequent intra-seasonal dry periods [6]. Thus, the cultivated lands require constantly a volume of water to maintain humidity in the oasis system, which is permanently supplied by groundwater resources in the area represented by the multi-layered SASS (Système Aquifère du Sahara Septentrional) resources [7–9]. Indeed, the increasing expansion of these agro-systems has induced, in the last decades, a continuous loss of the hieratical regional landscape intensifying alteration of natural resources. The multiplication of the uncontrolled private cultivation network, associated with the lack of systematic monitoring of the physico-chemical proprieties of irrigation water and agricultural land and the inappropriate scheduling of the applied water volume delivered to the cultivated crops are, according to the previously published works (Carr [10]; Sperling et al. [11]; Al-Muaini et al. [12]; Alotaibi and Schoenau [13]; AL-Omran et al. [29]) the key factors altering the healthy ecological functioning of the region [9]. The cumulative impacts of the "mining behavior" on natural resources (soil and water) have resulted in a progressive reduction of loss-to-benefit ratio of agricultural development. These high risks of ecological-economic unbalance, threaten food security, social livelihood and poverty ratio in the study area. Thus, fruitful management measures should be applied that requires a baseline study assessing the evolution of these natural resources with respect to natural features and in response to the continuous exploitation. In this context, this paper focuses on the main challenges facing agriculture sustainability in SW Tunisia related to water quality issues. It evaluates, furthermore, the appropriateness of farming practices and the efficiency of the adopted management actions. It highlights, moreover, the required management plans according to farmer's knowledge, and scientific-based results.

2. Site description

2.1. Study area

The study area, in SW Tunisia (Fig. 1) characterized by hot arid climate [14]. It represents a restricted region between the sandy dunes of the Great Oriental Erg in the South and the contemporaneous salt environment of Chotts depressions (Gharsa, Djerid and Fedjej) in the North. Some geomorphic features that give a desert outfit. The region undergoes progressive degradation resulted from different factors of which the weather conditions play a leading role. In fact, the rainfall is scare and irregular with an average of about 50 mm [3,15] that may reach 100 mm during extreme events. The region is characterized by elevated temperature (exceeding 45°C and 50°C during the summer periods) and by high evapotranspiration of about 1,800–2,600 mm.

In contrast with these arid aspects, the oasis agro-systems maintain the ecological value of the area and contribute to national and regional economic dimension. Thus, the conservation of the fertility of agricultural lands is of paramount importance for local residents as well as for national agricultural and agro-industrial stakeholders. This conservation requires appropriate farming practices and efficient institutional, engineering and technical management and financial support. In the study area, since late 1990's, various management plans have been adopted at national and regional scale however different forms of degradation have been reported from scientific committee and local residents namely decreasing land productivity and water suitability for irrigation purposes. However, the old school farming techniques and the increasing of agricultural illicit farms constrains the fertility and the productivity of the cultivated land leading to a progressive abandonment of oasis (Dhaouadi et al. [16–18]; Besser et al. [19–23]). To evaluate the main purposes behind this loss of fertile lands, this paper tries, by a reviewof published data, institutional annual report, sampling campaigns and analytical laboratory work (soil, water, etc.), to outline the relevant challenges in the study area related to natural resources availability and exploitation to facilitate the analysis of the feasible options for improving resources exploitation and maintaining the sustainability of these agro-systems.

2.2. Methodology

This study has involved three major phases:

- *Literature review and data collection*: the review of previously published data is of crucial importance for assessing the evolution of the natural resources statement in the study area. Different types of data have been analyzed (published data and internal unpublished annual and monthly reports. This review is completed by a field survey and discussion with local farmers. This analysis is required for a participatory shared management

Fig. 1. Localization of the study area (Dhaouadi et al. [24]).

task. The adoption of the commonly known indigenous knowledge of the population in rehabilitation programs facilitates social acceptance and make the procedure easier and faster. The field investigation was carried out to collect soil and water samples from different agricultural lands and deep water wells across the study area.

- *Samples analysis and laboratory work*: the collected samples have been carefully packed, and transported to the laboratory.
- *Data treatment and interpretation*: the obtained data from field investigation, literature review and laboratory analyses were treated using different software namely ArcGis 10.4; Excel 2016; diagram 5.6; Aquachem, etc. The aggregation of this multi-sources data for accurate proofreading of the management strategies.

3. Ecological impacts of agricultural activities/Land degradation evaluation

The effects of man-induced activities are closely linked to the viability water-agricultural system (water availability at sufficient quantity and valuable quality for agricultural practices) related principally to the vicious cycle between land degradation and poverty. In this study area, since early 2000's, a national awareness has been emerged about the potential risks of loss of soil fertility due to some farming practices and irrigation techniques. Thus, various types of individual and public engagement have been adopted. Despite their partial efficiency, reliable statistical data were available and non-systematic monitoring was performed in an active way to bring out synthetic results. However, since the revolution of 2011, uncontrolled expansion of agricultural land coupled with unavailable data for private owners and illegal agricultural projects amplified management issues as no reliable database for these new created zones was made and especially, the creation of these oasis systems are without any administrative or scientific-based relevance. All these factors coupled with natural conditions lead to continuous loss of soil fertile of an average 1.25 ha/y according to Besser et al. [19]. The spatial distribution of these issues across the study area shows an important heterogeneity ratio that may be explained by several factors (enablers and constraints) emerging from field observations and investigations namely the inequality in access to soil fertility replenishment technologies [3,8]. This variability defines social conflicts related to the progressively observed divergence between producers able to invest in soil fertility replenishment and the major part of producers who are unable or unwilling to make such investments. They are therefore unable to sustain the quality of their farm land and enter a vicious cycle of decreasing productivity and incomes (unsustainable natural resources security) [12].

In addition to rehabilitation and amendment techniques, irrigation scheduling and water distribution calendar may deeply influence the loss of soil fertility and decreasing land productivity or at least reducing the quality of the cultivated crops. In fact, irrigation water security is one of the major constraints to livelihood improvements and socio-economic development in such agro-based region. The irregular distribution of irrigation water and the inappropriate agriculture practices define costly system of providing water through conventional irrigation scheme. The frequent breakdown and rupture of distribution inhibit safe plant growth via modification of physiological crop proprieties and (or) soil pores sealing via important evapotranspiration of interstitial water leading to frequent gypsum crusts.

3.1. Issues challenging the sustainability of agriculture in the study area

Despite the multiple efforts made for securing safe permanent production of oasis agro-systems in southwestern Tunisia where the date palm cultivation is the major socio-economic activity, numerous environmental issues are observed and their cumulative impacts seem to reach progressively unrecoverable ecological level of pollution and mismanagement [9,26]. These key strategic changes appear in different ways as a result of complex picture of interrelations of natural cycles and socio-economic factors [3]. Some of these problems are discussed in the following sections.

3.1.1. Released water quantity

The abstraction from deep confined and semi-confined groundwater aquifers, the Continental Intercalaire (CI) and the complex terminal (CT), to meet agricultural supplies has reached higher levels of exploitation that are often superfluous [7–9,27]. The annual abstraction rate has exceeded 250% in Kebili region where it was of 90% for Tozeur region defining a quasi-permanent situation of overexploitation of deep low renewable groundwater resources. This situation threats the sustainability of these resources barely rain fed under present day conditions. Besides to the availability of these resources for long term use, the ineffective use of the released volume is manifested by the important ratio of efficient irrigation to loss to evaporation and drainage runoff since the applied quantity exceeds the real water requirements of the irrigated crops [2,3]. In fact, the water quantity distributed for date palm is more than 20,000–30,000 m^3/ha [28]. However, according to a number of scientific-based estimation in different countries, the real need defining effective consumption for safe date palm production range between 12,000 to 18,000 m^3/ha [29]. This surplus has undoubtedly, various environmental impacts. It induces progressively water logging problems due to the platitude to the oasis land the proximity of Chotts depressions with regard to the insufficient drainage. The high evaporation rate enhances salt precipitation and accumulation in the cultivated land surface which leads increasingly to soil salinization and reduction of water infiltration by progressive formation of gypsum crusts [7–9,27].

3.1.2. Distribution of water for irrigation is variable and irregular

The spatial and the temporal variation of irrigation scheduling have adversely impacted on the production and on the growth of the agricultural products. In fact, if the date palm is adapted to long drought conditions, the variation on the other cultivated types such short periods of water stress can have a serious effect on crop yields if occurring during water sensitive development stages [30].

Furthermore, with regard to the irregular distribution that may exceed three months of drought and the tower-irrigation method, the cumulative irrigation duration is about continuous 15–40 h. Many ecological impacts are induced by this mismanagement. In fact, besides to water lost to evaporation, and water logging issues, the increase infiltration in the sandy loam soils reaches the new formed oasis aquifer [2,3,27]. The increase of piezometric levels in these shallow aquifers, generally characterized by poor water quality (TDS between 8 to 19 g/L) has adverse impacts on soil structure and soil fertility via a development of frequent gypsum crusts in the deep soil layers and reducing soil aeration and water infiltration. The data from soil analysis indicate that soil salinities are between 3.6–5.9 mS/cm in different investigated oasis (Fig. 2). These issues are amplified by the uncontrolled expansion of agricultural lands for private owners.

Additionally, the agricultural land is progressively mined on soil fertility, soil structure destroyed by compaction and combustion of organic material and topsoil through soil erosion. The above points-out the necessity to address water constraints together with soil fertility constraints. It also suggests that the different water management technologies which lower the risks for crop failure can function as

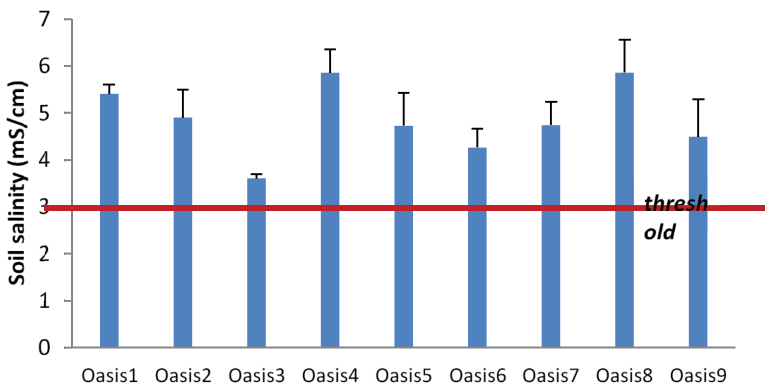

Fig. 2. Soil salinities.

an entry point for successful efforts of increasing investments in land productivity [30].

3.1.3. Leaching issues

The irregular distribution of irrigation water coupled with the old school irrigation technique and the insufficient drainage system result in continuous leaching of the oasis lands. These high mineralized waters are enriched by the trace elements concentrations relative to the used pesticides and fertilizers (triple superphosphate $Ca(H_2PO_4)_2$, potassium sulphate (SOP) and ammonium nitrate NH_4NO_3, etc).

Unfortunately, until present there is no reliable evaluation of the runoff volume released to the environment which may be used as a supplementary alternative to overcome water shortage periods. Indeed, the continuous decrease of conventional freshwater resources highlights the importance of the unconventional water resources in supporting agriculture water needs and in maintaining safe production of oasis system [31].

Additionally to the lost volume, the released runoff without preliminary treatment adversely impacts the ecological system of the region (Fig. 3). On the basis of the obtained data from drainage water analysis, the salinity of these waters varies from 12.5 to 26.8 mS/cm. This pollution has incurable effects because the salinity concentrations of soil around the drainage stations are very high (30–43 mS/cm).

3.1.4. Old school irrigation methods

The used irrigation techniques in these oases are traditional and they are based on flood/ basin irrigation via tower system. This technique has some negatives impacts on soil productivity and on resistance of the cultivated types [3,27]. It induces, a continuous water lost to evaporation and hinges on discharge of the excess of irrigation water on the Sebkhas, Chotts and (or) in other infertile lands. It creates as well new formed oasis aquifer just few meters below the surface inducing changes on soil structure and reducing water infiltration and soil aeration (Fig. 4). It enhances additionally the leaching of the different pollutants at the oasis surface leading, often to diffuse contamination of the groundwater resources fed by runoff of irrigation water [2]. This type of contamination as it is represented by multiple sources and large dispersion across the agricultural lands, seems to be difficult to manage. Thus, remediation efforts are limited to periodic physic-chemical characterization of these resources.

Fig. 3. Runoff release in the study area.

Fig. 4. Irrigation system and irrigation network in some agricultural land in the study area.

3.1.5. Irrigation water quality

The agricultural lands from oasis and greenhouses are irrigated principally with waters from deep confined and semi-confined CI and CT aquifers embodying low renewable resources under present-day conditions. The analytical data indicate that the salinity of these waters has exceeded 4–5 g/L reaching locally 20 g/L at Djemna area. These waters are classified as high mineralized saline to brackish waters with important permanent hardness ratio. These waters are unsuitable to be used in agricultural according to the commonly used quality indices namely EC > 3,000 μs/cm; SAR from 6.7 to 9.5; TH between 48 and 69; PI from 46 to 58% (Fig. 5).The continuous use of these waters induce, undoubtedly, growing issues of soil salinization, alkalization and permeability loss. However, the quasi-permanent water deficit and the frequent water shortage periods give less concern to query on the quality of water used for irrigation. In spite of the numerous works previously published indicating that these waters are unfit for agricultural activities and that the continuous irrigation with these resources of the poorly evolved soils and GYSOILS of southwestern Tunisia induce a progressive abandonment of the cultivated lands, management efforts and rehabilitation measures have partially been adopted without any effective evaluation at farm scale. Indeed, for such dynamic issues, policy responses to address water quality issues in agriculture need to be part of a policy package that encompasses water issues, soil fertility, land productivity, climate adaptation, social livelihood, economic value and a range of policy instruments institutional reforms and broader community engagement (Fig. 5).

3.1.6. Limited conventional water resources/Challenges for sustainable aquifer exploitation

In the agro-based regions of highly arid environment such as Southern Tunisia, the extreme water stress is amplified by the limited potential of the low renewable groundwater resources. Increasing exploitation of these reservoirs for decades have resulted in a huge reduction of the available resources. In fact, despite the huge stock of SASS aquifers covering more than one Million of km^2, the recent recharge of this multi-layered aquifer system reaches barley the 2.5% of the total volume of aquifers. The distribution of fresh water flows is, furthermore, irregular and unequal [27,29] while the exploitation exceeds 100% and reaches locally 200% in some localities of Kebili region. Correspondingly, the number of the pumping wells has increased from 2000 to 14000 water wells in less than five years of which more than 80% are private wells without any reliable assessment neither of their spatial implementation nor the abstracted quantity. In consequence, the water table in these aquifers has fallen by an annual average of 100 m in the last decades [8,26]. Aquifer decompression and local land subsidence issues were recorded by the local residents and scientific committee. Indeed, the "mining behavior" without resource-use balance consideration threatens the sustainability of these waters. The lack of governmental and institutional supervision network is the principal cause leading to this alarming situation of continuous reduction of agricultural productivity of these cultivated lands [3,26,29].

3.1.7. Uncontrolled use of energy

Besides to the loss of fresh water resources, the study area is characterized by uncontrolled use of different types of energy. The first is related to the heat loss from deep confined hot water of the CI aquifer. This aquifer has an average mean of temperature of 50°C that exceeds in some wells 85°C. However, the use of the traditional atmospheric cooling system permits the exploitation of these waters at appropriate temperature without conservation or recovery of the lost energy to the atmosphere (Fig. 6).

The second type is linked to the uncontrolled use of solar and wind energy for water pumping. Unfortunately, this project is one of the most important ecological scheme

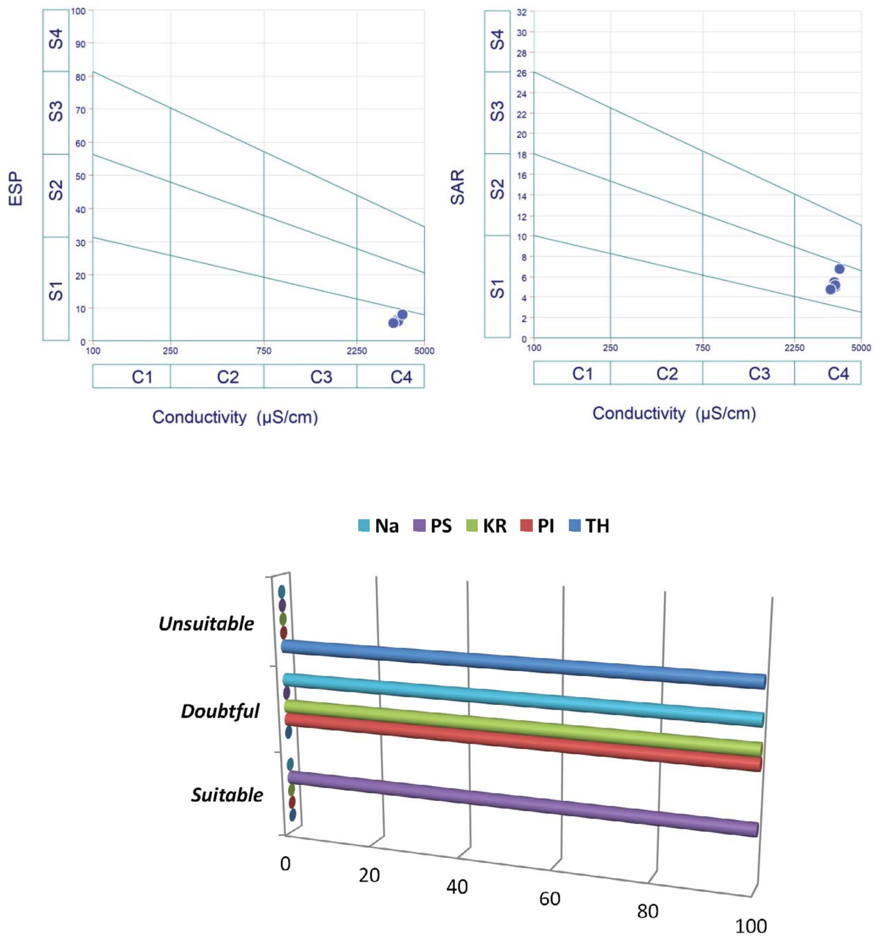

Fig. 5. Water characteristics.

Fig. 6. Use of solar energy in the study area.

in North Africa however the mismanagement and the lack of institutional and governmental supervision and systematic control has resulted in inappropriate use of these renewable energy to lead to irreversible environmental impacts of natural resources exploitation. In the quasi-total areas of the project, the instrumental implementation are relative to local residents and private owners associated with water well used for irrigation. Thus, the free use of these resources lead to uncontrolled abstraction from water wells largely above the recommended requirements of the cultivated crops. This situation is commonly observed in the study area leading to both continuous water loss and increasing soil infertility [3].

4. Discussion

In the study area, the ecological-economic unbalance has conducted to various environmental issues that are reaching the maximum tolerance limits of the quasi total ecological systems. Indeed, the natural conditions and the physiological features of the region constrain the safe development of agriculture activities and sustainable freshwater resources. At the same time, management issues have a great part on the degradation that has been reached. In fact, according to field investigation and the analysis of the collected data human, the lack of monitoring, vulgarization, information diffusion, institutional support, and especially governmental supervision and legislative control are the main reasons on behalf all these issues. The important number of illegal water wells (twice or three times the public legal wells), the expansion of private oasis lands, the open access to different alternatives of energy without control raises the inequality accessibility between different farmers, creating unbalanced competition on the one hand and reducing the optimal long term exploitation potential of natural resources. The review of rehabilitation measures indicates that there is quite a set of scattered development efforts on water management, but seemingly little research on the viability of the systems within the context of framing system. The Baselienn study for management has to be conducted on farm addressing different scales and address the system related issues above with regard to the equitable, efficient and sustainable use of different environment resources (Table 1 and Figs. 7 and 8).

Among the principal factors and measures of primary importance to be adopted in the study area, water quality and water productivity or water use efficiency. Thus, to get a fruitful natural resources management for sustainable development, a careful understanding of the principal key factors governing these major parameters is required as giving by the following points;

- Water quality used for irrigation should never be an isolated effort within a farming system. It should instead rather be seen as a catalyst to improvement a modernization of production systems. Indeed, to control the main entry point is essential for reducing risks for abandonment of oasis, to evaluate the uncertain degree of potential investment for unconventional water resources and more updated irrigation technique. The management of these resources requires increased emphasis on site specific manageable techniques precisely adapted to each location. Accepted approach towards the formulation of policies for development and natural resources management for mitigating land use and its impacts on water and soil resources. These policies must necessity be species and site-location specific.
- The opportunities of increasing efficiency of water use in agriculture, especially for date palm with special focus on the reuse of the available non-conventional resources for more reasonable management of groundwater resources using more effective irrigation system such as micro-irrigation which still limited under the palm trees in Tunisian oases. It requires, in addition, field experiences for the evaluation of the impacts of water quality from unconventional resources on the development of date palm and on crop yield (nutritive value).

The above points-out the necessity to address water constraints together with soil fertility constraints. The different water management technologies lowering the risks for crop failure can be used as an entry point for successful efforts of increasing investments in land productivity. This requires a rehabilitation of managing policies on real adapted responses to access the best available science-based evidence and operate in an open and transparent manner to regain confidence of local farmers which is of paramount importance to create a framework for a coherent and a valuable work

Table 1
Water and soil resources characterization in the study area

Ecological factors		Water resources		
	Overexploitation	Water quality	Pollution	Surface water
Oasis of Kebili	6.73% exploitation of shallow aquifer	TDS > 19 g/L	Petroleum contamination	Non-perennial
	164.96% exploitation of CT aquifer	>4 g/L	Nitrate contamination	
	218.38% exploitation of CI aquifer	>5 g/L		
Oasis of Tozeur	85.65% exploitation of shallow aquifer	>8 g/L	Nitrate contamination	Non-perennial
	87.30% exploitation of CT aquifer	>4 g/L	Fluoride contamination	
Ecological factors	Soil resources			
	Soil salinization		Soil alkalization	
Oasis of Kebili	Observed in the most parts of the region		High risks in the oasis lands	
	Increasing risks in other localities		Severe restriction for the greenhouses	
Oasis of Tozeur	Observed in El Hamma region		High risks in the cultivated lands	
	Increasing risks in the most parts of the region			

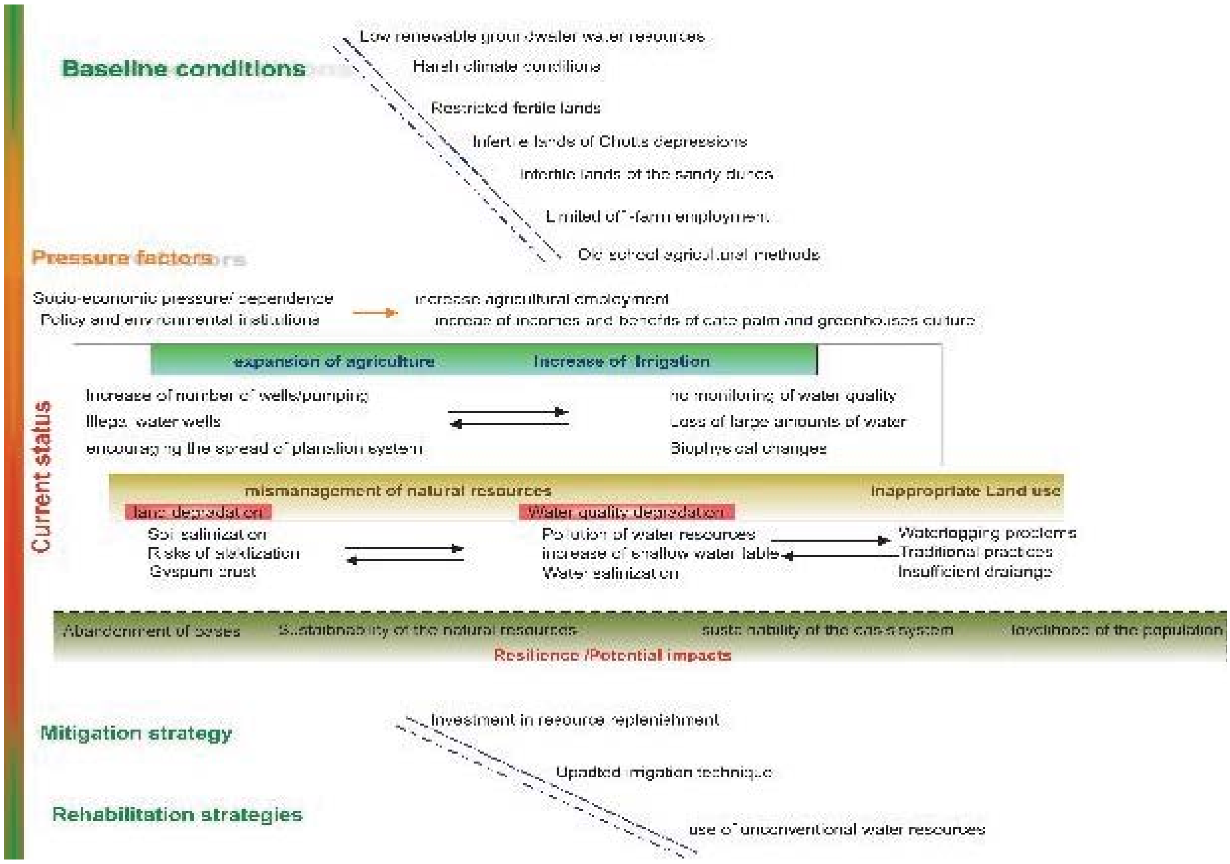

Fig. 7. Evolution of environmental features of the study area.

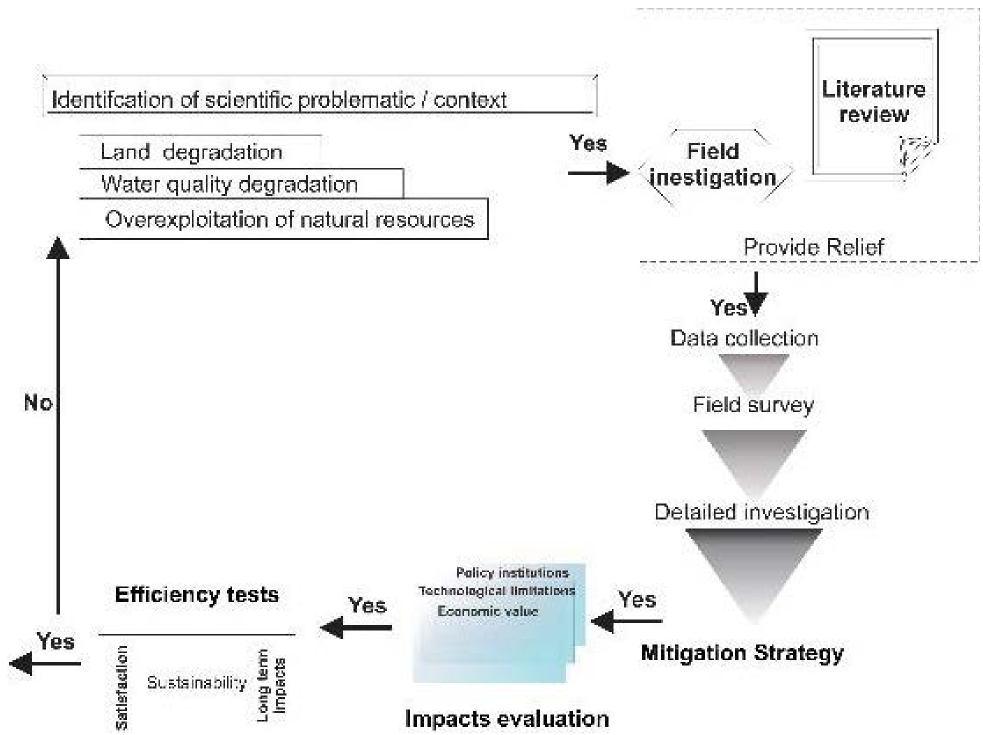

Fig. 8. Rehabilitation process.

of sharing responsibilities. Thus, to grantee the sustainability of integrated land and water management with respect to water multi-functionality, it is imperative to understand the linkage between economic production models, ecologic-environmental management, social framework for strategic management and decision-making model. The agricultural land is progressively mined on soil fertility, soil structure destroyed by compaction and combustion of organic material and topsoil through soil erosion.

5. Conclusion

The review of the different environmental features of Southern Tunisia highlights that the economic security and the ecological conservation are continuously threatened by high risks of oasis abandonment and loss of productivity. Given the difficulty to seek other means of living, the rehabilitation of these sites is recommended and the evaluation of different alternatives for securing land productivity is required.

The various decision made by the different partners have raised natural resources allocation without efficient participatory strategies. Thus, the observed issues should be overcome via controlled individual behavior of local farmers. The adoption of their indigenous knowledge is essential to have more fruitful promising rehabilitation strategies. Indeed, their participation in management process will reconstruct the links between different decision makers and give more reliable information diffusion, the key factor for participative remediation approach.

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Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2022.28210

263 (2022) 98–107
July

Risks associated with treated wastewater in greenhouse cooling system

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Received 28 February 2022; Accepted 3 May 2022

ABSTRACT

The hot climate in the Gulf region is forcing many farmers to use controlled environment agriculture by using evaporative coolers inside greenhouses. These coolers are consuming around 60% of the water used for the greenhouse. Replacing groundwater with treated wastewater will have a good impact in saving freshwater for other different applications. The problem is that treated wastewater is rich of nutrients that can support algae growth, block the cooling pads, and reduce the efficiency of the cooling system. Moreover, it is unclear if the water can be a source of any airborne diseases that could affect human health and crop quality. Unfortunately, few or no data is available related to the applications of treated wastewater in greenhouse cooling system. Therefore, the aim of this study is to evaluate the possibility of using treated wastewater in greenhouse cooling system and asses any potential risk to the environment that could affect human health and crop quality and safety. The greenhouse cooling system was connected to tertiary treated wastewater and the system was left to run for two months. Algae growth was observed in cooling pads. Samples from cooling pads, air, and water were taken for microbial analysis. The same sampling was made from other greenhouse running with freshwater. Using treated wastewater in cooling system did not show any negative impacts in plant growth. However, rapid growth of algae in cooling pad of treated wastewater was noticed compared to the groundwater cooling system. This could be minimized by covering cooling pads with shade net, or adding some anti-algae growth ($CaSO_4$) in cooling tanks, or using plastic cooling pads, or cleaning cooling pads from time to time. Moreover, more types of bacteria were found in treated wastewater cooling system but were not harmful for human and plants. Almost similar microbes were found in the air and water running in all greenhouses. Therefore, the study recommends the use of treated wastewater in the greenhouse cooling system with application of antifouling compounds or using plastic cooling pads that can be easily cleaned.

Keywords: Treated wastewater; Non-conventional water resources; Cooling pad; Algae growth; Gulf region

1. Introduction

Oman is categorized as an arid to semiarid country with a temperature exceeding 45°C in summer and an average annual rainfall of 100 mm. Therefore, Oman's climate is not highly suitable for open-field cultivation, especially in summer time that is almost 8 months of the year [1]. In addition, around 52% of the agricultural lands became unsuitable due to salt accumulation that came from saline irrigation as a result of seawater intrusion, which mainly happened in Batinah Region [2]. To overcome the problem of hot conditions, Controlled Environment Agriculture (CEA) was adopted, to improve the quality and quantity of crops through controlled environment in greenhouses [3]. Tabook and Al-Ismaili [4] reported that greenhouse production was 12 times more than open field grown crops in Oman. The number of greenhouses in Oman had increased from 782 in 2001 to 2491 greenhouses in 2008. The common cultivated crops in Oman greenhouses are cucumber (around 90%) and then tomatoes (about 5%–9%).

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

1944-3994/1944-3986

Greenhouses in arid and semi-arid areas utilize auxiliary fans and evaporative coolers to cool down the greenhouse and reach optimum temperature for plant growth. The evaporative coolers are made of honey comb cardboard pads that should be wetted with any source of water. When the hot and dry air from outside the greenhouse passes through the coolers, the water absorbs some of the heat from the air and therefore it evaporates and consequently it cools down (the temperature decreases). Then, the air inside the greenhouse becomes humid and cool and the ambient air temperature inside the greenhouse decreases [5]. The problem is that too much water is used for the cooling purposes, in some cases, it can be double the amount of water used to irrigate the crops inside the greenhouse. A study was done in United Arab Emirates (UAE) to estimate the consumed water and energy in a tomato greenhouse. They found that the total amount of water consumed during one season was 837,662 L in the cooling pad and 615,052 L in irrigation. This means that 58% of water was used only for cooling the greenhouse and the rest was for crop needs [6]. Another study was done in Sultanate of Oman and reported that 2/3 or 67% of water used in greenhouse is used only for cooling the temperature of the greenhouse using cooling pad system [3]. Furthermore, a study was conducted to compare water and energy consumptions of three greenhouses located in different places in Oman and the amount of water consumed for cooling purposes during cucumber production season were 11.88, 15.48, 14.4 m^3 and for the same three greenhouses, irrigation waters were 9, 9, 20 m^3, which means 57%, 63% and 42% of total water were used in cooling pad, respectively [4].

In Oman, "Haya Water" is a governmental company that is responsible for building, operating, and managing wastewater projects in most Governorates in Oman. Treated wastewater (TWW) is a by-product of sewage treatment process with total flow of 149,940 m^3/d, treated effluent of 77,503 m^3/d; where 52% of this treated wastewater is utilized [7]. It is a good source of good and clean water that can support agricultural lands with input of different nutrients. It helps in improving the fertility of different soils, increasing the yield of different crops and reduce usage of groundwater (GW) resources. Reuse of treated wastewater will result in the conservation of higher quality water that can be used for different purposes other than irrigation. However, the safe disposal of the treated wastewater is considered as a major concern for Haya Water and relevant authorities. Furthermore, reusing of treated wastewater produced from the wastewater treatment plants in sustainable, economic and environmental friendly ways are very important for a country like Oman. Therefore, there is a need to implement a comparative study on the potential reuse options for the treated wastewater produced by Haya Water.

Combining the need for large volumes of water in the greenhouses' cooling system with surplus of treated wastewater can be beneficial, taking into account the expected environmental and health impacts and how this treated wastewater will affect the human health and quality of crops grown inside the greenhouse. Therefore, the aim of this study was to evaluate the possibility of using treated wastewater in greenhouse cooling system and asses any potential risk to the environment that could affect human health and crop safety and quality.

2. Methodology

Two small greenhouses (3 m × 6 m) were constructed at Agricultural Experiment Station, College of Agricultural and Marine Sciences, Sultan Qaboos University (SQU), Oman (Fig. 1). One of them was connected with treated wastewater for irrigation and cooling systems. The other one was connected with groundwater, as a control, for comparison.

2.1. Experimental design

The experiment was conducted in two greenhouses for a total area of 18 m^2, were used to grow three species of roses, Rosa (Omani flower, Syrian flower and Pakistani

Fig. 1. Greenhouses connected with treated wastewater and groundwater.

flower) and lettuce in soil. Four replicates from each type of the flowers and twelve lettuces were planted in each greenhouse. Each greenhouse was running completely either by GW or TWW. Plant growth parameters were monitored and measured. Moreover, samples were taken from the air and cooling system of both greenhouses.

2.2. Plant growth

Treated wastewater is rich of different elements. Therefore, as expected, production of flowers was higher for the three different flower types in the greenhouse irrigated with treated wastewater compared to groundwater. The average number of flowers produced by Omani flower, Pakistani flower and Syrian flower in GW were 2, 1 and 2, respectively, while the average number of flowers produced by Omani flower, Pakistani flower and Syrian flower in TWW were 5, 2 and 5, respectively (Fig. 2). The result indicated that there was no significant difference in number of flowers between GW and TWW (P-value = 0.0578) and between the flowers species in both treatments (P-value = 0.234) (Table 1). The same observation was noticed with lettuce growth. The average weight of lettuce in treatment 1 and 2 were 277 and 308.5 g, respectively (Fig. 3). Whereas, there was no significant difference in weight of lettuce at different treatments ($P(T <= t)$ two-tail = 0.524) (Table 2).

Table 1
ANOVA test of number of flower produced by Omani flower, Pakistani flower and Syrian flower in GW and TWW

Source of variation	SS	df	MS	F	P-value	F_{crit}
Sample	28.03	1	28.03	3.97	0.058	4.26
Columns	21.8	2	10.9	1.54	0.234	3.40
Interaction	6.87	2	3.43	0.49	0.621	3.40
Within	169.6	24	7.07			
Total	226.3	29				

Water quality is one of the most important parameters affecting plant growth. The aim of the study was to determine the impact of treated wastewater in greenhouses cooling system and irrigation of different plants. Plants growth was better in TWW than GW. According to Irénikatché Akponikpè et al. [8], treated wastewater is more useful for plants irrigation due to the presence of different nutrients especially NH_4^+ and NO_3^-, which are considered as major ions needed for plant growth. According to Faizan et al. [9] and Urbano et al. [10] treated wastewater is more profitable for plants growth than groundwater.

Average flower yield of Omani roses, Pakistani roses and Syrian roses were higher in TWW (5, 2 and 5, respectively) compared to GW. However, in GW, the number of Omani roses, Pakistani roses and Syrian rose flowers were (2, 1 and 2, respectively). Similar result was found by Marinho et al. [11]. They found, the highest mean production of commercial rose stems was observed in rose that was irrigated by treated wastewater and the production increased by 31.8%. Whereas Nirit et al. [12], found no significant different in rosebushes productivity irrigated by treated wastewater and groundwater. According to Feigin et al. [13], treated wastewater contains organic and ammoniacal forms which contribute to the increase of flower yield. In addition, the average fresh weight of lettuce increased in TWW (308.5 g) due to the improvement in soil fertility.

2.3. Algae growth in greenhouse cooling system

Treated wastewater is rich with nutrients that could support algae growth and block the cooling system. Therefore, algae growth was studied and monitored in all greenhouses and it was observed that treated wastewater enhanced algae growth which could minimize the life-time of cooling pads (Fig. 4).

Algae samples were taken from different locations of both cooling pads. All samples were studied under microscope (Inverted microscope) (Fig. 5). Same type

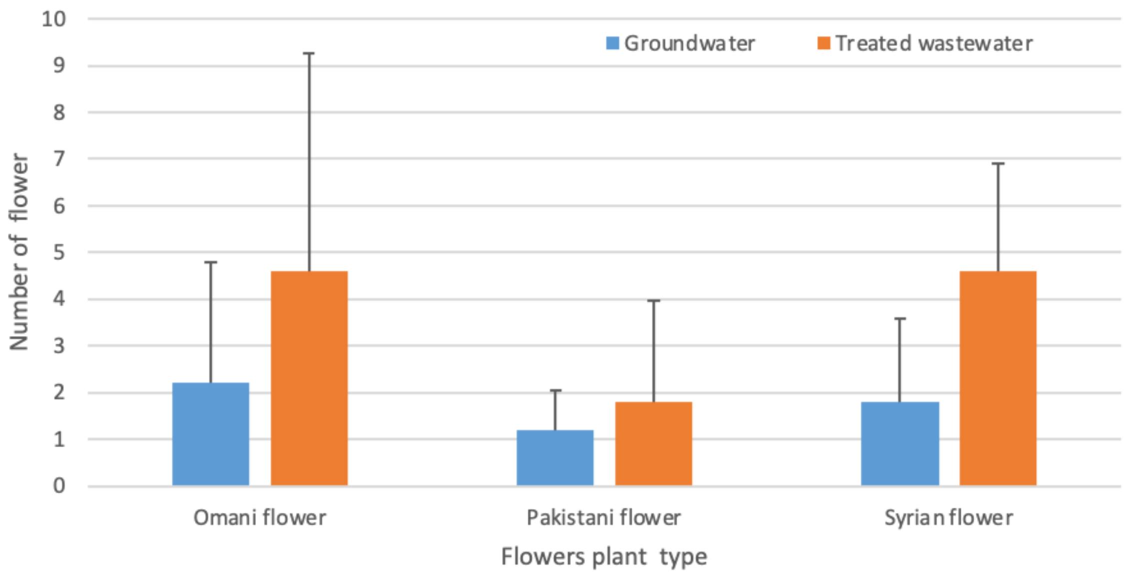

Fig. 2. Average number of flowers produced from each type of water (GW and TWW).

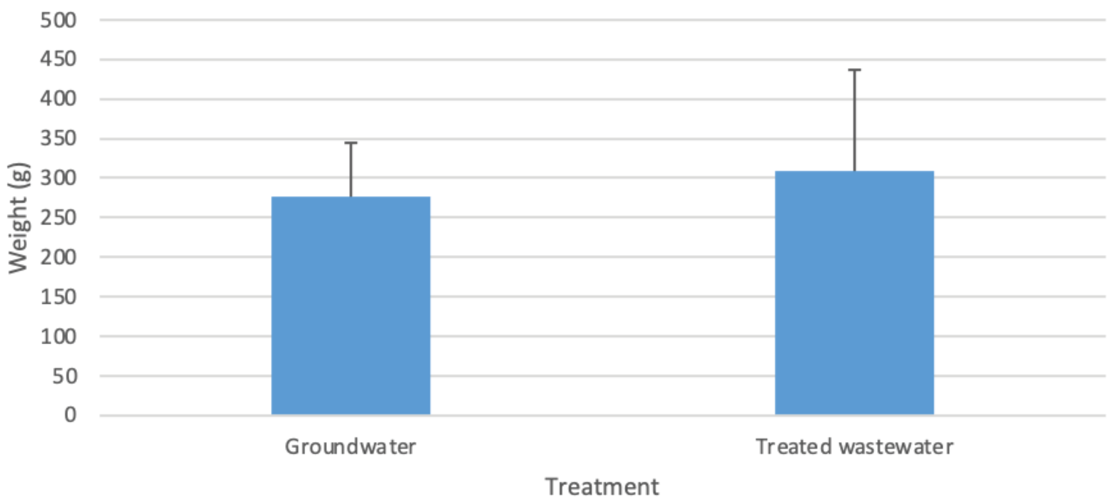

Fig. 3. Average weight of lettuce irrigated with GW and TWW.

Table 2
t-Test of lettuce weight in GW and TWW

	Groundwater greenhouse (GW)	Treated wastewater greenhouse (TWW)
Mean	277	308.5
Variance	5,101.11	18,111.39
Observations	10	10
Hypothesized mean difference	0	
df	14	
t-Stat	–0.653	
$P(T <= t)$ one-tail	0.262	
t-Critical one-tail	1.761	
$P(T <= t)$ two-tail	0.524	
t-Critical two-tail	2.14	

of algae (*Tetrastrum* sp.) was found in both greenhouses cooling systems (groundwater and treated wastewater). *Tetrastrum* sp. was reported as the major algae presented in both cooling systems. However, it had higher growth in treated wastewater cooling pads. According to Palmer et al. [14], *Tetrastrum* sp. is a type of algae and its presence is one of the most common issues of using treated wastewater, which is characterized as freshwater algae with four cell and flat surrounding a hole in the middle. Cells are shaped like triangle, ovoid or heart, and mostly found with one to four spines and usually with or without a phytoplankton or pyrenoid of lakes [14].

Algae growth can be minimized by different applications (options) such as:

2.3.1. Option 1: light effect

Algae from five random sampling points (around 1.5 cm × 1 cm) of greenhouse cooling system were collected for both systems (treated wastewater and groundwater) and mixed with 10 mL of cooling system water. Distilled water was used as a control. Light samples were incubated at 27°C and 12 h light while, dark samples were covered with aluminum foil. Every day during 4 d, total amount of Chlorophyll a was measured. Indicator of Chlorophyll a absorbance at wavelengths of 647 nm was measured using spectrophotometer.

The results indicate that Chlorophyll a of cooling pads in TWW and GW were different. However, Chlorophyll a was higher in TWW than GW in the presence and absence of light. Light increased algal growth due to enhancement of photosynthesis process (Fig. 6).

Based on this finding, all greenhouses were covered with green net so algae growth could be minimized as one step to reduce the sunlight and the biofouling problem (Fig. 7).

2.3.2. Option 2: addition of different chemicals ($CuSO_4$, $ZnSO_4$, chitosan and clorox) to the cooling tanks as antifouling compounds for controlling algal growth

Algae from five random sampling points (around 1.5 cm × 1 cm) of greenhouse cooling system were collected for both systems (treated wastewater and groundwater) and mixed with 10 mL of cooling system water. Samples were centrifuged at 5,000 rpm for 5 min. 100 µm of algae was mixed separately with four different chemicals at four different concentrations (copper sulfate and zinc sulfate 0.1 g/100 mL, 0.2 g/100 mL, 0.3 g/100 mL and 0.4 g/100 mL, chitosan 0.1 mg/100 mL, 0.2 mg/100 mL, 0.3 g/100 mL and 0.4 g/100 mL and clorox 100 µL, 200 µL, 300 µL and 400 µL). All samples were incubated in well plats at 27°C in light condition for 12 h (Fig. 8).

Lethal concentration LC50 (50% of the tested population) provides a data for the percentage of the organisms that were killed by different concentrations of each toxicant after specified lengths of exposure [15].

It was found that chitosan has more antifouling activity with less dose compared to other antifouling compounds (Figs. 9–10). According to Guo et al. [16], chitosan is a natural product from the shell of shellfish which is widely used as antifungal due to non-toxic properties.

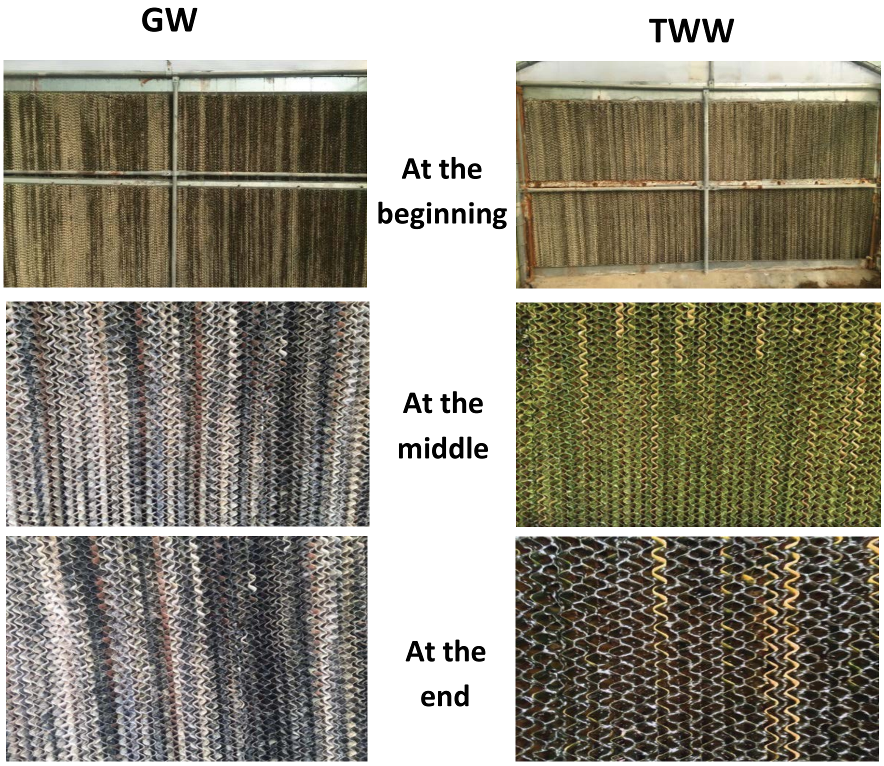

Fig. 4. Growth of algae in cooling system in both treatments during the experiment.

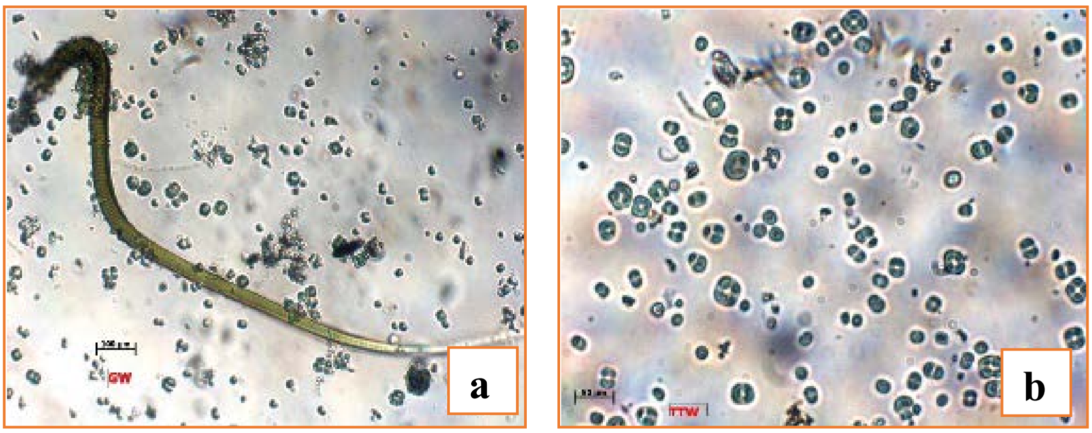

Fig. 5. *Tetrastrum* sp. algae in greenhouses cooling pad in GW and TWW: (a) groundwater algae and (b) treated wastewater algae.

Based on the lab findings, all four chemicals (copper sulfate, zinc sulfate, chitosan and clorox) were tested under field condition using greenhouse cooling system. However, chitosan is a natural product but it is costly and need some technical knowledge in application. Therefore, it will be difficult for the farmer to apply it. Clorox had a short term effect and later algae was growing faster than control treatments. Therefore, copper sulfate was the best option under field conditions. It was added in concentration of 0.31 mg/L in treated wastewater tank. Every week, algae from five sampling points (around 1.5 cm × 1 cm) from greenhouse cooling system were collected in all treatments (T1: cardboard cooling system running with treated wastewater, T2: cardboard cooling system running with groundwater and T3: plastic cooling system running with treated wastewater). For measuring the Chlorophyll a, samples were left in a filter paper of 0.74 µm mesh size and then 90% acetone was adding to all samples and kept for overnight. After 24 h, the extractions were purified using centrifuge (5,000 rpm) for 5 min. Chlorophyll a absorbance at wavelengths of 750, 664, 647 and 630 nm was measured using spectrophotometer. Total amount of Chlorophyll a was calculated using trichromatic equation: Chlorophyll a = $(11.85 \times A664) - (1.54 \times A647) - (0.08 \times A630)$ (Fig. 11) [17]. Moreover, air temperature was measured weekly inside all three greenhouses.

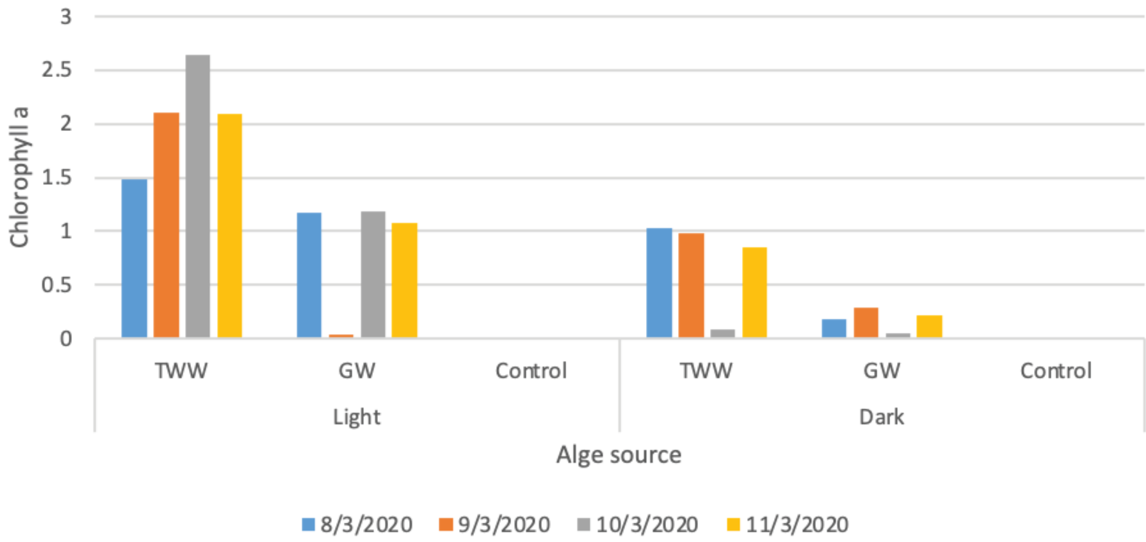

Fig. 6. Average Chlorophyll a of cooling pads in treated wastewater (TWW) and groundwater (GW) in light and dark conditions.

Fig. 7. Greenhouses covered with green shade.

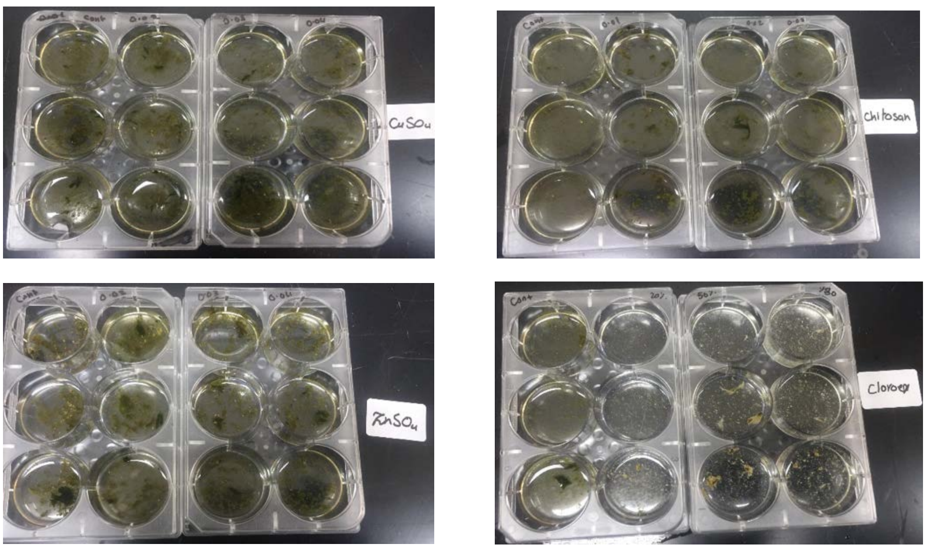

Fig. 8. Lab experiment for algae growth with different chemicals.

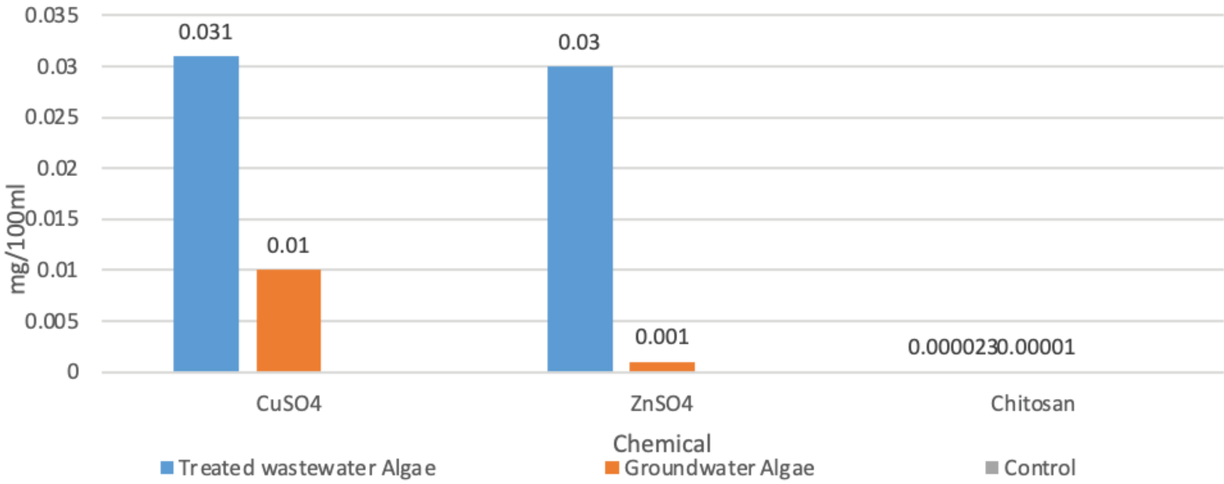

Fig. 9. Lethal concentration (LC50) of $CuSO_4$, $ZnSO_4$ and chitosan in algae growth of treated wastewater and groundwater cooling pads.

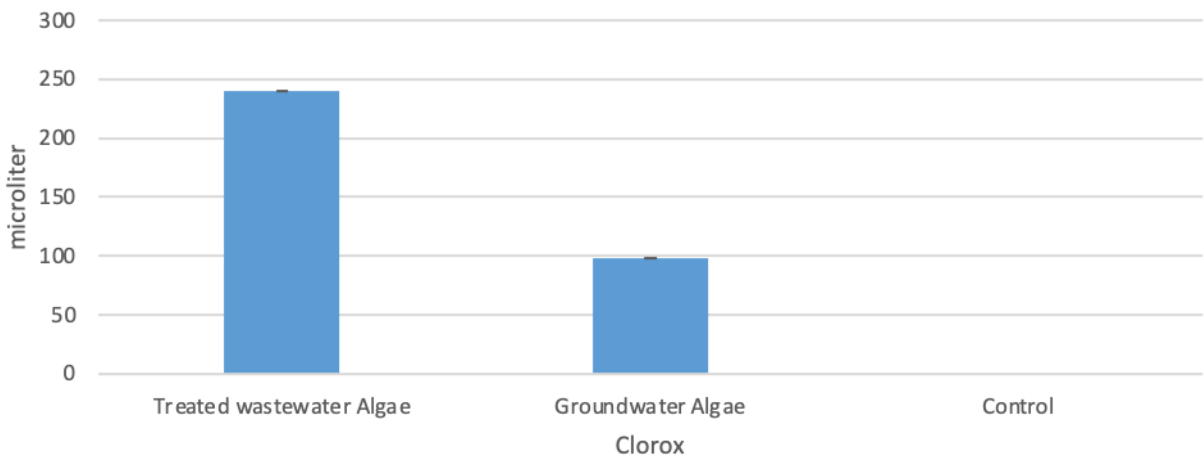

Fig. 10. Lethal concentration (LC50) of clorox in algae growth of treated wastewater and groundwater cooling pads.

It was found that algae growth decreased in cooling system that was running by treated wastewater with copper sulfate compared to the cooling system that was running by groundwater and plastic cooling system. Plastic cooling system had the highest values of Chlorophyll a which could be due to the shape of cooling pads (Fig. 12). According to Lauer [18], the optimal dose for killing *Tetrastrum* sp. algae is 0.02 mg/L of $CuSO_4$. However, we found that 0.31 mg/L of $CuSO_4$ is the optimal concentration for killing 50% of *Tetrastrum* sp. and that is because the difference in the experiment condition and period.

2.3.3. Option 3: cleaning effect

The easier method to overcome the algae growth was cleaning the cooling pads using brush and pressurized water. Cleaning process for the area of 3 m × 2 m in each system took around 10 min. Algae samples were taken before and after cleaning.

After cleaning, the growth of algae decreased by 90.93% in groundwater cooling system cardboard, 90.63% in treated wastewater cooling system cardboard and 98.47% in plastic cooling system (Fig. 13).

Treated wastewater is rich with nutrients that could support algae growth and cause biofouling [19]. Biofouling is undesirable deposition and growth of microorganisms on wetted surfaces and is considered an abiotic form of biofouling [20]. Biofouling blocks the cooling pads and affects the efficiency of the greenhouse cooling system and reduce the lifetime and efficiency of cardboard using in the cooling system. Moreover, it is unclear if the water could be a source of any diseases by spreading harmful microbes inside the greenhouse, affecting human health and contaminating crops. Although the wastewater treatment systems are designed to minimize the concentration of contaminants, including pathogens, many wastewater treatment plants release such effluents without chlorination [21]. One example is *Escherichia coli* which has been commonly used in aquatic environments as a faecal pollution predictor and most strains of it considered as a non-pathogenic while, some strains may be pathogenic [21]. As well, *Pseudomonas mendocina*, *Enterobacter kobei* and *Pseudomonas alcaligenes*

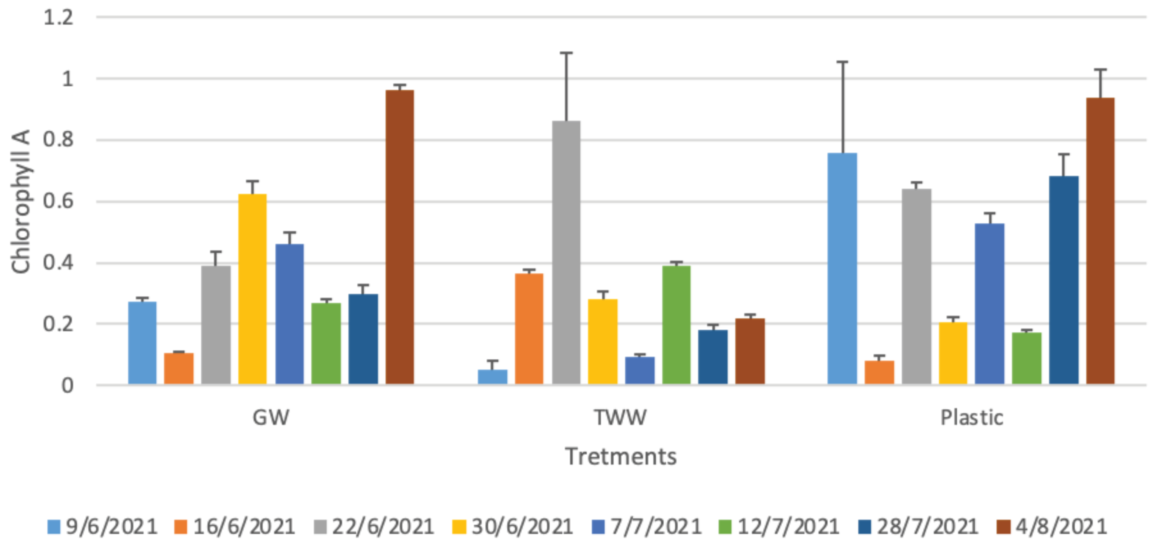

Fig. 11. Chlorophyll a level in cooling system pads in GW cooling system, TWW cooling system and plastic cooling system (Experiment 2).

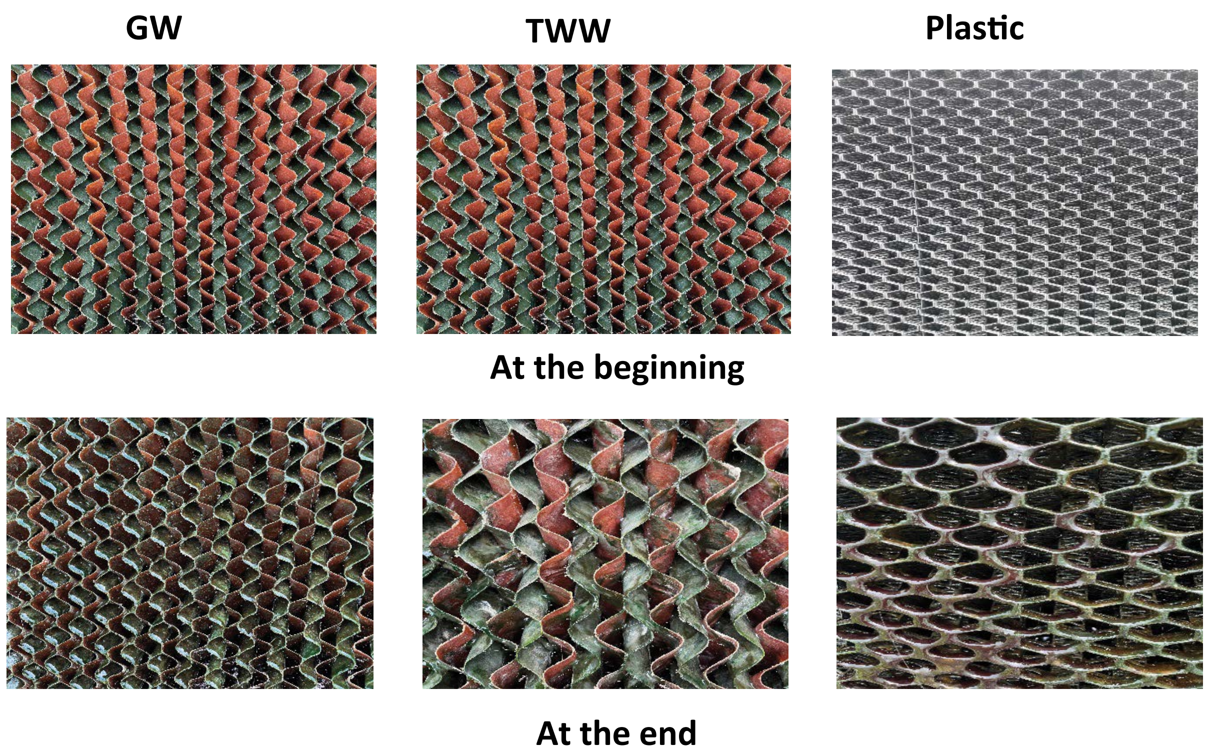

Fig. 12. Differences in algae growth with time in each greenhouse cooling systems.

are soil and water bacteria and considered as pathogenic bacteria [22,23].

2.4. Micro-organisms in water, air and cooling system

Tetrastrum sp. is a type of algae and it is one of the most common issue related to treated wastewater which is characterized as freshwater algae with four cell and flat surrounding a hole in the middle. Cells are shaped like triangle, ovoid or heart, mostly found with one to four spines and with or without a phytoplankton or pyrenoid of lakes [14]. Algae growth increased in the second month due to the start of summer season and then decreased due to the addition of $ZnSO_4$ to the cooling system tank of treated wastewater. According to Lauer [18], the optimal dose for killing *Tetrastrum* sp. algae is 0.02 mg/L of $CuSO_4$. However, we found that 0.31 mg/L of $CuSO_4$ is the optimal concentration for killing 50% of *Tetrastrum* sp. In addition, algae growth

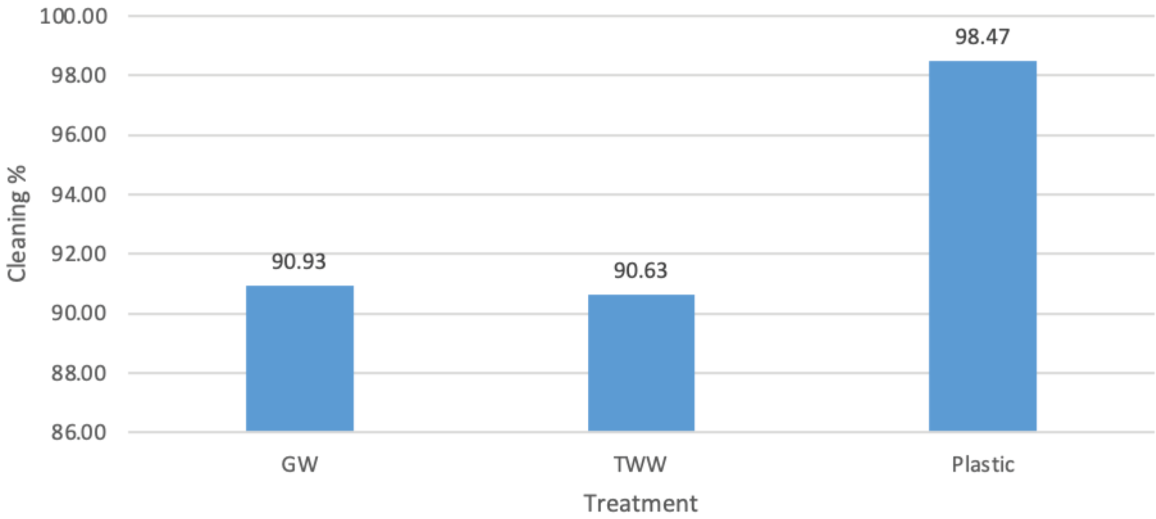

Fig. 13. Cleaning efficiency of the cooling systems in removing the algae.

was increased in the present of light compared to the dark conditions so more photosynthesis and higher growth.

Regarding microbial contaminants, treated wastewater from tap and cooling system had more bacterial growth. *Pseudomonas mendocina*, *Stenotrophomonas maltophilia*, *Microbacterium liquefaciens*, *Pseudomonas stutzeri*, *Pseudomonas oleovorans* and *Stenotrophomonas nitritireducens* are different bacteria found in treated wastewater. Whereas, *Pseudomonas mendocina*, *Aeromonas hydrophila*, *Bacillus infantis*, *Aeromonas jandaei*, *Enterobacter asburiae*, *Enterobacter kobei*, *Enterobacter ludwigii* and *Pseudomonas alcaligenes* were found in cooling system using treated wastewater. According to Al-Jassim et al. [24], treated wastewater include more pathogenic bacteria and species of bacteria were replaced by others due to changing bacteria environment. According to Wehr et al. [22] and Brooke [23], *Stenotrophomonas maltophilia*, *Pseudomonas stutzeri*, *Pseudomonas oleovorans*, *Stenotrophomonas nitritireducens*, *Pseudomonas mendocina*, *Enterobacter kobei* and *Pseudomonas alcaligenes* are soil and water bacteria and are considered as a pathogenic bacterium. According to Al-Jassim et al. [24], microbial risk will decrease when plants are irrigated for 20 min per irrigation and four times per week. In addition, reducing storage time in the tank will reduce the growth of pathogenic microbes. For air contamination, bacteria growth was higher within a distance of 6 m from cooling pad, which means it was close to the cooling fans and may enter the greenhouse through the fans.

3. Conclusion

This study indicates that treated wastewater is more productive for agricultural production compared to groundwater. Omani rose, Pakistan roes, Syrian roses and lettuce grew better in treated wastewater due to the presence of some nutrients needed for plant growth. *Tetrastrum* sp. was the algae species found in cooling system of both greenhouses. Using treated wastewater in cooling system did not show any negative impacts in plant growth. However, rapid growth of algae in cooling pad of treated wastewater greenhouse was noticed compared to the groundwater cooling system. Moreover, more types of bacteria were found in treated wastewater cooling system but there transfer to human and plants were limited due to no direct contact between them. Therefore, the study recommends the use of treated wastewater in the cooling system with some application of antifouling compounds. Further studies are suggested to find out the impacts of antifouling compounds to the surrounding environments.

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Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2022.28211

263 (2022) 108–108
July

Role of efficient management of non-conventional and brackish water resources in sustaining agricultural production and achieving food security in the United Arab Emirates

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ABSTRACT

Water scarcity is the main limiting factor to food production in the United Arab Emirates. The country is located in an arid to hyper-arid zone with limited renewable natural freshwater resources due to limited rainfall. Other considerable limiting factors include low agricultural water productivity, salinization of farmed areas, and low soil suitability for agricultural production.

The agricultural sector is the highest water consumer, with more than 56% of total water use, while its contribution to the GDP is less than 1%. The total agricultural area is about 1.1 million dunums. Only 51% of the agricultural area is cultivated with crops, including (1) fruit trees of more than 400,000 dunums (mainly date palm trees); (2) field crops and fodders of about 109,000 dunums; (3) vegetables of about 66,000 dunums. Although most farmers are using modern irrigation systems in their farmed areas, mainly drip irrigation, the agricultural water productivity is still low. Many farmers are not aware of the practical irrigation scheduling based on the actual crop water needs according to the growing stages of the crops and therefore over-irrigate their crops.

Groundwater is the main source of agricultural water in farming areas where the annual water use exceeds 2,500 million m^3. Usable groundwater is mostly non-renewable and brackish, with different levels of salinity ranging from low salinity of 2 ds/m to more than 15 ds/m. Groundwater quality degradation and declining groundwater levels are well-known problems in many farmed areas.

The soil is generally poor and lacks necessary natural soil elements and nutrients. Only about 13% of the UAE's existing farmed areas are located on suitable soil for agricultural production. The arable land is degrading in many locations mainly in the cultivated areas due to salinization.

In parallel, the demand for food is steadily growing. Ninety percent of food in the UAE is imported as the local agricultural production cannot meet the current domestic demand, which is anticipated to increase substantially. However, UAE's economic and political stability and its geographic location with high accessibility to trade centers and markets have created a stable environment for food security.

This paper presents the optimal use of alternative and natural water resources through improving water use efficiency. It entails the best practices to use water based on crop water needs, most profitable crops, best match of water and soil, and when crops to be grown, hence reducing the use of water resources significantly and boosting agricultural water productivity.

The paper will also highlight the importance of using these alternative water resources, particularly treated sewage effluent (TSE), in controlled-environment agriculture (CEA) and the expected benefits to farmers such as: saving freshwater resources, reducing water consumption, reducing crop loss, improving water productivity, and using less land. TSE is a reliable water supply source, particularly in water scarcity countries. The seasonal TSE supply can help bridge the seasonal gap of freshwater supply and reduce the use of fertilizers as it is rich with nutrients that are needed for plant growth. As such, the use of TSE in CEA could potentially increase agricultural productivity and economic return for farmers while reducing environmental pollution.

Keywords: Water resources; Agriculture; Sustainability

Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2022.28212

263 (2022) 109–115
July

Impact of deficit irrigation strategies on water use and productivity of vegetable crops in a semi-arid context of Tunisia

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Received 28 February 2022; Accepted 3 May 2022

ABSTRACT

Irrigated agriculture in arid and semi-arid environments is characterized by acute imbalance between rainfall and evapotranspiration and tough competition for water. It is against this backdrop that water use efficiency is becoming a must. This study is targeted to evaluate the effect of deficit irrigation on water requirements, yield and water productivity of potato and tomato crops under average and very high climatic conditions of 2016 and 2017 respectively. The case study is the Cherfech irrigation district located in the northern of Tunisia. For this purposes, the FAO/CROPWAT irrigation scheduling and simulation model was used to identify appropriate deficit irrigation strategies for improving water conservation with acceptable impacts on yields. Deficit irrigation strategies were evaluated through parameters of irrigation, relative crop evapotranspiration, relative yield loss as well as water productivity and economic water productivity. Results indicate that deficit irrigation is practicable under average water demand for both potato and tomato crops. For tomato, adoption of deficit irrigation is less feasible particularly under very high demand. For a relative yield losses threshold of 25%, results show that for potato, optimal season irrigation could be reduced by 43.3% and 31.6%, respectively for average and very high climatic conditions. For tomato crop, optimal irrigation requirements could be reduced by 33.3% for average demand and 31% for very high water demand. Regarding the water use indexes, results show that water conservation due to deficit irrigation strategies improves water productivity under the average water demand more than the very high demand. This improvement was more noticeable for potato than tomato. Furthermore, economic water productivity is more affected by the difference in potato and tomato prices for average (2016) and very high (2017) water demand conditions.

Keywords: Deficit irrigation; Irrigation simulations; Relative yield loss; Water productivity

1. Introduction

Tunisia is ranked among the countries most deprived of water in the Mediterranean basin with a water quota of less than 500 m^3/cap/y. Water demand of agriculture is constantly increasing due to the intensification of irrigation and the associated increase of irrigated acreages. Irrigation accounts for near 80% of the total water demand for an irrigated area of 435,000 ha [1]. Although the irrigated agriculture represents only about 8% of the cropped area, it nevertheless contributes to 30%–35% of the total agricultural production [2]. Among irrigated crops, potato and tomato are considered as strategic crops and are widely cultivated in various regions of the country. In 2018, the Tunisian

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

potato production accounts for 465,000 tons over a cultivated area of near 24,300 ha. For tomato crop, the tomato production was about 1.187 million of tones for a harvested area of 21,200 ha [3]. Many studies have shown that potato is sensitive to water stress; hence, water shortages may result in reduction in tuber yield and quality [4–6]. Tomato can tolerate moderate drought once good canopy cover is achieved. On the other hand, mild to moderate water stress early in the season, if lasting for many days, can result in a markedly smaller canopy, and hence, less biomass production resulting from reduced radiation capture [7]. In arid and semi-arid areas, as the most of Tunisia, where water is the main limiting factor for plant growth, optimization of water use efficiency is becoming a must for increasing agricultural productivity, improving food security and ensuring sustainability water-resources [8–10]. The increasing pressure of different sectors on water resources (agriculture, industry, tourism, water drinking, ecological needs) augurs a water stress, which should evolve crescendo. Several studies reported that the climatic change projections in Mediterranean region would be critical for the cropping systems considering the increase in the temperature and the significant rainfall decrease [11,12]. Given the recurrence of drought periods in recent years, Tunisian irrigation managers have even adopted severe restriction measures for water supply to cope with water scarcity. Indeed, in 2017 the volumes intended for irrigation were reduced by 20%–30% of the water requirement of the irrigated areas [13]. To cope with scarce water supplies, adoption of deficit irrigation stands as an important tool to reduce irrigation water use and potentially improve water productivity of many field crop [14,15].

The aim of this study was to assess the effect of deficit irrigation on crop water requirements, yield and water productivity under different water demand conditions. The FAO CROPWAT irrigation scheduling and simulation model is used to evaluate the effect of deficit irrigation on crop yield and irrigation requirements. The objective was also to identify appropriate deficit irrigation strategies that allow water conservation with acceptable impact on yields and thus ensuring sustainability of irrigation systems in the semi-arid conditions of the Medjerda lower valley of Tunisia.

2. Materials and methods

2.1. Case study

The case study for this research was Cherfech irrigation district, Medjerda lower valley, near Ariana, northeast of Tunisia (37°N, 10.5°E, elevation of 328). The climate is semi-arid Mediterranean with yearly average precipitation of 443 mm. The season distribution of rainfall is typical of a Mediterranean pattern, with a minima in summer, the period of maximum crop water requirements. The average reference evapotranspiration (ET_0) as computed by the Penman-Montheith method [16] is 1,105 mm. The water deficit (P-ET_0) extends from March to October with a peak in July, which corresponds to the water requirement peak month.

According to the USDA soil classification, the soil texture at the study area can be classified as silty clay loam (34.8% clay, 57.6% loam, 7.6% sand). The total available water is 160 mm/m (water content at field capacity and wilting point are 0.42 and 0.26, respectively). The average electrical conductivity of the irrigation water is 2.6 dS m^{-1}.

2.2. Crop water-yield simulations

Assessment of crop evapotranspiration and irrigation requirements under standard and deficit conditions were performed using FAO CROPWAT 8.0 irrigation scheduling and simulation model (http://www.fao.org/land-water/databases-and-software/cropwat/en/). CROPWAT is a decision support tool developed by the Land and Water Development Division of FAO for the calculation of crop water requirements and irrigation requirements based on soil, climate and crop data [16]. The soil is managed as a unique reservoir, refilled by irrigation water and precipitation and depleted by drainage and crop evapotranspiration. The model can be used to determine the optimum irrigation schedules and to evaluate the effect of deficit irrigation on water use and crop yield.

In this work, the irrigation simulations were performed for potato and tomato crops based on meteorological, agronomic, and soil data of the case study area in 2016 and 2017. Crop coefficients K_c during the crop season determined using the KCISA program [17] are presented in Table 1. Data on the

Table 1
Potato and tomato crop parameters for Cherfech region

		Crop development stages			
		Initial	Development	Mid-season	Final-season
Potato	Planting date: 10/02				
	Period length (days)	30	35	50	16
	K_c (2016)	0.91	0.91–1.12	1.12	0.4
	K_c (2017)	0.65	0.65–1.15	1.15	0.45
Tomato	Planting date (01/04)				
	Period length (days)	30	35	50	27
	K_c (2016)	0.83	0.83–1.15	1.15	0.68
	K_c (2017)	0.45	0.45–1.15	1.15	0.60

Table 2
Available soil water at planting for potato and tomato crops

	2016		2017	
	Potato	Tomato	Potato	Tomato
Initial soil moisture depletion (% TAW)	50	85	50	95
Initial available soil moisture (mm/m)	80	24	80	8

available soil water at planting used by CROPWAT for simulations purposes are shown in Table 2.

2.3. Deficit irrigation strategies

In this study, the CROPWAT model was used to simulate the crop response to irrigation management under different water availability conditions. For this purpose, deficit irrigation strategies corresponding to different levels of water restriction were adopted in order to assess the effect of deficit irrigation on water use and crop yield. This approach is based on the water restriction measures adopted by local irrigation managers in order to cope with water scarcity. CROPWAT model allows different timing options related to when irrigation is to be applied. Thereby, the deficit irrigation strategies were selected based on the irrigation timing options that allow for a stress level for agronomic reasons as described in Allen et al. [16]. When irrigation is applied before the depletion of the readily available moisture, the maximum yield is achieved. Conversely, the deficit irrigation strategies were selected by adopting soil moisture depletion levels that induce water stress and thus yield reduction. In CROPWAT, evaluation of the deficit irrigations strategies were performed using the yield – water stress function [18]:

$$\left(1-\frac{Y_a}{Y_m}\right)=K_y\left(1-\frac{\mathrm{ET}_a}{\mathrm{ET}_m}\right) \quad (1)$$

where Y_a is the actual yield, Y_m is the maximum yield, ET_a is the actual season crop evapotranspiration, and ET_m is the maximum season crop evapotranspiration and K_y is the yield response factor representing the effect of reduction in crop evapotranspiration on yield. ET_m, is determined through the product of the reference crop evapotranspiration (ET_0) times the crop coefficient (K_c) [16]:

$$\mathrm{ET}_m = K_c\mathrm{ET}_0 \quad (2)$$

Using the above original FAO water production function, deficit irrigation strategies were evaluated trough parameters of irrigation (mm), relative crop evapotranspiration $\mathrm{ET}_a/\mathrm{ET}_m$ (%), and relative yield loss, computed as RYL = $(1 - Y_a/Y_m)$ expressed in %. Previously, optimum irrigation alternative to meet the maximum yield (exercised when readily available moisture RAM is depleted) was determined for both tomato and potato crops.

2.4. Water productivity

Two water productivity indexes [19] were computed:

Water productivity WP (kg/m^3) defined as the ratio of actual crop yield achieved Y_a (kg/ha) to gross irrigation water use IWU (m^3/ha).

$$\mathrm{WP} = \frac{Y_a}{\mathrm{IWU}} \quad (3)$$

When replacing the numerator of Eq. (3) above by the monetary value of the actual yield (TND, Tunisian Dinar), the economic water productivity EWP (TND/m^3) can be defined by:

$$\mathrm{EWP} = \frac{\mathrm{Value}\left(Y_a\right)}{\mathrm{IWU}} \quad (4)$$

EWP was computed based on the prices of potato in the local market for 2016 and 2017.

3. Results and discussion

3.1. Climate analysis: rainfall and reference evapotranspiration

Statistical analysis of the 30 years' time series (1986–2015) shows that yearly average rainfall in the study area is 443 mm while maximum and minimum values are 703 and 282 mm respectively. Monthly rainfall and reference evapotranspiration (ET_0, estimated by Penman–Monteith method [16] for 2016 and 2017 vs. average year are presented in Figs. 1 and 2 respectively. In 2016, annual rainfall was 439 mm and ET_0 amounts 1,083 mm/y. The water deficit (P-ET_0) extends from February until October with a peak in July (Fig. 1). While Fig. 2 shows that 2017 was drier with annual rainfall of 283 mm and ET_0 of 1481 mm/y. In addition, the water deficit (P-ET_0) was spread over the whole year 2017 except for February including maximum values on July, August and September (Fig. 2)

Regarding the evaporative demand estimated by reference evapotranspiration ET_0, Fig. 1 indicates that water demand for 2016 was very close for the average year. Moreover, Fig. 2 exhibits the very high water demand conditions of 2017 compared to the average year particularly during the period lasting from July until the end of the year.

With respect to season rainfall, results show that 2016 was very close to the average year for potato growing season (February – June) and relatively deficient for tomato growing season (April – August) with a rainfall shortage of about 30 % compared to the average year. In addition, 2017 was marked by rainfall deficit of 60% with respect to the average year for both potato and tomato crop season.

3.2. Crop response to deficit irrigation strategies

In a first step, CROPWAT was used to identify the net irrigation requirements for optimal irrigation schedules. Results showed that potato maximum yield is achieved with net season irrigation of 300 mm under average climatic conditions of 2016 and 380 mm under very high climatic conditions of 2017. For tomato, maximum yield is reached

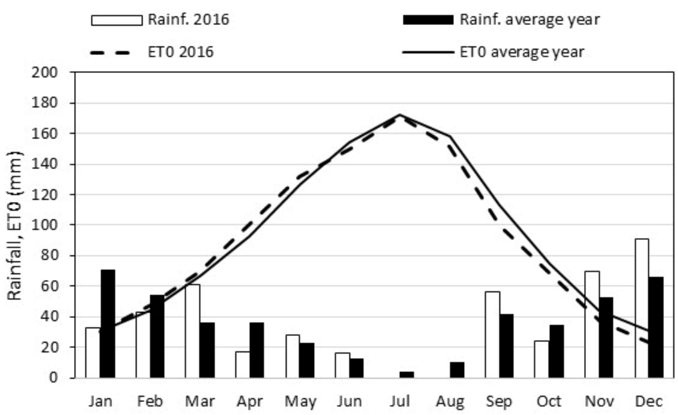

Fig. 1. Monthly rainfall and reference evapotranspiration in 2016 for Cherfech region.

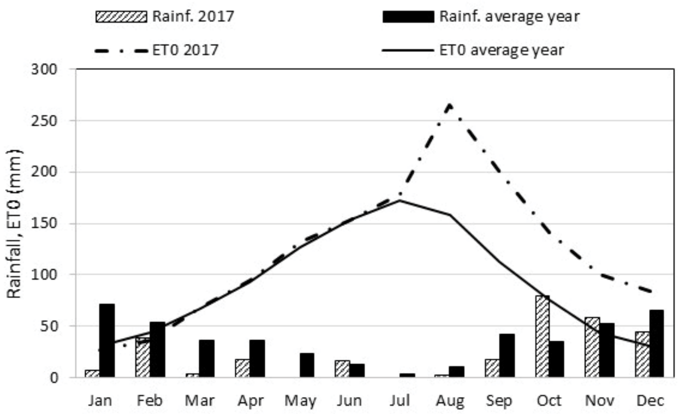

Fig. 2. Monthly rainfall and reference evapotranspiration in 2017 for Cherfech region.

applying 600 mm in 2016 and 720 mm in 2017. The deficit irrigation evaluations performed for the climatic conditions of 2016 and 2017 are displayed in Fig. 3 for potato crop and Fig. 4 for tomato crop.

Results indicate that under average water demand of 2016, reducing potato season irrigation by 46.7% (from 300 to 160 mm) induces a RYL of 26.7%. For the very high water demand of 2017, RYL would be 40.3% when potato irrigation requirements are reduced by 47.4% (from 380 to 200 mm). Furthermore, for average demand, results showed that small reduction in potato season irrigation from 300 to 260 mm would induce a RYL of 6%, easily acceptable by farmers. Conversely, for the very high demand, reducing irrigation to 260 mm would generate a much higher RYL (24.7%). These results indicates that adopting deficit irrigation is more practical for average water demand of 2016. While for very high water demand of 2017, only low to moderate water shortage are tolerated. Under limited water availability, and when considering a production target such that the RYL remains below a 25% threshold, results showed that potato optimal irrigation could be reduced by 43.3% and 31.6% respectively for average and very high climatic conditions (Fig. 3).

For tomato crop, results indicate that under average demand conditions of 2016, decreasing season irrigation from 600 to 400 mm generates a RLY of 25%. Under very high demand of 2017, it is worth emphasizing that applying 400 mm would result in a RYL of 40% making adoption of deficit irrigation more difficult particularly under water scarcity conditions. For a RYL threshold of 25%, results showed that tomato optimal water requirement could be reduced by 33.3% and 31%, respectively under average and very high water demands (Fig. 4).

This difference in crop response to deficit irrigation can be explained mainly by the season rainfall. In fact, for average water demand of 2016, precipitation beneficially reduces potato irrigation requirements, which are much greater under very high water demand of 2017. Consequently, when water is limited, adoption of deficit irrigation with acceptable RYL will be more feasible under average demand conditions than under very high conditions. Whereas for tomato, which is a summer crop, rainfall faintly contributes to crop evapotranspiration. For both average and very high demands, irrigation decrease generates a reduction in crop evapotranspiration and crop yield making it more difficult to adopt deficit irrigation mainly for very high demand of 2017. These results bolster those [20] who stated that in the semi-arid central of Tunisia, adoption of deficit irrigation is feasible for wheat, potato and tomato crops under average water demand.

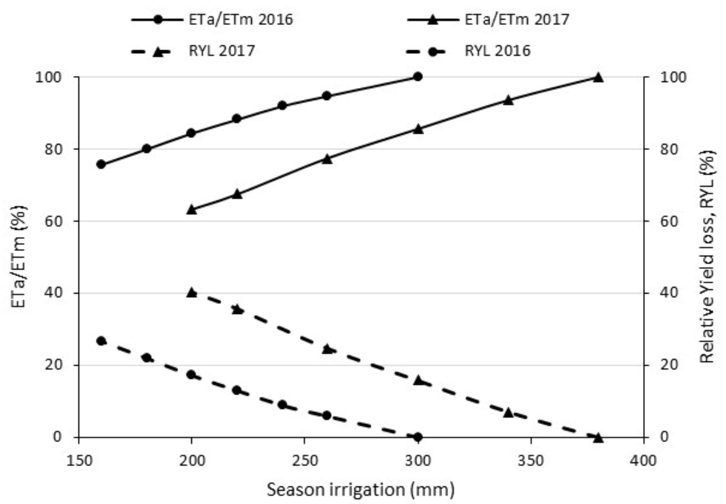

Fig. 3. Potato response to deficit irrigation in Cherfech for average (2016) and very high (2017) water demand conditions.

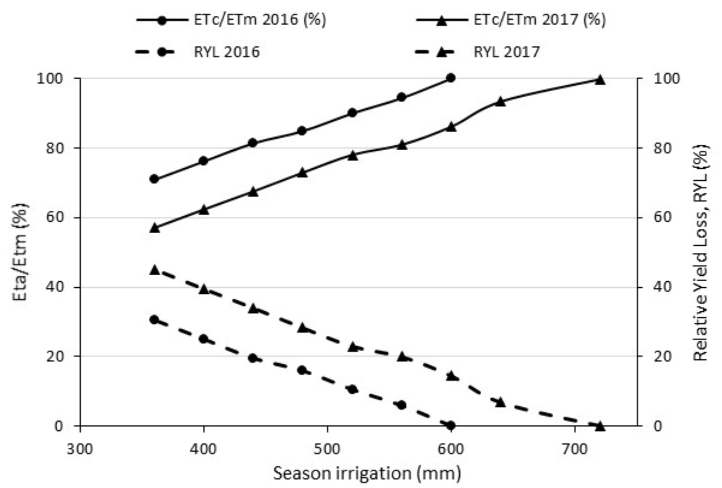

Fig. 4. Tomato response to deficit irrigation in Cherfech for average (2016) and very high (2017) water demand conditions.

Zairi et al. [20] indicated that deficit irrigation is not feasible for potato and tomato crops under high and very high climatic conditions; the alternative is to reduce the cultivated area.

3.3. Water productivity

For the water use indexes, results showed that water savings due to deficit irrigation strategies improve water productivity under average water demand more than very high demand (Figs. 5 and 6). This improvement was more noticeable for potato than tomato crop. Indeed, for average demand, a water saving of 150 mm increases by 30% potato water productivity. This result upholds the finding showing that reducing irrigation increases water productivity of potato in the Cherfech region [21]. However, for tomato the increase in water productivity would be 12.5% for a water saving of 250 mm. This result confirms that deficit irrigation is a difficult option for tomato crop.

For a RYL set at 25% threshold, results indicate that potato water productivity decreases by 34.9% under the very high demand of 2017 in comparison with average demand of 2016. This decrease was less discernible for the economic water productivity (21.3%) due to the increase of potato prices at local market in 2017. For tomato, although water productivity decreased by 20.7% from average to very high water demand, economic water productivity have even increased by 35.8% due to the substantial increase in tomato prices in 2017.

4. Conclusion

Beyond the regional implications of this work, the presented methodology represents a contribution to the use of a crop simulation model and water productivity

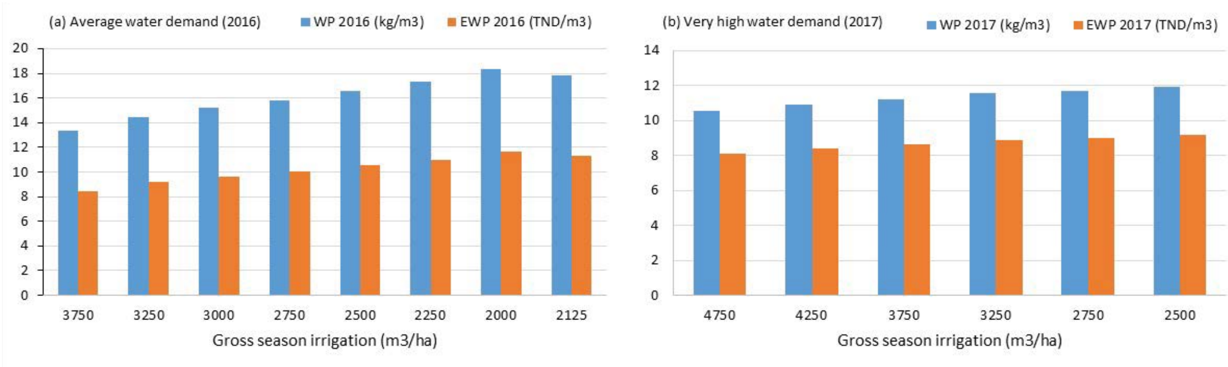

Fig. 5. Water productivity and economic water productivity for deficit irrigation strategies of potato crop in Cherfech region for average (a) and very high (b) water demand conditions (1 TND = 0.37 USD).

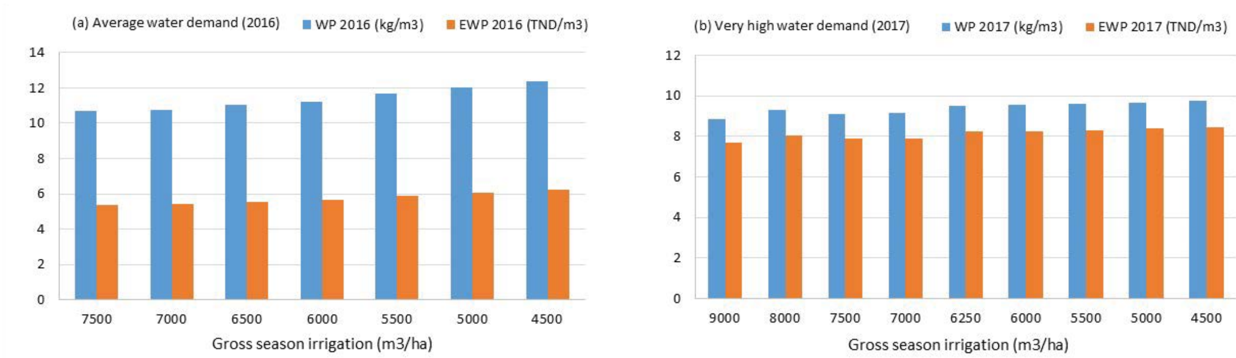

Fig. 6. Water productivity and economic water productivity for deficit irrigation strategies of tomato crop in Cherfech region for average (a) and very high (b) water demand conditions.

indicators as decision support tools leading to recommend proper deficit irrigation scenarios under limited water conditions. Results indicate that potato and tomato crops differently react to deficit irrigation strategies for the climatic conditions of the study area. Although the deficit irrigation strategies has been demonstrated as an appropriate water management choice under average water demand, the socioeconomic implications need to be more assessed under different climatic and water availability conditions. Additional research on coupling the crop model with an economic optimization model needs to be explored in order to evaluate the impact of deficit irrigation on the farmer's income and thus ensure sustainability of production systems in the arid and semi-arid conditions of Tunisia and in other regions where climatic conditions could be similar.

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Desalination and Water Treatment
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doi: 10.5004/dwt.2022.28215

263 (2022) 116–124
July

Economic and environmental evaluation of different irrigation systems for date palm production in the GCC countries: the case of Oman and Saudi Arabia

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Received 28 February 2022; Accepted 28 April 2022

ABSTRACT

This study evaluates the irrigation water volumes' effect on the date palm productivity and water use efficiency under several conventional and improved irrigation systems (surface, subsurface, bubbler, subsurface drip irrigation). The study is focusing on Oman and Saudi Arabia. Data on the water requirement, temperature, and evapotranspiration has been collected from the experimental study conducted at Al-Kamil and Al-Wafi Agricultural Research Station, Oman and Farm Al Briga – research station, Kingdom of Saudi Arabia. The socioeconomics data used was collected from several national and international sources. The partial budgeting method is used for economic comparison between different irrigation systems. In Oman, the performance of bubbler irrigation systems (BI) and subsurface drip irrigation systems (SDI) was studied in terms of water use efficiency, economic performance, and yield of date palms (Cv. *Khalas*). Three intervention levels on SDI have been used: at the rate of 60%, 40%, and 20% of water requirement. This experimental study showed that SDI under the three intervention uses water more efficiently than the BI system. The water use efficiency (WUE) of the SDI 20%, 40%, and 60% of water requirements were 2.0, 2.7, and 4.7 kg/m^3, respectively. Meanwhile, the BI water use efficiency was 1.3 kg/m^3. Economic findings confirmed using the SDI method vs. the BI method increased the cost of establishment but is economical in the long term. Therefore, measures can be taken to reduce the cost of equipment by promoting the production and supply of low-cost SDI systems. In Kingdom of Saudi Arabia, surface drip (SD) irrigation and SDI performance were evaluated in terms of water use efficiency, economic viability, and date palms

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

yield (Cv. *Khalas*). The results showed that SDI was more efficient in comparison to the drip irrigation (DI) technology. The SDI could save about 27% of irrigation water compared to SD. The results also confirmed that the SDI system produced the same date palm yield while saving the irrigation water. Findings indicate that the SDI compared to the DI could save between 125 and 205 $/ha. This result suggests water economic profitability by using the SDI system in date palm farming. These findings indicate a significant difference in net profit. Overall, the adoption of modern irrigation techniques such as drip and subsurface drip irrigation is essential today for this very arid region. This is mainly to increase WUE and Yield. In a short time, the capital cost associated with installing such a system limits adopting this technology. Thus, to accelerate the adoption process of these technologies, it is imperative to create favourable conditions so that a more significant number of farmers can benefit from the benefits of such technologies. The creation of strong networking among different institutions related to applying this modern irrigation technology and public and private financial institutions and support services could be an example of mechanisms to enhance adoption.

Keywords: Economic evaluation; Environmental evaluation; Irrigation systems; Oman; Kingdom of Saudi Arabia

1. Introduction

The project "Development of Sustainable Date Palm Production Systems in the GCC Countries of the Arabian Peninsula", funded by the GCC Secretariat, was implemented, in partnership, by ministries of agriculture, agricultural authorities, and agricultural research institutions and universities in the six GCC countries of the Arabian Peninsula (Kingdom of Bahrain, United Arab Emirates, State of Kuwait, State of Qatar, Sultanate of Oman, and Kingdom of Saudi Arabia) and the International Center for Agricultural Research in the Dry Areas (ICARDA). The project's primary objectives are to improve date palm productivity per unit of water and rationalize the available resources so that production becomes sustainable. The project also aims to: (i) define the nutritional requirements for the optimal growth of date palm through leaf tissue and soil analysis and establish the need to use macro and micronutrients; (ii) to improve date palm field practices and management for a vigorous tree with a high yield and better fruit quality at harvest; (iii) to develop sustainable and ecologically sound integrated pest management systems that reduce crop losses caused by significant pests and diseases and increase the quality and market value of the dates; (iv) to establish efficient post-harvest management protocols, including processing, marketing, and the use of a date palm value-added products; (v) to assemble a set of tools to enable researchers, extension workers, and growers to share the accumulated information, knowledge, and expertise, and strengthen national institutions and human resource capacity and enhance technology transfer. Within this project framework, researchers succeeded in introducing one promising technology: the subsurface drip irrigation. This technology has the advantage of potential water savings, and date palm yield increases. It has the potential to be the most efficient irrigation method available today. It is considered one of the most attractive and promising technologies for the Arab States of the Gulf countries, a region defined as the poorest in terms of water resources where arid conditions in these countries act as a natural constraint expansive agriculture. The objective of introducing this technology is to provide water application strategies that maximize yield, minimize water loss for a range of irrigation system designs, and apply for date palm farmers in the GCC countries. Therefore, while developing improved technologies is essential for farmers in rural livelihoods for this region, new technologies can positively affect livelihoods if they are profitable and adopted by farmers. In light of these challenges, this study's main objective is to evaluate the irrigation water volumes' effect on the date palm productivity and water use efficiency under several conventional and improved irrigation systems (surface, subsurface, bubbler, subsurface drip irrigation). It is mainly to investigate economically and environmentally the effectiveness of this introduced irrigation system in terms of water use and requirement and yield productivity. This is mainly to compare this irrigation system (SDI) to several conventional irrigation systems used in the GCC countries in terms of water use efficiency and date palm yield productivity. The study is focusing on Oman and Saudi Arabia.

2. Date palm irrigation systems in Oman and Kingdom of Saudi Arabia: an overview

2.1. Date palm irrigation systems in Oman

According to Al-Yahyai and Mumtaz Khan [1], irrigation water is traditionally delivered to date palm groves through open canals. Water sources are mainly underground aquifers and wells or via the Falaj – an ancient water system to farms in Oman. Other water sources have also been explored, such as utilizing treated wastewater [2,3], which is only used to a small extend. The timing and frequency of irrigation are mostly dependent on the allocated shares of water for each grove and is not based on empirical methods. Adopting new irrigation methods (such as bubbler irrigation, a localized, low pressure, reliable permanent installation drip irrigation system), particularly in well-irrigated groves, is slowly gaining momentum as the government is subsidizing the installation. Al-Yahyai and Al-Kharusi [4] also reported that chemical quality attributes of date palm (Cv. *Khalas*) grown in northern Oman varied in response to decreased frequency of irrigation water applied during fruit development. Several previous studies indicated that subsurface drip irrigation is a promising technology that contributes to improving water use efficiency and productivity. Besides, it is considered the mosteffectivewaytodirectlyprovidewaterandnutrienttotheplant and increase crop productivity [5–7]. This subsurface drip irrigation represents the recent improvement of irrigation as it significantly reduces losses of direct evapotranspiration, runoff, and deep percolation [8,9]. However, it is necessary to study and examine the performance and the efficiency of this irrigation technology compared with other irrigation systems such as bubbler irrigation systems, which are also being used in these areas. This study's main objective is to examine the efficiency of subsurface drip irrigation system for young palm trees in the Sultanate of Oman in terms of both water use efficiency, yield, and economic viability of this system compared to the existing bubbler irrigation system. Our results will help identify the most efficient technique for water conservation (environmentally and economically) and the most profitable.

2.2. Date palm irrigation systems in Kingdom of Saudi Arabia

Date palm production in arid areas, such as Saudi Arabia, is facing growing physical and quality water scarcity. Surface water resources are becoming increasingly scarce, while groundwater resources, which generally have low quality due to the high salinity levels, are often overexploited. In this context, water-saving became an imperative option for oases sustainability. If drip irrigation is currently recommended in many regions worldwide for saving water, its use in highly arid areas is becoming debatable since it does not keep water safe from high evaporation. The "Development of Sustainable Date Palm Production Systems" project in Gulf Cooperation Council Countries project aims to produce new knowledge and practices to improve date palm production systems in the Gulf countries. The project's main activities include improving the productivity of cultivars, managing natural resources (land and water) for optimal performance, optimizing the use of different inputs in the production process (including fertilizers, pollinators, wastewater, etc.), and studying the genetic diversity of date palms. Technology transfer and experience exchange among partner countries is an integral part of the project.

One promising technology introduced through the project is subsurface drip irrigation. This technique is defined as an application of water under the soil surface through drippers that deliver water at rates generally similar to the surface drip irrigation [10]. The comparison of the water use efficiency (WUE) and performance between different irrigation methods and systems of date palm (drip, flooding, and micro-jet) showed that drip irrigation system is the most efficient, followed by the flood irrigation system and micro-jet [11]. The optimal response of date palm on drip irrigation is due to the system operation in which drippers deliver water slowly for a relatively long period. This process enables better water control and distribution through the soil profile. Therefore, losses due to evaporation and deep percolation are reduced, and the date palm can use almost all of the applied water [12]. The subsurface drip irrigation (SDI) represents a successful irrigation improvement because it is considered the most efficient irrigation technique that significantly reduces water losses of direct evaporation, runoff, and deep percolation [8,9]. The precise application of water and fertilizers resulted in increased water use efficiency, application uniformity of water, and improved crop yield [13]. Besides, it prevents the growth of weeds around the crop [14]. Thus, subsurface drip irrigation is considered the most effective way to directly provide water and nutrients to the plants and increase crops' productivity [15,16]. A well-designed subsurface drip irrigation system provides values of the water use efficiency greater than 95% [17]. More than 95% of the supplied and maintained water in the root zone is beneficial for crops (i.e., date palm trees).

3. Experimental research design framework

3.1. Experimental research design process in Oman

In Oman, the study focuses on the evaluation of four interventions as follows: *Intervention I*: irrigation with bubbler irrigation system at the rate of 100% of water requirements; *Intervention II*: irrigation with subsurface drip irrigation at the rate of 60% of water requirements; *Intervention III*: irrigation with subsurface drip irrigation at the rate of 40% of water requirements; *Intervention IV*: irrigation with subsurface drip irrigation at the rate of 20% of water requirements. Water requirement was calculated based on the evapotranspiration coefficient and using the CROPWAT software. The KC coefficient used in the analysis has an average value of 0.9 for the date palm crop. The monthly water irrigation schedule and the measurements covered the year 2015–2016. The different measures and parameters used in the experience, such as evapotranspiration, crop water requirement, water applied, and total water applied, are detailed in Dhehibi et al. [18].

3.2. Experimental research design process in Kingdom of Saudi Arabia

3.2.1. Cropping details and measurements

Field measurements were taken during the productive cycle of 15 y old date palm trees during the 2015–2016 date palm cropping season. The experimental date palms had an average height of trunk 2.4 m, average trunk diameter of 0.80 cm, average leaf length of 400 cm, and an average number of 55 leaves per palm. The date palms were spaced at 8.0 m for both rows to row and tree to tree. The chemicals and pesticides were applied identically as necessary to all trees. Fertilizers were divided and delivered following farm management practice for palm trees. Date palm yields, yield components, agronomics parameters, and soil water data were determined for both drip irrigation (DI) and SDI systems.

3.2.2. Irrigation system description and scheduling

The date palm trees were separately irrigated with DI and SDI during the study period. The irrigation system consisted of head unit, central and sub-main delivery polyethylene pipes of 75 and 63 mm in diameter. The connected to the sub-main, which leads water to subareas through laterals. The laterals for both SDI and DI systems were 32 mm in diameter. The drippers/

emitters were either placed on the soil surface (DI) or buried at 40 cm soil depth (SDI) in concentric rings around the date palm trees. Trenches were excavated and dressed manually. The date palm trees were irrigated daily with a water volume according to the climatic data acquired from a nearby-automated weather station. The amounts of water were measured at each irrigation event by multi-jet dry type water meters fixed to the sub-main lines. Concerning the schedule of subsurface drip irrigation, around 70% of the water has been added more, as in surface irrigation.

3.2.3. Amount of applied water

The quantity of water applied varied with the period, depending on the atmospheric temperature and other climatic parameters. The quantity of water applied in mm per month is fluctuating between January to December (2015). The minimum and maximum monthly values of irrigation depth added in the initial growth stage through DI and SDI were 91, 185, and 64, 129 mm, respectively. With increasing temperatures starting from April, date palm trees looked more stressed, requiring more frequent irrigations. During the summer (May to July), the amount of water applied to DI and SDI increased to 292 and 204 mm/month, respectively. In the flowering and fruiting stages, the amount of water applied through DI and SDI decreased and fell to 115 and 81 mm, respectively. The following aspects, playing a significant role in influencing evapotranspiration, and consequently in this calculation, have been considered: (1) *Soil salinity*: If the soil is saline, more water must be given to enable a leaching process for clearing the salt from the soil; (2) *Temperature*: The higher the temperature, the higher the rate of evaporation and the more water the plant needs; (3) *Humidity*: The lower the humidity level, the more water needed; (4) *Wind (speed and occurrence)*: Higher constant wind speeds causes higher evaporation and thus higher water demands.

3.3. Methodological framework, data sources, and empirical analysis

3.3.1. Data collection and data sources

Data on the water application, temperature, evapotranspiration has been collected from the experimental study conducted at Al-Kamil and Al-Wafi Agricultural Research Station at South Sharqiyah Governorate, Oman, and from the experimental study conducted at the experimental Farm Al Briga – station at Centre for Date Palm and Dates, Al Hassa, Kingdom of Saudi Arabia. The socio-economic data was mainly collected from several national and international sources.

3.3.2. Water use efficiency

Water use efficiency – WUE was calculated as a ratio between the marketable yield and the seasonal values of actual evapotranspiration using the following equation [19]:

$$\text{WUE} = Y/W \quad (1)$$

where WUE is water use efficiency (kg/m^3), Y is the total marketable date palm yield (kg), and W is seasonal irrigation applied water (m^3).

3.3.3. Economic and statistical analysis

The partial budgeting method is used for economic comparison between both irrigation systems. Data collected was examined statistically by using the analysis of variance procedure from the statistical analysis software (SPSS). To compare treatment means, Fisher's protected least significant difference (LSD) was used for ($p \leq 0.05$) significant level.

4. Results and discussion

4.1. Empirical research findings and discussion: Oman

4.1.1. Economic evaluation: date palm yield

The irrigation interventions on the date palm productivity are presented in the table below (Table 1). The empirical figures displayed in the table below indicate that no significant difference in the date palm productivity under Intervention I, irrigation with bubbler irrigation system at the rate of 100% of water requirements, and Intervention II (irrigation with subsurface drip irrigation at the rate of 60% of water requirements).

Table 1
Date palm productivity under the four irrigation interventions level (kg/tree and kg/ha)

Irrigation intervention type	Yield – experimental irrigated area (kg/tree)	Yield – potential irrigated area (kg/ha)
INTER I: irrigation with bubbler irrigation system (BI) at the rate of 100% of water requirements	79.0	12,956
INTER II: irrigation with subsurface drip irrigation (SDI) at the rate of 60% of water requirements	78.3	12,841.2
INTER III: irrigation with subsurface drip irrigation (SDI) at the rate of 40% of water requirements	69.8	11,447.2
INTER IV: irrigation with subsurface drip irrigation (SDI) at the rate of 20% of water requirements	68.8	11,283.2

Source: Owen elaboration from experimental data – Date Palm Project Team in Oman (2017);
Note: Number of date palm trees/ha (10,000 m^2) = 164.

The productivity level under the first irrigation system is about 79 kg/tree, while it was around 78.3 kg/tree under the second system. However, under the third (irrigation with subsurface drip irrigation at the rate of 40% of water requirements) and fourth intervention (irrigation with subsurface drip irrigation at the rate of 20% of water requirements), the productivity of the date palm – variety *Khalas* decreased to reach an average of 69.8 and 68.8 kg/tree, respectively (Table 3). In general, the difference in productivity between Inter I, Inter II, Inter III, and Inter IV is, on average, for about 0.7, 9.2, and 10.2 kg/tree, respectively. This difference is about 114.8; 1,508.8; 1,672.8 kg per hectare, respectively. At the current market price (0.8 OMR/kg the *Khalas* variety), we note a difference of about US$238.78, US$3,138.30, and US$3,479.42 at the hectare, between the bubbler irrigation (BI) and the three SDI interventions, respectively. However, if we want to evaluate the real return and the net profit, we must consider the cost of water for each intervention in addition to the running costs in each case.

4.1.2. Environmental evaluation: water use efficiency

Empirical findings are presented in the table below (Table 2). Results show that water productivity (kg/m^3) increase with the decrease of water quantity. Findings indicated that the fourth intervention (irrigation with subsurface drip irrigation at the rate of 20% of water requirements) is the most efficient. Empirical findings demonstrate that WUE was significantly increased by 35%, 52%,

Table 2
Quantity of water consumed and saved under the four irrigation interventions level (m^3/ha and US$/ha) – DI vs. SDI

Irrigation intervention	Water use efficiency (kg/m^3)	Total water consumed (m^3/ha)	Total water saved (m^3/ha) BI vs. SDI	Potential water saving (US$/ha) BI vs. SDI Scenario I	Potential water saving (US$/ha) BI vs. SDI Scenario II	Potential water saving (US$/ha) BI vs. SDI Scenario III	Potential water saving (US$/ha) BI vs. SDI Scenario IV
INTER I	1.3	9,966.154	–	–	–	–	–
INTER II	2.0	6,420.6	3,545.554	74.456634	109.912174	145.367714	180.823254
INTER III	2.7	4,239.704	5,726.45	120.25545	177.51995	234.78445	292.04895
INTER IV	4.7	2,400.681	7,565.473	158.874933	234.529663	310.184393	385.839123

Source: Owen elaboration from experimental data – Date Palm Project Team in Oman (2017);
Notes: (1) Number of date palm trees/ha (10,000 m^2) = 164;
(2) *Water pricing scenarios:* the combined capital, maintenance and energy cost of pumping groundwater from a typical dug well for traditional irrigation is estimated at about US$0.021/m^3 (Scenario I) and US$0.031/m^3 (Scenario II) for average conditions. Pumping costs from a tube well for a modem irrigation system, requiring a larger pumping head, are between US$0.041 (Scenario III) and 0.051/m^3 (Scenario IV).

Table 3
Effect of irrigation method on total cost, total return and net profit – variety *Khalas*

Irrigation intervention	Yield – potential irrigated area (kg/ha)	Total return ($/ha)	Total variable costs ($/ha)	Water costs ($/ha)	Net profit ($/ha)
INTER I: irrigation with bubbler (BI) at the rate of 100% of water requirements	12,956	20,211.36	5,857.81	1,224.29	13,129.25
INTER II: irrigation with subsurface drip irrigation (SDI) at the rate of 60% of water requirements	12,841.2	20,032.27	5,857.81	1,349.43	12,825.02
INTER III: irrigation with subsurface drip irrigation (SDI) at the rate of 40% of water requirements	11,447.2	17,857.63	5,857.81	1,260.02	10,739.80
INTER IV: irrigation with subsurface drip irrigation (SDI) at the rate of 20% of water requirements	11,283.2	17,601.79	5,857.81	1,184.62	10,559.36

Source: Owen elaboration from experimental data – Date Palm Project Team in Oman (2017);
Notes: (1) Number of date palm trees/ha (10,000 m^2) = 164;
(2) The market price of the variety *Khalas* is estimated to be 0.8 OMR (2.08$). The total variable costs were estimated at US$5,202.57/ha (Dhehibi et al. [18]). In the total return, we consider only 75% of the production is marketable (25% are considered as waste);
(3) Water costs are calculated using the following estimations: for both irrigation systems (BI and SDI), the irrigation/water cost by hectare includes the equipment cost (depreciation), operating, maintenance cost, and the value of the consumed amount of water.

and 72% in case of subsurface drip irrigation (SDI) under the three intervention levels (60% with WUE = 2 kg/m^3, 40% with WUE = 2.7 kg/m^3, and 20% with WUE = 4.7 kg/m^3) compared to bubbler irrigation (BI with WUE = 1.3 kg/m^3). These findings confirmed that SDI contributes to saving 35% and 72% (depending on the implemented intervention) of irrigation water without decreasing the *Khalas* date palm productivity level. From the environmental point of view, these results suggest that a significant reduction in the volume of water can be achieved when using the SDI system. This amount of water saved by hectare under the three SDI options, 60%, 40%, and 20%, is estimated to be 3,545.554; 5,726.45; 7,565.473 m^3, respectively. At an estimated average price of US$0.041/m^3 of irrigation water, the average dollar value saved by hectare under the three options will be around US$145.36, US$234.78, and US$310.18, respectively. The results outlined in Table 4 reveals the potential cost of saving by using subsurface drip irrigation (under the tree intervention types) in comparison to the bubbler irrigation system (BI). This saving ranges from 74.45 to 385.8 $/ha, according to the SDI irrigation intervention category used. This result suggests that a considerable amount of water (in terms of quantity and value) could be potentially saved by using SDI, and consequently, a more sustainable farming system for *Khalas* date palm variety in the research site, in particular, and, in the Sultanate of Oman, in general.

4.1.3. Economic and financial analysis

Total annual date palm water use will undoubtedly have a significant impact on water costs. Thus, the irrigation method will affect the total return and net profit. We should also indicate that initial cost (equipment and installation) for the SDI system is higher than the BI system. Consequently, we outlined the hypotheses used in this economic analysis: the expected life of both (BI) and SDI systems is 10 y. Results are at the hectare level and per year; The price of 1 m^3 of irrigated water used in the analysis is US$0.041; 1 Omani Rial (OMR) = 2.60$ (average January–March 2017); The average cost of installing bubbler irrigation system (equipment and installation) at the hectare is estimated at 1,963 OMR (which is equivalent to US$5,098.04) ha. The cost of operation and maintenance is estimated at 6% of the equipment and installation cost per ha and year: US$305.88; The quantity of water used for one ha of *Khalas* date palm trees using a bubbler irrigation system is estimated at 9,966.154 m^3. The cost of this water used is around US$408.61; The average cost of installing subsurface drip irrigation (equipment and installation) is estimated at 2,614 OR (equivalent to US$6,788.73). The cost of operation and maintenance is estimated at 6% of the equipment and installation cost per ha and year: US$407.32; The quantity of water used for one ha of *Khalas* date palm trees using subsurface drip irrigation system at the level of 60%, 40%, and 20% of water requirement is estimated at 6,420.6; 4,239.704; 2,400.68 m^3, respectively. The cost of the used amount of water is US$145.36, US$234.78, and US$310.18, respectively. The empirical findings are presented in Table 3. This table shows the irrigation method's effect on water cost, total return, and net profit considered in average values at the hectare level. The results indicated that, under the bubbler (BI) irrigation system, the total return, total variable costs, water costs and net profit were 20,211.36; 5,857.81; 1,224.29; 13,129.25 $/ha, respectively. Besides, we noted a slight difference in net profit when using SDI at the rate of 60% of water requirements. This additional benefit will be about US$12,825.02/ha.

Furthermore, by using SDI at the rate of 40% and 20%, we note a significant difference in net profit compared to the benefit recorded when using the bubbler irrigation method. This difference ranges between 2,389.45 $/ha (SDI at 40% of water requirement) and 2,569.89 $/ha (SDI at 20% of water requirement). This analysis showed that the total return and net profit values of *Khalas* date palm trees increased with the BI irrigation method compared to the SDI (under the three interventions). This fact is due to two significant factors: The first one is the amount of water used by BI, impacting the yield and consequently the total return. The second factor is the increase in water costs generated mainly by the high upfront investment cost (both equipment and installation) of SDI compared to BI investment cost. The capital cost associated with installing such a system limits adopting this technology in a short time. Therefore, in the medium and long-run periods, the sensitivity of investment and water-saving indicate that SDI installation and its use under the three interventions could be a profitable investment. Thus, using SDI at the 60% rate of water requirement, if combination equivalent to 12,841.2 kg/ha/y, is valued at $20,032.27 ha/y, coupled with 35% water savings, valued average and per year and hectare, at 74.45 $. In 10 y, the total value of net profit is estimated to be US$3,040 ha. Therefore, the water-saving will be around 744.5 $/ha. This result suggests water economic profitability in the long term by using the SDI system in date palm farming.

Table 4
Date palm productivity under the DI and SDI irrigation systems (kg/tree and kg/ha)

Irrigation intervention method	Yield – experimental irrigated area (kg/tree)	Yield – potential irrigated area (kg/ha)
INTER I: irrigation with surface drip irrigation (DI)	78.04[a] (SD = 3.22)	12,800
INTER II: irrigation with surface drip irrigation (SDI)	75.00[a] (SD = 2.89)	12,300

Source: Owen elaboration from experimental data from Date Palm Project Team in Kingdom of Saudi Arabia (2017).
Notes: (1) Number of date palm trees/ha (10,000 m^2) = 164;
(2) [a]Not significantly different according to LSD (0.05); SD: is the standard deviation.

4.2. Empirical research findings and discussion: Saudi Arabia

4.2.1. Economic evaluation: date palm yield

The irrigation method (DI vs. SDI) on the date palm productivity is presented in Table 4. It is worth indicating that the irrigation method (DI or SDI) had no noticeable effect on agronomic traits of date palm trees in response to water applied. The decreased water supply from 100% of crop evapotranspiration (DI) to 70% of crop evapotranspiration did not show any significant differences in yield, fruit weight, fruit length, and fruit diameter [20]. Figures displayed in Table 4 above suggest that no significant difference exists in terms of date palm productivity under the two irrigation systems (DI and SDI). The DI scenario's productivity level is about 78.04 kg/tree while it was around 75.0 kg/tree under the SDI scenario. As it is noted, the comparison of the productivity of the date palm – variety *Khalas* – between both systems suggests that a slight decrease of this productivity under the SDI system will be recorded in comparison to DI. This difference of productivity between both interventions is average for about 3.04 kg/tree and about 500 kg by hectare. At the current market price, we note a difference for about 3,750 Saudi Riyal ($1,000) at the hectare if we consider the market price of *Khalas* at 7.5 SR (US$2) the kg. This is from the difference in using these two irrigation methods. Therefore, if we want to evaluate the real return and the net profit, we must consider the water cost for each intervention in addition to the running costs in each case.

4.2.2. Environmental evaluation: water use efficiency

Results show that water productivity (kg/m^3) is about 0.96 and 1.32 kg/m^3 under DI and SDI. This finding suggests that the SDI system is more efficient in comparison with the DI system. Such results also indicate that WUE was increased by 27% more in SDI cases where WUE = 1.32 kg/m^3 compared to surface drip irrigation (DI) where WUE = 0.96 kg/m^3. These findings confirmed that SDI contributes to saving around 27% of the irrigation water without decreasing the date palm productivity level during the study period. This amount of water saved by hectare under the SDI irrigation system is estimated to be around 4,013.65 m^3. Such results indicate a potential money-saving ranging from 124.42 to 204.67 $/ha, using SDI technology, under the three different water pricing scenarios, compared to DI (Table 5).

4.2.3. Economic and financial analysis

The irrigation method will affect the total return and net profit. We should also indicate that the installation system's initial cost is higher than surface drip irrigation due to the high cost of equipment, maintenance, and installation. The hypothesis considered for the economic and financial analysis are as follows: The average cost of installing surface drip irrigation (DI) systems is estimated at US$10,500/ha. The cost of depreciation, operation, and maintenance is estimated at US$1,680/ha; The expected life of the DI and SDI systems is expected to be 10 y; The quantity of water used for one ha of *Khalas* date palm trees using surface drip irrigation (DI) system is estimated at 13,331.83 m^3/ha; The cost of this water used is around US$546.605 ha/y, considering an average price of US$0.041/m^3; The average cost of installing SDI is estimated at US$12,396.4/ha. The cost of depreciation, operation, and maintenance is estimated at US$3,585.87 ha/y; The quantity of water used for one ha of *Khalas* date palm trees using SDI is estimated at 9,318.18 m^3/ha respectively. The cost of the used amount of water is US$382.04 ha/y considering the average price of US$0.041/m^3; The economic analysis was conducted taking into consideration the depreciation of the installation irrigation system in both cases (DI and SDI); The results are at the hectare level, and all date palm trees are in full production. Empirical findings displayed in Table 6 show the effect of irrigation method on the water cost, total return, and net profit considered in average values at the hectare level. Results indicated that, under SDI, the total return, total variable costs, water costs, and net profit were 18,450; 5,400; 3,967.91; 9,082.09 $/ha, respectively.

Table 5
Volume of water consumed and saved under DI and SDI irrigation systems (m^3/ha and US$/ha)

Irrigation intervention	Water use efficiency (kg/m^3)	Total water consumed (m^3/ha)	Total water saved (m^3/ha) DI vs. SDI	Potential water saving (US$/ha) DI vs. SDI Scenario I	Potential water saving (US$/ha) DI vs. SDI Scenario II	Potential water saving (US$/ha) DI vs. SDI Scenario III
INTER I: drip irrigation (DI)	0.96	13,331.83	–	–	–	–
INTER II: surface drip irrigation (SDI)	1.32	9,318.18	4,013.65	124.42	164.56	204.67

Source: Owen elaboration from experimental data from Date Palm Project Team in Kingdom of Saudi Arabia (2017)
Notes: (1) Number of date palm trees/ha (10,000 m^2) = 164;
(2) *Water pricing scenarios:* the combined capital, maintenance, and energy cost of pumping groundwater from a typical dug well for traditional irrigation are estimated at US$0.031/m^3 (Scenario I) for average conditions. Pumping costs from a tube well for a modem irrigation system, requiring a larger pumping head, are between US$0.041 (Scenario II) and US$ 0.051/m^3 (Scenario III).

Table 6
Effect of irrigation method on total cost, total return and net profit – variety *Khalas*

Irrigation intervention	Yield (kg/ha)	Total return ($/ha)	Total variable costs ($/ha)	Water costs ($/ha)	Net profit ($/ha)
INTER I: drip irrigation (DI)	12,800	19,200	5,400	2,226.605	11,573.39
INTER II: surface drip irrigation (SDI)	12,300	18,450	5,400	3,967.91	9,082.09

Source: Owen elaboration from experimental data from Date Palm Project Team in Kingdom of Saudi Arabia (2017).
Notes: (1) The market price of the variety *Khalas* is estimated to be 7.5 SR (US$2);
(2) The total variable costs were estimated at US$5,400/ha;
(3) In the total return, we consider only 75% of the production is marketable (25% are considered as waste);
(4) water costs are calculated using the following estimation: for the two irrigation systems (DI and SDI), the irrigation/water cost by hectare includes the equipment cost (depreciation), operating, maintenance cost, and the value of the consumed amount of water.

Furthermore, by using DI, we note a significant difference in net profit when using this irrigation system. This variation is about US$2,491.305 ha. Total return and net profit increase values of *Khalas* date palm trees increased with the DI irrigation method compared to the SDI. This fact is due to two significant factors: The first one is the amount of water used by DI, which impacts the yield and, consequently, the farmer's total return. The second factor is the increase in water costs generated mainly by the high upfront investment cost of SDI compared to DI investment cost. The capital cost associated with installing such a system limits adopting this technology in a short time. Therefore, in the medium and long-run periods, the sensitivity of investment and water-saving indicate that installation of SDI could be a profitable investment in the case of the following combination of 12,300 kg/ha/y, valued at $18,450 ha/y, coupled with 27% water savings, valued, on average and per year, at $164.56, could exist as the result of such an implementation. 10 y the total value of water-saving will be around 1,650 $/ha. This result suggests water economic profitability in the long term by using the SDI system in date palm farming.

5. Concluding remarks and policy recommendations

In this research paper, BI and SDI were examined at Al-Kamil and Al-Wafi Agricultural Research Station, Oman for water use efficiency, economic performance, and yield of date palms (Cv. *Khalas*). Three intervention levels on SDI have been used: subsurface drip irrigation at the rate of 60%, 40%, and 20% of water requirement. This experimental study showed that SDI under the three intervention uses water more efficiently than the BI system. Economic findings suggest that using the SDI method has an additional cost but is economical in the long term as the SDI found to sustain the date palm farming system in this region where arid conditions act as natural constraints for expansive agriculture. These findings suggest the following recommendations:

- The investment/capital cost required to install subsurface drip irrigation is relatively high. Therefore, measures can be taken to reduce the cost of equipment by promoting the production and supply of low-cost SDI systems.
- The adoption of modern irrigation techniques is essential for the region to increase water use efficiency and date palm productivity. Therefore, in a short time, the capital cost associated with installing such a system limits the probability of adopting this technology. It is imperative to create favorable conditions so that a more significant number of farmers can benefit from such technologies. The creation of networking among different institutions related to applying this modern irrigation technology and public and private financial institutions and support services could be an example of mechanisms to enhance adoption.

The SD and SDI systems' performance was also evaluated in terms of water use efficiency, economic viability, and yield of date palms (Cv. *Khalas*) at Farm Al Briga – station of Saudi Arabia. The results of this study showed that SDI was more efficient in comparison to the DI technology. Findings indicate potential money-saving using SDI, under the tree different water pricing scenarios, compared to DI. This saving is ranging from 124.42 to 204.67 $/ha. This result suggests the existence of water economic profitability by using the SDI system in date palm farming. Based on these findings, the following recommendations are developed for the Kingdom of Saudi Arabia case study:

- Extension education programs are to be developed and implemented to enhance farmers' adoption rates of modern irrigation methods such as SDI, given its technical efficiency and economic viability.
- Further studies to be carried out to investigate the barriers to adopting this new irrigation method and developing solutions to overcome these barriers to conserve limited water resources for obtaining Saudi sustainable agriculture goals.

Acknowledgments

This work was conducted as part of the ICARDA's Arabian Peninsula Regional Program (APRP) current project, "Developing Sustainable Production Systems for Date Palm in the Gulf Cooperation Council countries". The project is funded by the Gulf Cooperation Council (GCC) Secretariat (https://www.gcc-sg.org/en-us/Pages/default.aspx) under a grant agreement with the International Center for Agricultural Research in the Dry

Areas (ICARDA – https://www.icarda.org/). The authors also would like to thank the hard work and dedication of the national project partners in the Ministry of Agriculture, Fisheries and Water Resource, Sultanate of Oman, and the Ministry of Environment, Water and Agriculture, in Kingdom of Saudi Arabia.

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Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2022.28216

263 (2022) 125–126
July

Challenges and prospects of using treated wastewater to manage water scarcity crises in the Gulf Cooperation Council countries

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ABSTRACT

The Gulf Cooperation Council (GCC) countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates) are facing severe water shortages, which jeopardize sustainable development and restrict human, industrial, and agricultural expansion. Rapid urbanization and increasing living standards have further exacerbated the problem. Although arable land in GCC countries is averaging only 4.3% of the total land area, average water use for agriculture is 70% of the renewable water resources and is even higher in Saudi Arabia, UAE, and Oman. Despite this water use, the average contribution of agriculture to the gross domestic product (GDP) is only 0.8%. However, massive oil and gas reserves in the region compensate for the scarcity of land and water resources in GCC countries.

The increasing demand for water by domestic and industrial sectors is threatening the ecosystem services, food security, and the environment. The annual per capita water uses in the GCC countries is 560 L/d compared to the world average of 180 L/d. This four-fold increase in water consumption over the last two decades is caused by a rising population and unplanned agricultural expansion. Therefore, improving the productivity of marginal land and water resources in GCC countries is imperative to increase the food supply and avoid the adverse environmental effects of land degradation. The marginal water resources such as poor-quality saline water, treated wastewater, and produced water from the oil industry are now successfully used for agricultural crop production and aquaculture in many countries. Currently, an estimated 380 bm^3 of wastewater is collected annually across the globe and expected to reach 574 bm^3 by 2050. Currently, about 36 million ha are irrigated with the wastewater, of which 29 million ha are using untreated wastewater. Farmers in urban and peri-urban areas of nearly all developing countries are using untreated wastewater for irrigation.

The treated and untreated municipal wastewater is used for agriculture in several parts of the world because it supplies additional nutrients and improvements in crop production during the dry season. During the last two decades, the use of treated wastewater for agriculture has also increased in the GCC countries. The GCC countries are in the driest part of the world with an annual per capita water availability of 500 m^3 compared to the world average of 6000 m^3. Agricultural water demand, which is more than 80% of the total water consumption, is primarily met through the massive exploitation of groundwater. The imbalance between groundwater discharge (27.8 bm^3) and recharge (5.3 bm^3) is causing the excessive lowering of groundwater levels. Therefore, GCC countries are investing heavily in the production of nonconventional water resources such as desalination of seawater and treated wastewater (TWW).

Currently, 439 desalination plants are annually producing 5.75 bm^3 of desalinated water in the GCC countries. The annual wastewater collection is about 4.0 bm^3, of which 73% is treated with the help of 300 wastewater treatment plants. Despite extreme water poverty, only 39% of the treated wastewater is reused, and the remaining is discharged into the sea. Currently, more than one-third of the available TWW is used to irrigate nonedible crops and fodder. However, TWW use is primarily restricted to landscaping, gardens, and road ornamentals. The use of TWW to irrigate food crops is minimal due to health, environment, social, and religious concerns. Farmers are hesitant to grow food crops using TWW due to the fear of losing customers for their products.

Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

In all GCC countries, the gap between water supply and agricultural water demand is met through extensive groundwater exploitation. Uncontrolled and unregulated groundwater abstraction has resulted in excessive lowering of groundwater levels, degradation of groundwater quality, salt-water intrusion into freshwater aquifers, and rising pumping costs. The current trends of groundwater exploitation are not sustainable and immediate action is required to put a brake on groundwater abstraction to protect this vital natural resource to ensure potable water supply to urban and rural communities.

The TWW represents one of the most promising alternatives to meet agricultural water demand and make more fresh water available for domestic and industrial uses. The use of TWW in agriculture can contribute positively to improve the socio-economic conditions in the GCC countries. This is very important considering that large volumes of TWW will become available in the future due to population increase and the expansion of urban sewage networks in the large cities of the GCC countries. Therefore, robust plans need to be developed for the sustainable use of TWW; otherwise, vast quantities will have to be discharged into the sea. Since water is the key driver in achieving Sustainable Development Goals (SDGs), developing a global vision on wastewater use is needed to improve the effectiveness of national policies.

This paper reviews the status of available water resources in the GCC countries. It considers the future water demands and discusses the challenges and opportunities to use the TWW in GCC countries to bridge the gap between supply and demand. The increased use of TWW is also vital for this region because groundwater is fast depleting due to overexploitation, which will have direct consequences for the food security of this region. To increase TWW use for agriculture, a comprehensive awareness campaign needs to be initiated to address the social and religious concerns of farming communities and consumers. Several internal and external risks can jeopardize the sustainable use of treated wastewater in the GCC countries. These include climate change, increasing costs, technological and market-driven changes, and regional security issues. Therefore, effective response mechanisms should be developed to mitigate future risks and threats. For this purpose, an integrated approach involving all concerned local and regional stakeholders needs to be adopted.

Keywords: Wastewater reuse; Agriculture; Desalinated water; Heavy metals; Water scarcity

Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2022.28217

263 (2022) 127–138
July

The future of wastewater treatment and reuse in Kingdom of Saudi Arabia

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Received 28 February 2022; Accepted 8 May 2022

ABSTRACT

The Kingdom of Saudi Arabia (KSA) is an arid country facing the challenge of renewable freshwater availability. KSA has an area of about 2.25 million km^2. KSA has no perennial rivers or permanent freshwater bodies. KSA has low rainfalls with high evaporation rates which makes it very dry country. After discovering oil, KSA has witnessed remarkable economic development and rapid increase in population with migration to the urban areas in the past four decades. KSA population increased from about 4 million in 1960 to about 32.5 million in 2018. These developments lead to more pressure due to increased demand on the scarce freshwater resources. In order to meet the growing water demands, the limited renewable freshwater resources have been heavily overexploited. Groundwater aquifers are the main natural renewable freshwater source in the country. The average per capita municipal daily water use in KSA has been increasing since 2009 when it hit 227 L/d and recorded a gradual increase to touch 270 L/d in 2016 which is the 3rd highest in the world. Faced with increasing water scarcity and gaps between water supply and demand, policymakers in KSA started to consider the treated wastewater as a major renewable water source and aim to achieve full utilization and reuse of treated wastewater by 2025. With a desalination capacity of about 2,500 million cubic meters per year which represents 30% of the world's desalination capacity, KSA is the largest seawater desalination producing country. However, desalinated water alone will not be able to supply enough freshwater to meet the increasing future water demand. However, with only 10% of the total municipal wastewater generated currently being reused, KSA is projected as the third largest reuse market after China and the USA, and reuse capacities are projected to increase by 800% by 2025. The projected growth and change in water portfolios offer tremendous opportunities to integrate novel approaches of water reclamation and reuse such as aquifer recharge and groundwater quality enhancement, district cooling and irrigation of reactional areas. Recent statistics in 2018 indicated that the volume of treated wastewater used to produce freshwater in KSA was approximately 390 million cubic meters per year. This statistic shows the revenue of the industry "sewerage" in Saudi Arabia from 2012 to 2017, with a forecast to 2024. It is projected that the revenue of sewerage in Saudi Arabia will amount to approximately 739.3 million U.S. Dollars by 2024. The KSA's treated wastewater utilization status up to date and the main key challenges facing KSA such as the substantial growth in wastewater services demand; low coverage of existing wastewater collection systems, treatment facilities, and reuse options; and the needed governmental capital investment in wastewater infrastructure development were analyzed. It has been recommended that there are initiatives that should be taken thus far to tackle these challenges towards successful achievement of KSA's efficient wastewater treatment and reuse.

Keywords: Public acceptance; Wastewater revenue; Water quality; Aquifer recharge; Water reclamation

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

1. Introduction

Kingdom of Saudi Arabia (KSA) covers an area of about 2.25 million km^2 located in arid and hyper arid region has limited renewable freshwater resources with no perennial rivers or permanent freshwater bodies. KSA is considered as one of the driest areas due to low rainfall and high evaporation rates. After the discovery of oil reserves in early of 1950, KSA has witnessed remarkable economic development and rapid increase in its population in the past four decades. The population of KSA increased from less than 4 million in 1960 to more than 32.5 million in 2018. The population is expected to reach more than 56 million by 2050 [1]. In the 1980s, KSA started an ambitious agricultural development program to increase its food self-sufficiency ration and increase its agricultural production. Groundwater over abstraction from the non-renewable aquifer systems, resulted in substantial declines in groundwater levels and deterioration in groundwater quality [2]. Behaviors such as water supply-based policies, increasing population growth, and agricultural policies, urbanization, and rising living standards led to unsustainable scarce freshwater use [3]. KSA has limited non-renewable groundwater reserve with very limited recharge rates to renewable groundwater aquifer systems [4]. Despite the fact that renewable freshwater resources are very limited, the domestic sector in KSA consumes about 8.5 million cubic meters of water daily. While the global average renewable water resource per capita per year is 6,000 m^3, KSA has only 84.8 m^3/cap/y [5]. In spite of the water scarcity, Saudi Arabia has the third highest water consumption per capita at 250 l/cap/d. The country's water demand is expected to increase by 56% by 2035. Meanwhile, at the current rate of water withdrawal, ground water aquifers are expected to provide potable water only for the next 10–30 y. Recently, water sector in KSA is facing several challenges that threaten water, food, and energy security. Fuel subsidies and desalinated water production deplete the country energy resources along with consequent environmental cost, low water tariffs, and the increased leakage from water main transmission and distribution networks. These factors affect drinking water and wastewater production and treatment costs [6]. Sustainable development in KSA is facing the challenges of renewable freshwater resources scarcity and the ever-increasing water demand. With its present (2019) annual desalination capacity of nearly 2,500 million m^3 (about 30% of the world's desalination capacity), KSA is ranked as the first largest desalinated water producer. However, desalinated water alone will not be able to supply enough freshwater to meet the increasing future water demand. Only 10% of the total wastewater generated currently being reused. The projected growth and change in water portfolios offer tremendous opportunities to integrate novel approaches of water reclamation and reuse. Recent statistic in 2018 indicated that the volume of treated wastewater used to produce freshwater in KSA was approximately 390 million cubic meters per year. The statistic also indicated that the operating revenue from sewerage sector in KSA in 2018, was 629 million U.S. dollars. The main key challenges facing KSA wastewater sector are the substantial growth in wastewater services demand; low coverage of existing wastewater collection systems, treatment facilities, increasing the utilization and reuse ration and the needed governmental capital investment in wastewater infrastructure development.

2. Overview of the water resources in the Kingdom

With a semi-arid environment, KSA is exposed to temperature variability, low annual rainfall, no natural perennial water bodies such as rivers or freshwater lakes, and non-renewable groundwater aquifer systems with limited reserves [7]. KSA has an annual rainfall less than 100 mm with very high evaporation rates of about 2200 mm, which limits its surface water resources and supplies. Due to limited surface water, KSA relied on groundwater over abstraction which led to aquifers water levels decline and groundwater quality deterioration. Despite the increase of desalinated water, the percentages by different sources (i.e., surface water (11%), groundwater (73%); desalination (11%), and wastewater treatment (5%)) [8]. Water resources in KSA are classified into two main groups: conventional resources including surface water and renewable and non-renewable groundwater, and non-conventional resources including desalinated and treated wastewater. Various water resources with their share in KSA are shown in Table 1. The daily per capita average water consumption in KSA is considered high and ranges from 270 to more than 500 L/cap/d in some of the KSA cities as shown in Fig. 1, the government target is to minimize the per capita daily water use to less than 150 L by 2030. In the 5-years plan (2015–2019) KSA water sector financial requirements are more than USA$65 billion as shown in Fig. 2. In 2018 both renewable and non-renewable groundwater contribute by about 38% and surface water with about 3%, while the remaining is from desalination which is about 59%. The government target is to reduce the contribution of surface and groundwater to only 10% and 90% will be from desalination. Fig. 3 shows the targeted mix in water supply in KSA by 2030 [9]. Treated wastewater provides about 5% of the total water supply. Treated wastewater quality analysis results indicated that it is safe to be reused for industrial processes, district cooling, groundwater aquifer recharge, and for agricultural irrigation. The total annual treated wastewater produced in KSA in 2019 was 850 million m^3 (MCM). Out of them 375 MCM were reused and about 185 MCM were used in agriculture irrigation [10]. The use of recycled wastewater lessens the dependence and reduces the pressures on the limited freshwater resources. It also reduces the amount of treated and non-treated effluent into the environment. These effluents deposit organic and inorganic nutrients (e.g., nitrogen and phosphate) into water systems, which can cause eutrophication and algal blooms and severely degrade existing bodies of water [11]. Table 2 shows the summary of some major wastewater treatment plants in KSA.

3. Wastewater reuse options

KSA will increase the reuse of treated wastewater in future from 2.0 BCM in 2018 to more than 5.0 BCM by 2050 as shown in Fig. 4. Treated wastewater reuse is in practice

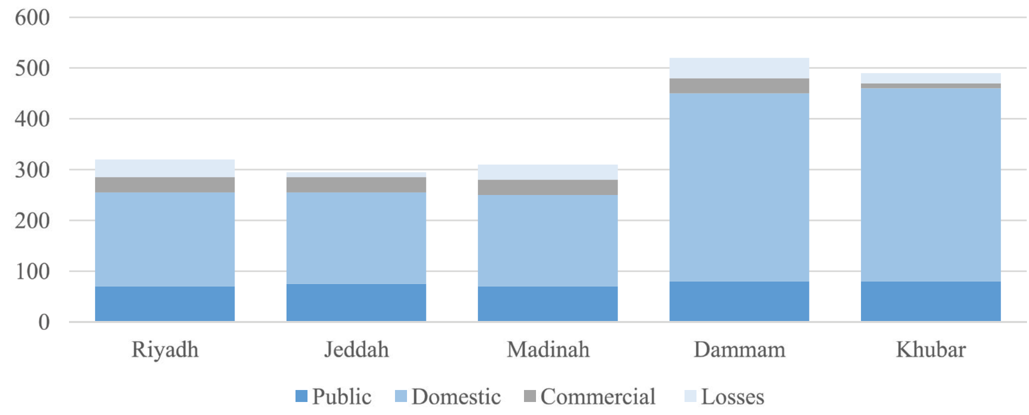

Fig. 1. Daily per capita average water consumption in the domestic sector (L/cap/d).

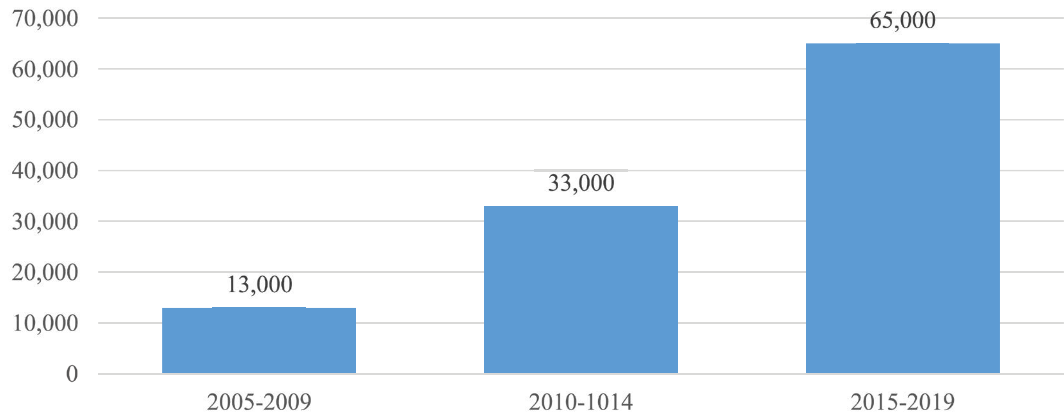

Fig. 2. Financial requirements of the water sector (million US$).

Table 1
Water resources in Kingdom of Saudi Arabia [9]

Water sources	Volumes (million m^3/y)-2019
Conventional water resources	
Groundwater (non-renewable)	2,060
Groundwater (renewable)	2,300
Surface water	100
Non-conventional water resources	
Desalinated water	2,200
Treated wastewater	2,044
Total water resources	8,704

in many countries specially in arid region which experienced renewable freshwater shortage. In KSA treated wastewater can be used for agricultural and landscaping irrigation, wetlands, industrial purposes, aquifer recharge and district cooling. KSA already using treated wastewater at present in agriculture irrigation and industrial purposes. However, a major fraction of wastewater remains unused and discharged to the environment.

The wastewater is treated in about 70 sewage treatment plants across the country [12]. Following treatments, a fraction of treated wastewater is recycled for reuse, while the remaining treated wastewater is discharged into the water bodies or into empty Wadies. MEWA (2018) reported that approximately 610 MCM/y wastewater was treated in KSA. The Food and Agriculture Organization (FAO) showed that approximately 547.5 MCM wastewater was treated in 2002 [13,14]. The Ministry of Economy and Planning (MOEP) reported that approximately 730 MCM of wastewater was treated in 2008 [15]. The plant specific treated wastewater volume, treatment types and disposal methods for some major sewage treatment plants are summarized in Table 2. The data show that the annual wastewater treatment capacity of these major plants is approximately 601.8 MCM/y, while these plants treat approximately 567.1 MCM/y. The current and forecasted sewage network covers about 50% of the total wastewater generated. 95%–100% coverage would be required by 2030. KSA has 5.6 million m^3/d of wastewater treatment capacity as of 2018 with 3.2 million m^3/d under construction with 0.4 million m^3/d planned for decommissioning. Additional 8.4 million m^3/d of capacity will be required by 2023 to achieve the treatment target. Fig. 5 shows cumulative sewage treatment capacity planned to reach commercial operational date (COD) between 2021 and 2030 [16].

In 2018 agricultural irrigation followed by landscape irrigation represent about two third of the treated water reuse.

The industrial water is equivalent to 13% of total water reuse as it shown in Fig. 6. The historical data on treated wastewater reuse indicate increasing trends. In next few years, it is likely that treated wastewater reuse may be increased significantly and treated wastewater will become a potential source for water supplies (preferably, for agriculture). Significant fraction of the remaining wastewater is likely to be discharged into the environmental system without treatment or with minimal treatment. Consequently, there is a risk of contamination of groundwater system. By reducing discharges of wastewater, environmental risks can be reduced. On the other hand, reuse of treated wastewater is subjected to satisfaction of certain regulatory criteria. If the regulatory criteria are not satisfied, use of treated wastewater might impose health hazards [17,18].

To minimize these effects, wastewaters are needed to be adequately treated prior to reuse. In case of secondary treatment, treated wastewater typically have 30–100 MPN (most probable number) fecal coliform per 100 mL, while the tertiary treatment produces effluent of 1–7 MPN fecal coliform per 100 mL [19]. The microbiological regulations for reusing treated wastewater in agriculture indicate that tertiary treatment is required for reusing treated wastewater in agriculture in Saudi Arabia. KSA has established numerous centralized and decentralized wastewater treatment plants. The system involves the collection of wastewater from individual homes, home clusters, isolated communities, industries, and institutional facilities [20,21]. Recently, a new sewage treatment plant producing a tertiary treated effluent with an average

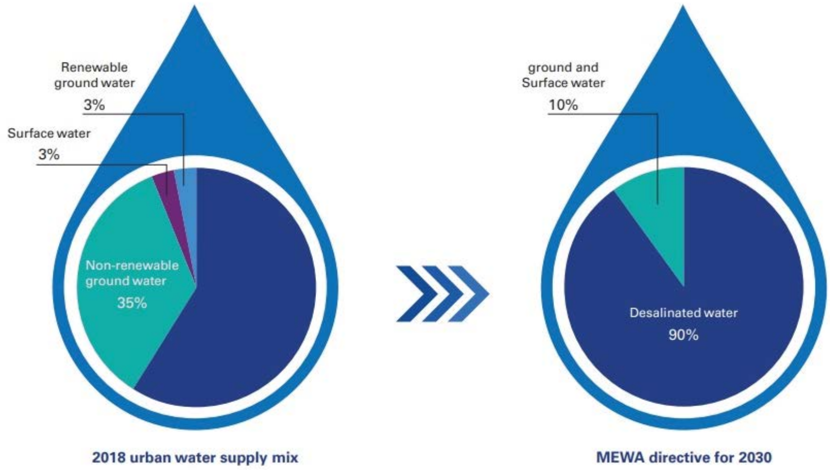

Fig. 3. Targeted change in water supply mix in KSA by 2030.

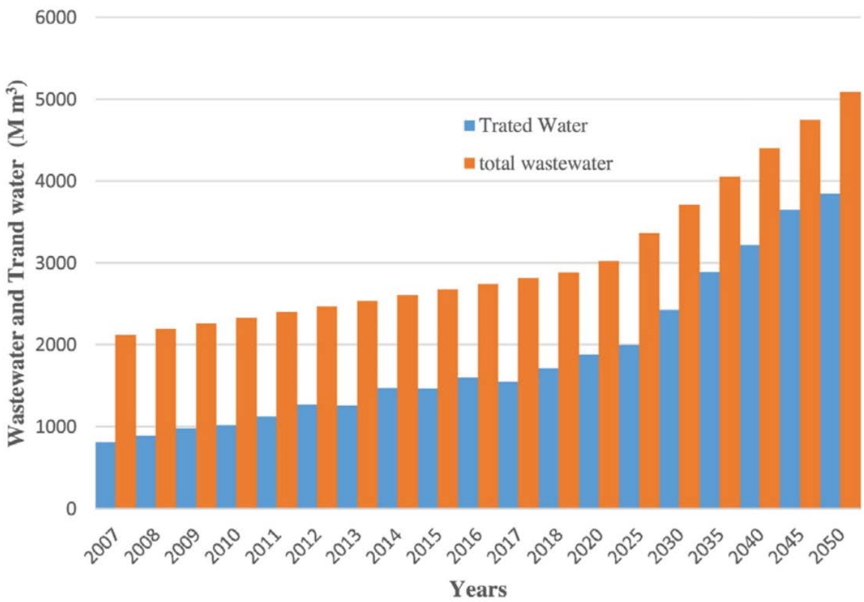

Fig. 4. Changes in the wastewater effluent and treated water to 2050 [12].

Table 2
Summary of some major wastewater treatment plants in KSA

No.	City	Plant name	Design (m^3/d)	Treatment scheme	Actual (m^3/d)	Disposal
1	Buraidah	Buraidah	11,000	Facultative + maturation ponds	13,000	To sand dunes
2	Unaizah	Unaizah	7,080	Aerated lagoons	9,900	To Wadi
3	Al-Kharj	Al-Kharj	21,000	Aerated lagoons + sand filters	21,600	To Wadi
4	Qatif	Sanabis	8,340	2 stage facultative	22,195	Gulf
5	Qatif	Gesh	8,990	2 stage facultative	15,930	Gulf
6	Qatif	Awamia	9,260	2 stage facultative	13,430	Gulf
7	Qatif	Qatif	210,000	Oxidation ditch	35,000	Gulf + L.I.
8	Al-Hasa	Oyoon	6,310	2 stage facultative	17,100	To Lagoon
9	Al-Hasa	Emran	13,320	2 stage facultative	22,100	To Lagoon
10	Al-Hasa	Hufuf-Mubarraz	29,500	2 stage facultative	136,780	To Lagoon
11	Khafji	Khafji	25,000	2 stage facultative	5,190	Gulf
12	Jeddah	Al-Khomra	36,000	Trickling filters (stone)	66,000	Red Sea
13	Jeddah	Plant C	40,000	Package contact stabilization	63,000	L.I. + Lagoon
14	Jeddah	Plant A	32,000	Package contact stabilization	55,000	L.I. + Red Sea
15	Jeddah	Bani Malik	8,000	Package contact stabilization	6,500	L.I. mostly
16	Jeddah	Al-Jamia	8,000	Package contact stabilization	7,000	Red Sea + L.I.
17	Jeddah	Tertiary (Al-Khomra)	30,000	Trickling filters + ozonation + clarification + sand filtration + reverse osmosis	20,000	Red Sea L.I.
18	Jeddah	Al Iskan	3,000	Activated sludge	3,500	
19	Makkah	Old plant	24,000	Trickling filters (stone)	65,000	Wadi + A.I.
20	Makkah	New	50,000	Plug flow activated sludge + nitrification–denitrification	—	
21	Riyadh	Al Hayer Old Plant (South)	200,000	Trickling filters (plastic) + polishing lagoons, anaerobic sludge digestion	200,000	Wadi + A.I. + Refinery
22	Riyadh	Al Hayer New Plant (North)	200,000	Activated sludge + nitrification–denitrification + filtration	200,000	Wadi + A.I. + Refinery
23	Riyadh	Refinery	20,000	Clarification + filtration + reverse osmosis + ion exchange	13,500	
24	Riyadh	KSU Plant	8,000	Settling, trickling filters	8,000	L.S. + Cooling power plant
25	Riyadh	Diplomatic Quarter	9,300	Screening, activated sludge	9,500	L.I.
26	Dammam	Dammam	208,000	Oxidation ditch	140,000	Gulf + L.I.
27	Al-Khobar	Al-Khobar	133,000	Oxidation ditch	100,000	Gulf
28	Madinah	New	120,000	Conventional activated sludge	100,000	Wadi + L.I. + A.I.
29	Safwa	Safwa	7,570	Completely mixed	8,600	Gulf
30	Khamis Mushait	Al-Dhoba	7,500	Oxidation ditch	10,000	Wadi + L.I. + A.I.
31	Abha	Abha	9,000	Extended aeration	11,500	Wadi
32	Taif	Taif	67,000	Activated sludge + nitrification–denitrification + filtration + activated carbon filtration	34,000	L.I. + A.I.
33	Jubail	Jubail Industrial City	12,500	Tertiary treatment	38,630	A.I.
34	Saihat	Saihat		Secondary aerobic biological	15,717	
35	Aramco facilities	Saudi Aramco (total 9 at different locations)	66,000	Variable	66,000	A.I. + Sea

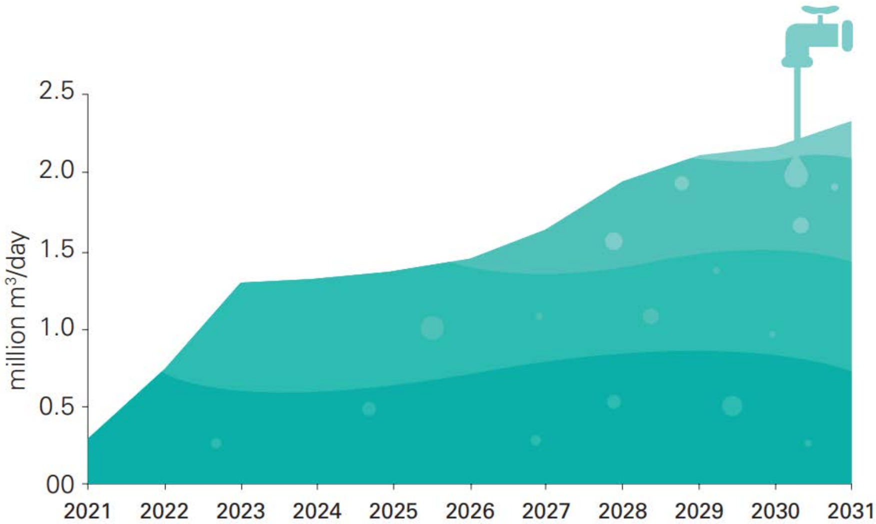

Fig. 5. Cumulative sewage treatment capacity planned to reach commercial operational date between 2021 and 2030 (KPMG, 2021).

capacity of 400,000 m^3/d and the maximum capacity of 640,000 m^3/d was built. The estimated total available supply of treated sewage effluent from the six largest cities exceeds 4.8 million m^3/d [22]. In 2012, all population in KSA was served with water supply and sanitation in all cities [23,24] with an invest of about US$23 billion including sewage collection and treatment infrastructure [25]. Looking forward, the country has aggressive long-term goals of increasing water reuse to more than 65% by 2020 and more than 90% by 2040, all by transforming more of its existing and planned wastewater treatment assets into source water suppliers across all sectors [26].

3.1. Wastewater reuse in irrigation

Water reuse and recycling are also viewed as a positive step toward climate change adaptation and mitigation. A project for irrigating an area of about 9,000 ha of date palms and forage crops near Riyadh was irrigated using about 146 MCM of treated wastewater in 2012. In cities such as Dhahran, Jeddah, Jubail, Riyadh, and Taif treated wastewater was reused for irrigating landscaping, road verges, and green areas in municipal parks [27]. The use of recycled wastewater in agriculture helped to save energy and reduces the cost of freshwater pumping, providing irrigation and reducing the water footprint of food production. It also can provide adequate nutrients and fertilizer for crops so that mining for mineral fertilizers can be decreased. For example, it has been demonstrated that reusing treated municipal wastewater for agricultural irrigation in Saudi Arabia provided adequate nutrients, lowered costs for irrigation and fertilization, and increased yield and profit for wheat and alfalfa. A large amount of treated wastewater was discharged to Hanifa Valley, which is located in eastern Riyadh and extends beyond the city into the surrounding rural areas. The vision for Hanifa Valley is to use treated wastewater to transform this urbanized valley into a ribbon of naturalized parkland to promote the area as a safe, green, and healthy environment. Moreover, this will connect the area with residential development, farming, recreation, cultural activities, and tourism [28]. In order to address the water deficit, Saudi Arabia has started an increased utilization of water recycling. The city of Riyadh has been very successful in using nearly 50% of its treated wastewater (about 120 million m^3). Treated wastewater is currently being used at various industrial and commercial enterprises of the city, which has the potential to expand in the future due to the high cost of desalinated water which is about USD0.8/m^3 [29]. The expected growth in wastewater collection and treatment services will produce more treated wastewater (i.e., about 2.5 km^3/y in 2035). The priority is expected to shift from the ongoing major agricultural use to industrial use, with higher anticipated revenue. Use of treated wastewater is projected to be greatest in the Riyadh, Makkah, Medina, and Eastern Province regions, which are home to the KSA's six largest cities [19].

3.2. Wastewater reuse in aquifer recharge

Depletion of water supplies for potable and irrigation use is a major problem in the rural Wadi valleys of KSA. Using managed aquifer recharge tool using treated wastewater conveyed can help to solve these challenges. In many cases, there are no local sources of water supply of any quality in the Wadi valleys. In Al-Kharj area, treated wastewater is transmitted through an open canal with a length of 40 km, where the water is stored in a pond and then filtrated through the sandy soil to recharge groundwater aquifer system. Economic analysis shows that the cost for supplying desalinated water is about USA$ 2–5/m^3 plus transmission and distribution cost. However, the cost of aquifer recharge with treated wastewater is USA$ 0.25–0.50/m^3 plus transmission and distribution cost. Several studies illustrated that, the cost of water treatment in Saudi Arabia varies with the type of technology, from US$0.34–0.75/$m^3$ for secondary treatment and US$ 1.19–2.03/m^3 for tertiary treatment. The wastewater reuse, indirect for potable use and direct use for irrigation,

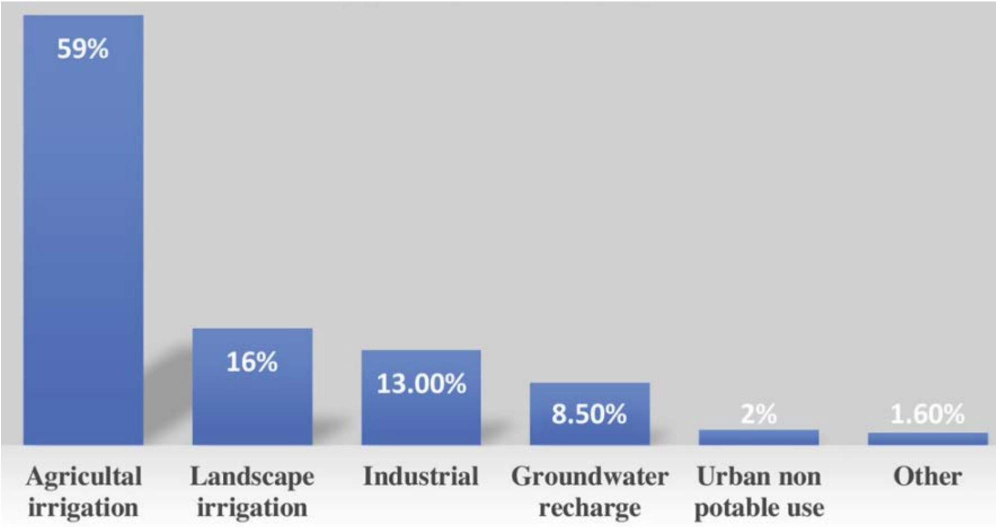

Fig. 6. Wastewater reuse in Saudi Arabia for 2018.

can have a zero-treatment cost because it is discharged to waste in many locations. In fact, the economic loss caused by the wastewater discharge to the marine environment can be greater than the overall amortized cost to construct an aquifer recharge system, including conveyance pipelines and the operational costs of reuse in the rural environment. The aquifer recharge and associated reuse system can solve the rural water supply problem in the Wadi valleys and reduce the economic losses caused by marine pollution, particularly coral reef destruction [30].

3.3. Environmental and recreational uses

Treated wastewater can be used for many non-potable purposes such as decorative water features (fountains), dust control, and fire protection. Irrigation of landscapes, parks, amenity plantations, road verges, maintenance of natural hydrological regimes and golf courses can also be a potential use. It also, can be used to create manmade wetlands, enhance existing natural wetlands, and sustain or augment stream flows. At present about 40% of treated wastewater is used in some Arab countries for environmental and Recreational uses such as UAE, Kuwait and Qatar [31].

3.4. Industrial

Treated wastewater reuse in industrial sector is another potential option. Industrial facilities can use treated wastewater for cooling system make-up water, boiler-feed water, process water, and general wash down uses. It can also be used for road maintenance, and concrete production in the construction projects. Industrial reuse proposes depend on the effluent quality and in some cases, it may require additional treatment.

3.5. District cooling

At present a huge amount of fresh water – mainly desalination – is used for district cooling in KSA. District cooling for residential areas could be an economic option and another application for treated wastewater use in the region where desalinated water is used. The used desalination water in district cooling is costly and the economic factor could play an important role for increasing the tertiary treated wastewater in cooling in the future in KSA.

4. Challenges facing wastewater reuse

The reuse of wastewater for different purposes depends on the degree of its treatment (primary, secondary and tertiary). The tertiary level treated wastewater is free from all health hazards and can be used to irrigate all crops. The secondary level treated wastewater is suitable for nursery flowers and palm trees, cotton, vegetables but should not be used for cattle rearing with milk or meat. The primary level treated wastewater can only be used for timber trees after taking strict precautionary measures such as isolated farms, and preventing direct contact of workers with the water. There are many barriers facing the treated wastewater reuse including technological, institutional, environmental, economic and social (public acceptance) barriers. Additionally, it is important to develop an economically viable model for the concerned stakeholders, to ensure the widespread sustained adoption of this strategy. Table 3 summarizes risks to be considered when selecting reuse applications [32]. Detailed surveys of the local situation will be required to be able to assess actual risks and constraints, and to select the most appropriate technology and applicable risk prevention measures. In the next step, these risks will be compared with the benefits linked with the specific application of wastewater reuse. Many factors decide on viability of reuse projects because such projects require the establishment or adjustment of existing infrastructure, change in water use habits, etc. In order to decide on viability of reuse projects, a more detailed evaluation of applications should cover suitability of soils and crops, environmental and health risks need for additional infrastructure and public acceptance of reuse.

Table 3
Categories of wastewater reuse and potential constraints

Agriculture and landscape irrigation	
Crop irrigation	Surface- and groundwater pollution, if not properly managed
Commercial nurseries	Marketability of crops and public acceptance
Park/school yards	Effect of water quality, particularly salts, on soils, grasses and crops
Freeways (median strips) courses, cemeteries greenbelts, and residential areas	Public health concerns related to pathogens (bacteria, viruses Golf and parasites)
Industrial recycling and reuse	
Cooling boiler feed	Constituents in reclaimed wastewater cause scaling, corrosion, biological growth and fouling
Pathogens in cooling water	Public health concerns, particularly aerosol transmission of process water
Groundwater recharge	
Groundwater replenishment and salt water intrusion control	Organic chemicals in reclaimed wastewater and their toxicological effects
Subsidence control	Total dissolved solids, nitrates and pathogens in reclaimed water
Recreational/environmental uses	
Lakes and ponds	Health concerns from bacteria and viruses
Marsh enhancement and stream flow augmentation	Eutrophication due to nitrogen and phosphorus in receiving water
Fisheries	Toxicity to aquatic life
Non-potable urban uses	
Fire protection	Public health concerns on pathogens transmitted by aerosols
Air conditioning and toilet flushing	Effects of water quality on scaling, corrosion, biological growth toilet and fouling
Potable uses	
Blending in water supply	Constituents in reclaimed water, especially trace organic reservoirs chemicals and their toxicological effects
Pipe-to-pipe water supply	Aesthetics and public acceptance Health concerns about pathogen transmission, particularly viruses

Treated wastewater reuse brings a number of challenges regarding which contaminants must be removed and to what extent the quality of the treated wastewater should be for each case, considering local environmental conditions, economic factors, scientific knowledge, awareness campaign, legislations, and regulations requirements. Treated wastewater reuse requires proper planned strategies that incorporate multiple factors and measures to minimize technical, public health and environmental and ecological risks. This means that combinations of source control, treatment processes, flow schemes, users' conditions, and other engineering and scientific factors should be the basis for treated wastewater reuse scenarios [32]. Many factors still prevent the increase in reusing treated wastewater including economic, environmental, technical, social, regulatory, institutional and political constraints. Social and public acceptance for reusing of treated wastewater is an important factor. Awareness and education programs are needed also to improve the public acceptance and attitude towards wastewater reuse. Policies, strategies, monitoring and regulatory framework are needed for better wastewater treatment and management in the Arab region to protect human health and environment.

4.1. Economics of wastewater treatment and reuse

The cost of water reuse is influenced by various factors such as treatment level, intended reuse options, location of treatment, wastewater collection and transportation. According to Qadir et al. [33], the average cost of recycling water is approximately USA$1.79/m^3. However, compared to desalination, wastewater reuse has the advantage of cost. Fryer [34] demonstrates that the relative marginal cost of seawater desalination is higher than water recycling and amounts to up to USA$2,000 per acre-foot. The water recycling represented a general fluctuation pattern between approximately USA$300 and USA$1,000 per acre-foot. Even so, water recycling appears cheaper than desalination.

4.2. Engagement of private sector

To support the future success of public private partnerships in wastewater treatment and reuse in KSA three-pronged approach should be considered:

- Financial sustainability
- Guaranteed revenue streams
- Infrastructural sustainability

Currently, the Kingdom of Saudi Arabia's National Water Company (NWC) is developing a clear business plan for privatization of wastewater treatment and reuse infrastructure through the special purpose vehicle (SPV) model, which is relatively new to Saudi Arabia. SPVs offer great potential in isolating and managing potential financial risk, allowing access to new revenue streams and wider markets, enabling the encashment of assets and contracts via transfer to the SPVs, and increasing opportunity to embrace global best practice [16]. NWC holds firm to the belief that a market-led approach, with suitable protections that reflect NWC's goals and objectives, will allow the market to maximize reuse and optimize arrangements for the benefit of all. Nevertheless, the process is still ongoing to quantify and structure the precise arrangements to ensure effective cost recovery, while staying true to NWC's principles of improving KSA's macroeconomic environment, promoting sustainable development, and promoting citizens' welfare.

4.3. Social acceptance

Treated wastewater reuse is increasingly important for sustainable water resource management, especially in water-stressed countries located in the world's arid regions that rely on groundwater and desalination process for meeting their water demands. Data were collected from 624 households in the Dammam Metropolitan Area, Saudi Arabia using a structured questionnaire and analyzed using descriptive and inferential statistics. The results from logistic regression indicates that the likelihood of a household to accept reusing treated mixed wastewater is influenced by gender with odds ratio (OR) of 2.71–2.18, residential location (OR = 1.32–1.03), age (OR = 1.22–0.18) and educational level (OR = 1.33–0.98), with a tendency for more acceptance of treated grey wastewater than mixed wastewater [35]. These findings showcase the difficulty that the country could face concerning the public acceptance of treated wastewater for non-domestic uses to augment current freshwater sources even among the educated class. This study is significant because sustainably meeting the country's rising water demands requires the stringent implementation of strategic wastewater reuse policy, including bold steps towards wastewater streams segregation, and intensive public awareness campaigns to change negative perceptions on treated sewage effluent. This study concludes that a substantial reduction in the country's reliance on costly desalinated water and fast depleting non-renewable groundwater requires complete reuse and recycling of treated wastewater for wider non-conventional purposes. For most uses, reclaimed water tends to have lower social acceptance than desalination. There are various reasons why people do not trust reclaimed water. First, most people do not understand the difference between treated and untreated water [36]. Secondly, they are often concerned about the type of wastewater, treatment levels and the availability of information. There are particular concerns with the wastewater produced by the petroleum industry, brought to the surface when drilling oil. This kind of wastewater is difficult to treat due to the high content of oil [37]. Therefore, though reclaimed water undergoes a very thorough treatment process which makes it entirely safe to drink, the public are reluctant to drink treated sewage. However, it is not impossible that people will accept drinking such treated sewage. For example, Singapore has successfully used reclaimed water, a product named NEWater, to supply drinking water [38]. This reflects that treated wastewater could become widely accepted through public education.

4.4. Environmental impacts

There are some environmental disadvantages of desalination. Since Saudi Arabia is rich in oil and gas, clean energy such as solar energy tends to be used less than fossil energy. The overuse of fossil energy may cause serious environmental pollution. For instance, oil might generate large quantities of carbon dioxide, which is the main factor leading to global warming. Furthermore, the gas emissions from oil could undermine the ozone layer and cause acid rain (ibid.). In addition to environmental pollution caused by fossil energy, brine discharge is another serious problem. After desalination, the brines generally have a higher concentration of salt, nearly twice that of natural seawater [39]. The brines are generally discharged back to the same place where the seawater comes from. This might lead to increased concentration of salt in the sea, which is a potential threat to aquatics. In contrast with the desalination, wastewater reuse is regarded as an eco-friendly way to supply fresh water. Recycling water can maximize the use of rainfall and other current water resources so that the limited underground water resources can be conserved. In the meantime, decreased energy consumption could reduce the pollution caused by the use of fossil energy. Therefore, recycled water is a sustainable and eco-friendly method to supply good quality fresh water.

4.5. Technical challenges for wastewater reuse

When considering wastewater reuse for irrigation, an evaluation of the advantages, disadvantages and possible risks has to be made very carefully. Advantages include improvement of the economic efficiency of investments in wastewater disposal, irrigation water, and conservation of freshwater resources and use of wastewater nutrients (e.g., phosphate and nitrogen). Wastewater is normally produced continuously throughout the year, whereas irrigation is mostly limited to the growing season. Most of the recent experiments in Saudi Arabia shown that the use of treated wastewater as a supplemental irrigation source not only increased crops production, water use efficiencies but also served as a source of plant nutrients and reduce fertilizers use [40]. Many different irrigation methods are used by farmers to irrigate crops with treated wastewater. They range from watering individual plants from a can of water, flooding irrigation, to highly automated irrigation methods by a center pivot system. The success of the irrigation with wastewater is safe when the national regulations for each country regarding its treatment and use are strictly followed and the irrigation method and technology selected carefully. After irrigation, the wastewater returned to the environment usually will be with higher quality than the wastewater produced by the treatment plants

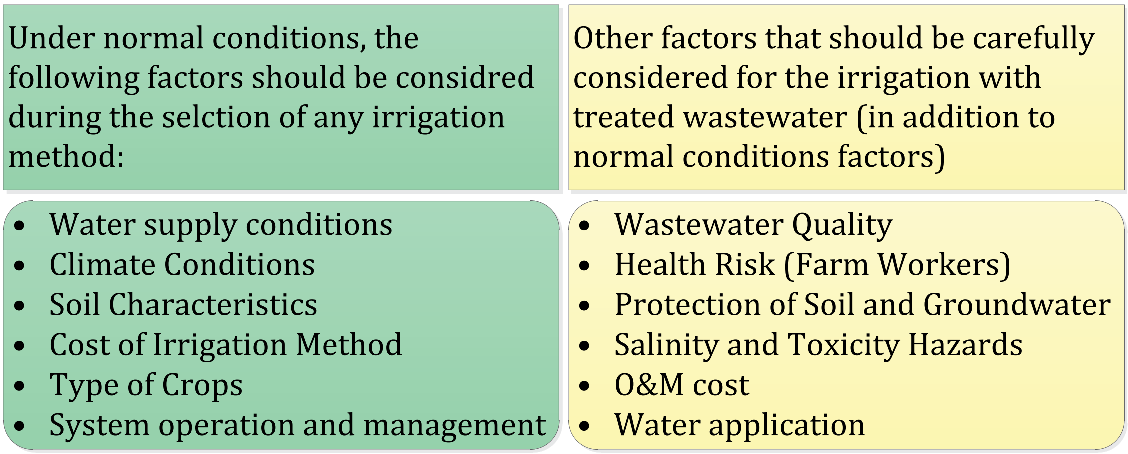

Fig. 7. Selection criteria for irrigation method with treated wastewater.

due to the additional treatment provided by the soil layers through the natural occurring of physical, biological and chemical process. Also, reuse of wastewater for irrigation is considered as an economic and environmental solution for wastewater discharge/disposal option. The selection of the most suitable irrigation methods with treated wastewater, many criteria should be considered as shown in Fig. 7.

4.6. Legal and institutional challenges

The treated wastewater reuse historically can be traced back to the 1970s in KSA. In 1978, the Council of Leading Islamic Scholars of KSA issued a fatwa (Islamic declaration) that encouraged the use of treated wastewater, and this fatwa paved the road to extensive use of treated wastewater in KSA: Impure wastewater can be considered pure water and similar to the original pure water, if its treatment using advanced technical procedures is capable of removing its impurities with regard to taste, color and smell, as witnessed by honest, specialized and knowledgeable experts. Then it can be used to remove body impurities and for purifying, even for drinking. If there are negative impacts from its direct use on the human health, then it is better to avoid its use, not because it is impure but to avoid harming human beings. The Council of Leading Islamic Scholars prefers to avoid using it for drinking (as much as possible) to protect human health. This fatwa alleviated any religious concerns that the public or officials might have concerning the use of treated wastewater. In KSA, the first regulation on wastewater treatment and reuse was published in May 2000, entitled 'Treated Sanitary Wastewater and Its Reuse Regulations', thus requiring secondary or tertiary wastewater treatment levels. Later on, in 2006, MWE published two booklets entitled 'Design Guidelines for Wastewater Treatment Plants in Saudi Arabia' and 'Using Treated Water for Irrigation: Controls, Conditions, Offences and Penalties'. These initiatives held an important role in the establishment of safe wastewater treatment and reuse practices standards. The 2006 standards for treated wastewater use specify the minimum treated wastewater quality requirements for restricted and unrestricted use.

5. Conclusions and recommendations

KSA treated wastewater reuse initiative provides large volumes of treated wastewater to customers for uses including agricultural, industrial, commercial, and district cooling uses among other non-potable purposes and has created an environmentally friendly and financially sustainable long-term market for treated sewage effluent. TSE benefits include: (i) addressing the water shortage challenges in KSA and conserving scarce water resources, (ii) developing new infrastructure and operating it efficiently and (iii) providing environmental benefits such as net carbon reductions, by indirectly contributing to lesser capital requirements for power and water generation.

KSA is progressing towards achieving its wastewater collection and treatment system coverage objectives and treated wastewater utilization goal. The ongoing initiatives are noteworthy and have had good success to date, but many more initiatives are still urgently required. The government's financial ability to support the wastewater vision is in doubt in view of the recent drop in crude oil prices, the heavily subsidized water tariff, and free wastewater services to the domestic sector. Therefore, the water and wastewater tariffs need adjustments that reflect the economic value of the service to secure the long-term sustainability of the system. A wastewater tariff system should be introduced to the domestic sector to complement the recently introduced tariff system for the governmental, commercial and industrial sectors. Moreover, the tariff system should provide financial sustainability for the wastewater system, and encourage water conservation given the country's social, cultural and political conditions. However, such water and wastewater tariff adjustments, if realized, might face strong public opposition given the low public awareness of the country's water shortage. Accordingly, there is a need for a proactive, long-term and well-designed public and institutional awareness campaign to promote water and wastewater tariff adjustments and treated wastewater use among various sectors of the society. Strong consideration should also be given to combining the recharge of alluvial aquifers by tertiary-treated wastewater with the development of downstream well production fields.

This will produce water supplies through the natural processes of the aquifer to use in industrial and urban supplies, and secure strategic reserves for emergency uses [30]. Therefore, new guidelines should be introduced into the treated wastewater guidelines for groundwater aquifer recharge and industrial uses. Further study is recommended to identify the optimum treatment technology for wastewater in the country and to evaluate and mitigate the potential impacts of treated wastewater contaminants on human health. The measures of the Saudi government for the development and implementation of the wastewater sector and the introduction of private-sector participation were an effective step in improving wastewater provision. However, a strong public-sector counterpart is required for the successful participation of the private sector. Therefore, further attention should be given to strengthening public-sector capabilities for the long-term sustainability of private-sector participation. Moreover, the public sector needs comprehensive human capacity building, regulation, institutional reform, and the development of a comprehensive treated wastewater database. All these measures will optimize the value of treated wastewater use and private-sector participation in wastewater provision.

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Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28218

263 (2022) 139–144
July

Fate of estrogens in Kuwaiti municipal wastewater treatment plants

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Received 28 February 2022; Accepted 27 April 2022

ABSTRACT

Estrogens are endocrine-disrupting chemicals that impact both human and animal health, even at very low levels. Fate of estrogens were evaluated for three municipal wastewater treatment plants (WWTPs) in Kuwait, through determination of estrogens concentrations in influent and effluent streams. The solid-phase extraction gas chromatography-mass spectrometry method was used for analysis of estrogens concentrations in wastewater. Obtained results indicated that concentration of estrogens in the influent streams ranged from 0.0 to 474 ng/L, while that in the effluent streams were between 0.0 to 233 ng/L. Both influent and effluent concentrations showed high variations around mean values. Total removal of estrogens were found to be 13%, 79%, 68%, for Kabd, Sulaibiya and Umm Al Hayman, respectively. Even with high influent loadings, Sulaibiya plant achieved the highest removal of all types of estrogens, except estrone. The obtained results demonstrated that WWTPs require upgrading/optimization to maximize estrogens' removal. The study also discussed the potential impacts of estrogens in treated wastewater reused as irrigation water and recommended that Kuwait urgently needs to develop regulations for estrogens discharges from WWTPs in order to prevent further pollution of marine environment and groundwater with estrogens.

Keywords: Wastewater; Municipal plants; Treatment; Estrogens; Removal efficiency

1. Introduction

Nowadays endocrine-disrupting chemicals (EDCs) are receiving great attention worldwide due to their potential adverse impacts on human and environmental health [1]. Estrogens hormones are a group of EDCs that are produced either naturally or synthetically. Natural estrogens are produced by humans and animals, whereas synthetic estrogens are man-made hormones. The most common types of natural estrogenic hormones are estrone (E1), estradiol (E2) and estriol (E3). Examples of the synthetic steroid are ethynylestradiol (EE2) and diethylstilbestrol (DES). EE2 and DES are commonly used in manufacturing birth control pills. Both natural and synthetic estrogens can adversely affect humans, animals or fish. Estrogens can disrupt the reproductive and sexual systems of fish, wildlife and humans [2]. According to the World Health Organization (WHO), the adverse impact of estrogens can appear at low concentrations as 1 ng/L [3].

Estrogens are often excreted as urine, and thus, they end ultimately in wastewater treatment plants (WWTPs). Since conventional WWTPs do not remove efficiently estrogens, they are considered to be the major point sources of pollution with estrogens [4]. In fact, the best control strategy for the problem of estrogens pollution is to remove estrogens efficiently during wastewater treatment [5]. This means that conventional WWTPs have to be upgraded/optimized for estrogens removal and regulations must be

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

issued to regulate discharges of estrogens from WWTPs. In Kuwait and many other countries, however, fate of estrogens in WWTPs is not even monitored due to absence of regulations [6].

Numerous studies have been conducted worldwide to investigate the occurrence and removal of estrogens by municipal WWTPs [7]. These studies have indicated that activated sludge WWTPs are generally effective in removing estrogens from wastewater [8,9]. However, the removal rates were found to depend on many factors such as estrogens type, estrogens load, plant design and plant operation mode [1].

Removals of estrogens in conventional activated sludge plants occur mainly during the secondary stage of treatment (biological treatment). In this stage, estrogens removals happen mainly through biodegradation and adsorption onto flocs. In fact, this stage alone was found to account for more than 80% of the removals of estrogens [10]. The removals of the primary stage (primary sedimentation) were found to be about 10%, while that of the preliminary treatment stage (bar screening and grit removal) were insignificant [11]. The operational parameters that have significant influence on the removal of estrogens in an ASPs were found to be the hydraulic retention time (HRT) and the solids retention time (SRT) [4,12]. Advanced treatment processes (e.g., membrane filtration and advanced oxidation processes) can also enhance the elimination of emerging contaminants such as estrogens [13].

The main objectives of this study were to determine the fate of estrogenic compounds in Kuwaiti municipal WWTPs. This information is urgently needed for assessing the environmental and health risks from estrogens pollution in Kuwait. The paper also discusses the potential adverse impacts of estrogens laden treated wastewater reused in Kuwait as irrigation water.

2. Materials and methods

Kuwait has four main activated sludge municipal WWTPs that have different design capacities and different treatment technologies. As shown in Table 1, Sulaibiya plant treats to advanced levels, using ultrafiltration (UF) and reverse osmosis (RO), while the other three plants treat to tertiary levels, using various activated sludge systems. During the study, however, estrogens concentrations were monitored for only three of these plants (Kabd, Sulaibiya and Umm Al Hayman WWTPs).

2.5-L grab samples of wastewater were collected monthly from the influent and effluent streams of the Kabd, Sulaibiya and Umm Al Hayman municipal WWTPs between October 2015 and August 2016. The samples were then transported to the laboratory for analysis in iceboxes and stored at 4°C until being analysed. Before analysis, however, the samples were allowed to come to room temperature. The sample preparation consisted of filtration through a prebaked glass fibre filter to remove suspended material. The filtered sample was then passed through Oasis HLB cartridge (Waters Corporation). The cartridge was preconditioned by passing methyl tert-butyl ether (MTBE) followed by methanol and finally ultrapure water. The sample was passed through the cartridge at 3–4 mL/min rate. The cartridge was then washed with methanol/water mixture (5/95). The dried cartridge was then eluated with methanol/MTBE to recover the retained estrogens. The eluate fraction was evaporated to dryness. The residue was transferred to a V-shaped vial for derivatization (conversion of a chemical compound into a product of similar chemical structures) with BSTFA and TMCS (100 μL). After derivatization, and evaporation, the residue was dissolved in hexane for GC/MS analysis by Shimadzu GC coupled to QP2010 Plus MS. Detailed description of the analytical condition and the standard method used for quantization of estrogens are given in our previous paper [14].

3. Results and discussion

3.1. Influent concentrations

The influent concentrations of both natural (E1, E2, E3) and synthetic (EE2) estrogens are given in Table 2. This table shows that the concentration of estrogens during the sampling period ranged from 0.0 to 474 ng/L. Although this is a bit of a wide range, it falls within the range of values reported for some countries [8,15–19]. Table 2 also shows that the concentrations of both natural (E1, E2, E3) and synthetic (EE2) estrogens in the influent stream of the Sulaibiya plant were the highest compared to the other two plants. This can be attributed to the fact that the Sulaibiya plant is the largest WWTP in Kuwait (Table 1), which treats about 60% of the wastewater generated in Kuwait. Furthermore, the catchment area of this plant cover almost 80% of the highly populated urban area of Kuwait City. In this area, most of the Kuwaiti and non-Kuwaiti families live. It is expected in such areas that large amounts of both natural and synthetic estrogens will be produced by menstruating females, pregnant women and users of contraceptive pills. In contrast, Kabd plant (250,000 m^3/d) and Umm Al Hayman plant are smaller and treat wastewater of suburb areas.

It is worth noting that standard deviations (STDs) of all types of estrogens concentrations, except for E1 in the

Table 1
Technical information about main municipal WWTPs in Kuwait

Plant	Type of ASP	Treatment level	Design capacity (m^3/d)
Kabd	Oxidation ditch	Tertiary (disk filtration and chlorination)	250,000
Sulaibiya	Oxidation ditch	Advanced (UF and RO and chlorination)	600,000
Umm Al Hayman	Carrousel	Tertiary (sand filtration, chlorination and UV)	27,000
Riqqa	Extended aeration	Tertiary (sand filtration and chlorination)	180

influent of Umm Al Hayman plant (Table 2), are larger than the mean values. This indicates that variations of influent concentrations around mean values were relatively high. This is also evident from values of coefficient of variation (C.V.) being greater than 100% in most of the cases (Table 2). The high variability of estrogens concentrations in the influent streams can partly be attributed to the grab sampling method adopted. Grab sampling method often represents wastewater quality at the instant of sampling, which can be different for the same time in another day. Usually wastewater quality changes continuously. However, it often shows diurnal, weekly and seasonal patterns.

Table 2 shows that the mean influent concentrations of E1 were determined to be 4, 72 and 11 ng/L for Kabd, Sulaibiya and Umm Al Hayman plants, respectively, which were the highest compared to the natural estrogens E2 and E3. This can be attributed to biodegradation and transformation of E2 and EE2 into E1 conjugates during transportation in the sewerage system [18]. In fact, Kabd, Sulaibiya and Umm Al Hayman plants are located at distances of 6, 25 and 10 km, respectively, from the catchment areas. Thus, the influent concentrations of E1 seemed to increase with the increase of the distance between the plant and its catchment area.

3.2. *Effluent concentrations*

Table 3 shows that the determined effluent concentrations of estrogens were between 0.0 to 233 ng/L, which fall within the range reported in literature [8,20–27]. As expected, the highest effluent concentrations of both natural estrogens (E1, E2 and E3) and synthetic estrogens (EE2) of the effluent streams were found out for the Sulaibiya plant. Sulaibiya plant experienced the highest estrogens loading during the sampling period (Table 2). Except for E1 concentrations, there were no significant difference between the average concentrations of estrogens in the effluent stream of Umm Al Hayman plant and that of Kabd plant. However, Umm Al Hayman achieved much lower concentration of E1 (1 ng/L) compared to Kabd plant (12 ng/L).

Table 3 indicates that the standard deviation (STD) of the effluent concentrations is greater than the mean effluent

Table 2
Influent concentrations of estrogens (ng/L)

Estrogenic type	WWTP	Minimum	Mean	Maximum	Std. deviation	C.V. (%)
E1	Kabd	0	4	14	5	147
	Sulaibiya	0	72	372	148	205
	Umm Al Hayman	6	11	14	3	29
E2	Kabd	0	3	9	4	128
	Sulaibiya	0	32	160	63	195
	Umm Al Hayman	0	5	10	4	83
EE2	Kabd	0	19	50	15	80
	Sulaibiya	0	194	474	199	102
	Umm Al Hayman	0	36	90	42	116
E3	Kabd	0	3	20	8	265
	Sulaibiya	0	65	360	145	225
	Umm Al Hayman	0	25	88	32	127

Table 3
Effluent concentrations of estrogens (ng/L)

Estrogenic type	WWTP	Minimum	Mean	Maximum	Std. deviation	C.V. (%)
E1	Kabd	0	12	54	19	155
	Sulaibiya	0	45	233	92	205
	Umm Al Hayman	0	1	4	2	243
E2	Kabd	0	1	8	3	265
	Sulaibiya	0	4	7	3	78
	Umm Al Hayman	0	2	8	4	155
EE2	Kabd	0	10	28	12	124
	Sulaibiya	0	14	70	28	200
	Umm Al Hayman	0	16	40	15	96
E3	Kabd	0	7	18	8	122
	Sulaibiya	0	12	22	10	83
	Umm Al Hayman	0	7	19	10	144

values for most of the cases. As for the influent, this also indicates that effluent concentrations varied highly from mean values. This was also confirmed by C.V. values greater than 100%. In other countries, removals of EDCs by activated sludge WWTPs were also found to have fluctuating trends [8,28–31]. However, the very high variations (STD > mean) in effluent concentrations may points out that the operation of the Kuwaiti WWTPs need to optimized/upgraded for the removal of estrogens.

3.3. Removal efficiencies

The average removal efficiencies of estrogens were calculated from the average influent and effluent concentrations and presented in Table 4. In spite of high loading, the Sulaibiya plant achieved the highest removal of both synthetic (93% for EE2) and natural estrogens (87% for E2 and 82% for E3), except E1. The best removal of E1 (94%) was achieved by Umm Al Hayman plant. This plant had also performed relatively better than Kabd plant in removing EE2 and E3.

The overall average removal of estrogens achieved by Sulaibiya, Umm Al Hayman, and Kabd plants were calculated to be 79%, 68% and 13%, respectively. The removal rates of Sulaibiya, Umm Al Hayman were consistent with the rates reported in literature for activated sludge systems [1,18]. As given in Table 1, Kabd and Umm Al Hayman treat up to tertiary level, whereas Sulaibiya plant treats up to advanced level that consist of UF and RO. Thus, the highest removal of estrogens at the Sulaibiya plant may be partly attributed to the advanced treatment level used there. However, this study did not investigate the contributions of the different stages of wastewater treatment (preliminary, secondary, tertiary or advanced) on estrogens removals nor monitored the operational variables of the plants. Thus, it is difficult to attribute the superior performance of the Sulaibiya plant to only advanced treatment nor give scientific explanations of the relatively poor performance of the Kabd plant.

3.4. Potential impacts of treated wastewater reused

As shown above, the final effluents of the three plants studied in Kuwait contain significant and highly fluctuating concentrations of estrogens that can adversely impact the human and environmental health. In a very recent study, it had been found that concentrations of EDCs, including estrogens, near the sewage outlets in the coastal area of Kuwait were high enough to initiate alterations in the hepatic tissue of fish in a period of two weeks [32].

On the other hand, threats to human health arises from ingesting estrogens via drinking water (un)intentionally mixed with treated wastewater or eating food irrigated by treated wastewater [33–36]. The likelihood of mixing treated wastewater with drinking water, intentionally or unintentionally, is zero in Kuwait as treated wastewater is not reused in any potable applications. Also treated wastewater is not allowed to be used for irrigating edible crops. In Kuwait treated wastewater is reused mainly for irrigating fodder crops. Nonetheless, there is a probability of indirectly ingesting estrogens via eating meat of animals fed on grass irrigated with treated wastewater. Although this risk seems to be very low, it needs to be carefully assessed in order to help in developing appropriate regulations for estrogens in effluents reused as irrigation water in Kuwait. Such regulations are urgently needed because estrogens may not only contaminate the food indirectly, but they may also pollute the groundwater [37]. Development of regulations for the discharges of estrogens into the environment has recently started in EU, USA, Japan and Canada. So far, however, only the EU has proposed some regulations for estrogens in agriculture waters [38].

4. Conclusions and recommendations

To assess the fate of estrogens in municipal WWTPs of Kuwait, influent and effluent concentrations of three plants (Kabd, Sulaibiya and Umm Al Hayman) were determined through solid-phase extraction gas chromatography-mass spectrometry method. Accordingly, the following conclusions and recommendations were drawn:

- Concentration of estrogens in the influent streams ranged from 0.0 to 474 ng/L, while that in the effluent streams ranged between 0.0 and 233 ng/L.
- Estrogens concentrations in both influent and effluent streams of the three plants varied highly from mean values.
- Influent concentration of E1 seemed to increase with the distance of plant from catchment area.
- The average removal of total estrogens were 13%, 79% and 68% for Kabd, Sulaibiya and Umm Al Hayman, respectively.
- Despite high influent loading, the Sulaibiya plant achieved the highest removal of EE2, E2 and E3
- Umm Al Hayman plant accomplished the best removal of E1.
- Operations of WWTPs in Kuwait need to be upgraded/optimized in order to maximize estrogens' elimination.
- Kuwait needs to regulate estrogens discharges from WWTPs in order to prevent further pollution of marine areas and ground water by estrogens.

Table 4
Removal efficiency of estrogens (%)

	E1	E2	EE2	E3	Total
Kabd	–234	66	49	–131	13
Sulaibiya	37	87	93	82	79
Umm Al Hayman	94	52	56	74	68

Acknowledgement

The authors wish to gratefully acknowledge the partial funding of this study by Kuwait Foundation for the Advancement of Sciences (Code: P214-42WE-01).

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Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28219

263 (2022) 145–151
July

Investigations on pharmaceuticals and radioactive elements in wastewater from hospitals in Kuwait

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Received 28 February 2022; Accepted 27 April 2022

ABSTRACT

A research studies were performed to characterize the wastewater generated from four hospitals located in Kuwait. In general, the wastewater generated from hospitals is discharged directly without any pre-treatment to public sewage treatment plants supervised by Ministry of Public Works (MPW). In this study, wastewater samples were collected on weekly basis from four hospitals (Al-Sabah, Al-Razi, Maternity and Chest diseases). Field wastewater measurements were carried out onsite for all sites including temperature, pH, electrical conductivity and oxidation–reduction potential. The collected samples were analyzed for determination of chemical parameters (total suspended solids and total dissolved solids), organic parameters including total organic carbon, chemical oxygen demand, biochemical oxygen demand and five dominate pharmaceutical compounds (four antibiotics sulfamethoxazole, metronidazole, ranitidine and trimethoprim plus paracetamol) and concentrations of radioactive elements in the wastewater (I-131, K-40, Tc-99m). The laboratory results indicated that all wastewaters from hospitals contained high levels of Tc-99m (0.14–14.151 Bq/L), I-131 (13.56–27.1 Bq/L), and low levels of K-40 (0.45–0.86 Bq/L). In addition, the pharmaceutics' concentration results revealed a high concentration of paracetamol (580 μg/L), where the maximum was detected in wastewater from Al-Razi hospital. The study recommends construction of onsite wastewater pre-treatment units.

Keywords: Radioactive isotopes; Hospital wastewater; On-site wastewater pre-treatment; Pharmaceutical compounds

1. Introduction

Wastewater from healthcare institutions usually contains disinfectants, antibiotics, pharmaceuticals and magnetic resonance imaging (MRI) contrast agents. Residues of pharmaceuticals are present in all wastewater treatment plants' effluents. The conventional activated sludge systems are usually not efficient for pharmaceuticals removal [1]. Inefficient removal of pharmaceuticals from wastewater treatment plants was also confirmed by other researchers [2–4]. Pauwels and Verstraete [5] discussed many aspects of chemicals present in wastewater belong to groups like antibiotics, disinfectants, pharmaceuticals and MRI contrast agents. El-Morhit et al. [6] investigated wastewater from hospitals in Morocco and found that mean value for chemical oxygen demand (COD) was 828.4 mg/L, which did not exceed the maximum limit for domestic wastewater. Novo and Manaia [7] studied factors influencing antibiotic resistance in municipal wastewater treatment plants and confirmed that longer hydraulic retention time corresponded to higher bacterial removal rates but still such rates were not efficient enough.

In Kuwait, there is lack of information regarding characterization of wastewater from hospitals. Kuwait Institute

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

for Scientific Research conducted two projects. The first one is WT013C [8], which presented parameters for wastewater from two hospitals namely, Al-Razi and Al-Sabah Hospital. The reported results were based on only one sampling from both hospitals which cannot represent actual fluctuation in concentrations or even considered averages of parameters. Alajmi [9] studied removal of the pharmaceuticals as metronidazole, trimethoprim, sulfamethoxazole, paracetamol and ranitidine from the wastewater coming to Sulaibiya Wastewater Treatment and Reclamation Plant in Kuwait. He has chosen these pharmaceuticals as the most frequently used in Kuwait and stated that their removal was above 97%. In the second project titled "A Baseline Screening Survey of Human Pharmaceuticals in Wastewater Treatment Plants in Kuwait (EM049C)", samples were collected from inflow and effluent of two wastewater treatment plants. The results indicated that influent concentrations of pharmaceuticals were higher than in final effluents and it was on the level of microgram per liter. The highest concentration was mainly for analgesics and anti-inflammatory drugs Gevao et al. [10] confirmed that pharmaceuticals are not fully removed in wastewater treatment plants during the standard biological process. In this study, the obtained field and lab results are compared with KEPA requirements regarding domestic wastewater effluent discharged to sewage network.

Prayitno et al. [11] investigated wastewater from three hospitals in Malang City in Indonesia and reported that COD ranged between 110, 351 mg/L, and total suspended solids (TSS) between 43 and 83 mg/L, respectively. These wastewater parameters exceeded the Indonesian quality standards. Al-Ajlouni et al. [12] evaluated wastewaters discharged from twelve hospitals in Jordan. High COD values (725–1,356 mg/L) and highly differential values for TSS (45–1,419 mg/L) were obtained. The current study includes collection of wastewater from four hospitals (Fig. 1). The aim of this research is to assess the concentration of antibiotics and radioactive elements in wastewater generated from four hospitals in Kuwait. The wastewater generated from four hospitals represents a combination of domestic and industrial water type. The generated wastewater sent to the public sewage network any treatment.

2. Materials and methods

Full chemical and microbiological characteristics of wastewater from studied hospitals were conducted at KISR and external laboratories. The main part of analyses was carried out at Sulaibiya Research Plant Laboratory, which belongs to Wastewater Treatment and Reclamation Technologies Program. Prior sampling, the following wastewater parameters were examined: temperature, pH, electrical conductivity (EC) and oxy-redox potential. The sampling was carried out on the weekly basis from beginning of August 2019 until 31 March 2021. Due to spread-out of Covid-19, the sampling was suspended from March 2020 until 18 January 2021. Samples were collected manually and all analyses were carried out in accordance to standard methods of APHA [13]. Analyses of radioactive isotopes (I-131, K-40, Tc-99m) presence were carried out by Laboratory of Environmental and Life Sciences Research Center in KISR by application of gamma spectroscopy. 4 L samples were prepared in the geometry of Marinelli Beaker (3,000 mL). Two gamma spectrometry system, equipped with High Purity Germanium Detectors (Ortic Coaxial GMX40-83-LB-C (relative efficiency 40%, FWHM at 1,332 is 1.95 keV), and Ortic Coaxial GEM50-83-LB-C (relative efficiency 50%, FWHM at 1,332 is 1.9 keV)) have been used. Both detectors were shielded with low background lead. The spectrometer was calibrated using a mixed nuclide standardized solutions QCYB41 (Eckert & Ziegler Nuclide GmbH).

The gamma spectrometers used were calibrated using standard reference materials. All analyses were carried out in accordance with APHA standards [13]. Presence of pharmaceuticals (four antibiotics such as metronidazole,

Fig. 1. Location map for Al-Sabah, Al-Razi, Chest and Maternity hospitals in Kuwait.

trimethoprim, sulfamethoxazole and ranitidine plus paracetamol) was determined by external laboratory (Biofocus in Germany).

3. Results and discussion

3.1. Analysis of wastewater pH from studied hospitals

The results of seasonal pH changes for wastewater from all the discussed hospitals are presented in Fig. 2. All statistical values for Al-Sabah hospital wastewater were the highest among all studied hospitals.

3.2. Analysis of wastewater EC from studied hospitals

The changes of electrical conductivity for wastewater from all hospitals is shown in Fig. 3. All presented values are smaller than maximum required by KEPA (2,000 µS/cm) for wastewater discharged to sewage network in Kuwait.

3.3. Analysis of wastewater oxy-redox potential for studied hospitals

The results of oxidation–reduction potential (ORP) are presented in Fig. 4. The minimum and maximum values of ORP were observed for Al-Razi hospital. Moreover, the mean value was also the highest.

3.4. Radioactivity in wastewater of all studied hospitals

The efficiency calibration curve of the Marneli Beake counting geometry used (3,000 mL) is shown in Fig. 5.

The collected gamma spectra were analyzed by Canberra Genie-2000 gamma acquisition and analyses software. Fig. 6 shows a gamma spectrum generated by the Genie-2000 software using the HPGe detector.

The activity concentration was calculated using the calibration parameters and the created radionuclide library that including the radiopharmaceuticals nuclide.

It should be noted that the concentration of the radionuclides was decay corrected, as most of the radiopharmaceuticals are short-lived radioisotopes. The obtained results were compared with maximum limits established by Environment Public Authority in Kuwait for materials discharged to environment (2017).

^{99m}Tc radio-pharmaceutical, which is extensively used for diagnosis has been found as a common radionuclide used in the four discharging points; while ^{131}I was found only in Al-Razi and Al-Sabah hospitals. The natural radionuclide ^{40}K was found in all samples within the natural

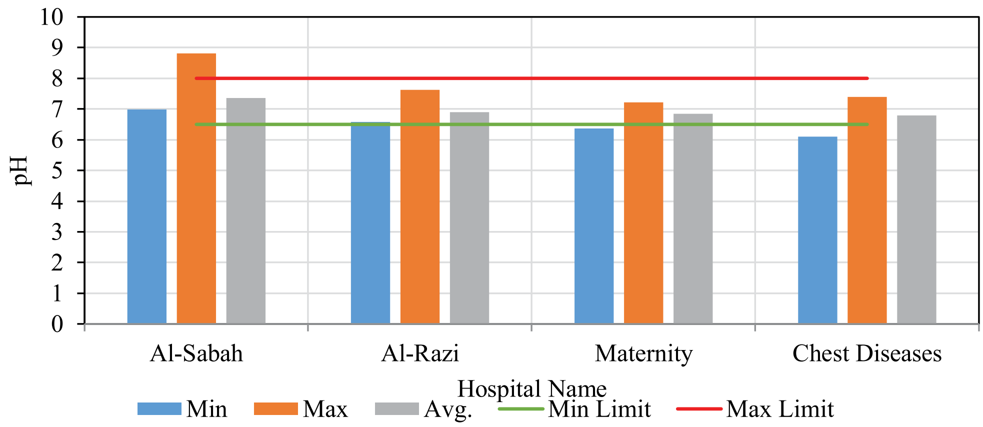

Fig. 2. pH variation for hospital wastewater in Kuwait.

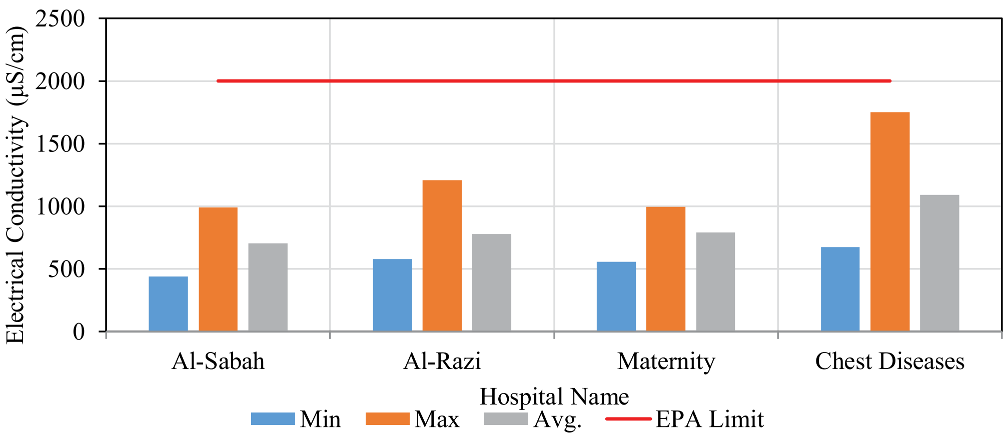

Fig. 3. Electrical conductivity variation for hospital wastewater in Kuwait.

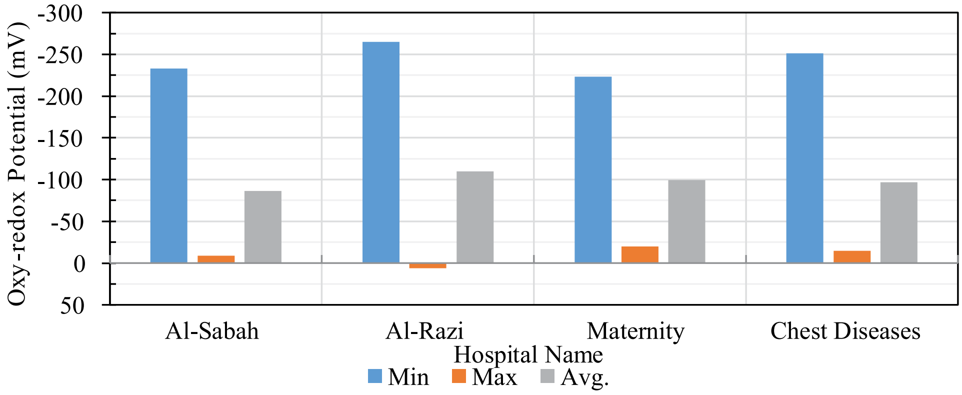

Fig. 4. Oxidation–reduction potential (ORP) variation for hospital wastewater in Kuwait.

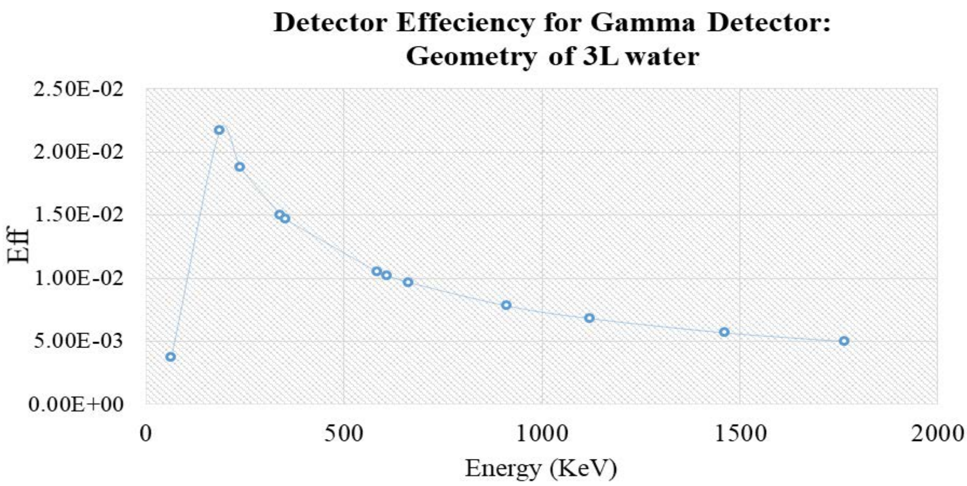

Fig. 5. Detector efficiency curve of the Marinelli Beaker counting geometry.

background level. According to the activity concentration observed in all healthcare centers, the ^{131}I varied from 0.03 to 27.1 Bq/L with an average of 5.48 Bq/L. Fig. 7 showed that ^{131}I was detected only on the discharge point of Al-Sabah healthcare center in frequent dates. The highest activity value belongs to the sample collected in 19 Sep 2019, which reached 27 Bq/L (Fig. 7).

On the other hand, ^{99m}Tc activity concentration varied from 0.14 to 14,151 Bq/L with an average value 717 Bq/L. The highest concentration was found in the sample of 25 January 2021 from Chest Diseases hospital (Fig. 8). The daily discharge of ^{99m}Tc from all hospitals exceeded daily maximum limit set by EPA in Kuwait for this radioactive isotope. The concentration of natural radionuclide ^{40}K presented in Fig. 9, which was in the natural background level, however the variation found was due to the amount of suspended particles in the sample.

3.5. Pharmaceutical compounds in wastewater generated by hospitals in Kuwait

The obtained mean concentrations of the five most common pharmaceuticals in wastewater generated from the four hospitals in Kuwait are presented in Table 1.

The highest value for all five studied pharmaceuticals was found in wastewater from Al-Razi hospital and it was equal 580 µg per liter. The lowest values of antibiotic concentration in studied wastewater were found for metronidazole and trimethoprim, which were below 0.01 µg/L.

4. Conclusion

Five pharmaceuticals including metronidazole, trimethoprim, sulfamethoxazole, paracetamol and ranitidine were analyzed and it was found that the maximum concentration among them appeared for paracetamol, which was equal 130 µg/L for the sample from Chest diseases hospital when for Al-Sabah and Al-Razi, the concentration reached 370 and 580 µg/L. Other antibiotics were frequently present in wastewater from all studied hospitals. Several researches indicated that advanced oxidation methods through using ozone and hydrogen peroxide gases were suggested to treat the wastewater antibiotics generated from the hospitals [14]. Therefore, the obtained low concentrations of pharmaceutical compounds might be treated through advanced oxidation techniques and not through the biological treatment (resistant to antibiotics) in municipal wastewater treatment plants.

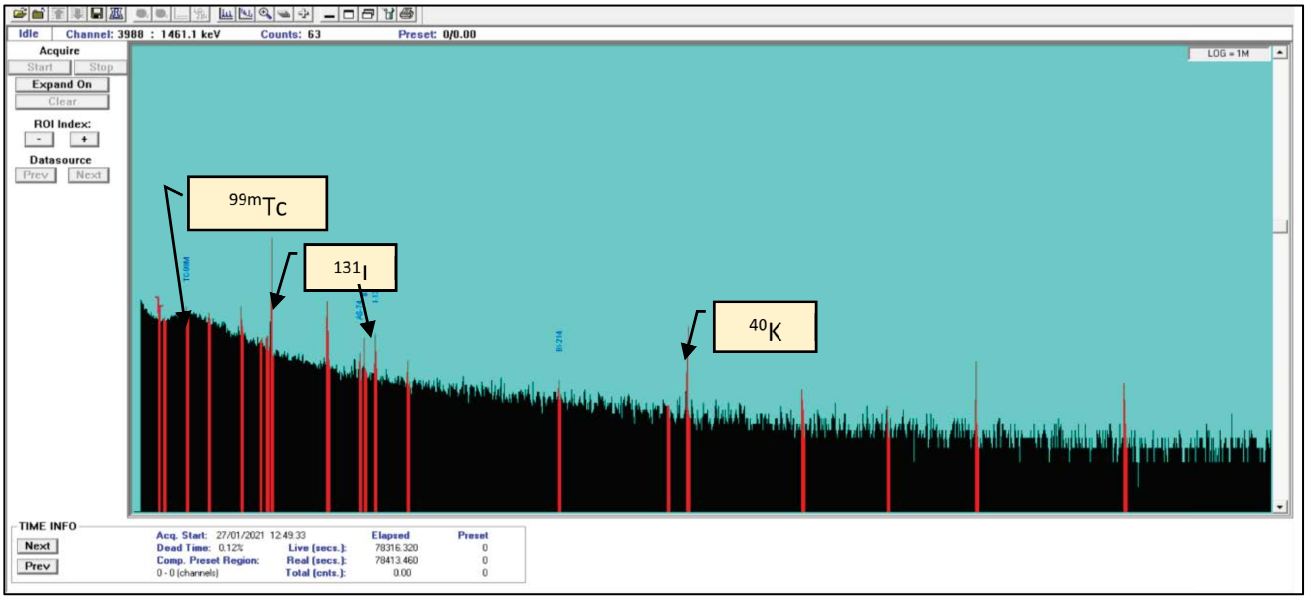

Fig. 6. Gamma spectrum generated by the Genie 2000 Software using the HPGe detector.

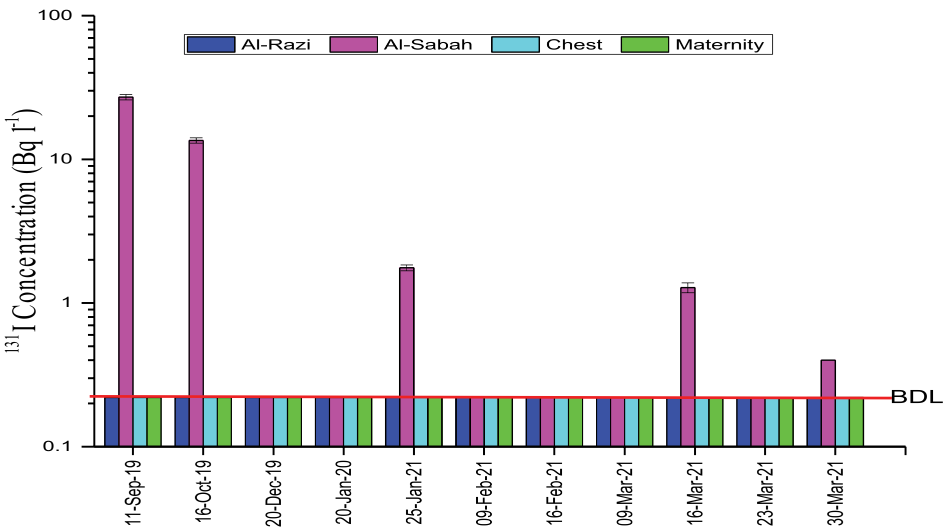

Fig. 7. ^{131}I activity concentration in wastewater from all studied hospitals in Kuwait.

5. Recommendation

- Yearly wastewater monitoring program should be established for all hospitals. The wastewater sampling campaign should cover full analysis of physical, chemical, organics, microbial, radioactive isotopes, toxicity, human hormones and pharmaceutical compounds. In addition, onsite field measurements should be conducted prior to sampling. Automatic online sampling equipment should be implemented to obtain fully representative samples.
- Onsite treatment units should be constructed within each hospital premises to treat and if possible reuse of generated wastewater. The capacity of treatment units should be designed based on the volume of wastewater generated by each hospital daily.
- The suggested onsite treatment unit should consist of the following stages: preliminary treatment, extended aeration, membrane bioreactor, and adsorption by activated granulated carbon, ozone oxidation for permeate disinfection by UV and excess sludge utilization.

Acknowledgment

The authors would like to extend their appreciation to the Kuwait Foundation for the Advancement of Science (KFAS) for its generous financial support. The overall support from the management of the Kuwait Institute for Scientific Research (KISR) is also gratefully acknowledged. Special thanks are extended to the staff of Technical Division

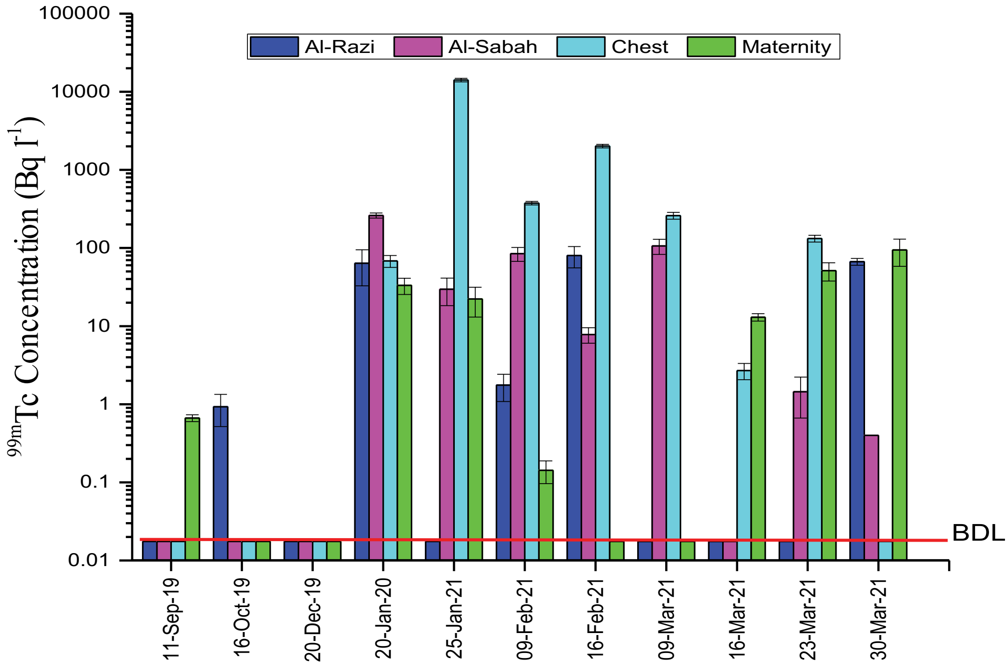

Fig. 8. ^{99m}Tc activity concentration in wastewater from all studied hospitals in Kuwait.

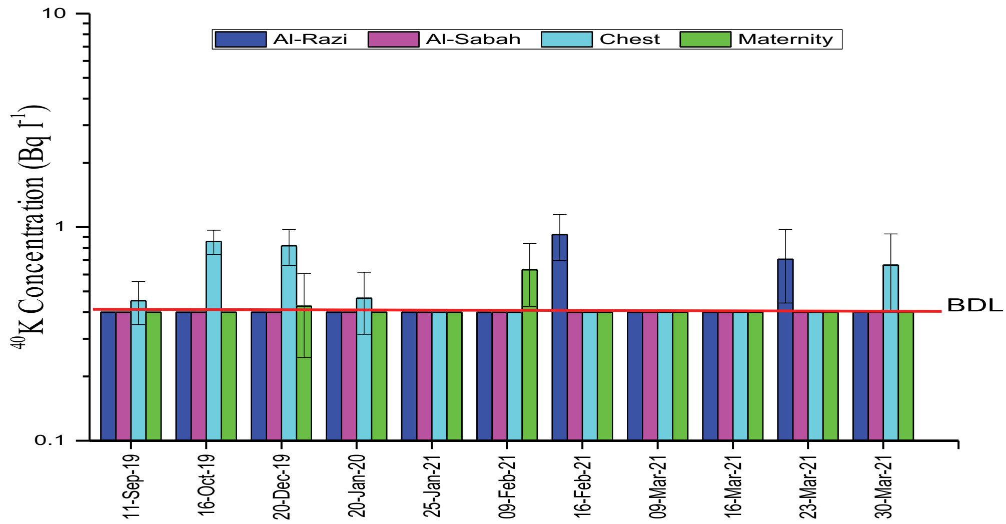

Fig. 9. ^{40}K activity concentration in wastewater from all studied hospitals in Kuwait.

Table 1
Mean concentrations of pharmaceutics in wastewater from four hospitals in Kuwait

S. No.	Name of pharmaceuticals	Names of hospitals			
		Al-Sabah	Al-Razi	Maternity	Chest
1	Metronidazole (µg/L)	10.12	0.403	45.8	0.159
2	Paracetamol (µg/L)	141.6	179.2	66.55	49.04
3	Ranitidine (µg/L)	0.26	0.05	0.07	0.10
4	Sulfamethoxazole (µg/L)	0.42	0.71	0.06	0.03
5	Trimethoprim (µg/L)	0.08	0.11	0.02	0.01

of Ministry of Health for assistance in weekly sampling. The authors also acknowledge the efforts of the staff from the Water Research Center (WRC) and the Environmental and Life Science Research Center (ELSRC) at KISR who were contributing in evaluation of radioactivity in analysis of wastewater.

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Desalination and Water Treatment
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doi: 10.5004/dwt.2022.28220

263 (2022) 152–159
July

Testing of an optimization model for optimal sewer system layout and wastewater treatment locations

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Received 28 February 2022; Accepted 19 June 2022

ABSTRACT

Wastewater systems are one of the most crucial systems for urban infrastructure, especially in regions with large population densities. Determining the optimal (minimum cost) sewer pipe layout and the location of wastewater treatment plants (WWTPs) must take into considerations of economic, environmental, and hydraulics of pipe flows. This paper presents an optimization model for minimum cost design of sewer system layout and wastewater treatment plant locations of the combined systems. The model can be used to minimize the total costs associated with a sewer network and WWTPs by determining an optimal layout of sewer pipes and the locations of WWTPs that meet connectivity, continuity, and capacity requirements. The model is formulated as a 0–1 Integer nonlinear programming (INLP) problem solved using in the general algebraic modeling system (GAMS). The application of the model is illustrated using a simple example to demonstrate that the method allows for significant cost savings.

Keywords: Water resources; Sewer layout; Optimization models; Wastewater planning

1. Introduction

The problem of regional wastewater systems planning is determining the minimum cost sewer system layouts and locations of wastewater treatment plants (WWTPs). The primary goal in this paper is to develop an optimization model for sewer system layouts and locations of regional wastewater treatment systems minimizes total costs. The concept of iso-nodal lines (INL) to define dendritic or branching piping systems originally introduced by the study of Mays [1] are important to this work.

There are various types of collection systems from the local level, as in storm sewer systems, to the regional level, as in planning wastewater systems. In addition, the INL method can be used for any system that has a dendritic or tree-type network. Brand and Ostfeld [2], Mays et al. [3] and Cunha et al. [4] provide background work that is very important to the concepts of regional wastewater pipelines and treatment plant systems. Haghighi and Bakhshipour [5] & Karovic and Mays [6] provide background information on the optimal layout of dendritic piping systems.

2. Cost functions

The cost functions for wastewater systems, including installation, maintenance, and operating costs are usually strictly non-linear [2]. Mays et al. [3] developed cost functions for regional water/wastewater systems, including installation, operating, and maintenance costs. These functions are strictly non-linear equations and are hard to define for different regions and economies of scale. This indicates that solutions would concentrate treatment into one or very few plants rather than in many plants. The influence of the degree of economies of scale can be seen in the results in Table 1.

The results concern a case study where all data is maintained except the cost function ($C = aQ^b$). Therefore, if only

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

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the level of the economy of scale is changed, the solutions will be different. As the economy of scale level increases (*b* value is lower), the solution is obtained for a smaller number of WWTPs. The solution of the wastewater problem at the regional level is a compromise. On the one hand, the solution where each community treats its own wastewater does not take into account the important economies of scale. On other hand, the solution where there is only one WWTP implies higher costs for taking wastewater from all discharge points to the WWTP (centralized system). Neither solution is an efficient, sustainable solution. Therefore, to find the best solution, there must be a trade-off between transportation costs and savings provided through economies of scales. Haghighi and Bakhshipour [5], Karovic and Mays [6], Swamee and Sharma [7] used cost functions to determine such things as considered costs per unit length, commercial diameter, or per unit volume, such as manholes. In reality, the system will be highly complex. It is anticipated that the parameters that will be the most dominant in determining the total cost will differ as a function of the particular systems' layout, components, cost functions, and imposed loadings. Table 2 provides a summary of information about the overall cost functions associated with wastewater reuse systems that can be used in the project.

3. Iso-nodal line and connectivity model

An iso-nodal line (INL) is defined as an imaginary line connecting nodes and pipes that a total number of INLs must be equal to the total number of pipes connected to outlines of the sewer system as shown in Fig. 1. Mays and Wenzel [11] applied the concept of INL for determining the minimum cost design of storm sewer system using discrete differential dynamic programming (DDDP). Mays et al. [12] used the INL concept for simultaneously determining the minimum cost layout and design of sewer systems considering physiographic, topographic, and hydrologic conditions. Other researchers used the concept of iso-nodal lines [13,14].

Recently, Alfaisal and Mays [15] used the concept of INL in an optimization model for simultaneously determining minimum costs of layout and pipe design of storm sewer systems using a 0–1 integer nonlinear programming (INLP). The application of INLP to the optimal layout design of a sewer system includes two INLs, which represent ground surface elevations (i.e., from an upstream INL to the next downstream INL), a recursive procedure. Now, considering the flow of the system (i.e., from INL *i* to INL *j*), the computations are performed over the possible set of drops in crown elevations for each vector of possible connection of nodes on INLs *i*, *j*, and *k*. Flow directions for the set of nodes for all upstream and downstream node connections (outlets) denote which of these nodes' connections are possible for a sewer system layout. A vector of possible connections is needed for each connection.

Table 1
Wastewater system costs for different cost functions [4]

Number of WWTP	14	10	5	2	1
Low economies of scale $C = aQ^{0.95}$	100	101.4	104.4	112.1	121.1
Medium economies of scale $C = aQ^{0.86}$	101.1	100	100.8	106.8	112.9
High economies of scale $C = aQ^{0.75}$	106.9	103.1	100	104	107.3

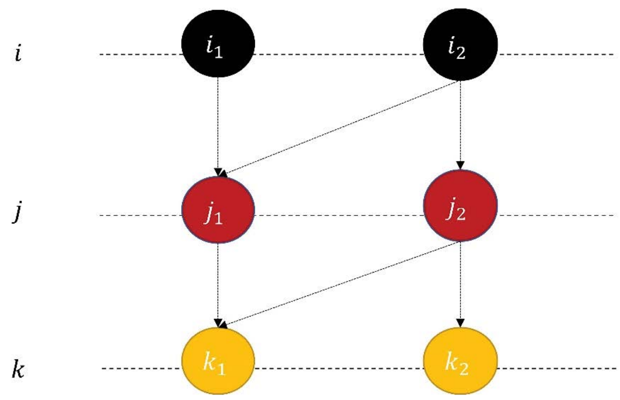

Fig. 1. Iso-nodal line layout and possible nodes connections.

Table 2
Overall cost functions associated with wastewater reuse systems

Reference	Overall cost
Brand and Ostfeld [2]	= 0.33 \$/m^3 (capital costs of WWTP)
	= 2.88 $Q^{0.99}$ (capital cost of WWTP).
	= 0.0825 $Q^{0.96}$ (operation and maintenance costs of WWTP).
Mays et al. [3]	= 80 $Q^{0.461}$ (capital cost of pipeline).
	= 4.56 × 10^{-3} L (distance in mile) $Q^{0.495}$ (operation and maintenance costs of pipeline). All flow rates *Q* are in gallons per day.
	= 1.85 \$/m^3.
Al-A'ama and Nakhla [8]	capital cost (= 1.33 US\$/m^3), tertiary treatment (= 0.16 US\$/m^3), collection (= 0.3 US\$/m^3) and distribution (= 0.06 US\$/m^3).
Kajenthira et al. [9]	Secondary WWTP in the range of 0.13–0.63 US\$/m^3. Tertiary WWTP in the range of 1.19–2.03 US\$/m^3.
Al-Zahrani et al. [10]	WWTP reuse ranges from 0.82 to 2.03 US\$/m^3 with an average cost of 1.43 US\$/m^3.

This vector has a dimension equal to the number of possible flow directions from each upstream node on INL i to downstream nodes on INL j and the same from the upstream node on INL j to downstream node on INL k. Each position in the vector of possible connections: which either has a value of 1, implying possible connection of the nodes, or a 0, implying no possible connection.

Fig. 2a shows the drainage directions for a stage n between INLs i and j. For each of the upstream nodes (i_n = 1, 2, 3) on INL i, there are four flow directions: one to each downstream node (j_n = 1,2,3,4). As an example, if the only possible connection of node $i_n = 3$ is to node $j_n = 3$, then $T_{3,3} = 1$, $T_{3,1} = 0$, $T_{3,2} = 0$, and $T_{3,4} = 0$. The concept of the vector of possible connectivity is shown in Fig. 2b. Indeed, more than one node on INL i may have a possible connection to a node on INL j, allowing for branches, so that the tree type network of a storm sewer system can be defined. Each node on INL i must have a possible connection to a node on INL j. The total vector of possible connectivity T_n at any stage n includes all possible connections.

The optimization computations are performed for each possible connection in stage n of INLs (i, j, and k) by considering flows at nodes at the upstream and downstream of each possible open flow connection. Once the decisions for each possible connection at stage n of the system have been considered by the optimizer, the next step is to determine the minimum cost layout (connection of nodes) for that pipe connection. For connectivity optimization, it is difficult to incorporate the flow directions from upstream nodes as a second decision variable at the GAMS optimization. The main difficulty is the inability to compute the flow rates for the succeeding downstream pipes. To solve this difficulty, a special equation was built up in the optimization code. In order to compute these flow rates for the optimization in the next downstream node, connectivity must be defined for the previous upstream node. However, connectivity can be defined using MINLP in GAMS after the computational procedure over all pipes (minimum costs) is completed. The total vector of possible connectivity T in Fig. 2b shows as following:

A connectivity model at nodes (i_n = 1 or 2) on INL i can be formulated using the costs required to continue draining each node (j_n = 1 or 2) on INL j through the next downstream node on INL j for each of the possible connections in node (i_n = 1 or 2). The possible connections for a simple network are shown in Figs. 3 and 4. The total minimum cost for each connection to drain the nodes on INLs i and j to INL k through the nodes on INL j can be computed. From the optimization computations, the minimum cost design for each possible connection and each downstream node up to INL j are known. The minimum total cost up to INL k can be computed by performing the computations for each possible connection between INLs j and k, taking into account the minimum costs up to INL j.

This gives a minimum total cost for portions of the system up to INL k, considering each of the possible connections between INLs i and j in addition to the costs to continue draining the flow through the next downstream INL. Essentially, this amounts to performing designs for each possible drop within the corridors defined by the possible connections from INLs j to k. The cost of placing nodes on INL k is included. Once the minimum cost required to continue draining each node on INL j through the next downstream pipe for each possible connection in connection pipe is known, a model can be formulated to select the connectivity or layout for each pipe connection.

3.1. Mathematical formulation

The connectivity approach is used to define the minimum cost connections of nodes once the computations have been completed for each possible connection between

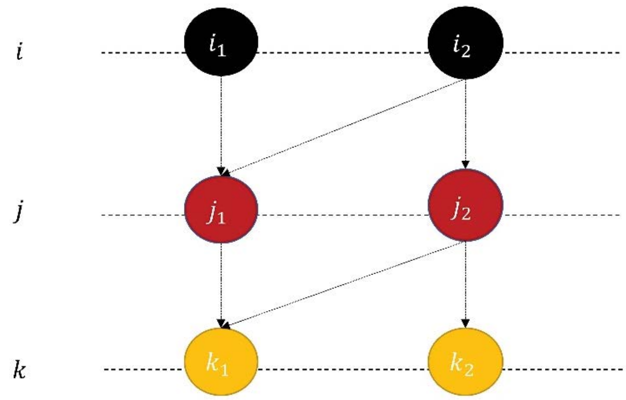

Fig. 3. Possible layouts to drainage line k.

$$T_{1,1} = 1 \quad T_{2,1} = 0$$
$$T_{1,2} = 1 \quad T_{2,2} = 1$$
$$T_{1,3} = 0 \quad T_{2,3} = 1$$

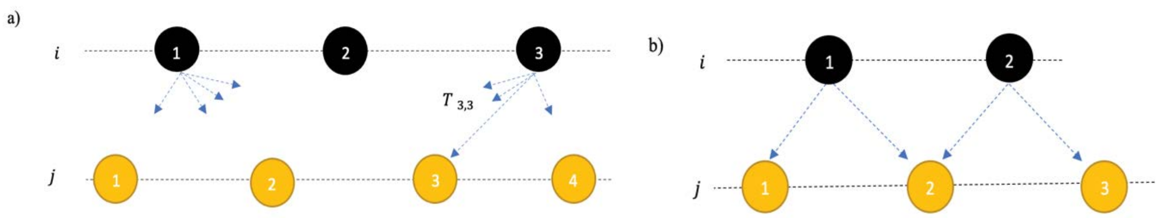

Fig. 2. (a) Drainage directions and (b) possible connections (adapted from Mays [1]).

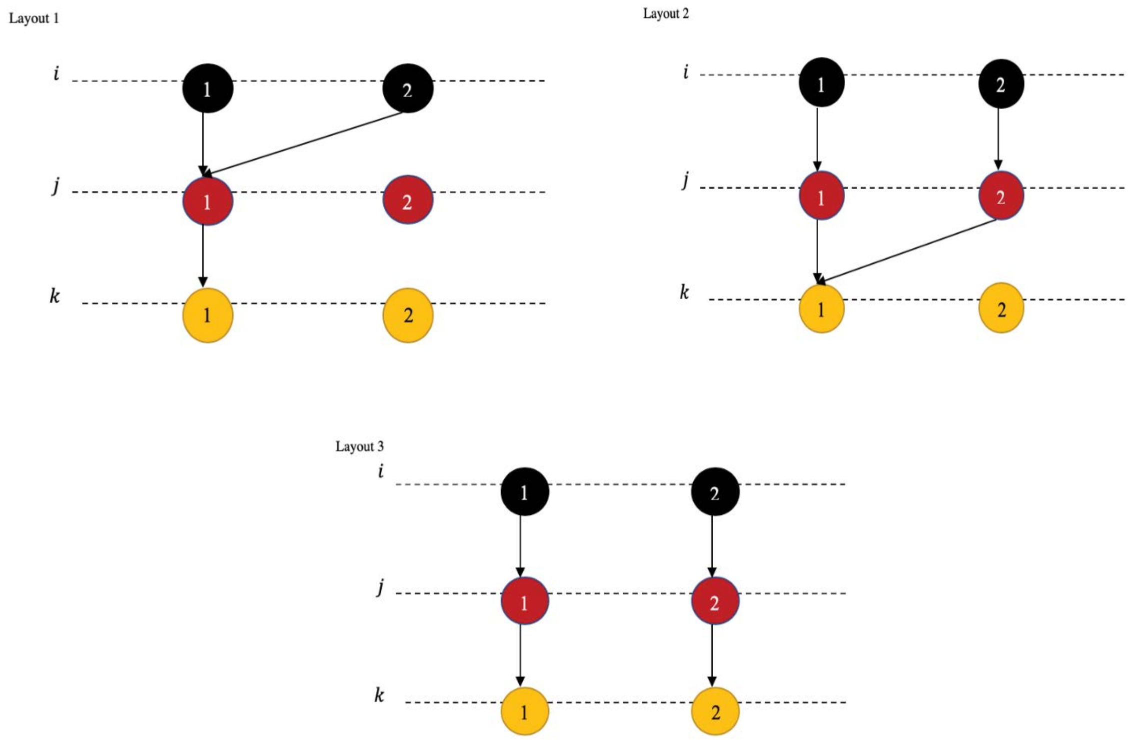

Fig. 4. Possible layouts.

nodes n on INL i and nodes n on INL j before proceeding to the downstream nodes n on INL j to nodes n on INL k. The minimum cost layout must be chosen so that each upstream node on INL i is connected to downstream nodes on INL j by only one pipe, which must be one of the possible connections.

The model constraints allow for only one pipe to drain node n (i.e., the summation of the 0–1 variables, each representing a layout that allows node n to be drained, is equal to 1). Because each upstream node n must be drained, a constraint exists for each of these nodes n = 1, 2, 3, … N. Similarly, constraints can be developed to satisfy the restriction that each node on INL j is drained by only one pipe connecting to node n on INL k.

- The flow in pipes from each source node i must flow through one collection node j, which can be satisfied as follows:

$$\sum_j a_{i,j} x_{i,j} = 1 \quad \forall\, i \tag{1}$$

where $a_{i,j}$ is equal to 1 if there is a possible pipe connection from node i to node j and is equal to 0 if there is not a possible pipe connection from node j to node k; the binary decision variable $x_{i,j}$ is defined as either 0 or 1 where $x_{i,j}$ = 1 indicates a pipe connection between nodes i and j and $x_{i,j}$ = 0 indicates no connection.

- The flow from each collection node j must flow through one WWTP node on INL k, which can be satisfied as follows:

$$\sum_k b_{j,k} y_{j,k} = \begin{cases} 1 & \text{if } \sum_k QI_{j,k} > 0 \\ 0 & \text{if } \sum_k QI_{j,k} = 0 \end{cases} \tag{2}$$

where $b_{j,k}$ is equal to 1 if there is a pipe connection from node j to node k and $b_{j,k}$ is equal to 0 if there is not a possible pipe connection from node j to node k; the binary decision variable $y_{j,k}$ is defined as either 0 or 1 where $y_{j,k}$ = 1 indicates a pipe connection between nodes j and k and $y_{j,k}$ = 0 indicates no connection.

- Continuity constraints for flows in the system states that all the system must be in equilibrium, so that the flow produced at source nodes on INL i must be sent to WWTP nodes on INL k. The continuity equation at source nodes on INL i to collection nodes on INL j is

$$QR_i = \sum_j QS_{i,j} a_{i,j} x_{i,j} \quad \forall\, i \tag{3}$$

The continuity equation at collection nodes on INL j to WWTP nodes on INL k is

$$\sum_i QS_{ij} a_{i,j} x_{i,j} - \sum_k QI_{j,k} b_{j,k} y_{j,k} = 0 \quad \forall\, j \tag{4}$$

- Lower and upper bound constraints. However, bounds play a significant role in nonlinear (NLP) models. To avoid an undefined operation, such as division by zero, it may be essential to provide bounds. In NLP, a definition of a reasonable solution space will assist in efficiently finding a solution.

$$Q_{\min_{i,j}} a_{i,j} x_{i,j} \leq QS_{i,j} \leq Q_{\max_{i,j}} a_{i,j} x_{i,j} \quad \forall (i,j) \tag{5}$$

and

$$Q_{\min_{j,k}} b_{j,k} y_{j,k} \leq QI_{j,k} \leq Q_{\max_{j,k}} b_{j,k} y_{j,k} \quad \forall (i,j) \tag{6}$$

where $Q_{\min}$ and $Q_{\max}$ are respectively the minimum and the maximum amount of wastewater through the system.

The objective is to select a set of possible layouts to satisfy the above constraints such that the minimum cost of the complete layout is selected for two stages of the system. The cost of each possible layout is determined by selecting the cheapest layout of the possible connections associated with flows. The cost of all upstream pipes, the WWTP, and the cost of the possible layout represent the cost coefficients, CPIP, CPIP1, and CWWTP, for the objective function. The objective function can be expressed as:

$$\text{Min cost} \sum_i \sum_j \text{CPIP } QS_{i,j} a_{i,j} x_{i,j} + \sum_j \sum_k \text{CPIP2 } QI_{j,k} b_{j,k} y_{j,k} + \sum_j \sum_k \text{CWWTP } QI_{j,k} b_{j,k} y_{j,k} \tag{7}$$

The optimization model, defined by the above equations, represents a 0–1 integer nonlinear programming optimization problem.

3.2. Test Example 1

To build the model in GAMS and ensure that the model formulation is correct, two examples were considered: the vector of possible connections with different costs associated with the flow and the vector of possible connections with same costs associated with flow, Fig. 5. Overall, continuity and connectivity constraints were used to ensure that the model would run perfectly through these two examples, changing the costs of pipelines and of WWTPs, and a possible path either way from source nodes on INL *i* to collection nodes on INL *j* or collection nodes on INL *j* to WWTP nodes on INL *k*). In test Example 1, the possible paths for $a_{i,j}$ and $b_{j,k}$, are considered, as shown in Tables 3 and 4:

It was assumed that all total costs of installation, operation, and maintenance from source nodes on INL *i* to collection nodes on INL *j*, CPIP, and total costs of installation, operation, and maintenance from collection nodes on INL *j* to WWTP nodes on INL *k* CPIP2 were included, as shown in Tables 5–7.

The optimum configuration of Example 1 shows that the flow tries to go through the possible paths allowed in the system and, at the same time, takes a minimum cost path, so

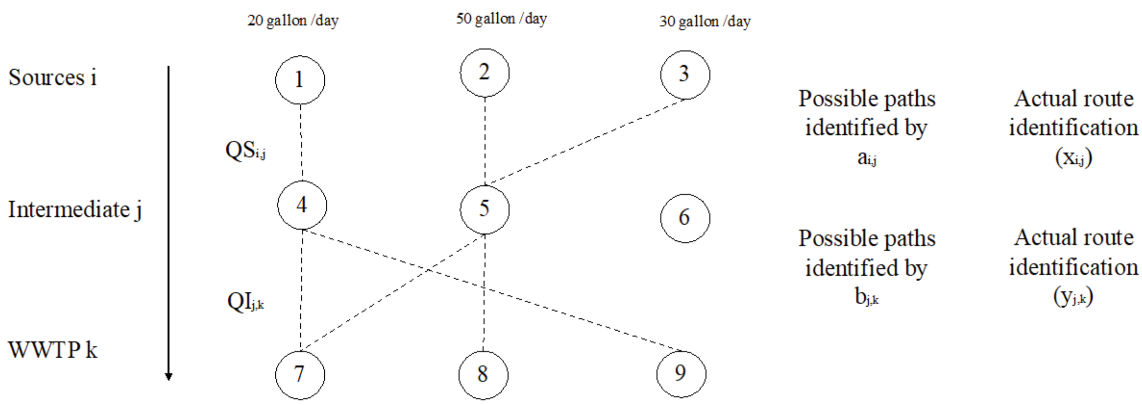

Fig. 5. Input values for the model in GAMS for Example 1.

Table 3
Possible paths of draining wastewater from sources nodes *i* to intermediate nodes *j*, $a_{i,j}$, for Example 1

Possible paths		Candidate intermediate nodes		
		n4	n5	n6
Sources node	n1	1	No possible path	No possible path
	n2	No possible path	1	No possible path
	n3	No possible path	1	No possible path

Table 4
Possible paths of draining wastewater from intermediate nodes *j* to WWTP nodes *k*, $b_{j,k}$, for Example 1

Possible paths		Candidate WWTP nodes		
		n7	n8	n9
Candidate intermediate nodes	n4	1	No possible path	1
	n5	1	1	No possible path
	n6	No possible path	No possible path	No possible path

Table 5
Assumption of the total costs of installing, operating and maintenance from sources nodes i to intermediate nodes j, CPIP, $/gallon for Example 1

Total costs		Candidate intermediate nodes		
		n4	n5	n6
	n1	$2	No possible path	No possible path
Sources node	n2	No possible path	$5	No possible path
	n3	No possible path	$1	No possible path

Table 6
Assumption of the total costs of installing, operating and maintenance from intermediate nodes j to WWTP nodes k, CPIP2, $/gallon for Example 1

Total costs		Candidate WWTP nodes		
		n7	n8	n9
	n4	$3	No possible path	$3
Candidate intermediate nodes	n5	$3	$5	No possible path
	n6	No possible path	No possible path	No possible path

Table 7
Assumption of the total costs of new plant construction and operating and maintenance of wastewater treatment plants, CWWTP, $/gallon for Example 1.

Candidate WWTP	$/gallon
n7	$2
n8	$2
n9	$3

all discharges are ended by n7, which has the lowest WWTP cost ($2/gallon/d). Fig. 6 with total costs of $820/d.

3.3. Test Example 2

Example 2 performed the model for a different model parameters inputs that considered more possible paths and the same cost values for objective functions. The flowing Tables 8 and 9 and Fig. 7 are the input data for the example system. In test Example 2, the possible paths for $a_{i,j}$ and, $b_{j,k}$, are as follows:

The total costs of installation, operation, and maintenance from source node i to intermediate node j, CPIP, and total costs of installation, operation, and maintenance from intermediate node j to WWTP node k, CPIP2 are assumed to be equal to $1 /gallon as shown in Tables 10 and 11.

Table 8
Possible paths of draining wastewater from sources node i to intermediate nodes j, $a_{i,j}$, for Example 2

Possible paths		Candidate intermediate nodes		
		n4	n5	n6
Sources node	n1	1	1	No possible path
	n2	No possible path	1	No possible path
	n3	No possible path	1	1

Table 9
Possible paths of draining wastewater from intermediate node j to WWTP nodes k, $b_{j,k}$, for Example 2

Possible paths		Candidate WWTP nodes		
		n7	n8	n9
	n4	1	1	No possible path
Candidate intermediate nodes	n5	No possible path	1	No possible path
	n6	No possible path	1	1

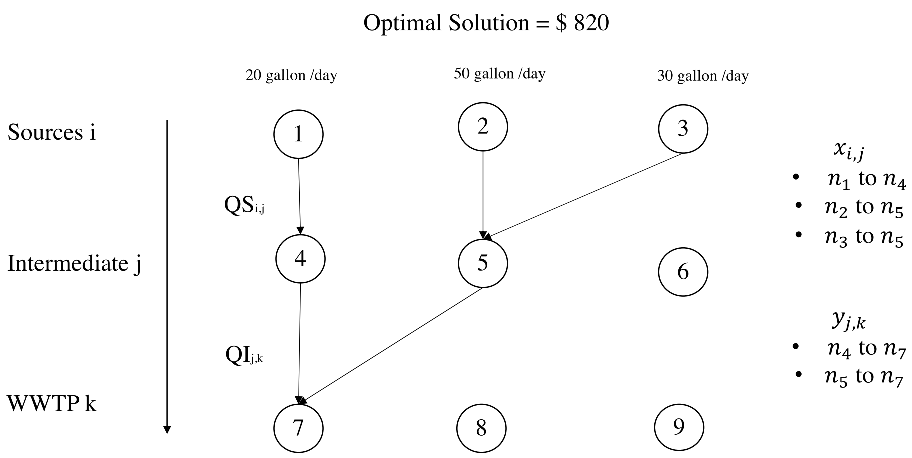

Fig. 6. Optimum configuration for Example 1.

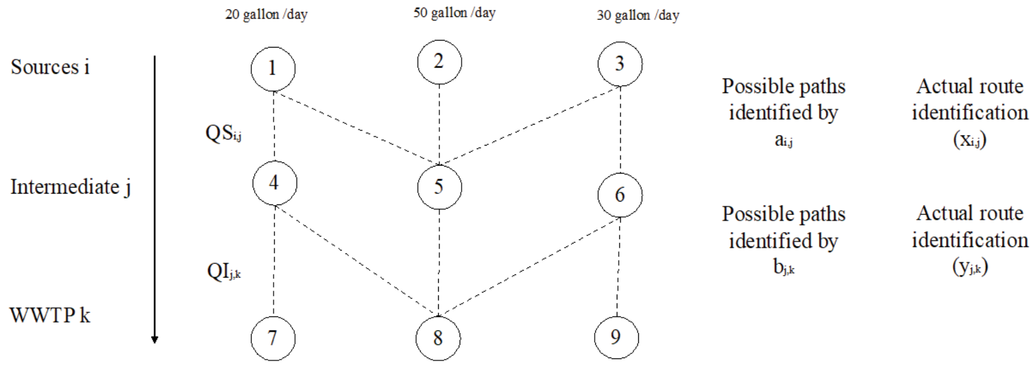

Fig. 7. Input values for the model in GAMS for Example 2.

Table 10
Assumption of total costs of installation, operation, and maintenance from source node *i* to intermediate node *j*, CPIP, $/gallon for Example 2

Total costs		Candidate intermediate nodes		
		n4	n5	n6
Sources node	n1	$1	$1	No possible path
	n2	No possible path	$1	No possible path
	n3	No possible path	$1	$1

Table 11
Assumption of total costs of installation, operation, and maintenance from intermediate node *j* to WWTP node *k*, CPIP2, $/gallon for Example 2

Total costs		Candidate WWTP nodes		
		n7	n8	n9
Candidate intermediate nodes	n4	$1	$1	No possible path
	n5	No possible path	$1	No possible path
	n6	No possible path	$1	$1

Assumed costs of new WWTP construction, operation, and maintenance would be equal to $1/gallon for all nodes. The optimum configuration for test Example 2 is shown in Fig. 8, with total costs of $300/d.

4. Conclusion

The application of the model is illustrated through two example systems and the results are discussed. The simple examples demonstrate that using the method allows for significant cost saving for large systems while further testing and developments may be needed. In the model formulation, it minimizes costs without considering the capacity limitation of a WWTP. The objective function minimizes total costs subject to continuity constraints and the connectivity model. At the starting point, the costs for each path are defined (paths from source nodes to collection nodes and paths from collection nodes to WWTP nodes), as are costs of new plant construction, operation, and maintenance. The reason for using this procedure is to check the quality of the model from a coding perspective. From a coding perspective, the mathematical formulation should be applied to the objective function, continuity constraints, and connectivity constraints only, so that later it can add more constraints for different purposes. This was applied to make sure that the model would work perfectly without any issues and it examined the mathematical formulation for continuity and conductivity constraints.

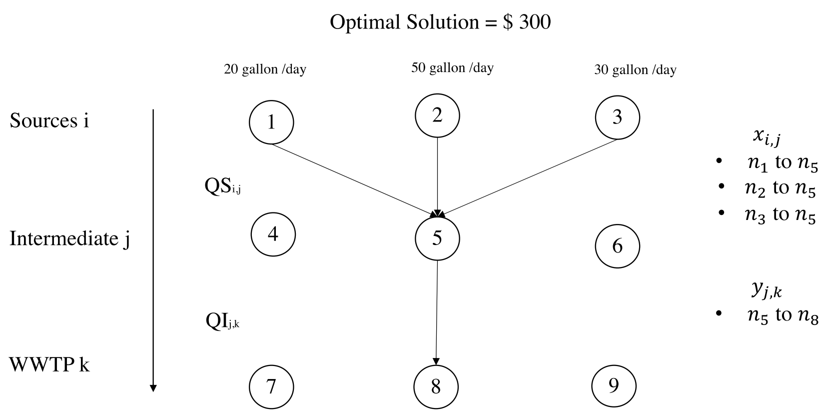

Fig. 8. Optimum configuration for Example 2.

The primary purpose of developing such models is to encourage decision-makers to plan regional wastewater systems with minimum costs. In the future, one thing can be added to the design purpose model is hydraulic constraints [16,17]. Hydraulic constraints include: (1) only commercial pipe diameters are considered, (2) minimum and maximum pipe slopes allowed, (3) continuous slope, (4) minimum pipe cover depths allowed, and (5) WWTP facilities elevations.

Symbols

Sets

i — Set of wastewater sources nodes on INL i

j — Set of the possible location of intermediate (collection) nodes on INL j

k — Set of possible location WWTP nodes on INL k

Parameters

QR_i — Amount of wastewater produced at sources for a node on INL i

$QWWTP_{max}$ — Maximum amount of wastewater that may be treated at a node on INL k

Q_{min} — Minimum flow allowed in the pipe system

Q_{max} — Maximum flow allowed in the pipe system

CPIP — Discount cost of installation, operation, and maintenance from source node i to intermediate node j

CWWTP — Discount cost of new WWTP construction, operation, and maintenance.

CPIP2 — Discount cost of the installation, operation, and maintenance from collection nodes on INL j to WWTP nodes on INL k.

$a_{i,j}$ — Possible paths of draining wastewater from source node to intermediate node j.

$$a_{i,j} = \begin{cases} 1 & \text{possible path from node } i \text{ to node } j \\ 0 & \text{no possible path from node } i \text{ to node } j \end{cases}$$

$b_{j,k}$ — Possible paths of draining wastewater from collection nodes on INL j to WWTP nodes on INL k.

$$b_{j,k} = \begin{cases} 1 & \text{possible path from node } j \text{ to node } k \\ 0 & \text{no possible path from node } j \text{ to node } k \end{cases}$$

Variables

$QS_{i,j}$ — Flow carried from source node i to intermediate node j

$QI_{j,k}$ — Flow carried from intermediate node j to WWTP node k

$x_{i,j}$ — Binary variable defined as either 0 or 1 where $x_{i,j} = 1$ indicates a pipe connection between nodes i and j and $x_{i,j} = 0$ indicates no connection

$y_{j,k}$ — Binary variable defined as either 0 or 1 where $y_{j,k} = 1$ indicates a pipe connection between nodes j and k and $y_{j,k} = 0$ indicates no connection

Acknowledgements

Authors would acknowledge the support from Researchers Supporting Project number (RSP-2021/297), King Saud University, Riyadh, Saudi Arabia.

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Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28221

263 (2022) 160–167
July

Feasibility of anaerobic digestion as an option for biodegradable and sewage sludge waste management in the Kingdom of Bahrain

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Received 28 February 2022; Accepted 6 June 2022

ABSTRACT

Solid waste management (SWM) represents a main challenge to the developing countries. Almost all of the solid waste in these countries are dumped into landfills, which harms the environment, public health, as well as affecting the economy and society. Dumping of biodegradable waste including sewage sludge resulted from wastewater treatment plants into the landfill results in methane emission, which is a greenhouse gas 25 times more potent than carbon dioxide. Thus, finding a sustainable solution to manage the biodegradable and sewage sludge waste tend to be crucial. This study aims to explore the feasibility of anaerobic digestion (AD) technology to manage the biodegradable and sewage sludge waste in the Kingdom of Bahrain. AD is an important waste-to-energy technology that leads to produces biogas, an important and promising renewable energy resource for the country. Cost-benefit analysis (CBA) was used in this study that shows the feasibility of the AD project. In addition, the contribution in reduction of the landfill methane emission was estimated. The study may provide sufficient information for future adoption of evidence-based technology selection in order to adopt SWM technologies in Bahrain, which contributes to the decision and policy-making processes.

Keywords: Biodegradable waste management; Sewage sludge; Anaerobic digestion; Kingdom of Bahrain

1. Introduction

Municipal solid waste (MSW) generation rises steeply with the increase in population growth rate, developmental activities, economic and industrial development and urban growth. It has become a globally addressed issue [1,2]. If it is not managed properly, negative consequences will appear and affect the public health, environment and economy [3,4]. In developing Asian countries, the organic waste represents the majority of municipal solid waste which it is disposed in landfills. As a result, it degrades in anaerobic conditions and generates landfill methane, the greenhouse gas that is 25 times more potent than CO_2. Accordingly, biodegradable waste represents a promising resource that can be used to produce bio-energy as well as soil fertilizer. On the other hand, the sewage sludge resulted from wastewater treatment plants is also dumped into the landfill, which is considered a main part of the biodegradable waste. Thus, sustainable management of this waste can significantly contribute to climate change mitigation [5–7]. With regard to greenhouse gas (GHG), organic household waste has contributed the most to the emissions from various types of waste. In most developing countries where the organic content of waste is high, improper management of waste (e.g., open dumping and landfill of organic waste without gas recovery and open burning of plastic waste) may lead to higher GHG emissions in the future [8].

Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

2. Waste management in the GCC countries

Waste generating per capita ranked among the highest in the world in the Gulf Cooperation Council (GCC) countries [4]. The estimated total amount of waste generated in the GCC countries range from 90 million to 150 million metric tonnes annually, with the UAE being the highest generator at approximately 2.2 kg per capita daily. The amount of recycled waste is around 5% of the total, with the rest being accounted for landfills or, even worse, to illegal dump sites. The amount of waste generated is expected to grow rapidly to anywhere between 1.5 and 2 times of the current volume in 2021. Changes in consumption patterns of the GCC countries, have led to an increase in the MSW dumping. Al-Ansari [2] and MWMUPA [8] have argued that waste management protocols need to be re-evaluated in order to establish methods that contribute to minimizing greenhouse gas emissions, improving the efficiency of resource management, and designing more eco-friendly management plans in GCC countries. The composition of the waste would generally suggest that a large part of it is biodegradable. However, this is not reflected in common waste management practices in the GCC Countries, where most waste goes to landfill. In countries like Bahrain, Qatar, and the UAE, landfill space is running low and this practice is becoming a major problem.

3. SWM in the Kingdom of Bahrain

The Kingdom of Bahrain is located in the heart of the Arabian Gulf, west of the Asian Continent. It is an archipelago of 33 islands with Bahrain Island being the largest land mass which represents approximately 80% of the total land area of the Kingdom of Bahrain and amounts to 770 km^2. The Kingdom is split into four Governorates namely the Capital, Muharraq, Northern, and Southern Governorates. The Kingdom of Bahrain is one of the GCC countries. Oil and natural gas are the primary natural resources in Bahrain. The population growth rate is 7.4% on average.

Since organic waste is considered as the most harmful portion of the SW content due to its hazardous environmental impact, organic waste management becomes a concern in many of the developing countries with the highest organic portion within their MSW content. Waste composition is considered to be one of the main factors influencing emissions from solid waste treatment, as different types are known to contain varying amounts of degradable organic carbon (DOC), and fossil carbon.

3.1. Anaerobic digestion

Organic waste in landfills undergo degradation process, mainly anaerobic digestion, resulting in methane gas production, which is considered to be the most harmful GHG that causes global warming and as a consequence, climate change. The biodegradable waste (consisting of garden and green waste, papers and cardboards, food waste) represents the highest composition percentage in Bahraini domestic waste, according to MWMUPA [8]. It was above 60% in 2017, while it continues the average of 63% for 2018 and 2019, which shows that biodegradable waste continues to be one of the biggest components (percentage wise) of Bahrain's MSW.

Anaerobic digestion (AD) is a complex biochemical process for the treatment of organic waste, which occurs in a vessel in the absence of oxygen. In this process, breaking down of the organic material occurs by micro-organisms, which leads to the formation of mixture of carbon dioxide and methane gas known as "Biogas", which is typically used to provide electrical power generation, heat, and a solid and liquid digestate. The digestate quality is dependent on availability of source- segregated organic waste stream [8,9]. The relevance of biogas technology lies in the fact that it makes the best possible utilization of organic waste as a renewable clean energy source [8].

Anaerobic digestion of the organic fraction of municipal solid waste (OFMSW) is being widely utilized globally because this technology complies with the philosophy of sustainability. The energy recovered from anaerobic digestion of OFMSW is renewable and the effluent can be returned to the agricultural land, thus recovering the remaining organic matter and nutrients [10].

According to Appels et al. [11], energy from biomass and waste is one of the most dominant renewable energy sources to be used in future. It has been found that different types of biomass and waste are suitable for AD, including OFMSW, Waste oils, animal fats, crops and agricultural, manure and sludge.

Furthermore, AD technology strongly relies upon the input material. Therefore, it is crucial that the waste is separated before the treatment. Materials such as plastics will reduce process' efficiency [12]. This is consistent with the views of the American Biogas Council as per which pre-sorting is necessary to prevent clogging of the pumps and to reduce the amount of reactor volume occupied by inert material. Even source-separated waste inevitably contains metal and plastic contaminants and hence, must be pre-sorted.

The biogas produced by anaerobic digestion primarily comprises of (CH_4 ≈ 60% by volume), carbon dioxide (CO_2 ≈ 40% by volume), and small traces of hydrogen sulphide (H_2S), hydrogen (H_2), nitrogen (N_2), carbon monoxide (CO), oxygen (O_2), water vapour (H_2O) or other gases as well as vapors of various organic compounds [13]. According to the American Biogas Council, many different anaerobic digester systems are commercially available based on organic waste stream type (manure, municipal wastewater treatment, industrial wastewater treatment and municipal solid waste). Anaerobic digestion of the organic fraction of MSW provides an engineered and highly controlled process of capturing methane. It is claimed that the current trend is toward anaerobic digestion of source separated from organic waste streams, including food waste, yard trimmings and soiled paper. Therefore, segregation at source is a main enabler to AD adoption in large scale SWM [8,15].

The number of plants treating the digestible fraction of household waste in Europe grew from three biogas plants in 1990 to 195 in 2010, with a total capacity of 5.9 million tonnes, with a predicted expansion of current capacity every 5 y [16]. In 2010, about 3% of the organic fraction of municipal solid waste produced in Europe was treated by the AD, representing 20%–30% of the biological treatment capacity of organic wastes from households

(Al Seadi et al. [16]). Analogously, (McKendry [17]) claimed that AD is a commercially proven technology and is widely used to treat high moisture content organic wastes that may reach 80%–90% moisture.

American Biogas Council [14] has specified the anaerobic digestion systems for MSW, which include:

(1) *Single-stage wet digesters*: Typically simpler to design, build, and operate and generally less expensive, the organic loading rate (OLR) of single-stage digesters is impeded by the ability of methanogenic organisms to tolerate the sudden decline in pH resulting from rapid acid production during hydrolysis.
(2) *Dry fermentation*: Type of single-stage digester, but distinctive from other AD categories because feedstock are in a solid state that can be handled using a front-end loader; normally, no additional water is added. Digestion takes place at 20%–45% total solids, and can be done in either a batch or continuous mode. In the batch mode, materials are loaded into chambers before being inoculated and maintained until the end of the retention time. In continuous mode, fresh feedstock is continuously fed to the digester and the digestate is continuously removed.
(3) *Two-stage digesters*: System separates the initial hydrolysis and acid-producing fermentation from methanogenesis, which enables higher loading rates for high nitrogen containing materials but requires additional reactors and handling systems. Another important design parameter is the total solids (TS) concentration in the reactor, which is expressed as a fraction of the wet mass of the prepared feedstock. The remainder of the wet mass is water by definition. Feedstock is typically diluted with process water in order to achieve the desirable solids content during the preparation stages.

Moreover, Cioabla et al. [9] outlined the factors affecting the performances of an anaerobic digester. They claimed that these factors can be divided into three main classes: (i) feedstock characteristics, (ii) reactor design and (iii) operational conditions. Among the operational conditions, temperature and pH are found to be important parameters.

Kang and Yuan [18] have stated the conditions required for a successful AD. They contended that moisture content is considered as one of the most important factors affecting the waste stabilization which play an important role in:

(1) Controlling cell turgidity;
(2) Reacting in polymer hydrolysis;
(3) Solubilizing and transporting nutrients, intermediates, products, inhibitors, enzymes, and microorganisms;
(4) Modifying the shapes of enzymes and other macromolecules;
(5) Exposing more of the waste surface to microbial attack.

Raising the moisture content of an anaerobic digester is known to increase the generation of methane. According to previous studies, the minimum moisture content is 36% for a mechanically mixed, mesophilic digester fed with the putrescible fraction of MSW. They mentioned three temperature ranges for AD process that is predicated on the bacteria type:

(1) cryophilic, less than 20°C (very slow, so rarely used for digestion of MSW);
(2) mesophilic, 20°C–45°C (35°C is generally used for mesophilic operation);
(3) thermophilic, above 45°C (55°C is generally used for thermophilic operation), digestion is faster in the thermophilic range.

According to American Biogas Council [14], captured biogas is transported via pipe from the digester, either directly to a gas use device, or to a gas treatment system (e.g., for moisture or hydrogen sulphide removal). According to them, high concentrations of sulphur lead to the formation of hydrogen sulphide in the digester, which cause the corrosion of the combustion device or other downstream equipment.

Meanwhile the chemical oxygen demand (COD) is a measure of the capacity of water to consume oxygen during the decomposition of organic matter and the oxidation of inorganic chemicals, such as ammonia and nitrite. On the other hand, biological oxygen demand (BOD) is a measure of the amount of biological substrate materials within a water or wastewater [19]. BOD is similar to the function of chemical oxygen demand (COD) in that both measure the number of organic compounds in water. The American Biogas Council has shown that the high chemical oxygen demand (COD) and solids loading make the feedstock well-suited for treatment using anaerobic processes. Hence, a high COD is required in order to achieve a successful AD process.

3.2. Feasibility of AD for Bahrain biodegradable waste

Abbas [15] empirically characterized the organic household waste in Bahrain and found that the moisture reached 73%, which is optimum for the AD process. According to Al Sabbagh et al. [4], the organic fraction of the MSW in Bahrain reached (60% wt.) and is comparable to that in middle- and low-income cities (50%–80% wt.). Since organic waste is considered as the most harmful portion of the MSW content due to its hazardous environmental impact, organic waste management becomes a concern in many of the developing countries with the highest organic portion within their MSW content. Waste composition is considered to be one of the main factors influencing emissions from solid waste treatment, as different types are known to contain varying amounts of degradable organic carbon (DOC), and fossil carbon.

According to the MWMUPA [8], the total waste going to Askar Landfill – the only landfill in Bahrain which already reached its limits- is about 2,131,683 ton, the details of waste composition are shown in Table 1. Accordingly, the total biodegradable waste in the landfill comes from: – Domestic waste (food, papers and cardboard, green), Garden waste, and Dead animals. – Commercial waste: Food, green, paper and cardboard. – Industrial waste: Food, green, paper and cardboard. – Sludge from wastewater treatment plant (WWTP). Based on the Waste Audit Report [8,20], the average of the last 2 y was considered in this study. Therefore, the percentages of the biodegradable fraction under each of the above categories were calculated and found to be as shown in Table 2, while Table 3 represents the total

Bahrain's biodegradable waste composition in ton per year in details.

4. Methodology: cost-benefit analysis (CBA)

CBA provides a means for systematically comparing the value of outcomes with the value of resources achieving the desired outcomes. It measures the economic efficiency of the proposed technology or project.

Hochman et al. [21] has evaluated four available waste treatment technologies: direct combustion, landfilling, composting, and anaerobic digestion in New Jersey – USA using the CBA method. Since the economic criterion is a priority worldwide among governments, this research took the economic feasibility into consideration as a main criterion for technology selection. Furthermore, Moutavtchi et al. [22] showed that CBA is useful for decision making in MSW management because it can be utilized as an efficient tool for information support for implementation of waste management technologies. Sadiq and Kaneesamkandi [23] claimed that it is necessary to predict the biogas yield and to perform cost analysis in order to investigate whether the waste conversion into biogas and digestate is financially feasible [15].

In order to commence the CBA for the AD technology project, the considered project period in this study was 15 y. Data in this section is based on the cost estimated from waste management technologies plants in developing countries ($/ton) in Germany [24]. Further Investigations done by the author through communications with experts of supplying companies in the industrial sector. AD technology has a fixed direct cost (capital cost), which includes the cost of: Consultant fees, environmental and social impact assessment (ESIA) and permits, equipment, engineering design and building. This cost is paid at the first year of the project. Next, the indirect costs that need monthly payment (operation and maintenance cost) include: land lease agreement, loan repayments, electricity, water, labour of maintenance, insurance, labour of operations and transportation. The benefit of AD technology is realized through two different ways: by sales estimated depending on the type of technology and product market price; and through the savings realized by stopping the dumping in the landfill.

In a comparable study held in the Kingdom of Saudi Arabia (KSA) by the study of Sadiq and Kaneesamkandi [23], biogas yield of an average value of 450 m^3/ton organic waste was approved based on experimental based literature. For this reason, the approximate biogas yield from organic waste generated in the KSA found to be 3,420.50 million m^3/y from which 1 ton OW can generate about 398 kWh of energy. However, the Official Information Portal on Anaerobic Digestion in the UK outlined that digesting 1 ton of food waste can generate about 300 kWh of energy, considering the electricity cost by Electricity and Water Authority (EWA) in Bahrain which is 0.02 USD/kWh. Since the KSA is a Gulf country and shares many similarities with Bahrain in terms of lifestyle, culture, etc., the value considered to estimate the electricity generated from the biogas yield is 398 kWh/ton biodegradable waste and therefore, was used as a reference in this study. Table 4, outlines the benefit from electricity sales in USD. The baseline case is considering 10% discount rate, which represents the current status. Sensitivity analysis was conducted to assess the feasibility at two different scenarios: Discount rate at 5% and 20% as shown in Tables 7 and 8, respectively.

Table 1
Waste categories by weight in ton in the last 2 y in Bahrain, which are dumped into Askar Landfill

Waste category	2018	2019	Average
Dead animals	8,031	11,971	10,001
Building waste	831,609	322,472	577,041
Commercial waste	347,827	333,093	340,460
Construction waste for recycling		355,690	355,690
Domestic waste	563,915	566,125	565,020
Garden waste	124,324	126,107	125,216
Industrial waste	81,577	81,175	81,376
Buhair Area waste	509,449		509,449
Total	2,466,733	1,796,633 Avg. total:	2,131,683

Table 3
Total Bahrain's biodegradable waste composition in ton/y

Description	Ton/y
Total domestic biodegradable waste (food, papers, green)	221,942
Total garden waste	125,216
Dead animals	10,001
Total commercial biodegradable waste	136,184
Total industrial biodegradable waste	21,158
Total WWTP sludge	20,750
Total biodegradable waste in Bahrain	535,251

Table 2
Total biodegradable waste under each category in Bahrain

Biodegradable waste in Bahrain ton/y	Commercial	Industrial	Domestic, garden and dead animals	Sludge from WWTP	Total
Total waste	340,460	81,376	567,542	20,750	1,010,128
Total biodegradable waste	136,184	21,158	357,159	20,750	535,251
Percentage of biodegradable waste from total waste	40	26	63	100	53

Table 4
Biogas yield and electricity sales estimation for Bahrain

Total BDW	Biogas m^3/ton	Total biogas yield (m^3)	kWh/ton	Total energy output (kWh)	Total energy output (GWh)	Electricity cost (USD)	Annual revenue (USD)
535,251	450	240,862,950.00	398.5	213,297,523.50	213.30	0.02	4,265,950

5. Results and discussion

From Table 4, it is obvious that the AD Plant is expected to generate 213.3 GWh/y, with annual revenues of USD 4,265,950 from electricity sales. Furthermore, according to the MWMUP, the cost of dumping of 1 ton of waste in the landfill is USD 16, so there will be a saving by discontinuing the total biodegradable waste dumping. In addition, from the literature, it was found that each ton of organic waste produces 0.2 ton of fertilizer. Cost estimates of an anaerobic digestion plant in developing countries were mentioned by the study of Cioabla et al. [9] who showed that the capital cost of AD is 18$/ton in average. While he stated that the O&M cost is 14.5$/ton. Accordingly, the total capital cost and the total O&M cost were calculated based on these prices for an AD of 536,000 ton/y capacity for Bahrain. Table 5 presents the cost-benefit analysis of an AD plant for the Kingdom of Bahrain assuming that the capital cost is a fixed cost which is paid during the first year of the project, whereas the operation and maintenance cost (O&M cost) represents the cash out flow, which is the annual cost considered in calculating the net profit. The benefit is expressed as sales revenues from the digestate that can then be used as fertilizer to enhance the soil in agriculture. Since the net profit number is positive and is high, it can be inferred that the AD project itself is primarily considered to be a viable solution to manage the biodegradable waste in the Kingdom of Bahrain, after calculating the Net Present Value (NPV) that must also be positive. The NPV is the difference between the present value of cash inflows and the present value of cash outflows. NPV is used in capital budgeting to analyse the profitability of an investment or project. It measures the excess or shortfall of cash flows, in present value terms, once financing charges are met [24]. In addition, the internal rate of return (IRR) is defined as the interest rate at which the net present value of costs (negative cash flows) equals the net present value of the benefits (positive cash flows). An investment is considered acceptable if its IRR is greater than an established minimum acceptable rate of return or cost of capital [24]. Furthermore, the payback period (PBP) indicates the amount of time it takes for a capital budgeting project to recover its initial cost. In capital budgeting, payback period denotes the period of time required for the return on an investment to "repay" the sum of the original investment. To calculate it, the payback period equals Investment required divided by Net annual cash inflow [24]. Considering the discount rate of 10%, the net present value (NPV), the internal rate of return (IRR) and the payback period (PBP) were calculated in this study for the AD plant project based on the CBA as shown in Table 6. The cash flow of the baseline case suggests that the AD is a viable project, since the NPV is positive and worth around USD 33.5 M, with an internal rate of return (IRR) that reached 59%, and a payback period of 1.7 y, which indicated the viability of the project.

By applying a sensitivity analysis, considering discount rate 5% and 20%, the project remains feasible and viable. The NPV is USD 49.3M when the discount rate is 5%, while it is USD16.9M considering the discount rate 5%.

Table 5
Cost-benefit analysis of AD plant for the Kingdom of Bahrain

Description	USD
Capital cost/ton	18
O&M cost/ton	14.4
Total capital cost	9,634,518
Total O&M cost	7,707,614
Benefits/y	
Electricity	4,265,950
Fertiliser	642,301
Direct saving by discontinuing waste dumping	8,473,705
Total benefit/y	13,381,957
Net profit	5,674,342

Table 6
Cash flow with NPV, IRR and PBP of the AD plant project for Bahrain (Baseline case: discount rate 10%)

Period	Cash flow
0	(9,634,518)
1	5,674,342
2	5,674,342
3	5,674,342
4	5,674,342
5	5,674,342
6	5,674,342
7	5,674,342
8	5,674,342
9	5,674,342
10	5,674,342
11	5,674,342
12	5,674,342
13	5,674,342
14	5,674,342
15	5,674,342
Discount rate	10%
NPV	33,524,979
IRR	59%
PBP	1.7

In the other hand, if the project was achieved under the discount rate 10%, with continuing the dumping with no saving earned from it accordingly, the project will not be feasible nor viable, at all discount rates (5%, 10% and 20%), as shown in Tables 7–11, thus discontinuoing dumping and earn the savings is a condition to guarantee ensure the project feasibility and viability for Bahrain.

5.1. Environmental benefit

According to Mutz [25] and Lee et al. [26], the conversion of organic waste to biogas is associated with a number of environmental benefits. Biogas from organic waste reduces the emission of greenhouse gases into the atmosphere [25] resulting from organic waste dumping [26]. Each tonne of organic waste dumped in the landfill releases about 1 ton of carbon dioxide equivalents (CO_2-e) in the form of methane [27]. Consequently, dumping of 535,251 ton/y of biodegradable waste in the landfill results in 21,410 ton CH_4/y (1 ton biodegradable waste results in 0.04 ton CH_4), which is equivalent to 535,251 ton CO_2-e/y. Therefore, the AD project contribute to GHG emission reduction since the landfill methane has a global warming potential of approximately 25 times higher than that of CO_2 [25]

6. Conclusion

Accordingly, the cost-benefit analysis in this study gives an economic evidence to recommend AD to the decision makers as a feasible option to manage the biodegradable waste in the Kingdom of Bahrain, which can then be embedded into the national legal and policy frameworks. AD is receiving increasing attention as a possible option of energy recovery from waste in the urban context. However, the operation of biogas plants from heterogeneous MSW

Table 7
Sensitivity analysis: cash flow with NPV, IRR and PBP of the AD plant project (discount rate 5%)

Period	Cash flow
0	(9,634,518)
1	5,674,342
2	5,674,342
3	5,674,342
4	5,674,342
5	5,674,342
6	5,674,342
7	5,674,342
8	5,674,342
9	5,674,342
10	5,674,342
11	5,674,342
12	5,674,342
13	5,674,342
14	5,674,342
15	5,674,342
Discount rate	5%
NPV	49,263,212
IRR	59%
PBP	1.7

Table 8
Sensitivity analysis: cash flow with NPV, IRR and PBP of the AD plant project (discount rate 20%)

Period	Cash flow
0	(9,634,518)
1	5,674,342
2	5,674,342
3	5,674,342
4	5,674,342
5	5,674,342
6	5,674,342
7	5,674,342
8	5,674,342
9	5,674,342
10	5,674,342
11	5,674,342
12	5,674,342
13	5,674,342
14	5,674,342
15	5,674,342
Discount rate	20%
NPV	16,895,713
IRR	59%
PBP	1.7

Table 9
Sensitivity analysis: cash flow with NPV, IRR and PBP of the AD plant project when continuing dumping (discount rate 10%)

Period	Cash flow
0	(9,634,518)
1	(2,799,362)
2	(2,799,362)
3	(2,799,362)
4	(2,799,362)
5	(2,799,362)
6	(2,799,362)
7	(2,799,362)
8	(2,799,362)
9	(2,799,362)
10	(2,799,362)
11	(2,799,362)
12	(2,799,362)
13	(2,799,362)
14	(2,799,362)
15	(2,799,362)
Discount rate	10%
NPV	–30,926,688

Table 10
Sensitivity analysis: cash flow with NPV, IRR and PBP of the AD plant project when continuing dumping (discount rate 5%)

Period	Cash flow
0	(9,634,518)
1	(2,799,362)
2	(2,799,362)
3	(2,799,362)
4	(2,799,362)
5	(2,799,362)
6	(2,799,362)
7	(2,799,362)
8	(2,799,362)
9	(2,799,362)
10	(2,799,362)
11	(2,799,362)
12	(2,799,362)
13	(2,799,362)
14	(2,799,362)
15	(2,799,362)
Discount rate	5%
NPV	–38,690,938

Table 11
Sensitivity analysis: cash flow with NPV, IRR and PBP of the AD plant project when continuing dumping (discount rate 20%)

Period	Cash flow
0	(9,634,518)
1	(2,799,362)
2	(2,799,362)
3	(2,799,362)
4	(2,799,362)
5	(2,799,362)
6	(2,799,362)
7	(2,799,362)
8	(2,799,362)
9	(2,799,362)
10	(2,799,362)
11	(2,799,362)
12	(2,799,362)
13	(2,799,362)
14	(2,799,362)
15	(2,799,362)
Discount rate	20%
NPV	–22,722,858

poses a major challenge in terms of operational, safety and financial requirements. As a consequence, there are very few successful examples of biogas from biodegradable waste and sewage sludge in developing countries, due to the absence of segregation at source and mixed waste [7].

This study has concluded that the establishment of an AD plant in Bahrain for the treatment of biodegradable waste going to the landfill annually, is expected to generate 213.3 GWh/y, with annual revenues of USD 4,265,950 from electricity sales. The second source of revenues from this project is expected from the sales of the fertilizer produces as another end product with the biofuel, with a sales revenues of USD 642,301 considering that each ton of organic waste produced 0.2 ton of digestate, so this project is expected to produce 107,050 ton of digestate to be used as a fertilizer, with the international sale price of USD 6/ton. The direct saving earned by discontinuing biodegradable waste dumping of 535,251 ton/y in the landfill, is about USD8.47 M which will be saved annually and increase the viability of the project.

The cash flows suggests that the AD is a viable and feasible project with a condition of discontinuing waste dumping and earning the savings. The NPV is positive and worth around USD 33.5 M, with an internal rate of return (IRR) that reached 59%, and a payback period of 1.7 y, which indicates the viability of the project, considering the discount rate 10%. While it reaches USD49.3 M when the discount rate is 5%, while it becomes USD16.9 M considering the discount rate 5%.

In the other hand, if the project was achieved under the discount rate 10%, with continuing the dumping with no saving earned from it accordingly, the project will not be feasible nor viable, at all discount rates (5%, 10% and 20%).

Moreover, 535,251 ton/y of CO_2-e can be reduced by discontinuing biodegradable waste dumping into the landfill after implementing the AD plant project, assuming the existing biodegradable generation rate in the Kingdom of Bahrain.

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Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28222

263 (2022) 168–174
July

Adsorptive removal of chromium(VI) using Cu/Fe impregnated activated carbon prepared from solid sludge

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Received 28 February 2022; Accepted 22 May 2022

ABSTRACT

Chromium(VI) can be introduced to the environment from different industrial activities. This study focuses on the removal of chromium(VI) using activated carbon. In this work, solid sludge obtained from a treatment plant in Nizwa, Oman was used to prepare the activated carbon. The preparation was done following two processes. The first one was pyrolysis of dried solid sludge for 2 h at a temperature of 700°C under nitrogen gas flow of 150 mL/min. The second process was physiochemical activation using potassium hydroxide with an impregnation ratio of 1:1 under a mixture of nitrogen and carbon dioxide gases with a flow of 150 mL/min for 2 h. The morphology and chemical composition of the prepared carbons were characterized using scanning electron microscopy-energy-dispersive infrared spectroscopy. The prepared carbons were used for Chromium(IV) removal and the removal was performed at different dosages, metal concentrations, and pH at a temperature of 30°C for 6 h. Chromium levels were analyzed using flame atomic absorption spectroscopy (FAAS). The highest removal of chromium(VI) was found to be 23% at 1.5 g of activated carbon (AC) dosage and pH 3. The influence of impregnating the prepared activated carbon with Fe(III) and Cu(II) metals on Chromium removal was investigated. The treated activated carbon with copper achieved the highest removal efficiency of 94.5% at pH 3. Therefore, addition of Cu(II) metal to sludge AC is efficient in enhancing the removal of chromium(VI).

Keywords: Adsorption; Chromium(VI); Activated carbon; Sludge; Removal

1. Introduction

Wastewater is produced by combination of industrial, domestic, commercial, agricultural uses, storm water and sewer water [1–3]. It contains various physical, chemical, and biological pollutants that depends on the original source. A wide range of pollutants such as organic, inorganic hazardous, gasses and vapors can be found in wastewater [4]. The organics include halogenated organic compound, natural organic matter, compound with phenol group, nitro and amino compound, dyes, pesticides, drugs and toxins and miscellaneous organic compound. The reported inorganics content in wastewater are copper, chromium, selenium, nickel, cadmium, mercury, zinc, arsenic, lead, gold, silver, iron, tin, molybdenum, cobalt, manganese, and aluminum [5]. Therefore, wastewater treatment is necessary before discharging to water bodies. Various physical and chemical treatment methods have been used such as biological degradation, chemical precipitation, ion exchange, adsorption, reverse osmosis, flocculation, and coagulation [4].

Heavy metals such as chromium, lead, vanadium, arsenic, cadmium, and mercury are harmful to the environment

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

and human health [6]. Usually, heavy metals discharged in municipal wastewater to be carried by water, while those in industrial effluents can be caused by different process such as catalysts, instrumentation leaks and corrosion product [7,8]. Chromium is one of these heavy metals that can be in the industrial discharges [9]. The two most stable species of chromium are the trivalent (Cr(III)) and hexavalent (Cr(VI)) species [10]. Chromium(VI) is a highly toxic metal compared to chromium(III). There are different industrial sources of chromium(VI) which come from cooling tower, leather tuning, plating, electroplating, rinse water and anodizing baths, chemical process, etc. [9]. According to World Health Organization (WHO) the allowable limit for Cr(VI) in drinking water is 0.05 mg/L [8,11,12]. It can cause various cancer disease, skin, and stomach irritation. At high exposure, can lead to liver damage, dermatitis, kidney circulation, nerve tissue damage, death in high concentration and exposure [9]. Therefore, the removal or reduction of chromium(VI) to chromium(III) is a key process to treat or eliminate chromium(VI) from contaminated water and wastewater [12]. Different methods that have been used for heavy metals removal from wastewater including adsorption [13], ion exchange [8,14], membrane filtration [15], and electrocoagulation [16]. Because it is simple process, high removal efficiency and low treatment costs, adsorption is widely used to remove Cr(VI) from wastewater compared to other methods [14].

Adsorption using activated carbon is used extensively for gold, air, water purification, sewage treatment, gas respirators and medicine as well in the removal of heavy metals [17]. Activated carbon can be produced from different materials such as rice husk, coconut husk, wood, bamboo, coir, coal, petroleum pitch and lignite [9,18]. These materials might contain inorganic material (lignin, cellulose, sugars) and the rest is silica [7,19]. Activated carbon can be prepared by two steps. In the first step, the raw material is carbonized at 800°C temperature in presence of inert gas [20]. The second step is the activation of the carbonized product which is carried out in atmospheric conditions then under air or CO_2 flow at 800°C–900°C [7]. The resulting activated carbon properties will be different depending on the carbonaceous materials, the activating agent used and the conditions of the previous two steps [19,21]. The produced activated carbon is characterized by carbon density, total surface area, adsorptive capacity and particle size distribution [22]. Activated carbons have relatively high pore volumes and surface areas [22]. Due to this they have effective adsorptive capacity or removal efficiency of heavy metals, biological oxygen demand, chemical oxygen demand, color from wastewater phenol number (index of carbons ability to remove odor) [19]. Regeneration of saturated activated carbon is important to reduce the operational and product sewage. For regeneration activated carbon there are several methods including steam, thermal and chemical regeneration [23]. There are different factors that was found to contribute significantly to Cr(VI) adsorption such as pH, adsorbent dose, metal concentration, the size of adsorbent particles [14,18].

Sewage sludge is produced at huge amounts in Oman. Part of it is used as fertilizers while the most is remained unused. This sewage sludge can be converted to activated carbon that can be used for heavy metal removal [1,21]. The aim of this study is to prepare activated carbon from sewage solid sludge collected from one of the sewage treatment station in Oman and use it to remove chromium(VI) from wastewater. Hence the objectives of this study are the preparation of activated carbon from sludge using chemical/physical activation, optimize the removal of chromium(VI) and improve this removal by using Cu or Fe metals impregnation.

2. Material and method

2.1. Materials and chemicals

Chromium standard, HCl, KOH, DDW, carbolite reactor, scanning electron microscopy (SEM), energy-dispersive infrared spectroscopy (EDX). Sodium hydroxide, potassium dichromate, sulfuric acid, ethanol, ethylene glycol, ferric nitrate, $CuCl_2$, and deionized distilled water. Activated carbon prepared from sludge.

2.2. Adsorbate: chromium(VI)

A stock solution of chromium(VI) was prepared (1,000 ppm) by dissolving 2.827 g of $K_2Cr_2O_7$ salt in 1,000 mL of distilled water. The desired concentrations ranging from 0.25 to 10 mg/L were made by diluting the stock solution with distilled water.

2.3. Preparation of activated carbon using physiochemical activation method

The raw materials of sludge were collected from Nizwa treatment plant, Oman. About 90.056 g of sample was collected and dried for 24 h in oven at 105°C. Then, it was grinded to powder and stored for further use. Approximately 100 g of sludge powder was carbonized using an electric furnace (carbolite reactor). The sample was heated at 700°C with a rate of 10°C/min under inert atmosphere for 2 h. The carbonized sample was chemically activated by potassium hydroxide at a 1:1 w/w ratio. It was then dried overnight in an oven under 100°C. After drying it was placed in a horizontal tube furnace under high purity nitrogen with flow rate of 150 mL/min till it reached 700°C. The N_2 gas was switched to CO_2 and the physical activation was completed in 2 h. The activated carbon was washed with HCl and then with DDW until reached neutral pH 7. After that it was dried, grinded, and sieved with size 40–120 mm.

2.4. Removal of chromium(VI) using the prepared sludge activated carbon

Adsorption technique is applied for purification and removal of toxic compounds from wastewater. In this study, the removal of chromium(VI) using activated carbon produced from solid sludge was investigated. The effect of dosage and concentration and catalyst addition on chromium removal were reported. The analysis of the treated samples was done using atomic absorption spectroscopy (AAS). Calibration curve was used to determine the concentration of chromium in the samples in contact with the activated carbon. The concentration of the calibration standards (1–15 mg/L) were prepared from $K_2Cr_2O_7$ salt within the range of the FAAS (Model Thermo iCE 3000 series) instrument (Yang et al. [24]). Calibration standards preparation was done by taking 0.1, 0.2, 0.4, 0.5 and 0.75 mL from 1,000 ppm Cr. Then, they were transferred into 50 mL volumetric flasks and filled up to the mark with 1% HNO_3 trace metal grade.

The prepared activated carbon was used for chromium(VI) removal. The removal experiment of chromium(VI) using different masses of sludge activated carbon (AC) was maintained at conditions (shaking speed = 170 rpm, T = 30°C, pH = 3, C = 10 mg/L and t = 6 h). Chromium levels in each solution was measured using flame atomic absorption spectroscopy (FAAS). Removal efficiency and adsorption capacity were calculated using the following equations [24];

$$\text{Removal efficiency}(\%) = \left[\frac{C_0 - C_e}{C_0}\right] \times 100\% \quad (1)$$

$$q_e = \left[\frac{C_0 - C_e}{m}\right] \times V \quad (2)$$

where C_0 and C_e (mg/L) are the concentrations of Cr(VI) at initial and equilibrium in the solution respectively, q_e is the adsorption capacity (mg/L), V is the volume of the solution (L) and m is the mass of AC used (g).

2.4.1. Effect of dosage

The influence of sample dosage on chromium removal was investigated. This factor was studied by keeping other factors constant. The dosage effect was investigated by the following procedures. First, 10 ppm stock solution was prepared and transferred into a beaker, then H_2SO_4 (2M) was added to adjust the pH to 3. Different masses of AC (0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 1.0 and 1.5) g were weighted and transferred into 500 mL conical flasks. Then, 50 mL of the 10 ppm (pH = 3) standard was added to each conical flask. All comical flasks were kept in a shaking incubator at the following conditions: shaking speed = 170 rpm, T = 30°C, pH = 3 and t = 6 h. After 6 h the solutions were taken and filtered. Standards and samples were measured by AAS [24].

2.4.2. Effect of concentration

This experiment was done to study the effect of increasing the concentration on the percentage removal. A series of chromium standards (0.25, 0.5, 1, 2, 4, 5, and 10 mg/L) were prepared from 1,000 ppm chromium stock solution in 100 mL volumetric flasks and filled with distilled water. The pH of each standard was then controlled to pH 3. Then, 0.5 g of the AC was added to each conical flask containing 50 mL the prepared concentrations. The remaining 50 mL of each prepared standards was poured without addition of AC into another 500 mL conical flasks. All conical flasks were put in the shaking incubator at conditions (shaking speed = 170 rpm, T = 30°C, pH = 3 and t = 6 h). After 6 h all solutions were filtered and analyzed for chromium levels using AAS [24].

2.4.3. Effect of pH

The influence of pH on the percentage removal was examined. A series of chromium standards (pH 2, 3, 4, 5, 6, and 7) were controlled. The concentration of each standard equal 10 ppm was prepared from 1,000 ppm chromium stock solution in 100 mL volumetric flasks and filled with distilled water. Then, 0.5 g of the AC was added to each conical flask containing 50 mL of the prepared solution. The remaining 50 mL of each prepared standards was poured without addition of AC into another 100 mL conical flasks. All conical flasks were kept in the shaking water bath at conditions (shaking speed = 170 rpm, T = 30°C, conc. = 10 ppm and t = 6 h). After 6 h, all solutions were filtered and analyzed for chromium levels using AAS [24].

2.5. Activated carbon treated with iron and copper

2.5.1. Synthesis of AC/Fe

In this experiment 10% hydrated ferric nitrate was added to AC by weighing 7.0 g of AC and dispersed in 150 mL of DDW, 100 mL of ethanol was added and sonicated for 5 h. Then, 20 mL ethylene glycol was added followed by shaking for 2 h. Next, 12.53 mL solution containing 5.06 g of ferric nitrate was added dropwise to make 1 M solution. After that, the pH was maintained at 8–9 pH, followed by heating at 80°C for 6 h with stirring. Finally, precipitate was filtered, washed with DDW and dried at 110°C overnight [12].

2.5.2. Synthesis of AC/Cu

The prepared activated carbon was treated with copper. 3.3625 g of $CuCl_2$ was added to 50 mL of DDW in 100 mL conical flask. This solution was poured in 4 g sludge AC, then left for 6 h under sonication. After that, product was filtered and dried at 90°C for 48 h [25].

2.5.3. Chromium(VI) adsorption using AC/Fe and AC/Cu

This experiment was used to investigate effect of adding iron and copper to the activated carbon as catalyst in chromium(VI) removal. The pH was controlled to pH 3 for several 10 mg/L Cr(IV) standards. Then, 0.5 and 1.0 g of the sludge AC/Fe was added to 100 mL conical flask of each of the prepared solution. All conical flasks were kept in the shaking water bath at conditions (shaking speed = 170 rpm, T = 30°C, conc. = 10 ppm and t = 6 h). After 6 h all solutions were filtered and analyzed for chromium levels using AAS [26]. Similar procedure was followed with using sludge AC/Cu.

2.5.4. Leaching of Fe and Cu after adsorption process

Treated standards with AC and AC/Cu sample from sludge with (1 g, pH3 and 10 ppm Cr(VI)) were analyzed for Fe and Cu levels [27].

3. Results and discussion

Chromium(VI) is one of the heavy metals that are harmful to the environment and human health. This paper is aiming to test the effectiveness of activated carbon prepared from sewage sludge for Cr removal. To achieve this aim, activated carbon was prepared using physical and chemical activation. The influence of experimental parameters such as adsorbent dosage, adsorbate concentration and pH on Cr removal was examined

Moreover, the results of the addition of other ligands (iron or cupper) to improve the efficiency of activated carbon removal for chromium will be detailed.

3.1. SEM-EDX results of the prepared activated carbon

Different methods are used to remove chromium from waste such as ion exchange, chemical reduction and precipitation, reverse osmosis, and adsorption using activated carbon [28]. Conventional methods are limited because of high costs and long treatment times; however, adsorption is simple and cost effective. Adsorption using activated carbon prepared from waste materials is an effective technology because of its well-developed porous texture and high surface area. Conversion of waste sludge to an adsorbent is considered a challenge for many researchers due to its association with human waste [29]. In this paper, activated carbon was prepared from waste sludge to address the issue of waste accumulation.

Fig. 1 shows SEM images of the surface morphology of the prepared activated carbon. The chemical composition of the prepared activated carbon was done by energy-dispersive X-ray spectrometer (EDXS) as it is shown in Fig. 1. The activation is clearly shown in the image with the highest peak is for carbon which shows 79.8%. The carbon atom has highest percentage which is 79.8%, then the oxygen element with 15.4%. Other elements such as Si, K, Al, Cl, Mg are of very small percentage (4.9%). These elements can be from the original sludge.

3.2. Removal of chromium(VI) using the prepared sludge activated carbon

3.2.1. Effect of adsorbent dose on adsorption

Fig. 2 displays the adsorption results for adsorbent dose of 0.05g/50 mL to 1.5 g/50 mL. The removal of 10 mg/L chromium(VI) was studied at pH = 3 with different dosage of activated carbon (AC).

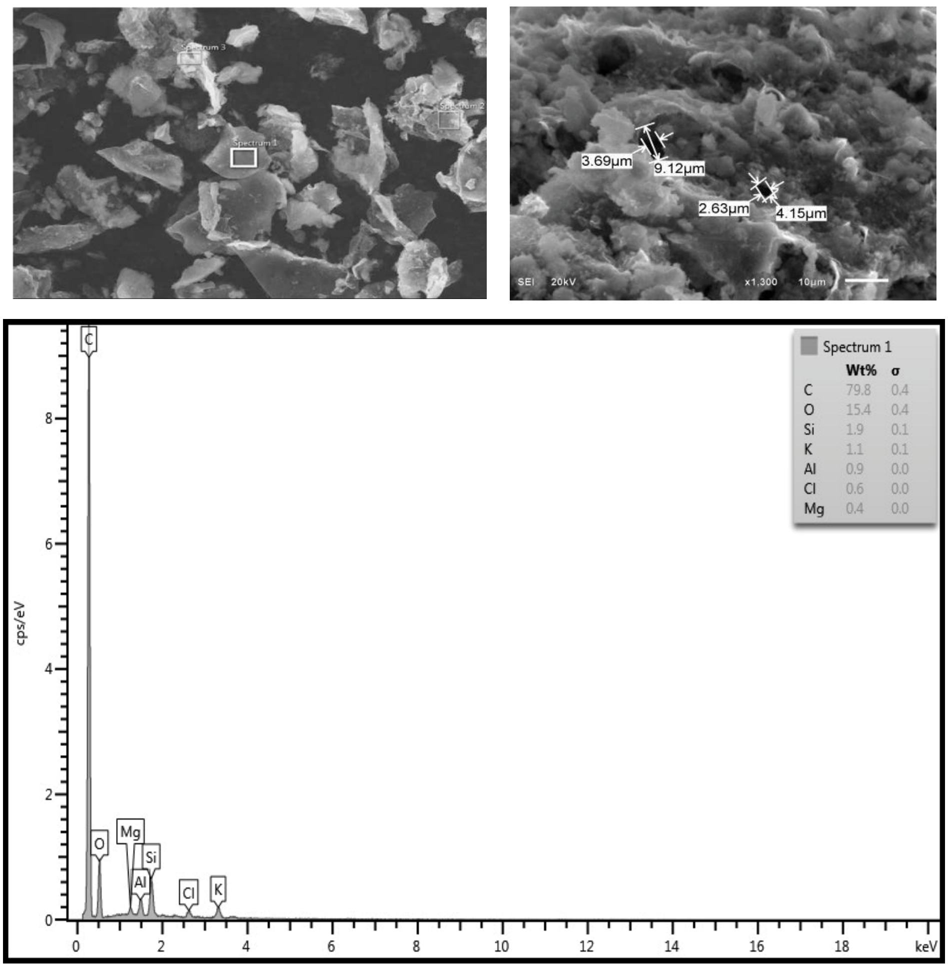

Fig. 1. SEM and EDX images of the prepared activated carbon (AC).

Fig. 2 shows that the removal has increased from 5% to 23% when the dosage was increased from 0.05 to 1.5 g respectively. This can be directly linked to the availability increasing adsorbent dose active sites leading to an increase in the effective surface area resulting from the increase of adsorbent dose [24,30]. Adsorption takes place via mass transfer by which substances are transferred from wastewater by adsorption on the solid surface. It permits a large surface area for adsorption which is then bonded by chemical and physical interactions [31].

The equivalent (mg/g) of chromium with initial concentration 10 mg/L at pH = 3 was studied at different dosage. Fig. 3 shows that the equivalent at 0.05 g was 0.40 mg/g. When a mass of 0.4 g of AC was added the equivalent was 0.19 mg/g. The addition of 1.5 g AC showed the lowest equivalent 0.07 mg/g. indirect relationship between AC dosage and percentage of equivalent of chromium was observed in Fig. 3. Hence, when the mass of AC increases the equivalent of chromium decreases according to Eq. (1) [24].

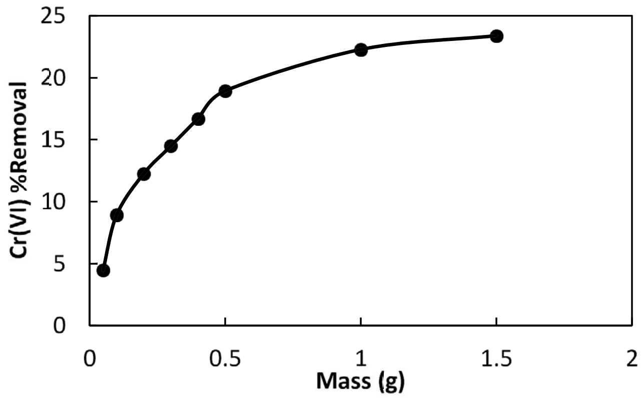

Fig. 2. Effect of dosage on the percentage of Cr(VI) removal. Conditions: shaking speed = 170 rpm, T = 30°C, pH = 3, C = 10 mg/L and t = 6 h.

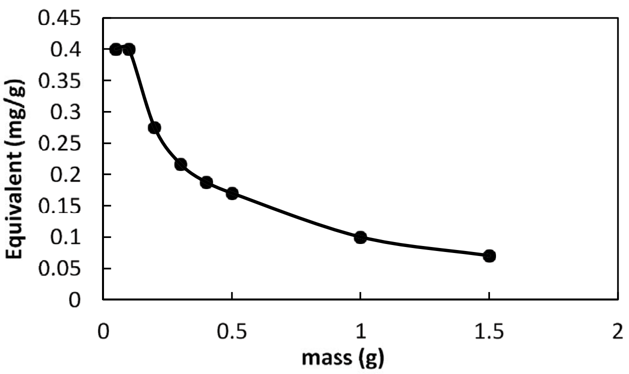

Fig. 3. Effect of adsorbent dose on metal uptake (q_e) of Cr(VI) (shaking speed: 170 rpm, temperature: 30°C, pH 3, initial conc.: 10 mg/L and time: 6 h).

3.2.2. Effect of initial concentration of chromium(VI)

The effect of initial concentration of chromium(VI) on the percentage removal by the prepared sludge activated carbon is illustrated in Fig. 4. It is clear from the figure that the removal increased with increasing chromium(VI) concentration. The maximum removal of 80% was achieved for the initial chromium concentration of 10 mg/L. In Labied et al. [32] study, the maximum Cr removal of 90% was also observed at an initial concentration of 10 mg/L at pH 2 and adsorption time of 2 h. However, the adsorption efficiency was observed to decrease after this concentration, and it reached 78% at initial concentration of 50 mg/L.

Table 1 shows a comparison between this study and two other studies used activated carbon for the removal of Cr(IV). The two studies used different raw materials of activated carbon including shaddock peels [9] and longan seeds [24]. According to the table mentioned above, raw material used to prepare the activated carbon affected the adsorbent metal removal efficiency. The solid sludge activated carbon (1.5 g) showed a higher removal efficiency (78.89%) with lower equivalent (0.79 mg/g) compared to longan seeds. This can be due to the differences in deferent factors such as porosity, surface area, condition of preparation and condition of process [24].

3.2.3. Effect of solution pH

The uptake of heavy metals from wastewater is controlled by the pH. It strongly influences the degree of

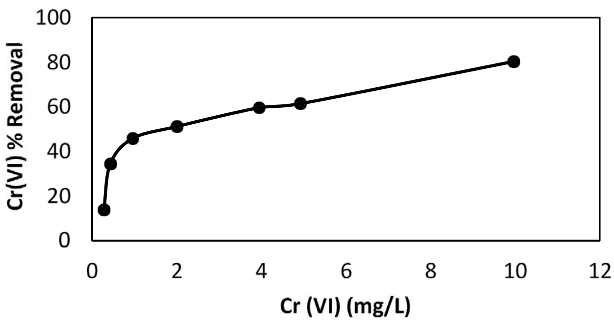

Fig. 4. Effect of concentration on the percentage of removal of Cr(VI). Conditions: shaking speed = 170 rpm, T = 30°C, pH = 3, m = 1.5 g and t = 6 h.

Table 1
Comparing removal % with different types of AC

Raw material of AC	Equivalent (mg/g)	C_0 (mg/L)	pH	Removal %	References
Solid sludge	0.79	10	3	78.89	This project
Shaddock peels	9.95	50	2	99.2	[9]
Longan seed	35.02	100	3	62.5	[24]

ionization of adsorbate and the surface charge of the adsorbent during reaction.

The removal of 10 ppm chromium(VI) by sludge activated carbon at different initial metal pH was studied. The pH of the adsorption medium was varied between 2 to 7 and other adsorption parameters were kept constant at shaking speed = 170 rpm, T = 30°C, m = 0.5 g and t = 6 h). The maximum removal was observed at pH 3. Yang et al. [24] reported similar results where they also got maximum adsorption of Cr(VI) by longan seed activated carbon at pH 3. After pH 3, there was a sharp change in adsorption of Cr(VI) because of the competitive adsorption between chromate ions and hydroxyl ions [24].

3.3. Removal of chromium(VI) using sludge S-AC/Fe and S-AC/Cu

To enhance the adsorbent activity, activated carbon was impregnated with iron and copper. It has been reported that activated carbon loaded with copper and iron is effective for removal of different contaminants from aqueous solution [32]. For this reason the prepared sludge activated carbon was impregnated with copper and Iron for the purpose of enhancing chromium(VI) removal. Fig. 5 shows that the modification of sludge activated carbon (0.5 g) using copper resulted in enhancing the Cr(VI) removal to 94% at pH 3. The high Cr (IV) removal with carbon modified with copper is attributed to the increase of carbon stability due to formation of strong metal-carbon complexes that could be as Cu^{+}/Cu^{+2} or as metal oxides at the surface. The presence of these complexes has been reported to increase the positive charge density of the surface [32]. The presence of these complexes results in the electrostatic attractions between positively charged surface and the negatively charged chromium ions. The improved sorbent efficiency for contaminant removal using metal-doped activated carbon has been reported in other studies [32]. However, in this study the Cr(VI) removal decreased sharply to 2.7% with impregnation of iron.

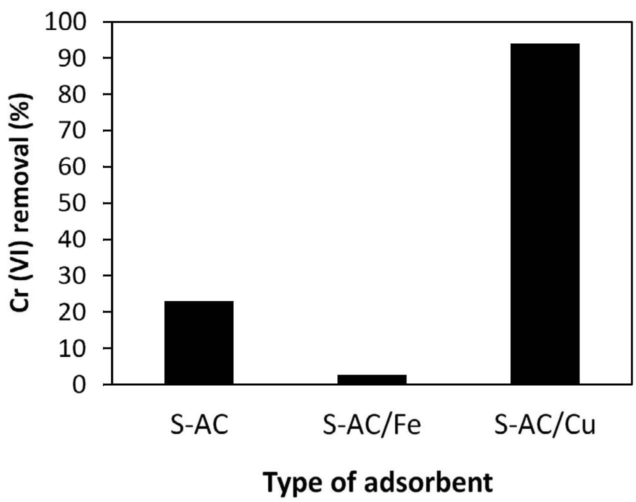

Fig. 5. Percentage removal of Cr(VI) using the modified activated carbons.

Table 2 shows the effect of adding Cu(II) metal to the prepared sludge activated carbon in order to enhance Cr(VI) removal in comparison with other studies that used the activated carbon without metals. This study shows that treating sludge AC with Cu(II) resulted in increasing the % removal from 23% to 94.57% at pH 3. Malwade et al. [33] used *Leucaena leucocephala* for preparing AC and 54% removal of Cr(VI) was observed at pH 4 and 100 ppm initial concentration. Moreover, Yang et al. [26] used Cassava Sludge AC and reported 60% removal of Cr(VI) with initial concentration of 10 ppm Cr(VI) and pH 4 [26]. As can be seen from Table 2 Cu(II) impregnated AC is showing better efficiency in Cr(VI) removal compared to other studies as it can increase the stability of the formation of metal-AC complexes.

3.4. Leaching of Fe and Cu after adsorption process

Leaching experiment was done to test the possible leaching of the catalysts from the activated carbon to the treated water sample. After adsorption process using S-AC/Fe it was found that solution has very low levels of iron (0.09 ppm). This mean that there is very minimal leaching of Fe from AC to solution after adsorption process [26].

The same experiment was done for the S-AC/Cu. After adsorption process using AC/Cu sludge, 0.01 ppm Cu was found in the treated water after adsorption. This mean that there is less leaching of Cu from AC to solution after adsorption so the AC/Cu should be washed after synthesis [27].

4. Conclusion

This study focuses on the removal of chromium(VI) using sludge activated carbon. The results showed the removal of 10 mg/L chromium at different dosage. The removal of chromium was studied at different concentrations. There was a direct proportional between AC dosage and percentage removal of chromium. The removal of chromium was studied at different pH. The % removal was high at pH 3. The removal of Cr is always greater at high dosage of AC and high concentration of Cr. The maximum removal of Cr from wastewater can be achieved by using

Table 2
Comparing Cr(VI) removal % with different types of activated carbon

Raw material of activated carbon	Heavy metal	Catalyst	C_0 (mg/L)	pH	Removal %	References
Solid sludge	Cr(VI)	Cu(II)	10	3	94.57	This project
Leucaena leucocephala	Cr(VI)	–	100	4	54	[33]
Cassava sludge	Cr(VI)	–	10	4	60	[26]

the following conditions; shaking speed = 170 rpm, T = 30°C, pH = 3, m = 0.5 g and t = 6 h. To enhance the Cr removal efficiency, the sludge AC adsorbent was impregnated with Fe(III) and Cu(II). The chromium(VI) removal increased to 94.57% with treating the activated carbon with Cu(II). However, the highest removal of sludge AC/Fe was found to be 3.53%. Therefore, sludge AC impregnated with Cu(II) is an efficient adsorbent for chromium(VI) removal.

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Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28226

263 (2022) 175–187
July

Hydrometeorological study on the impact of the weather state "Rahw" on the water resources in southwestern regions, Kingdom of Saudi Arabia

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Received 28 February 2022; Accepted 19 May 2022

ABSTRACT

In the arid regions, some heavy rainstorms and weather states may be happened annually and continued for few to many days resulting in large, or extreme flood events. The western and southwestern regions in the Kingdom of Saudi Arabia (KSA); Al Madinah, Makkah, Al Bahah, Asir, Jazan, and Najran, as well as some parts of the neighboring countries such as Oman, United Arab Emirates, and Yemen have been exposed to a summer weather state which is locally named by Saudi Committee of Nomenclature of Distinguished Weather States as "Rahw". This weather state lasted for 18 d started from 24 July 2020 to 10 August 2020 and resulted in moderate to heavy daily rains. The present study deals with the hydrometeorological impacts of the weather state "Rahw" depending upon the statistical analyses and ARC GIS spatial distribution of 193 rainfall and weather stations, as well as daily records of water levels in 165 constructed and under construction dams' reservoirs. The total geographic areas of Al Madinah, Makkah, Al Bahah, Asir, Jazan, and Najran Regions attain 522,000 km^2, representing 26.6% of the total area of KSA. According to the present study, the total geographic areas that have received rainfall precipitation in these regions during "Rahw" are estimated as 212,672 km^2 and the average total rainfall depth over these regions only is estimated as 69.59 mm, representing 45.8% of the total annual average rainfall depth over these regions. Also, the average total rainfall depth over all KSA during "Rahw" is estimated as 32.56 mm, representing 30.1% of the total annual average rainfall depth over all KSA regions. On the other hand, the calculated average precipitation depth in July 2020 only, attains 32.9 mm and 9.4 rainy days, compared to 20 mm and 5 rainy days of the same month during the interval from 2010 to 2019. Also, the present study concluded that the average precipitation depth in August 2020 is estimated as 27.5 mm and 9.2 rainy days, compared to 27 mm rainfall depth and 7 d rainy during August in interval from 2010–2019. The total rainfall volume received during "Rahw" weather state estimated as 10,894 million m^3 representing 20.2% of the total annual average rainfall volume in these regions, and 7.2% of the total annual average rainfall volume over all KSA regions. Also, the total rainfall volume received during "Rahw" weather state resulted to 1,308 million m^3 direct surface runoff, among of these 352 million m^3 were retained behind 147 constructed dams, and 18 million m^3 behind 8 under construction dams, and the remaining 938 million m^3 is recharged in wadi deposits aquifers in those areas. Also, 201.6 million m^3 of water was released from dams' gates to meet the demands of farmers on the downstream of dams during the rainy state, in addition 8.3 million m^3 was supplied for drinking waters

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and treatment plants. The net increase in the water volume behind the dams as a result of "Rahw" weather stations estimated as 142 million m^3. The present study recommends developing and update the operational plans of dams in western and southwestern regions to maximize the benefits from the surface runoff and enhance the water resources during the occurrence of such weather states.

Keywords: Weather state, Hydrometeorology, Water resources, Rainfall, Dams, Saudi Arabia

1. Introduction

Water is vital for human welfare, socio-economic development as well as for supporting the ecosystem [1]. Arab region receives only 2.1% of the world's average annual precipitation and contains as little as 0.3% of the world's annual renewable water resources [2]. The climate of Saudi Arabia is considered as "arid climate zone BW according to the global Climate Classification map based on [3,4] Therefore, the amount of rainfall precipitation that have been received over the country is very important factor in preparing the water budgets and assessing the available surface water allocates to meet various demands. In Saudi Arabia, some heavy rainstorms and weather states may be happened on few days in a year and in some regions of the country [5]. Also, rainfall storms exhibit strong spatial variability, especially during heavy thunderstorms and localized torrential rainstorms [6,7]. Ministry of Agriculture and Water in Saudi Arabia [8] has prepared and published good and more comprehensive water atlas including monthly and annual average rainfall distribution maps over all regions in the country. The average annual rainfall depth over Saudi Arabia was estimated as 79 mm by Qureshi and Khan [9], whereas it was estimated as 82.29 mm by Almazroui [10] based on the observed data of 29 ground stations of the General Authority of Meteorology and Environment GAME former PME. Recently Al Qahtani and Mattar [11] estimated the average annual rainfall depth over Saudi Arabia as 105 mm based on the 50 y records of 190 ground stations of the hydro networks of the Ministry of Environment, Water and Agriculture (MEWA). Hydrometeorology provides ever-advancing knowledge about the hydrological cycle, which is an integral part of the wellbeing of humankind on Earth [12].

The spatial distributions of rainfall over Saudi Arabia have been studied by many authors, among of these is Almazroui [13] who analyzed the rainfall amounts records and concluded that the wet seasons are extending from November–April, whereas the dry season are from June–September. Also, the author [13] considered that the spring is the highest and winter is the second highest rainfall-occurring season, resulting in large amounts of rainfall during the wet season over most of the country. Almazroui [13] employed the regional Climatic Model RCM to simulate and understand the life cycle of the two systems that produced heavy rainfall spells over western Saudi Arabia in November 1996 and compared their spatial patterns with rain-gauge data and with the Climate Prediction Center (CPC). Abdullah and Al-Mazroui [14] studied the rainfall in the south-western region of Saudi Arabia and discussed the rainy seasons and the aridness of the area. Subyani [15] studied the annual and seasonal mean rainfall patterns in southwestern Saudi Arabia. On the other hand, very little studies have been dealt with the study of the hydrological impact of the sever rainstorm that have affected the Kingdome of Saudi Arabia. Rakhecha [16] conducted hydrometeorological studies for the development of water resources in India and concluded that the total water resources of the India are 2,301 km^3.

The Saudi Committee for Nomenclature of Distinguished Weather States Over Saudi Arabia was established on 28 January 2011 to give significant names for the distinctive weather states to facilitate its follow-up during its formation and movement, hydrometeorological analysis and to prevent any confusion when comparison with another weather states. About 30 Distinctive Weather States have prevailed in Kingdom of Saudi Arabia during different climatic seasons. Among of these are "Moghdeqah" which has extended from 22 March to 21 April 2012, "Al Baydaa" has extended from 25 April to 8 May 2013, "Sabeghah" has extended from 22–26 November 2015, "Al Rabab" has extended from 28 July to 3 August 2016, "Joud" from 11–18 April 2017 and "Ghadaq" from 25 October to 20 November 2018. Jeddah city in Makkah Region was affected by three severe thunderstorm events; the first was on the 25 November 2009, where 90 mm of rain fell in just 4 h on that day, where it was described by civil defense officials as the worst in 27 y. The second severe thunderstorm events were on 30 December 2010, whereas the third was on 26 January 2011. Recently, in 2020, the western and southwestern regions of Saudi Arabia; Al Madinah, Makkah, Al Bahah, Asir, Jazan, and Najran, as well as some parts of neighboring countries such as Oman, United Arab Emirates, and Yemen have been exposed to a summer distinctive weather state has lasted for 18 d starting from 24 July to 10 August 2020. During this rainstorm, daily medium to heavy rains have been prevailed. This weather states is locally named by the Saudi Committee for naming distinctive weather states as "Rahw".

2. Aim of study

Very little studies have been dealt with the study of the hydrometeorological impact of the sever rainstorm that have affected the Kingdom of Saudi Arabia. The aim of the present study is to:

- Understand how was the rainfall pattern during the weather state "Rahw".
- Investigate the hydrometeorological impact of the weather state "Rahw" on the water resources in southwestern regions in Saudi Arabia.
- Estimate the rainfall harvesting volume of rainfall, runoff have been stored in the dams' reservoirs for different demands.

- Mange and optimize the benefits from the renewable surface water behind dams in water supply, irrigation, aquifer recharge.

3. Methodology and data collection

The statistical and spatial distribution analyses of daily time series records of the hydro networks of the Ministry of Environment, Water, and agriculture (MEWA) were carried out using ARC GIS techniques. This includes 193 rainfall and weather stations (Table 1), as well as daily records of water levels in 165 constructed and under construction dams' reservoirs. The data of rainfall precipitation and water levels in dam reservoirs were collected from MEWA daily Bulletins within 18 d starting from 24 July 2020 to 10 August 2020. The locations of MEWA hydrologic network stations recorded during "Rahw" state is shown in Fig. 1. The daily and monthly rainfall precipitations of the stations have been correlated with the corresponding records of these stations during interval from 2010 to 2019. The spatial distribution maps of the affected area by the weather state "Rahw" have been also utilized. The total affected areas that have received rains during the weather state "Rahw" attained 212,672 km^2, representing 40.7% of the total area of the southwestern regions only.

4. Spatial distribution and statistical analysis of rainfall

MEWA has installed a good hydrologic network covering all the Kingdom of Saudi Arabia regions as early as 1958 and up to date. This hydrologic network is considered as one of the largest hydrologic networks in the Arabian and Gulf countries. The hydrologic network includes 1,073 gauges with different types and purposes including 573 rainfall ground stations, 73 weather ground stations, 315 monitoring wells, 40 runoff gauges and 7 water level gauges in the dam reservoirs. The weather state "Rahw" has begun on the Friday, 24/7/2020, where 57 rainfall and weather stations of MEWA, have recorded rainfall precipitation in 4 regions; these are Al Bahah, Makkah, Jazan, and Asir, in ascending order. On the second day 25/7/2020, the number of rainfall stations that recorded precipitation in the southwestern regions decreased and attained 23 stations only in four regions, including 10 stations in Al Madinah region, 6 stations in Makkah Region, 4 stations in Asir Region, and 3 stations in Riyadh region. It is noted that on the second day, none of the hydrological network stations throughout Jazan Region have recorded any precipitation. Over time, the geographical distribution of the rainstorm "Rahw" was gradually expanded, and on the third day 26/7/2020, precipitation was recorded at 86 ground stations. Fig. 1 shows NASA daily accumulated precipitation in 26/7/2020 during "Rahw" state in KSA.

The maximum extension of the weather state "Rahw" has reached on 27/7/2020, where the number of rains was recorded in 133 stations in 6 regions, which is the largest number of stations recorded during the weather state "Rahw" with 31 stations In the Jazan Region, 23 stations in the Asir Region, and 15 stations in the Makkah Region, then 8 stations in the Al Madinah region, and 2 stations for the first time in the Najran Region in the Rahw state. On 30/7/2020 the number of stations that recorded rain reached 102, and on 31/7/2020 recorded 111 stations, then on 4/8/2020 it recorded 93 stations. Then, the gradual decline in the spread of the rain situation began, reaching its lowest level on 9/8/2020, with 4 stations in only 3 regions, namely, Jazan Region, with 2 stations, and one station in each of the Asir and Al Madinah regions. Spatial distribution of the total rainfall precipitation within Jazan, Asir, Makkah, Al Madeinah, Al Bahah and Najran regions during "Rahw" state are shown in Figs. 3–8, respectively.

4.1. Maximum daily rainfall

The hydrological network ground stations of MEWA have recorded relatively high amounts of precipitation for

Table 1
Distribution of the rainfall and weather stations recorded rainfall during the weather state "Rahw" 2020

Region	Number of hydrologic network recorded rainfall during Rahw 2020	Number of weather and rainfall stations in MEWA hydrologic network	Average rainfall depth (mm) in the region within 50 y record
Riyadh	3	78	90
Makkah	53	108	100
Al Madinah	28	80	53
Eastern Region	0	34	60
Asir	49	83	210
Najran	2	6	75
Jazan	34	41	275
Al-Jouf	0	14	40
Northern Borders	0	12	70
Al-Qassim	0	34	90
Tabuk	2	36	35
Al Bahah	22	22	200
Hail	0	25	70
Total	193	573	103

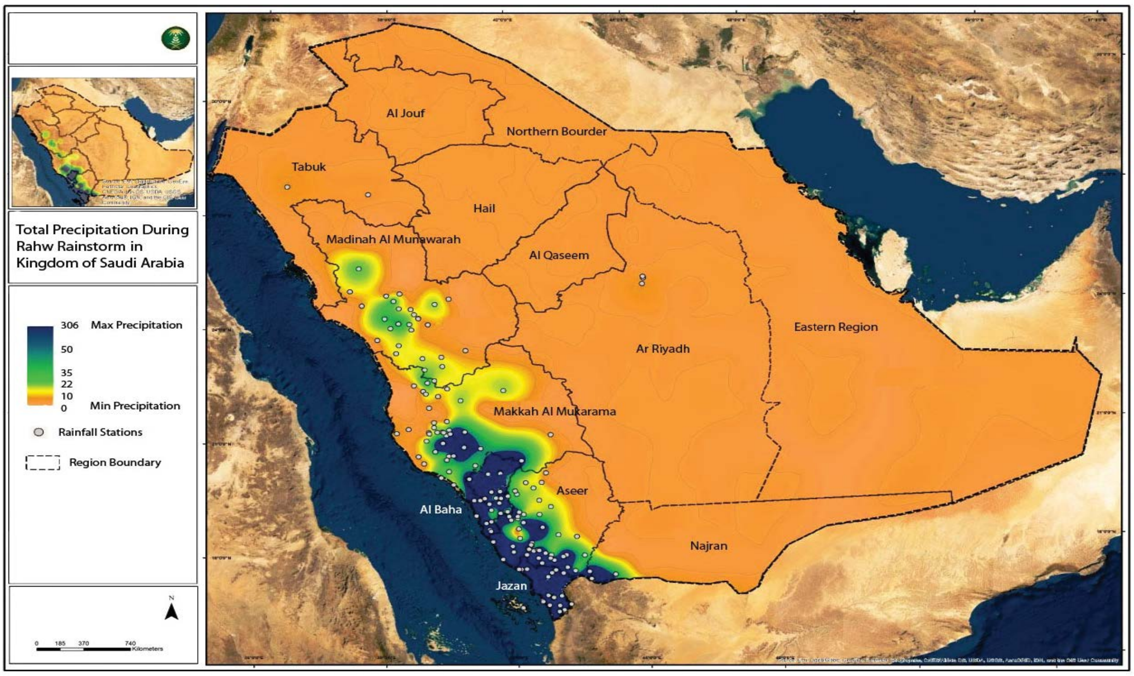

Fig. 1. Location of MEWA hydrologic network stations recorded during "Rahw" rainstorm in KSA.

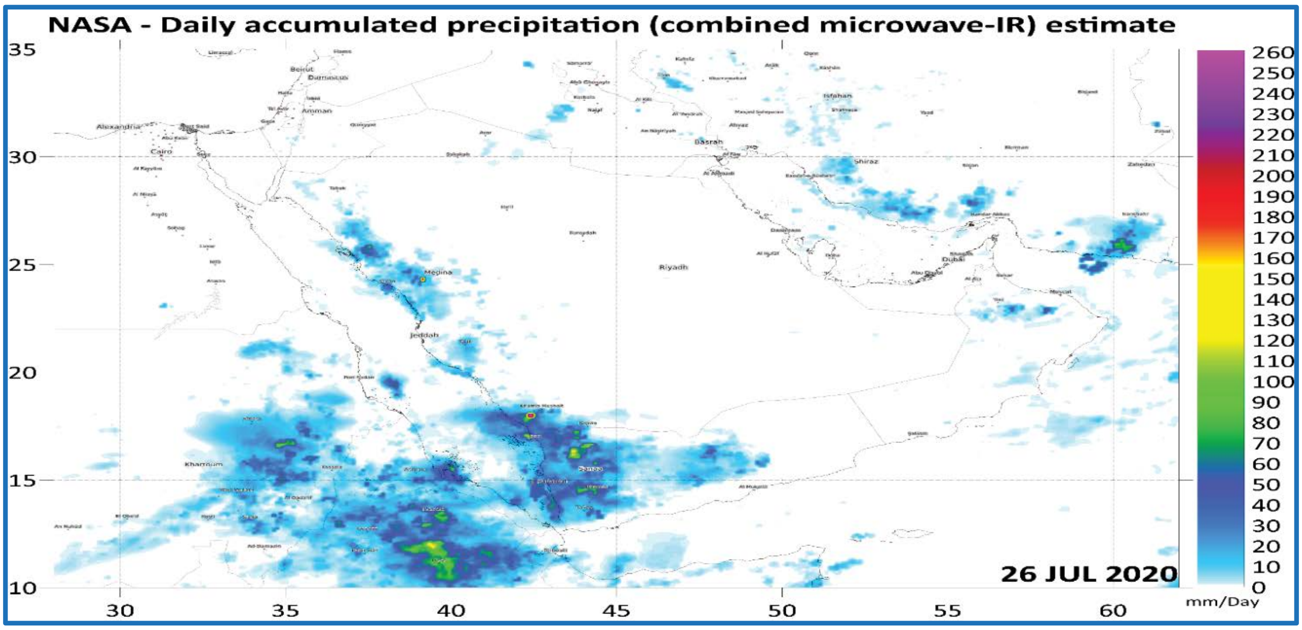

Fig. 2. NASA daily accumulated precipitation in 26/7/2020 during the weather state "Rahw".

1 d (24 h), and nearly 90% of the total amount of daily precipitation has received during a period of 2–6 h only. The rain station Damad in Jazan Region has recorded the maximum amount of daily precipitation during "Rahw" state attaining 83.1 mm, followed by Al-Shifa rain station located in Al Taif, Makkah Region 71.6 mm, Mensab in Bahr Abu Sakina in Muhayil, Asir Region 61 mm, then Al Bahah Station 45.4 mm, followed by Najran 36.8 mm, North Al-Fereash station in Al Madinah region 28.4 mm, as shown in Table 2. Whereas the maximum accumulative rainfall precipitation during the weather state "Rahw" is illustrated in Table 3.

4.2. Average depth and volume of rainfall precipitation

The daily rainfall precipitation records for all rainfall and weather stations during the weather state "Rahw" were obtained and the accumulated precipitation depths

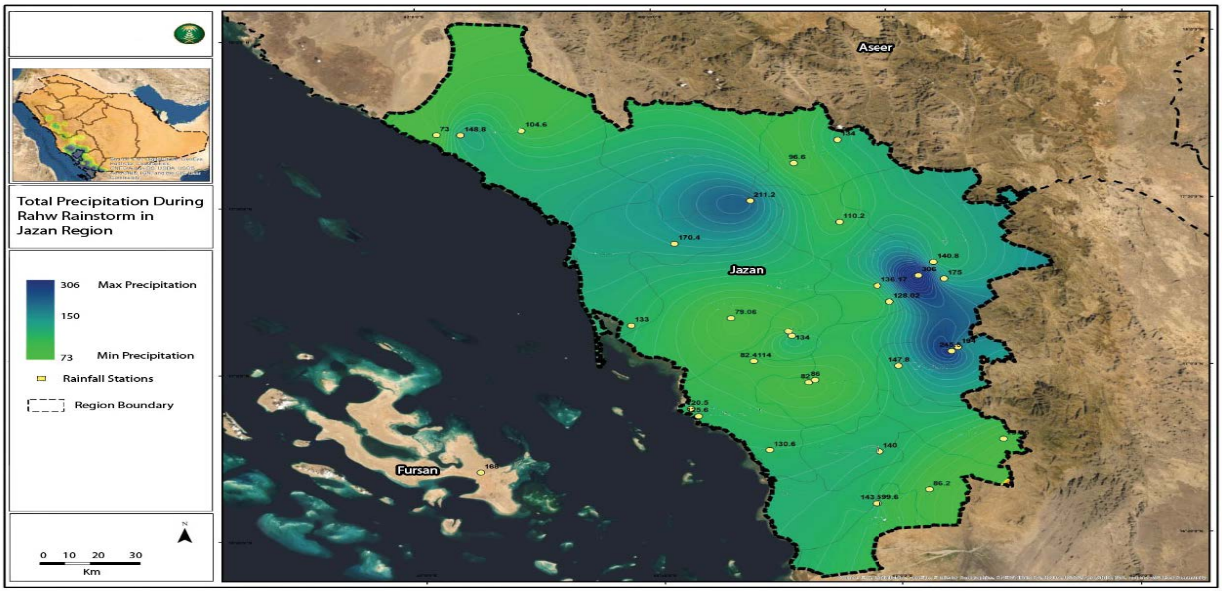

Fig. 3. Rainfall distribution in Jazan Region during the weather state "Rahw".

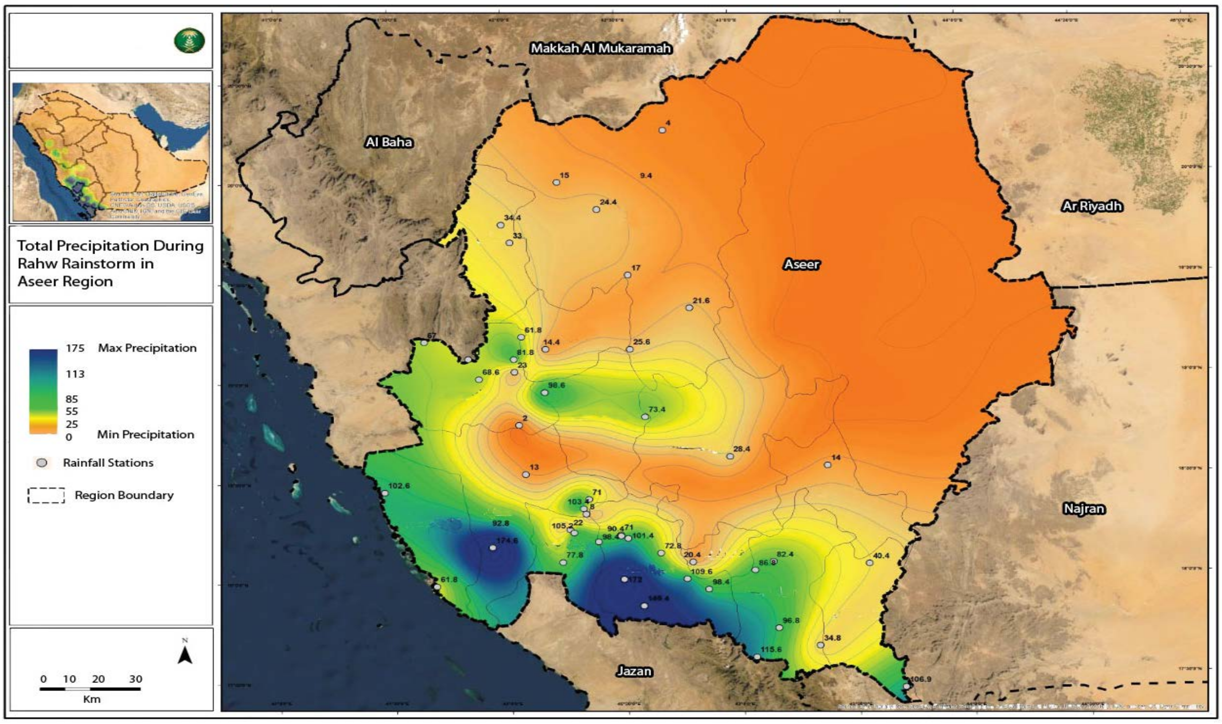

Fig. 4. Rainfall distribution in Asir Region during the weather state "Rahw".

were calculated. Then the total weighted areal precipitation depths and volumes were calculated for each region using Thiessen Polygons method. The total geographic area affected with "Rahw" state in Al Bahah, Jazan, Asir, Makkah, Al Madinah and Najran Regions have been calculated as 212,672 km^2, representing only 40.7% of the total area of those regions which attained as 522,355 km^2 Saudi Geological Survey, 2016. The lowest precipitation value was in Riyadh region as 2.6 mm, followed by Tabuk Region 3.1 mm, Al Madinah region 17.8 mm, Makkah Region 42.3 mm, then Asir Region 64.5 mm, Najran 69.6 mm, Al Bahah Region 89.6 mm and Jazan Region 133.8 mm. Generally, the average total precipitation depth over all Kingdom of Saudi Arabia (KSA) regions during the weather state "Rahw" was estimated as 32.56 mm, representing 30.90% of the total average depth of the annual precipitation

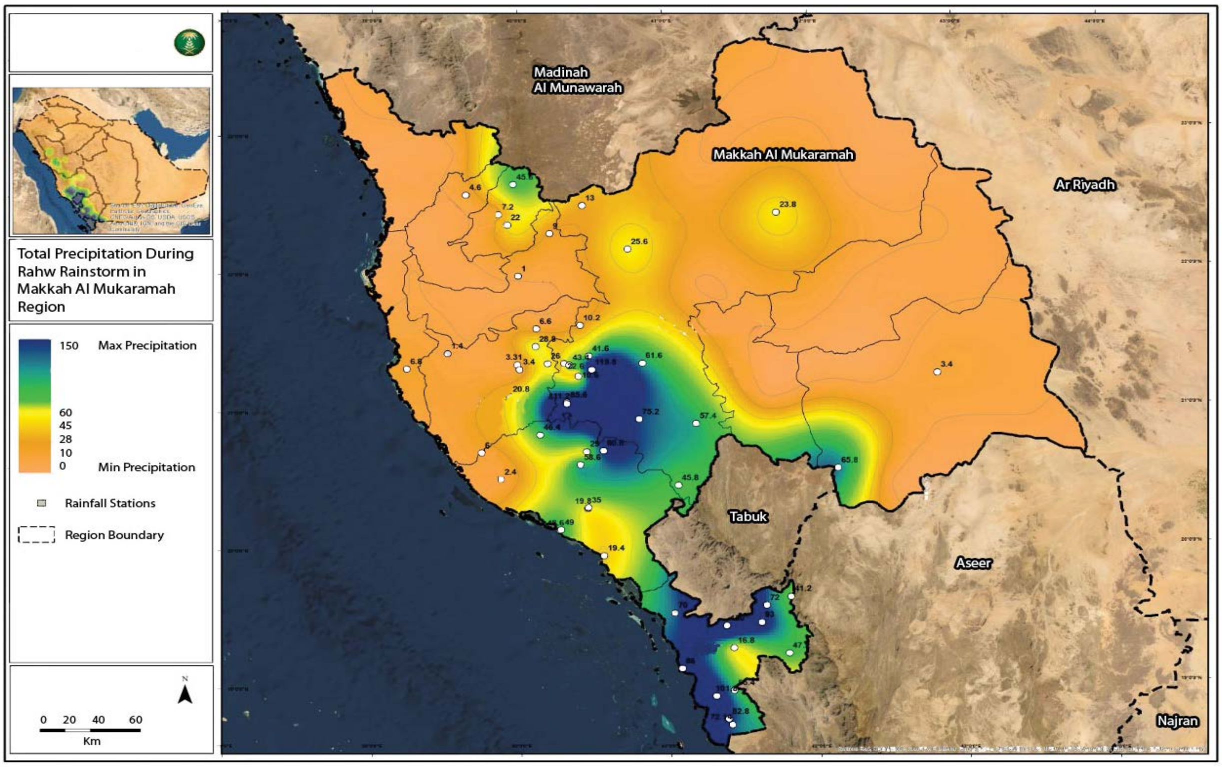

Fig. 5. Rainfall distribution in Makkah Region during the weather state "Rahw".

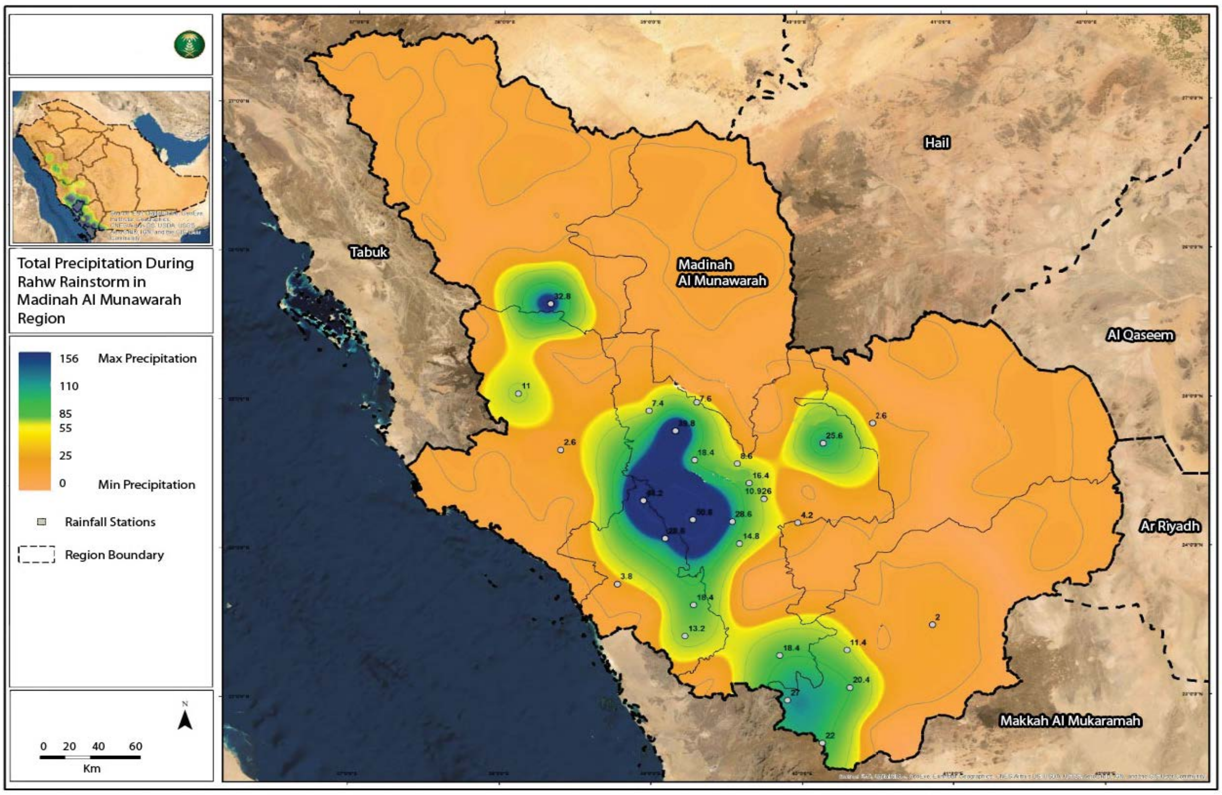

Fig. 6. Rainfall distribution in Al Madinah Region during the weather state "Rahw".

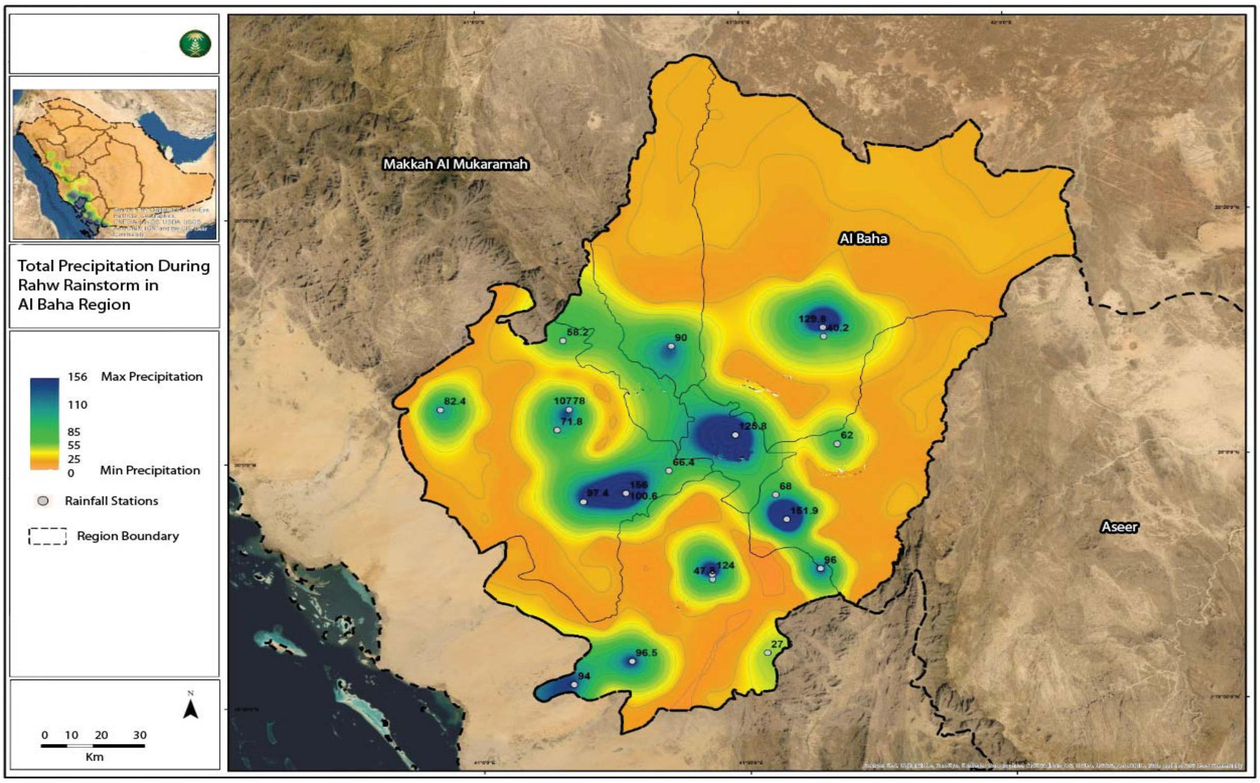

Fig. 7. Rainfall distribution in Al Bahah Region during the weather state "Rahw".

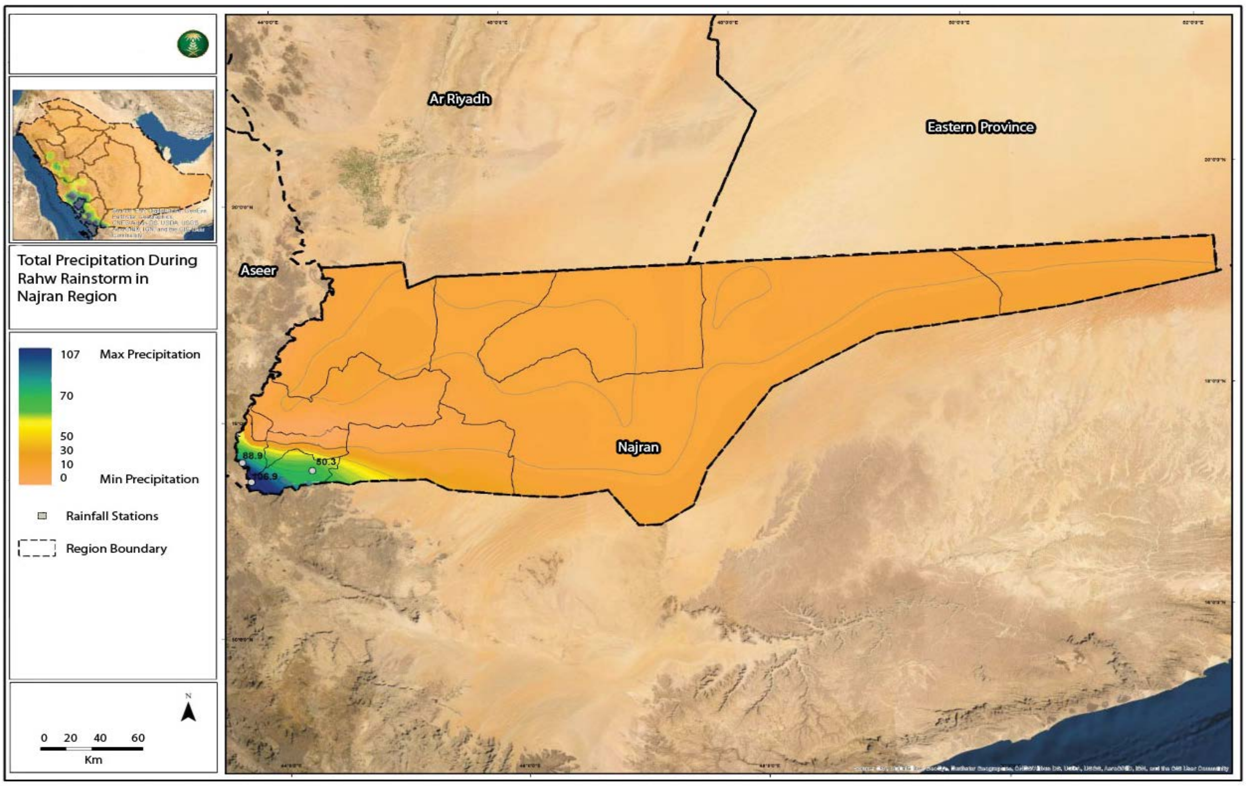

Fig. 8. Rainfall distribution in Najran Region during the weather state "Rahw".

Table 2
Maximum daily rainfall precipitation during the weather state "Rahw"

Region	Rainfall station	Maximum daily precipitation depth during Rahw (mm)
Jazan	Damad	83.1
Makkah	Al Shifa/Al-Taief	71.6
Asir	Mensab/Muhayl	61
Al Bahah	Al Bahah City	45.4
Najran	Najran City	36.8
Al Madinah	North Al Fereash	28.4

Table 3
Maximum accumulative rainfall precipitation during the weather state "Rahw"

Region	Rainfall station	Maximum accumulative precipitation (mm)
Al Bahah	Qilwah	156
Jazan	Abian	306
Asir	Mensab/Muhayl	174.6
Makkah	Tholatha Al Khurma	130
Al Madinah	Northern Al Fereash	50.6
Najran	Al Namasah	88.9

over all the Kingdom regions within 50 y record, is estimated as 103 mm by Mattar and Al Qahtani [17]. Whereas the average accumulated precipitation depth during the weather state "Rahw" over the western and southwestern six regions was estimated as 69.59 mm, representing 45.8% of the total average annual precipitation over these regions within 50 y record. Table 4 shows the average depths and volumes of precipitation for each region during Rahw state and correlated them with the crossponding average annual precipitation in all KSA regions within 50 y record. The time series of rainfall intensity and cumulative rainfall depth of Damad weather station in 6/8/2020, Jazan Region is shown in Figs. 9 and 10, respectively. Whereas Fig. 11 shows the corresponding air temperature and air relative humidity in the same station.

4.3. Comparison of the average rainfall depth for July and August months

The number of rainy days and the average depth of precipitation during the July and August months in the period from 2010 to 2019 were calculated and compared with the corresponding precipitation values recorded for the same months in 2020. The average precipitation depth for July 2020 was 32.9 mm and 9.4 rainy days, compared to the average precipitation depth of 20 mm and 5 rainy days during the period from 2010 to 2019.

4.4. July precipitation

It was found that the July is considered as a distinctive rainy month during the period from 2010 to 2019 with an average precipitation depth of 56 mm in Najran Region, 44 mm in Jazan Region, and 23 mm in Asir Region, 17 mm in Al Bahah, and 17 mm in Makkah, while rain was rarely recorded during the July month in the Eastern Region with an average of 8 mm, Tabuk Region 5 mm, and Riyadh region 2 mm. While no rain was recorded in July during the period from 2010 to 2019 in Al Madinah, Al-Jouf, Hail, and the Northern Borders regions.

4.5. Precipitation features of July 2020

- July 2020 was marked by an increase in the rainfall precipitations in Jazan Region 81 mm, Najran Region

Table 4
Average precipitation depth and volume over all KSA regions during the weather state "Rahw"

Region	Average annual precipitation depth for 50 y record	Average precipitation depth (mm) during Rahw	Geographic area (km^2) affected by Rahw state	Percentage of the affected area %	Average precipitation volume (M m^3)	Average runoff volume (M m^3)
Riyadh	90	2.6	0	0	0	0
Makkah	100	42.3	89,736	66	3,799	460
Al Madinah	53	17.8	39,916	27	709	28
Eastern Region	60	0	0	0	0	0
Asir	210	64.5	53,800	67	3,467	451
Najran	75	69.6	12,025	09	837	70
Jazan	275	133.8	12,242	94	1,638	246
Al-Jouf	40	0	0	0	0	0
Northern Borders	70	0	0	0	0	0
Al-Qassim	90	0	0	0	0	0
Tabuk	35	3.1	0	0	0	0
Al Bahah	200	89.6	4,954	41	444	53
Hail	70	0	0	0	0	0
Total	103	32.56	212,672	11	10,894	1,308

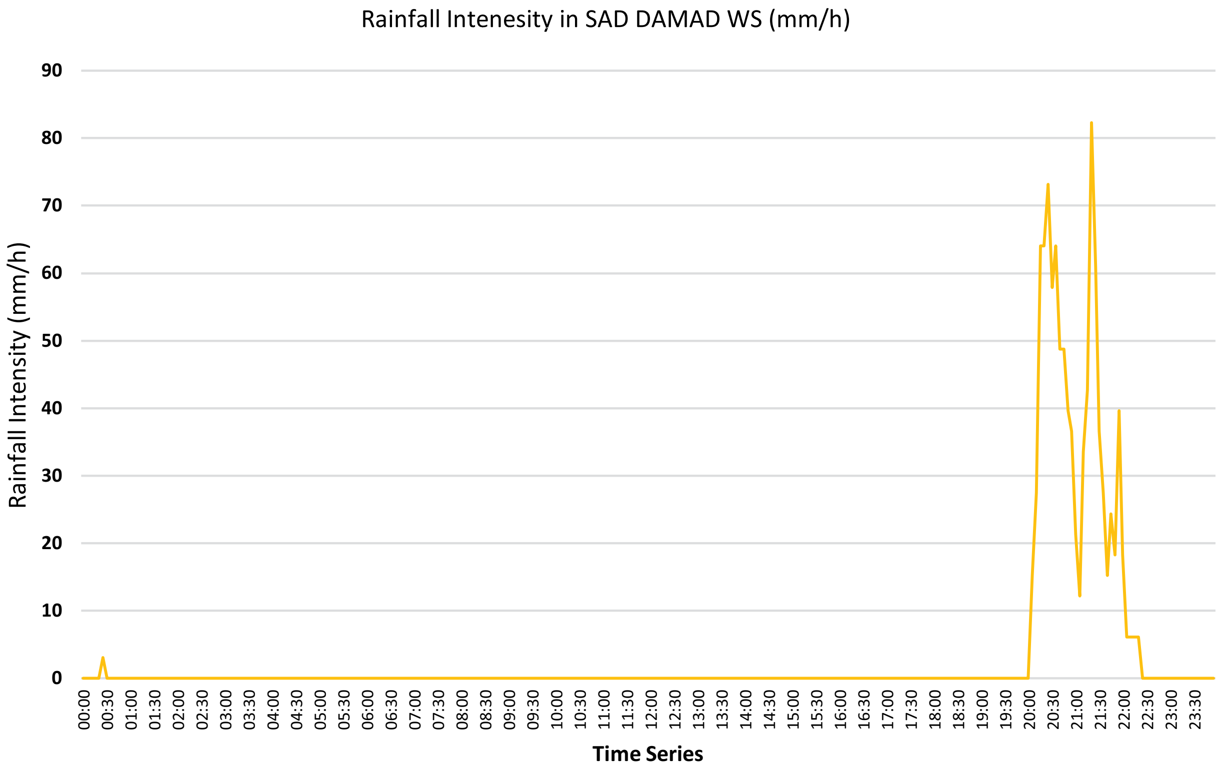

Fig. 9. Time series of rainfall intensity in Damad weather station in 6/8/2020, Jazan Region.

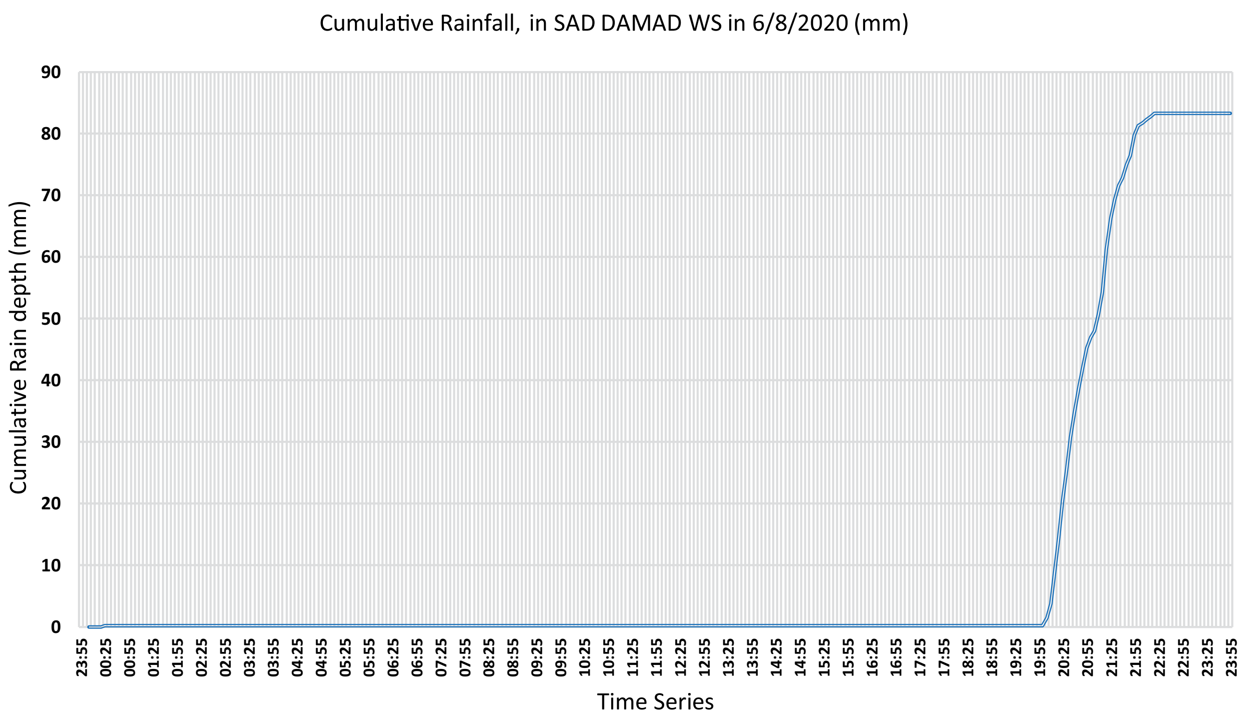

Fig. 10. Cumulative rainfall depth in Damad weather station in 6/8/2020, Jazan Region.

62 mm, Al Bahah Region 59 mm, Makkah Region 21 mm, Al Madinah 12 mm. Note that July in the regions of Jazan, Asir, and Makkah recorded the highest rainfall in the same month in 2016 at an average of 134 mm in Jazan, at an average of 59 mm in Asir, at an average of 47 mm in the Makkah Region.

- The highest number of rainy days were recorded in July 2020 with an average of 25 rainy days in the Asir Region, 17 rainy days in the Al Bahah Region, 12 rainy days in Al Madinah region, 10 rainy days in the Makkah Region and 8 rainy days in Najran Region, as illustrated in Table 5.

4.6. August precipitation

The meteorological statistical analyses of the rainfall records of MEWA stations showed that August was a rainy month during the period 2010–2019 in Jazan Region with an average depth 58 mm, and Asir Region 38 mm, Makkah Region 28 mm, Al Bahah Region 20 mm, Al Madinah region 10 mm, and Najran 8 mm. While no rain has been recorded in August in the rest of the Kingdom's regions during the same period. The average depth of precipitation for August 2020 was 27.5 mm, and 9.2 rainy days, compared to 27 mm precipitation and 7 rainy days during August within the period from 2010–2019, as illustrated in Table 6.

4.7. Precipitation features of August 2020

- August 2020 was characterized by an increase in the monthly average rainfall depth in Jazan Region 66 mm, Al Bahah Region 27 mm, and Najran Region 14 mm.
- August 2020 has recorded the highest average monthly rainfall in Jazan, Asir, Makkah and Al Madinah during 2016, at a rate of 167, 99, and 103 mm respectively.
- August 2017 recorded the highest rainfall of 37 mm in Al Bahah Region during the period from 2010–2019.

4.8. Frequencies of "Rahw" climate state

The statistical analyses of the rainfall records of MEWA hydrologic networks concluded that more than thirty distinctive weather states have prevailed over Saudi Arabia during different climatic seasons between 2011 and 2021, but

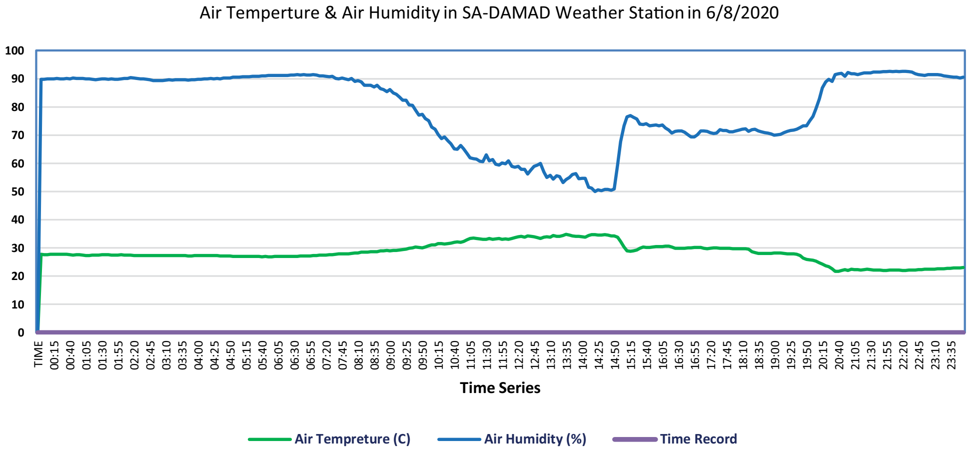

Fig. 11. Air temperature and air relative humidity in Damad weather station in 6/8/2020, Jazan Region.

Table 5
Average precipitation depth and rainy days in July in KSA regions

Region	Average precipitation depth (h mm) in July	Maximum precipitation depth (mm) in July	Record year	Average rainy days in July	Maximum rainy days in July	Record year	Average precipitation depth (h mm) in July 2020 mm	Average rainy days in July 2020
Al Bahah	17	59	2020	5	17	2020	59	17
Jazan	44	134	2016	5	12	2019	81	11
Asir	23	59	2016	12	25	2020	43	25
Makkah	17	47	2016	5	10	2020	21	10
Al Madinah	8	12	2020	4	12	2020	12	9
Najran	56	62	2020	7	8	2020	62	8
Riyadh	3	3	2020	1	1	2020	3	1
Tabuk	5	6	2020	2	2	2020	6	2
Eastern Region	8	9	2020	2	2	2020	9	2
Al-Jouf	0	0		0	0		0	0
Northern Borders	0	0		0	0		0	0
Al-Qassim	0	0		0	0		0	0
Hail	0	0		0	0		0	0

Table 6
Average precipitation depth and rainy days in August in KSA regions

Region	Average precipitation depth (mm) in August	Maximum precipitation depth (mm) in August	Record year	Average rainy days in August	Maximum rainy days in August	Record year	Average precipitation depth (mm) in August 2020	Average rainy days in August 2020
Al Bahah	20	37	2017	6	21	2019	27	9
Jazan	58	167	2016	13	18	2013, 2016	66	13
Asir	38	99	2016	14	23	2019	28	17
Makkah	28	103	2016	5	23	2019	21	10
Al Madinah	10	22	2016	3	7	2015	9	4
Najran	8	14	2020	3	3	2020	14	3
Riyadh	0	0		0	0		0	0
Tabuk	0	0		0	0		0	0
Eastern Region	0	0		0	0		0	0
Al-Jouf	0	0		0	0		0	0
Northern Borders	0	0		0	0		0	0
Al-Qassim	0	0		0	0		0	0
Hail	0	0		0	0		0	0

little weather states have prevailed in the summer season, among of these was called as "Al Rabab" and has extended from 28 July to 3 August 2016. Therefor the authors have the opinion that the weather state "Rahw" is considered as the frequency of "Al Rabab" weather state which have approximately occurred in the same interval in 2016.

5. Average runoff volumes on the regions

The total average cumulative precipitation volume over the affected areas by the weather state "Rahw" was estimated as 10,894 million m^3. The direct surface runoff volume in the areas affected by "Rahw" was estimated based on the averages of the cumulative rainfall and the empirical runoff coefficients of Al Hasan and Mattar [18] as shown in Table 7. Figs. 12 and 13 show the average precipitation and average runoff volumes, respectively during the weather state "Rahw" in KSA. The direct surface runoff is estimated as 1,308 million m^3. Among this runoff, 352 million m^3 were received into the constructed dams' reservoirs and 18 million m^3 into the under-construction dams' reservoirs.

Table 7
Total precipitation and runoff volumes in the western and south-western regions during the weather state "Rahw"

Region	Total precipitation volume during Rahw M m^3	Average total runoff volume during Rahw M m^3
Makkah	3,799	460
Al Madinah	709	28
Asir	3,467	451
Najran	837	70
Jazan	1,638	246
Al Bahah	444	53
Total	10,894	1,308

5.1. Runoff in dam reservoirs

The daily record of the water levels of the retained water behind the dams in Saudi Arabia showed that the flowing of many wadies and the runoff reached to the reservoirs of 165 dams, and this led to increasing in the volume of water in these reservoirs by 370 million m^3. Whereas the volume of retained water behind these dams was estimated as 596.1 million m^3 before Rahw weather state and 738.2 million m^3 at the end of Rahw state. To meet the demands of the farmers downstream the dams during the rainy state, about 201.6 million m^3 of surface runoff was released from dam gates of which the volume of 89 million m^3 was released from Najran surface dam only. As well as 8.3 million m^3 was supplied for the treatment plants constructed on some dams. Therefore, the net increase in the storage volume of dam's reservoirs because of "Rahw" is estimated as 142 million m^3.

5.2. Releasing of dam gates during Rahw

During "Rahw" climate state, many dams in the south-western regions have received considerable amounts of daily surface runoff resulting to rising of the water levels in the dams' reservoirs to more than 75% of the spillway height. The emergency operational plans of these dams have been applied. The gates of some dams were released to drain water in the downstream to meet the demand of farmers and enhance the groundwater recharge in the wells. The total volume of released water from the dams' gates attained 201.62 million m^3, of them. 93.87 million m^3 were drained from the dams of Najran Region, 61.7 million m^3

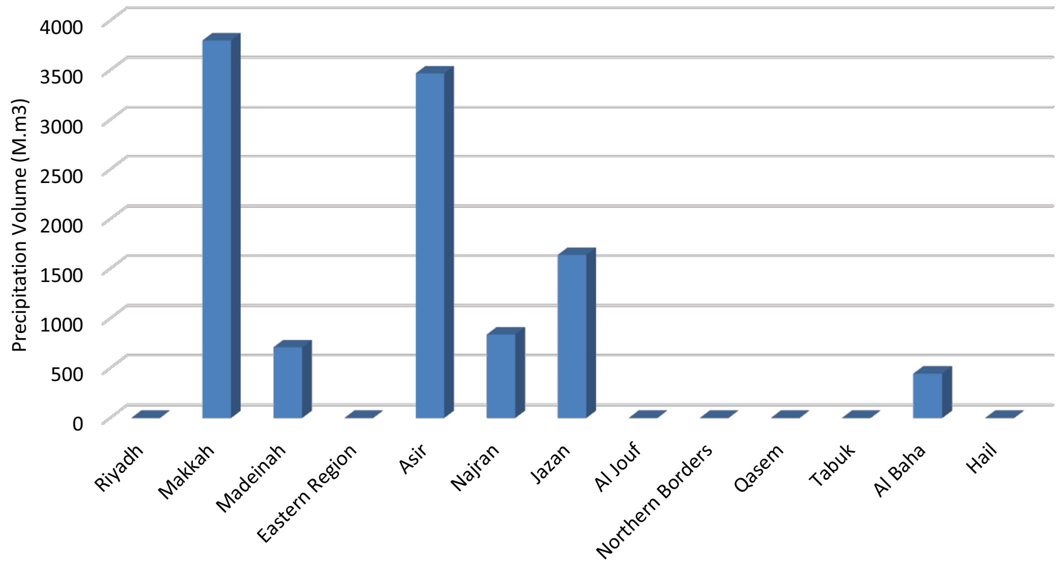

Fig. 12. Average precipitation volume (M m^3) during the weather state "Rahw".

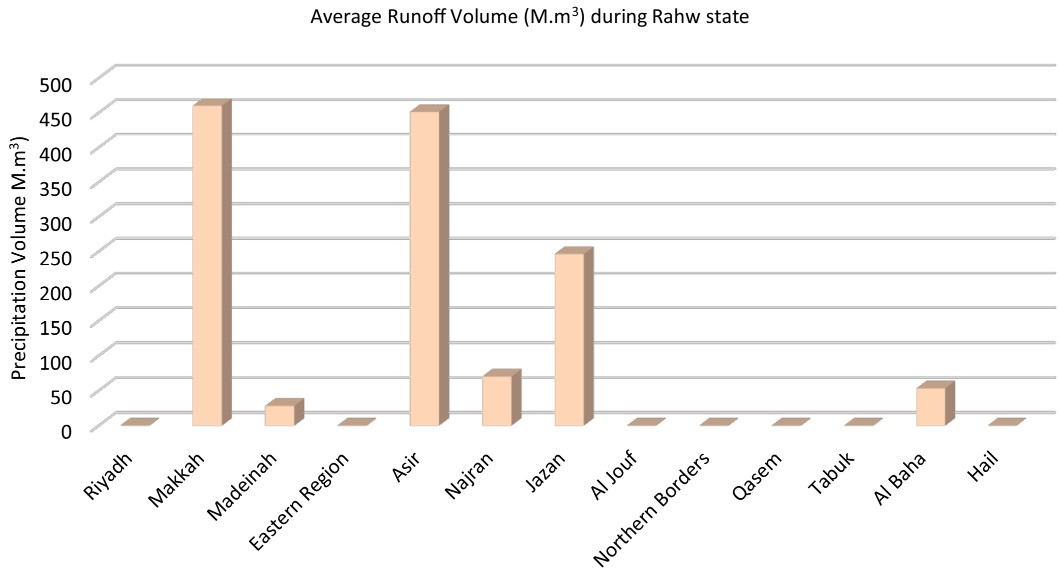

Fig. 13. Average runoff volume (M m^3) during the weather state "Rahw".

from the dams of Jazan Region, 29.0 million m^3 from the dams of Makkah Region, 10.87 million m^3 from dams of Asir Region, 3.18 million m^3 from dams of Al Bahah Region, and 3.0 million m^3 from dams of Al Madinah region.

6. Conclusion

More than thirty distinctive weather states have prevailed over the Kingdom of Saudi Arabia during different climatic seasons between 2011 and 2020, but very little climate states have prevailed during the summer season, among of these is "Al Rabab" weather state which has extended from 28 July 2016 to 3 August 2016.

The western and southwestern regions of the Kingdom of Saudi Arabia; Al Madinah, Makkah, Al Bahah, Asir, Jazan, and Najran have been subjected to a distinctive summer weather state locally named as "Rahw", which has lasted for 18 d, from 24 July 2020 until, 10 August 2020, and resulted on medium to very heavy rains.

The total geographic area affected with Rahw was estimated as 212,672 km^2, representing only 40.7% of the total area of these regions.

The average cumulative rainfall depth on the affected areas of the southwestern regions is estimated as 69.59 mm and the corresponding precipitation volume is estimated as 10,894 million m^3.

The average rainfall received in July 2020 is greater than the average rainfall has been received in the same month during the last 10 y in each Jazan, Najran, Al Bahah and Makkah Regions.

August month recorded in Jazan, Asir, Makkah and Al Madinah regions the highest rates of rain during the year

2016, at a rate of 167 mm in Jazan, 99 mm in Asir, and 103 mm in Makkah Region. While August recorded the highest rainfall of 37 mm in 2017 in Al Bahah Region in the last 10 y.

Releasing of dam's gates during "Rahw", and the flow of wadies in the areas affected by Rahw led to the strengthening of the groundwater recharge of the wadi deposits which led to the significant rise in the groundwater level in the farmers' wells.

It is advised to use the "Rahw" rainstorm as a guideline in the design of rainstorms of flood mitigation projects, and for studying the meteorological zones in Kingdome of Saudi Arabia.

The present study recommends developing and update the operational plans of dams in western and southwestern regions to maximize the benefits of the surface runoff and enhance the water resources during the occurrence of such rainstorms.

Continuous coordination with the Civil Defence and the emirates of the regions is highly recommended to warn citizens not to be near the wadi streams because of the possibility of opening the gates of the dams at any time.

A free storage volume must be maintained in the dam's reservoirs corresponding to 50% of the total storage capacity of the dam to accommodate any runoff volumes may reach the dam during rainstorms.

Acknowledgements

The authors would like to acknowledge H.E. Dr. A. Alshaibani; the Deputy Minister for Water Affairs in MEWA for his usually support and encouragements during this study. Also, we wish to thank Prof. Walid. Al Zubari for his critical review of the manuscript and his valuable comments that helped to improve the quality of the manuscript. Our colleagues in the department of surface water and department of dams are also acknowledged for providing the daily record of precipitation, and water levels behind the dams respectively.

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Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2022.28227

263 (2022) 188–196
July

A hydroecological technique to improve infiltration of clogged bed of recharge dam in Oman

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Received 28 February 2022; Accepted 30 April 2022

ABSTRACT

Recharge dams represent one of few engineering techniques to harvest flashfloods water in arid zones for augmenting the limited water resources. Formation of a low-permeable cake by deposition of suspended particles transported by ephemeral floods is a common problem for dams in arid regions (e.g., Oman, Saudi Arabia, Iran, and Tunisia). Accumulation of surface sediments affects many hydrological properties of dam's reservoir area, including reduced infiltration and deep percolation rates, higher water loss via evaporation, and ultimately lower aquifer recharge and higher flood peaks. The recharge basin downstream the dam receives pulses of suspended sediments after each major flashflood. This causes a "hopping" downward translocation of fine particles into the coarse-texture matrix of the alluvium bed, clogging of the pores which significantly reduces the saturated hydraulic conductivity (K_s). The intermittent flashfloods forms multilayered heterogeneous soil profile and a resultant non-monotonic cumulative infiltration curves have intricate hydro-engineering implications, for example, we observed that the runoff water, released from the dam, instead of a fast vertical infiltration, forms a shallow quasi-horizontal Darcian flow that out-seeps further downstream into local topographic depressions and contributes to undesired runoff-evaporation. Hence, finding practical solutions to overcome the consequences of the siltation problem of dam beds is of a paramount importance. In this work, we investigated the possibility of applying a hydro-ecological method to combat the cake-clogging curse. We experimentally (using pots experiment) and numerically (using HYDRUS-2D code) quantified the effect of roots of indigenous trees, namely Sidr (*Ziziphus spina-christi*) grown in soil pots on increasing infiltration through a clogged layer. The pots were exposed to two flood events over 12 months period of cultivation. The average initial infiltration rates for vegetated pots (240 and 147 mm/h for F1 and F2, respectively) which is 2.4 and 2.1 times higher than that for pots without plants, bare soil (around 85 mm/h in average). For vegetated pots, the final infiltration rates (K_s) were higher by 1.7 and 3.3 times than that for the control pots, ($p < 0.05$). The numerical modeling illustrated the effect of the root system on the dynamics of soil water. The root system enhances the propagation of the soil water in both lateral and vertical directions. The results indicate the feasibility of this hydroecological technique in improving the infiltration rate and hence the recharge efficiency of recharge dams in arid areas.

Keywords: Clogging; Pore space; Infiltration; Arid zone; Recharge dams; HYDRUS-2D; Root water uptake; Ziziphus spina-christi

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

1. Introduction

Siltation is a serious common problem for recharge dams in arid regions. As these sediments are brought by ephemeral flashfloods and accumulate at the surface of the dam's reservoir area and hence alter the hydrological properties of the dam's bed and that of the vadose zone. These include reducing infiltration and deep percolation rates, as well as reducing the storage capacity of dams. This adversely affects the recharge to underlying aquifers [1–8]. Therefore, it is very important to find practical solutions to cope with siltation.

The recharge efficiency and the original storage capacity on the upstream area of Al Khoud Dam reservoir bed (located in Muscat Governorate in North of Oman) are greatly influenced by substantial changes in the Pedological and physico-hydrological properties. This is because of the deposition of the brought-in sediments by the detained infrequent Wadi flows. The recharge basin downstream of the dam is continually shrinking because of expanding urbanization. The currently undertaken practice to remove the deposited materials by bulldozers seems to be impractical due to the huge amount of sediments and macro-pores clogging by fine particles migration [4].

This almost-zero salinity silt cake is good as a substrate for plants to grow. Plant roots are well known for improving the permeability of the soil as the roots provide extra passage channels for water to flow through [9,10]. Along with improving infiltration ability of the soil, roots of the plant are expected to break the capillary barrier formed at the interface of the deposited fine texture soil and the original gravely coarse-textured material underneath. Studies have shown that plants' roots are capable to penetrate fine and compacted soils and create preferential channels where water can seep through and ultimately increase the infiltration rate [9–13]. The growth of the plants and their roots can further enhance the infiltrability of the soil. A study by Leung et al. [14] found that the infiltration rate in silty sand soil was directly related to the increase of plant age, root biomass, and root length density. In another study, the roots of *Eucalyptus largiflorens* were found to increase the infiltration by 2–17 times as compared to none vegetated clay-floodplain [11]. Al-Maktoumi et al. [15] found that the growing indigenous *Ziziphus spina-christi* trees can significantly increase the infiltration rate of silt loam sediments by 1.9–5.9 times as compared with bare soil ($p < 0.05$). Additionally, their study demonstrated that the infiltration rate was significantly improved with the growth of plants roots over time.

This paper explores experimentally (using pot experiments) and numerically (using HYDRUS-2D software) the effect of roots of the indigenous trees (*Ziziphus spina-christi*) locally named "Sidr" on improving infiltration. In practical implementation, the plantation zone has to be far away from the embankment because plant roots may threaten the safety of the clay core of the dam and hence jeopardize its structural stability. The study also investigates the impact of trees' roots and water supply frequency (irrigation scheduling) on moisture dynamic using HYDRUS-2D.

The study assesses the suitability of the suggested eco-hydrological solutions to combat or reduce the potential adverse effects of siltation and growing urbanization and hence improve recharge efficiency in the vicinity of recharge dams and similar reservoirs in arid areas. The study contributes to a better understanding of the water dynamics within the vicinity of the dam under the designed ecological technique, which is of critical importance for better management strategies and augmentation of water resources that will provide the foundation for future decision making by the concerned water agencies.

2. Methodology

2.1. Pots experiment

Circular pots of 40 cm high were packed with soil collected from Al-Khoud dam area. The pots have soil layering similar to the layering observed in Al-Khoud (reservoir). Fig. 1 presents the layout of the experimented pot. The soil was sieved using a big 2 mm soil sieve. A certain volume of water was occasionally applied to the pots during the experiment period. This represents irregular flood events that are due to erratic and sporadic rainfall pattern that characterizes the Omani climate (and arid zone in general). During each flood experiment, the infiltration rate was measured. The infiltration date experiment was analyzed using Horton equation to calculate the final infiltration rate. The experimental site is the Agricultural Experiment Station (AES) at Sultan Qaboos University, where all facilities/necessary logistics needed for the experiment are available (23° 35′ 37.0″ N, 58°09′03.7″ E). The AES is only a few kilometers from the dam area and the weather conditions at both sites are almost the same.

The planted Sider trees were subjected to irrigation as the soil in the tank is of limited volume, while in reality these trees are well known to survive without irrigation because they are water hunters. The irrigation stopped before the flooding (infiltration experiment). The evapotranspiration rate in the pot was estimated at the experimental site and modeled for the dam area.

Out of 12 small pots (of 39 cm in length, 14 cm in diameter), 3 pots were considered as control (without plants).

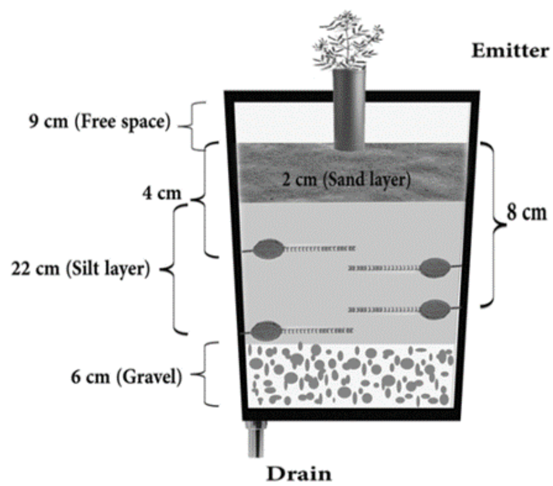

Fig. 1. Schematic diagram for a cross-section of pot experiment.

The inner walls of the pots were plastered with coarse sand and cement to create a rough surface. This helped to reduce the development of macro and micro-cracks between the soil body and the inner wall of the pot because of variation in material affinity between the soil and the pot surfaces. All pots were packed with a small gravel layer (about 5–6 cm) at the bottom, then silt layer of 22 cm depth), and finally sand layer with 2 cm thickness (Fig. 1). The root density and distribution patterns were studied by scarifying one pot at a time for destructive analysis. The bottom side of the pot was equipped with controlled valves to measure the volume of percolating water. The experiment was run for 12 months period.

2.2. Plantation and irrigation

Initially, 9 replicates for Sider were selected for the experiment. The reason behind choosing these trees is lagged behind their morphology and root characteristics since they are indigenous, coarse with deep root trees, and presumably can survive the climatological and water stress condition as observed in the vicinity of Al Khoud Dam and along wadis in Oman (Fig. 2a). The initial height of the seedlings was 72 cm. The seedlings were transferred to a 30 cm high PVC pipe to provide support to the seedlings and space for irrigation (Figs. 1 and 2b).

The average number of leaves/branches and the average height of the plants were measured. A total number of six observations were made during the experiment. The root topology and features were investigated. Additionally, the length of roots and shoots were measured. The dry biomass of roots and shoots was estimated.

All pots were irrigated daily with 133 mm of good quality water (ECi = 0.5 dS/m) using a pressure compensating Heavy Wall drip line (Netafim, USA) attached with a pressure compensated emitter for uniform and constant dripping (4 L/h). The emitters were positioned in the PVC pipes. Hunter controller (Hunter NODE) was used to manage both the timing and frequency of the irrigation.

According to the soil texture analysis, the packed soil was classified as silt loam using the hydrometer approach. This soil has 75.5% silt, 19.8% clay, and 4.7% sand (Table 1). This soil also has a pH of 8.4 with an electrical conductivity of 1.25 dS/m. The irrigation water has a pH of 8.2 and electrical conductivity of 0.23 dS/m. Generally, the physico-chemical properties of soil and water support the good growth of plants. The soil pH and the electrical conductivity (EC_{e-} for saturated extract) were measured using pH meter and electrical conductivity meter respectively [16].

Table 1
Physico-chemical properties of the soil

Soil properties	Values
Sand (%)	4.7
Silt (%)	75.5
Clay (%)	19.8
Textural class	Silt loam
pH	8.4
Ece (dS/m)	1.25

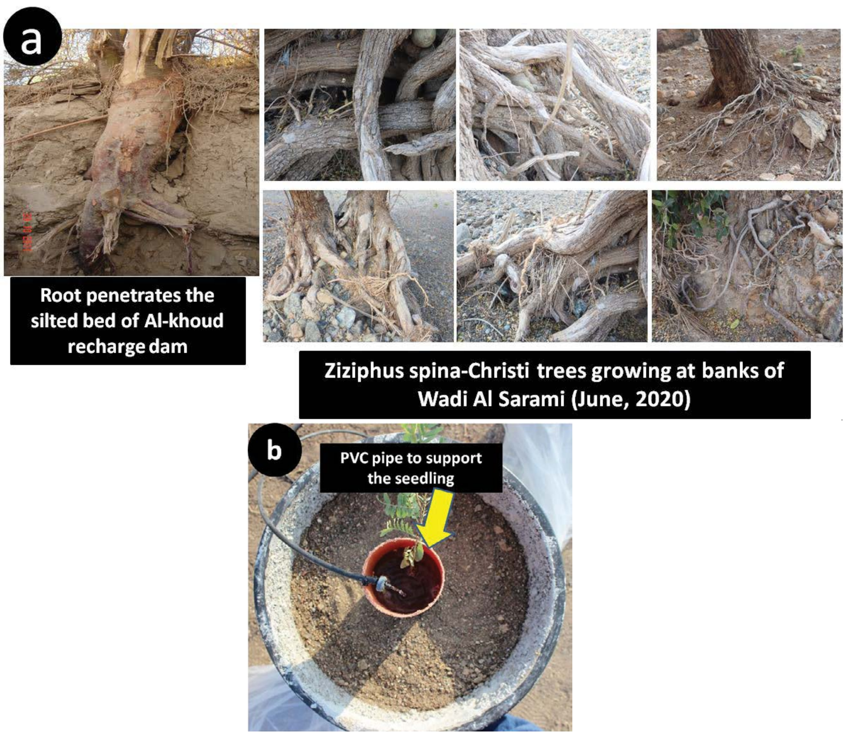

Fig. 2. (a) Photos showing the root system of Sider trees. (b) Sider seedlings in the PVC pipe.

2.3. Infiltration measurements

All pots were ponded during the infiltration tests. In order to prevent direct disturbance of the soil, date palm residues (leaf sheath) were placed at the topsoil of each pot. Then the water slowly poured and the falling of the water level in the pots was measured with the aid of a 15 cm graduated ruler at 2-min intervals for the first 10 min, 5-min intervals for the next 20 min, and, finally, 10-min intervals until reaching a steady-state condition.

2.4. Set up of the numerical modeling using HYDRUS-2D

HYDRUS-2D [17] was used to simulate axisymmetric moisture dynamic in a hypothetical soil cylinder with root water uptake (RWU) by a tree (resembling Sider tree) under three different water supply patterns (irrigation regimes). The first regime models the experiment with Sidr (*Ziziphus spina-christi*) of Al Yamani et al. [18]. The irrigation flux for this scenario was 0.273 cm/h for a duration of 7 h every day. The second-scenario was the same as for the first scenario (i.e., same flux and duration) but with deficit irrigation (i.e., irrigation done once every 2 d). In the third scenario, the irrigation flux was doubled (=0.546 cm/h) while maintaining the same duration (7 h) and frequency (once every 2 d) as for the second-scenario.

The length of time for each scenario in HYDRUS was 720 h (30 d) with a print time equal to 30. The geometry of the HYDRUS-2D model is axisymmetric with z = 10 m and r = 3.95 m (Fig. 3). The origin of the Cartesian coordinate system was at the bottom left corner of the domain geometry. The mesh size for the domain was 10 cm and was refined to 1 cm near the vicinity of the tree. The domain was discretized into 11,125 nodes (475 and 21,773 1D and 2D elements, respectively). The maximum number of iterations was 10 and the water content tolerance was 0.001. van Genuchten–Mualem (VG-M) hydraulic model with no hysteresis was used for the simulations.

The soil texture for all three scenarios was assumed to be homogeneous sand (Table 2). We used the HYDRUS Rosetta package to estimate the VG-M properties of this sand based on the textural properties and bulk density. The predicted K_s and θ_s were modified to measured values reported by the study of Al Yamani et al. [18]. We also used Eq. (1) from Ghezzehei et al. [19] to convert α_G of Al Yamani et al. [18] into α_{vG} We then put the converted value into HYDRUS.

$$\alpha_G = 1.3\alpha_{vG}n \quad (1)$$

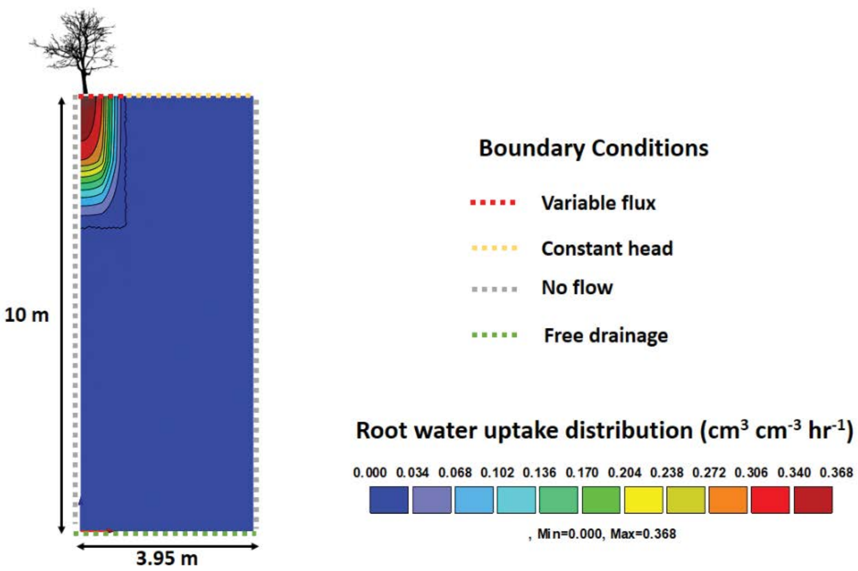

Fig. 3. Geometry and selected HYDRUS boundary conditions.

Table 2
Soil properties for the sand: θ_r and θ_s are the residual and saturated water contents, respectively; α and n are shape parameters for the van Genuchten–Mualem equation; and K_s and L denote the saturated hydraulic conductivity and pore-connectivity parameter, respectively

Soil type	Soil particles (%)			Bulk density (g/cm³)	θ_r (cm³/cm³)	θ_s (cm³/cm³)	α (cm)	n (–)	K_s (cm/h)	L (–)
	Sand	Silt	Clay							
Sand	95	1	4	1.54	0.055	0.41	0.046	3.34	900	0.5

Note: Soil particles, bulk density, θ_s, and K_s were obtained from Al Yamani et al. [18] while n and L were obtained by Rosetta.

where α_G (constant > 0) is sorptive number (1/m) [20], $n \geq 1.5$ and α_{vG} are shape parameters for the van Genuchten–Mualem equation.

HYDRUS-2D uses [20] equation to model RWU as a function of soil water pressure head. The 2D form of Feddes et al. [21] equation is given by Eq. (2):

$$S(h, x, y) = \propto (h) S_p(x, y) \quad (2)$$

where $S(h,x,y)$ is the actual RWU or volume of water removed from a unit volume of soil per unit time (t^-), $\infty(h)$ is a dimensionless stress response function of the pressure head ($0 \leq \infty \leq 1$), and $S_p(x,y)$ is the potential RWU rate (t^-). This equation assumes that the actual RWU is zero close to saturation and the permanent wilting point (PWP). At saturation, the root zone experiences lack of oxygen, and at the PWP plants cannot extract water [22]. Plants are also considered water-stressed if the actual RWU is below 0.5 cm/d [23].

The initial condition was constant pressure head and was set at –1,000 cm. The boundary conditions were set as follows: variable flux boundary condition for the top surface at 1 m radial distance from the tree trunk, constant pressure head = –1,000 for the remaining part of the upper boundary condition, free drainage at the bottom boundary, and no flow boundary allowed through the vertical sides of the transport domain due to symmetry (Fig. 3).

HYDRUS also requires partitioning reference evapotranspiration (ET_0) into evaporation (E) and transpiration (T). To do so, we first selected and obtained the average reference evapotranspiration (ET_0) (mm/d) for a summer month (i.e., June; ET_0 = 7.15 mm/d) from Al Yamani et al. [18]. We also obtained the value of leaf area index (LAI = 1.97) for *Ziziphus spina-christi* from Zait and Schwartz [24]. Next, we used Eq. (3) to calculate surface cover fraction (SCF) from LAI as follows:

$$\text{SCF} = e^{(-\text{rExtinct} \times \text{LAI})} \quad (3)$$

where rExtinct = 0.463. Then, we calculated E and T by using Eqs. (4) and (5), respectively:

$$T = \text{ET}_0 \times \text{SCF} \quad (4)$$

$$T = \text{ET}_0 \times (1 - \text{SCF}) \quad (5)$$

The calculated values of SCF, T, and E were 0.598, 4.276, and 2.874 mm/d, respectively. Next, the values of T and E were input in the HYDRUS time-variable boundary condition table. HYDRUS-2D asked about surface area associated with transpiration. We assumed that the canopy cover 1 m around the tree. Therefore, the area associated with transpiration for the axisymmetric domain was calculated by ($\pi r^2/2$ and found to be 15,707.96 cm^2).

Table 3 shows the RWU parameters for the water stress response function in the model for *Ziziphus spina-christi*. P0 in Table 3 is the value of the pressure head below which roots start to extract water from the soil. POpt is the value of the pressure head below which roots extract water at the maximum possible rate. P3 is the value of the pressure head below which root water uptake stopped (usually set at the PWP). r2H and r2L are upper and lower threshold potential transpiration rates, respectively. P2H is the value of the limiting pressure head below which roots can no longer extract water at the maximum rate (assuming a potential transpiration rate of r2H). P2L is defined as P2H but it assumes a potential transpiration rate of r2L. The vertical and horizontal distribution parameters for the root are shown in Table 4. The maximum vertical and horizontal root distribution were 3 and 1 m, respectively.

Table 3
RWU parameters for the water stress response function for Sider trees (*Ziziphus spina-christi*)

Parameter	Value
P0 (cm)	–10
POpt (cm)	–25
P2H (cm)	–400
P2L (cm)	–400
P3	–8,000
r2H (cm/d)	0.5
r2L (cm/d)	0.1

Finally, three observation points (OP) were placed parallel to surface with the variable flux boundary condition (OP1 (x = 0, z = 9.7 m); OP2 (x = 0.75 m, z = 9.7 m); OP3 (x = 1.4 m, z = 9.7 m)).

3. Results and discussions

The graphically presented results of the pots experiments (Fig. 4) shows that the average initial infiltration rates for vegetated pots (240 and 147 mm/h for F1 and F2, respectively) were 2.4 and 2.1 times higher than that for the control pots (100 and 70 mm/h for F1 and F2, respectively). The steady-state infiltration rates for pots with Sider trees were approximately 10 mm/h for F1 and 19.5 mm/h for F2, which are significantly higher by 1.7 and 3.3 times than that for the control pots ($p < 0.05$).

At the end of the experiment, the bulk density was measured using a core sampler for four planted and one-control pots. It varied from 1.49–1.53 g/cm^3 for the Sider pots and was 1.51 g/cm^3 for the control pot.

At the end of the experiment, the average plant height of the Sider tree was about 69–73 cm (Fig. 5). The Sider showed no significant increase in height during the relatively short period of the experiment; however, their canopy developed as quantified by the average number of the leaf. The number of leaves increased from 63 to 500 during the experiment (Fig. 5a). By the end of the experiment, the average dry biomasses of the shoot and roots of the Sider were 26 and 15 g, respectively. The fast growth of the shoot and the canopy of the plants likely correspond with a similar growth rate of the root system. Sider plant is known to have a high root-to-shoot ratio [25]. Its root development is tightly coupled to canopy photosynthesis [26]. This was evidenced by the topology of the root system of the Sider after cutting the pots (Fig. 5b).

Table 4
Spatial distribution parameters of the roots

	Value
Vertical distribution	
Maximum rooting depth (m)	3
Depth of maximum intensity (m)	1.5
Parameter P_z (–)	1
Horizontal distribution in *x*-axis	
Maximum rooting radius (m)	1
Radius of maximum intensity (m)	0.5
Parameter P_x (–)	1

Note: P_x, P_y and P_z are empirical parameters.

The roots of the planted Sider tree penetrated the full depth of the pot and proliferated all over the soil. The average height of the Sider at the end of the experiment was about 85 cm (Fig. 5a). The roots of the plants create biochannels that can increase macroporosity of the soil, especially when the roots decay [27–30]. The roots also may cause the formation of cracks and hence preferential flow occurs [31]. At the end of the experiment, the bulk density was measured using a core sampler for four planted and one control pot. It varied from 1.49 to 1.53 g/cm^3 for the Sider and was 1.51 g/cm^3 for the control pot.

4. Numerical simulations

Figs. 6a–c show HYDRUS simulated water content curves at the three selected observation points for the three scenarios. The consistent sinusoidal oscillations in these curves indicate that the soil reaches the steady-state condition. It can be also observed that the oscillation of OP1 and OP2 are concise with almost the same amplitude and period as compared to OP3, indicating the impact of roots on the distribution of moisture content in the soil profile. The root water uptake for the three scenarios is higher closer to the vicinity of the tree (RWU = 0.0000995 h^{-1}) but it decreased till it reached 0 h^{-1} as you move away (with depth or horizontally) from the tree. Although all the three observation points are located at the same depth (about 0.3 m from the soil surface), OP1 and OP2 are located within the highest horizontal distribution density of the roots (Fig. 3 and Table 4). Our results also illustrate that the change in the water supply regime (or irrigation pattern) can influence the distribution dynamics of moisture content and roots in the soil profile (Figs. 6a–c and 7a–c). When deficit irrigation or irrigation with reduced frequency and increased flux are applied, a clear perturbation in OP3 can be more observed than that of scenario a. This may be attributed to the fact that plants tend to send their roots deeper and laterally away from the trunk to hunt for water [32]. The penetration of roots creates channels or also known as bio-pores that increases the macroporosity of the soil and ultimately infiltration rate [27,33]. The actual root water uptake for the three scenarios is shown in Fig. 8. In scenario a, the actual root water uptake attained steady-state at 0.018 cm/h after 120 h. Applying deficit irrigation can delay the time needed to attain steady-state actual root water uptake by 65 h. However, reducing the frequency and increased irrigation flux regime lead to earlier arrival by almost 16 h to a steady-state actual root water uptake as compared to scenario a.

5. Conclusion

This study explored the feasibility of applying a hydro-ecological technique to improve the infiltration of ponded water in recharge dams in Oman. We experimentally

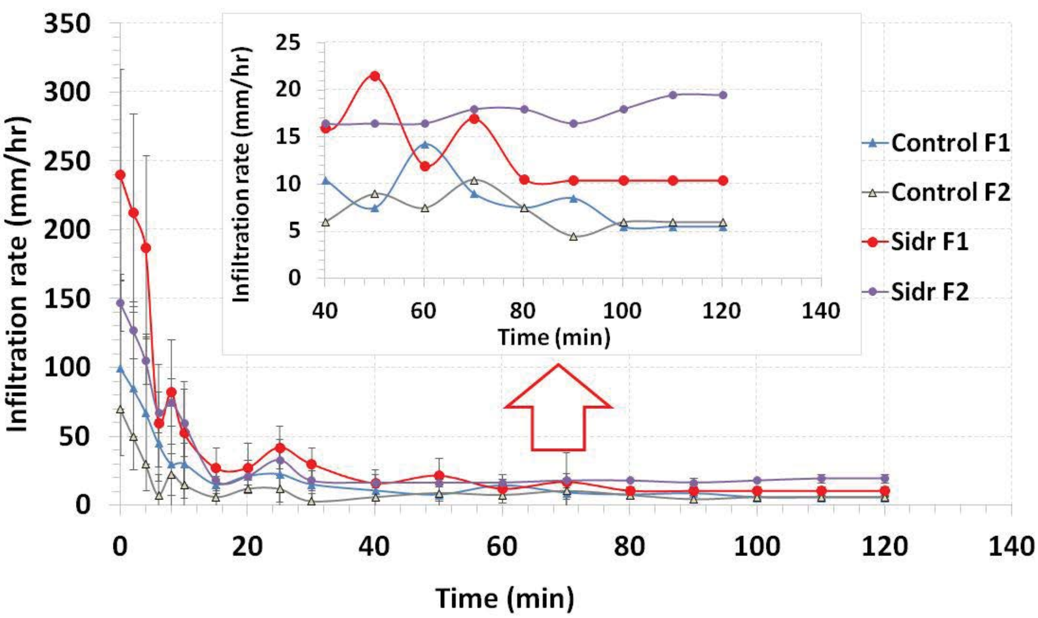

Fig. 4. Infiltration for Sider trees for F1 and F2 experimental runs.

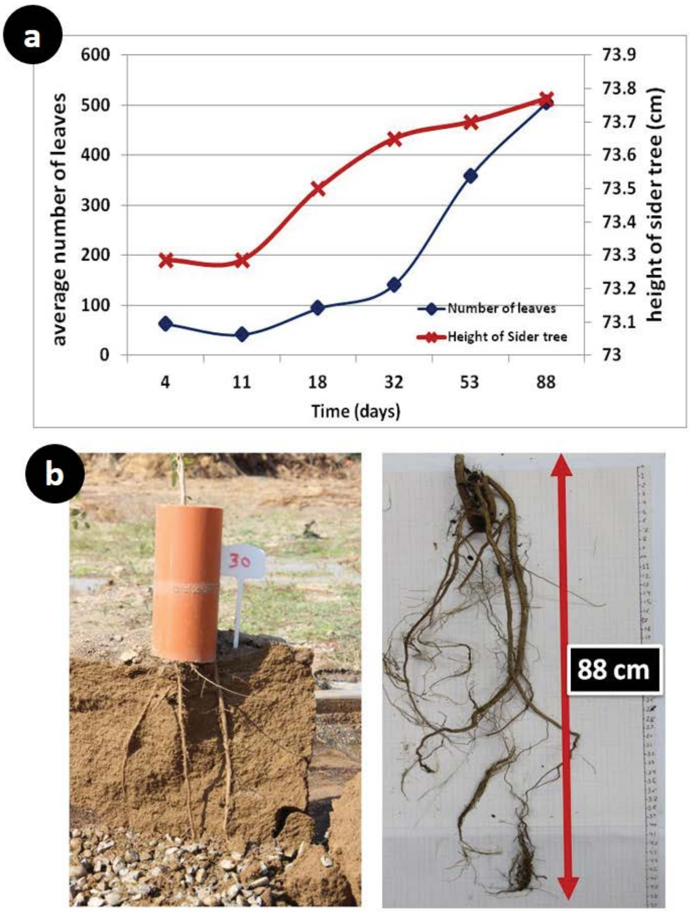

Fig. 5. (a) Plant growth parameters: average plant height and average leaf number for Sider trees. Error bars are standard deviations. (b) Main and fibrous roots penetrated the silty loam sediment reaching the bottom of the pot (left photo), and washed roots, length reached about 48 cm (right photo) – (Adapted from Al-Maktoumi et al. [15]).

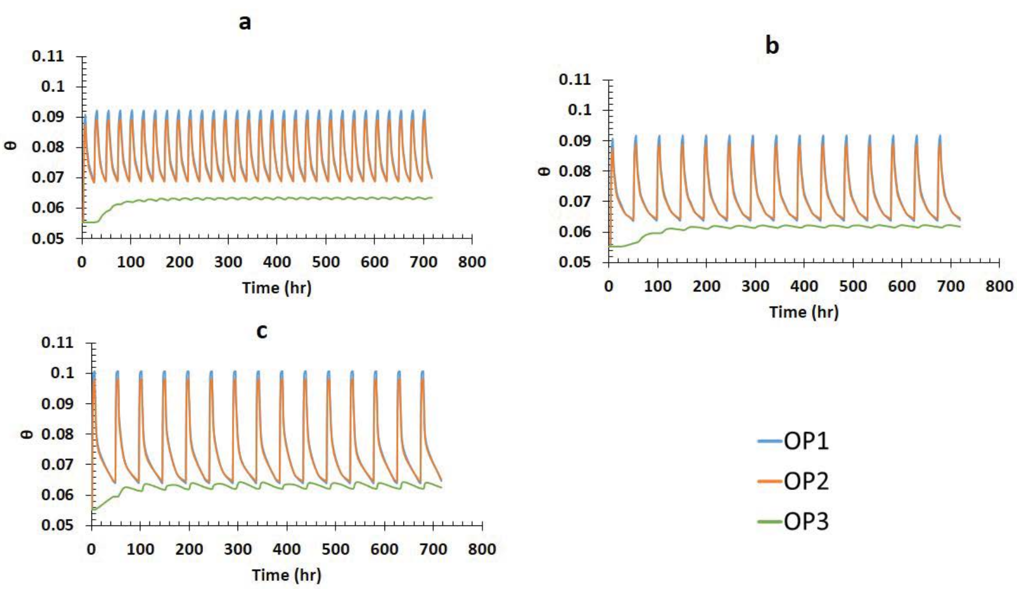

Fig. 6. HYDRUS simulated water content curves at the three-set observation points for the three scenarios: (a) background regime, (b) deficit irrigation, and (c) irrigation under reduced frequency and increased flux as compared to scenario a.

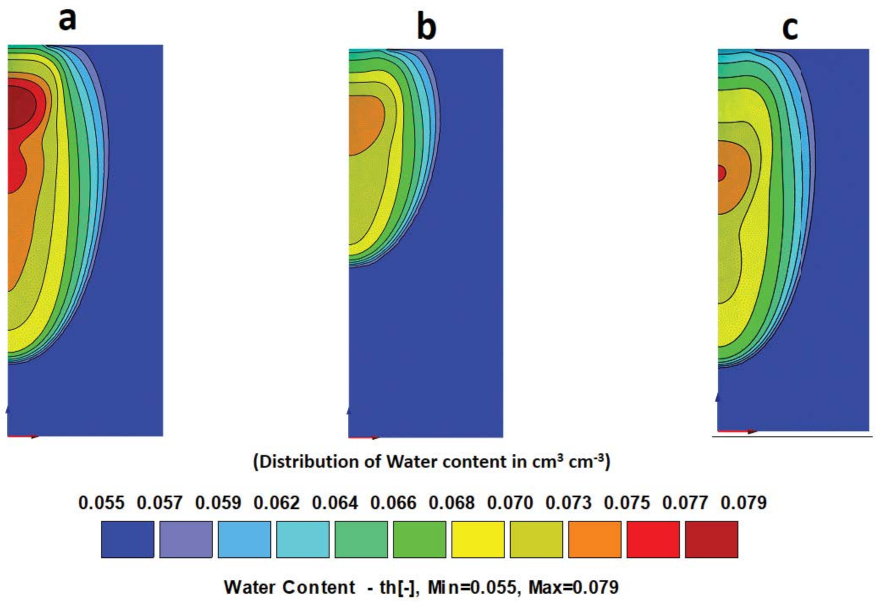

Fig. 7. Distribution of water content in HYDRUS domain after steady state was attained (t = 720 h): (a) background regime, (b) deficit irrigation, and (c) irrigation under reduced frequency and increased flux as compared to scenario a.

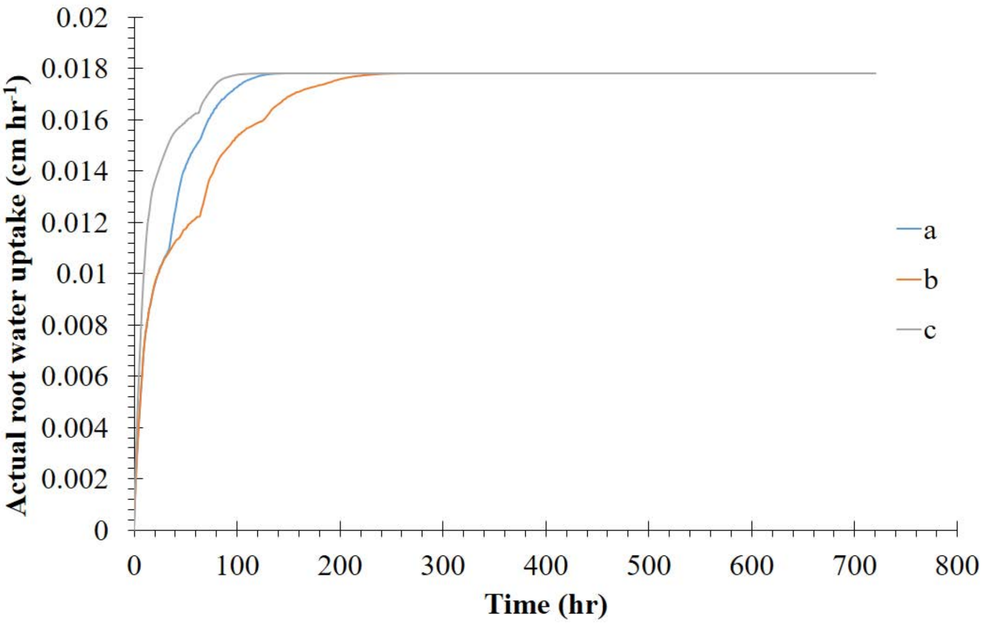

Fig. 8. Actual root water uptake (cm/h) obtained from HYDRUS: (a) background regime, (b) deficit irrigation, (c) irrigation under reduced frequency and increased flux as compared to scenario a.

quantified the effect of roots of indigenous trees, *Ziziphus spina-christi* (Sider) grown in soil pots on increasing infiltration through a cake layer. The results of the pot experiment and the numerical simulations show that the trees significantly increase the steady state infiltration rate of the sediments by 1.7–3.3 times compared to the control (bare soil) in the ($p < 0.05$). The numerical modeling illustrated the effect of the root system on the dynamics of soil water. The root system enhances the propagation of the soil water in both lateral and vertical directions.

The results indicate the potential of this hydro-ecological technique for improving the infiltration rate and hence the recharge efficiency of dams in arid areas. Moreover, intensified infiltration through dams' lakes would contribute to decrease the possibility of flashfloods to the intensely urbanized area downstream of the dam.

For practical application to a silted recharge dam, a detailed field study to measure the entire water budget for the study area is required. Moreover, the interactions between surface water and the underneath unconfined aquifer are needed. This will support the optimum design of aquifer recharge to avoid all possible complications as waterlogging due to groundwater mounds under the afforested area of the dam lake.

Acknowledgments

The authors acknowledge financial support from the Sultan Qaboos University, Oman, through the grants IG/AGR/SWAE/10/02 and IG/AGR/SWAE/14/02 and the support of the Research Group DR\RG\17. Comments and critiques by two anonymous referees are highly appreciated. Photographing a number of Christ's thorn trees by Mr. Mohammed Khamis Al-Maktoumi is highly acknowledged.

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Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28230

263 (2022) 197–203
July

Flood damage assessment of vulnerable area in Riyadh city, Saudi Arabia — case study: Al-Thumama Bridge

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Received 28 February 2022; Accepted 14 May 2022

ABSTRACT

Flood damage assessment is becoming now more important because of flooding disasters around the world. Severe rainstorms are common occurrences in some regions of Saudi Arabia that result in hazardous floods damaging the infrastructure and development plans. This study is applied in order to assess the flood hazards in the study area and to propose some countermeasures to reduce the flood damage. In recent years, Riyadh has experienced several flooding events that caused damages in and around the city in different locations due to the change in climate and land use. The paper presents a framework for a study of flood damage assessment of vulnerable area in Riyadh that was exposed to severe damages occurred by flash floods. As well as, conducting analyzes of morphology, metrology, hydrological and hydraulic analysis are included. Then, proposing a plan to mitigate the damages happened to the study area. The prediction of rainfall depths for 50 and 100-y were estimated using the frequency analysis to be 46.5.6 and 52.2 mm, respectively. The peak flow rates at the catchment outlet for 50- and 100-y return periods were estimated to be 256.0 and 291.0 m^3/s, respectively. The weighted Curve Number value of Wadi basin was estimated to be 81. In the hydraulic modelling, the Manning roughness coefficient was increased to 0.03 to dissipate the energy at the baffles and drops. The scour depths at the bridge piers were estimated assuming that the valley cross section does not tolerate the high water velocities. The study recommended taking into account the expected scour depth which obtained from the hydraulic modelling and the Wadi bed condition to guide the designer to use deep foundations at the piers of the bridge to overcome and alleviate from the flash flood impact.

Keywords: Flood damage; Mitigation; Curve number; Water flow

1. Introduction

Flood is a natural process that occurs when water inundates land that is ordinarily dry especially in arid and semi-arid regions and occurs when rainfall volume is not absorbed by ground soil due to the very low infiltration capacity which results in the huge amount of surface runoff [1,2]. The amount of this runoff depends on the nature of the catchment, the rainfall intensity, the soil moisture content and the drains. Areas that are prone to flooding include those that are located downstream of dams and low lying areas. The ability of flood water harvesting in one of the ungauged sites of Riyadh region was evaluated by [3]. They calculated high-frequency flood discharges and runoff volumes using various methods including Soil Conservation Service (SCS) Dimensionless Unit Hydrograph (DUH) method.

Flooding causes losses which include loss of life, soil erosion, damages of properties, and environmental damages. Flood waters are usually polluted with harmful bacteria resulting from sewage. This means that people affected by the floods are at greater risk of getting infected

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

diseases. Iloeje et al. [4] considered that flooding is a major environmental phenomenon creating severe impacts on the socio-economic and environmental aspects of human endeavour. Most regions around the world have experienced extreme climate change rainstorms in recent years [5–7]. Such incidents contribute to life, property and economic damage disasters. Saudi Arabia has suffered unprecedented events that caused serious damage in roads, railways, urban zones and farmland [8]. The combination from all theses factors climate change, and heavy rainfall, lack of drainage systems and unexpected urban expansion is the main cause of the flash flood hazards in Saudi Arabia.

Saudi Arabia is one of the countries that are prone to the risk of floods that cause different types of damages. The highest past flood events and their damages in different regions of Saudi Arabia were on the 24th of December 1985, heavy rains poured on north-western regions of Saudi Arabia, leading to what has been described as the worst flood in the area in 50 y. Estimates of damage were not recorded, except at least 32 people were killed from the flood. Heavy rains poured on western Saudi Arabia in January 1997, mainly affected Yanbu and peripheries of Jeddah. It was noticed that the rain lasted for 24 h where 10 people were killed and an area of over 130,000 km^2 of land was damaged. Also, in Asir, a province in the Southwest of Saudi Arabia, on Monday, 25th of March 1997, the area was exposed to heavy rains causing floods and resulted in 16 fatalities and an area about 100,000 km^2 of land was damaged. Recently, flash flooding in Saudi Arabia areas has been triggered by heavy rainfall as what happened in Jeddah city (years 2009, 2011, 2017 and 2018) and Al-Riyadh (2015 and 2018), as was mentioned in General Directorate of Civil Defense of Riyadh Region [9].

In the western part of the country, especially in Jeddah (November 2009 and January 2011), different areas have been affected [8,10]. In 2016 a heavy rain storm lasted for more than 12 h on AlDulm located in the south of Al-Kharj town, has resulted in the detention of many vehicles inside and causing damage to many properties. The damage extended to different districts of AlDulm.

Al Saud [11] utilized space techniques supported by GIS with a focus on IKONOS satellite images, which are characterized by high resolution in identifying terrain features. Thus, damaged areas and the mechanism of flooding process were recognized in the study area and this helps avoiding further urban expansion in areas under flood risk and will aid decision maker to put new strategies for hazard management.

Al-Momani and Shawagfah [12] highlighted the capability of GIS and satellite images for quantifying and mapping the flood characteristics in the city of Tabuk, Saudi Arabia. Various thematic maps including drainage, lineament, lithology, slope and land use have been generated using those techniques, which are efficient tools to define topography and morphological changes. Generated results and maps helped to analyze and manage flood hazards, and also to formulate remedial strategy such as evacuation, flood routing and provision of water retaining structures.

Rahman et al. [13] identified city areas and residents vulnerable to flash floods recognized that under the evident climatic warming, the Riyadh city has increased risk of exposure to frequent flash floods in the next 25 y. While the physical vulnerability of the city to flash flooding was assessed by simulating 6 h of intensive rainfall and measuring the depth of flood water, its social vulnerability was assessed by standardized ranking of census data on seven demographic, social, economic, and urban built-up environment variables.

Abo Salima et al. [14] have developed a systematic methodology for estimating flood hazard areas in Jeddah region using GIS. The flood hazard map from their study can be used to identify zones of the study area that are prone to high flooding risk and to design flood preventing structures and plan new land use for future developing areas.

Sharif et al. [15] examined flood hazards in a rapidly urbanizing catchment in Riyadh city, Saudi Arabia. They used remote sensing data and GIS techniques to prepare inputs for hydrologic and hydraulic models. The impact of urbanization on run-off volume and peak discharge resulting from different storms was investigated, with various urbanization scenarios simulated. The catchment response was found to be quite sensitive to an increase in the urbanized fraction. Flood hazard zones and affected streets were also identified through hydrologic/hydraulic model simulation.

2. Study area

Riyadh city is considered one of the cities are vulnerable to flood risk in Saudi Arabia due to urbanization and recent development as well as climate changes. Al-Thumama Bridge is one of the bridges located at the Wadi Banban pathway in Riyadh. The bridge has consisted of 13 openings with a total length of 195 m. Fig. 1 shows the catchment area and location of Al-Thumama Bridge. The flood damages at Al-Thumama Bridge were due to one of the heaviest storms that hit Riyadh city in November 2013 that caused many damages to people and properties. The storm in whole Riyadh caused an evacuation of people in danger and then sheltering them; two families were consisting of 23 people. And many 78 people were detainees rescued and the numbers of vehicles taken out were 74 cars. The total economic and life losses due to the 2013 storm in Riyadh are as follows: number of deaths 3 people, number of injuries 11 people, number of missing 2 people, with a total of 19 sites where tunnels or roads had an increase of the water level within the city.

3. Research methodology

The most important step involves defining the geomorphology of the study area by using Watershed Modeling System (WMS) software. These involve the main basin and sub-basins of all the catchment, drainage networks and the longest stream path in each sub-basin. The second-step relates to the flood assessment method formed using HEC-HMS and HEC-RAS software.

3.1. Meteorological analysis

Riyadh station (R001) was selected due to the long record, which it has about 30 y of data records where intensity duration frequence (IDF) curves can be constructed to include most of the storm events that occurred in the region. Hyfran-plus software was used to find the design rainfall rate of the catchment. The results obtained have shown that the Gumbel method is better to use than Log Person III. It was found that the value of maximum rainfall of 100 y return period is 52.2 mm, and the value of maximum rainfall of 50 y return period is 46.5 mm, and for 20 y is 38.9 mm. Fig. 2 shows one of the Hyfran-plus output for developing the rainfall depth, duration and frequency curves.

3.2. Determination of the drainage basin and the morphological data

Watershed Modeling System (WMS) was used to determine the drainage basin, boundaries of the drainage basin, the pathways of the channels and branches of Al-Thumama Bridge catchment area.

The DEM with resolution 90m × 90m from the Shuttle Radar Topography Mission (SRTM) topography is available from the United States Geologic Survey (USGS) was the main input to Watershed Modeling System (WMS) to determine the catchment boundary and the stream network.

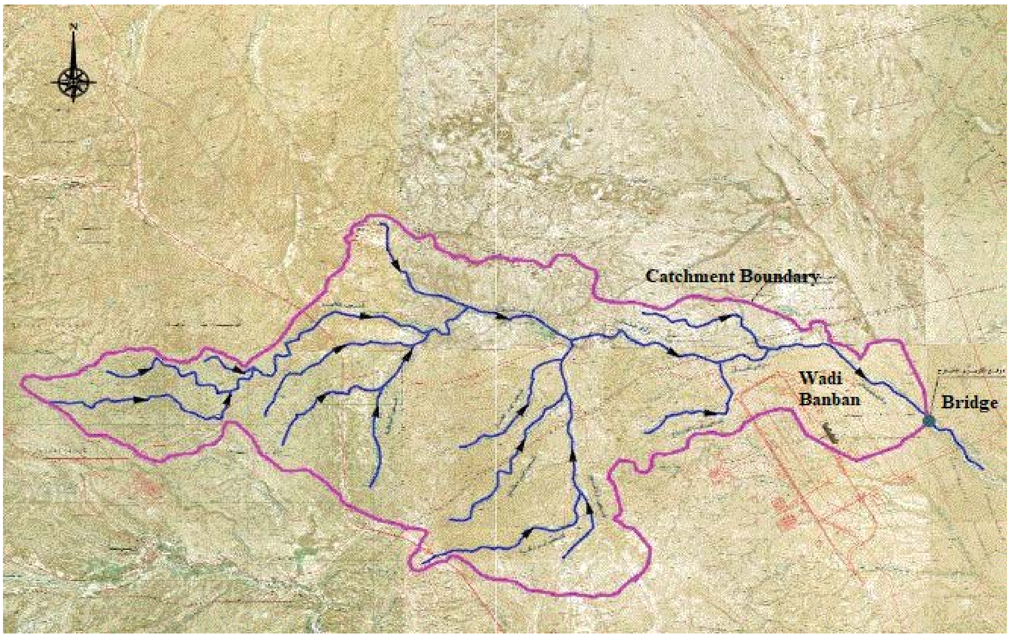

Fig. 1. The catchment area and location of Al-Thumama Bridge.

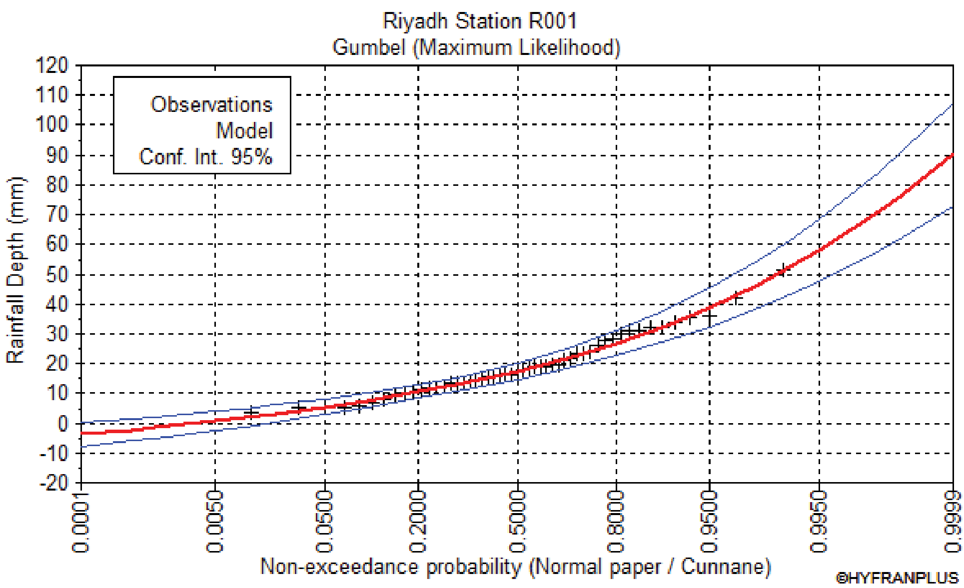

Fig. 2. Gumbel fit of maximum daily data of Riyadh station (R001).

The catchment area of Wadi calculated by WMS is equal to 381.0 km^2. The catchment boundary and the stream network are shown in Fig. 3.

3.3. Equivalent curve number (CN)

There are several types of land use inside the drainage basin as shown in Fig. 4. The curve number refers to functions of various factors which include hydrologic soil groups, cover type, treatment, hydrologic condition, soil moisture content, and impervious area in the catchment. Hence, theoretically, the curve number may range between 0 and 100 [16]. The weighted CN value of the basin was estimated to be 80.71 according to the land uses and the hydrological soil groups.

3.4. Hydrological analysis

Hydrological analysis is conducted to define the hydrological parameters for the main Wadis contributing with

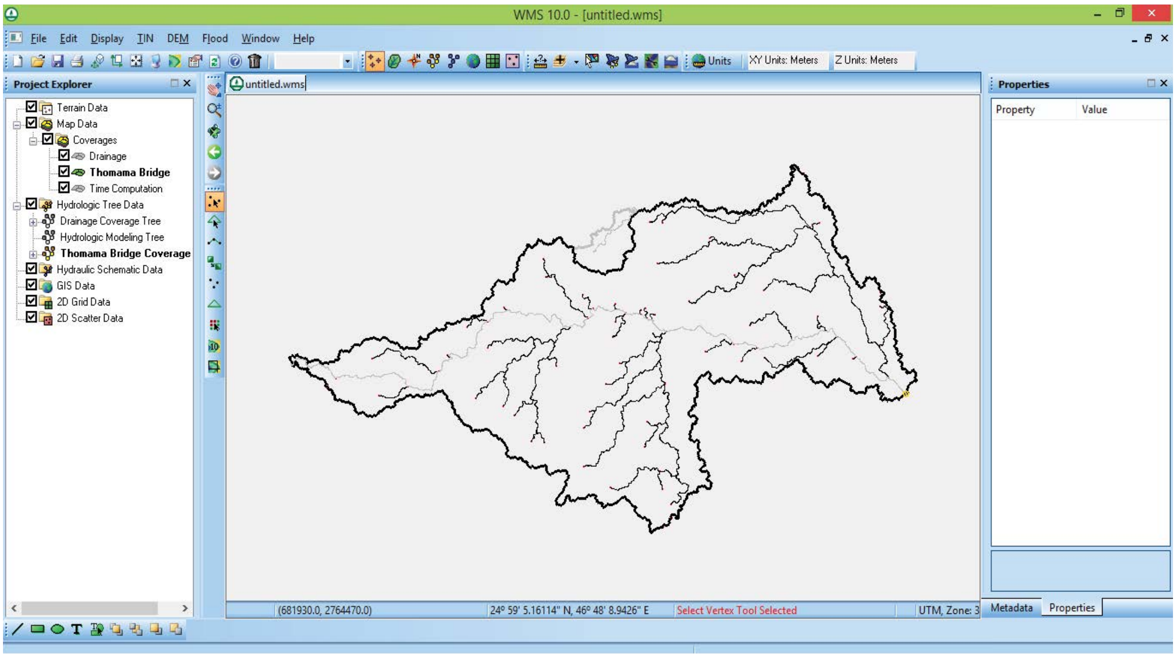

Fig. 3. The catchment boundary and the stream network.

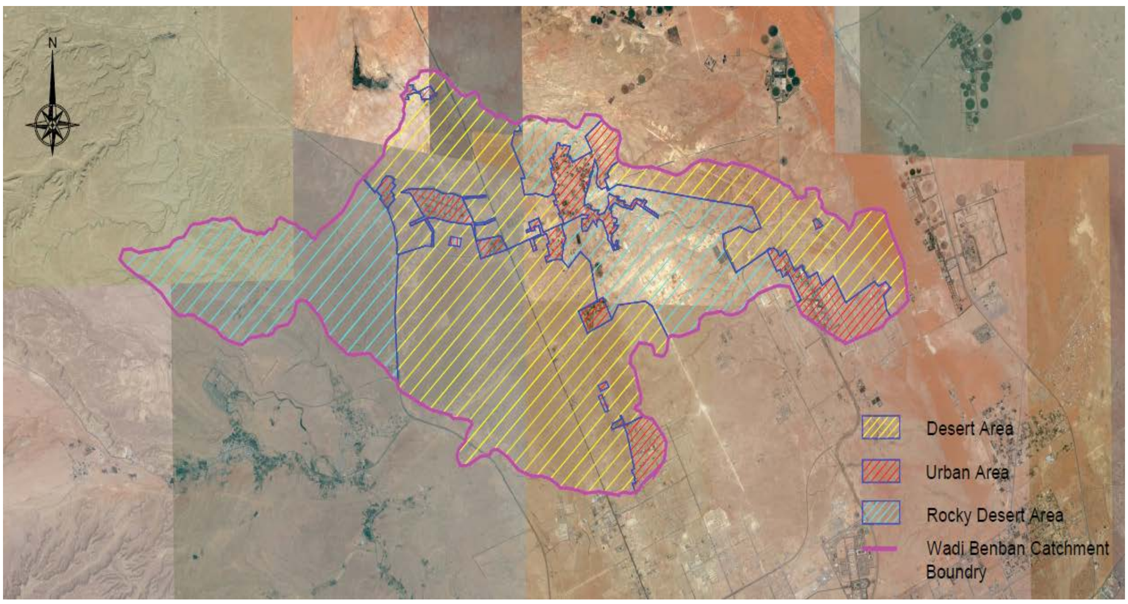

Fig. 4. Boundaries of the catchment and land use [17].

the study area such as time of concentration (t_c), Lag time (T_{lag}) as well as the peak discharges resulting from their catchment areas. This is done by the Hydrologic Modeling System (HEC-HMS) (the methodology of SCS-CN method). After adding the rainfall depths probabilities for 50 and 100 y return periods in the HEC-HMS model, the result findings were collected as outlet hydrographs. Additionally, for both return periods, the peak flows at the catchment outlet point 256.0 and 291.0 m^3/s were estimated for 50 and 100 y return period respectively. The basin lag time of the catchment was estimated to be 610.94 min.

3.5. Hydraulic analysis and HEC-RAS computation

The purpose of the hydraulic analysis is the determination of hydraulic characteristics such water depth, water velocity, the water levels in front of and behind the bridge, in addition to the dimensions of the water section at a specific location as well as the scour depth at the piers.

Definitions of reaches and geometry of floodplain and Manning roughness values are required by the Hydraulic model (HEC-RAS). WMS and HEC-HMS were used in the preparation of HEC-RAS input data in this study. The extractions of channel centerlines and the flood plains were made from the DEM.

4. Results and discussions

Hyfran plus prohram was used to perform the frequency analysis for the historical rainfall data to get the daily maximum rainfall depths for different frequencies. The prediction of rainfall depths for 50 and 100 y were estimated to be 46.5.6 and 52.2 mm, respectively. The Watershed Modeling System (WMS) and Arc-Hydro tools were used with the help of Digital Elevation Model (DEM) to define the main Wadi, its tributaries, drainage basin area and the morphological characteristics. The methodology of SCS-CN method was performed to estimate the peak flows at the catchment outlet point to be 256.0 and 291.0 m^3/s for 50 and 100 y return period respectively. The weighted Curve Number value of Wadi basin was estimated to be 81. Hydraulic modeling was done using the HEC-RAS program to determine the characteristics hydraulics for different sectors of water level and velocity, as well as determining the expected depth of scour around the bridge piers. In the hydraulic modelling, the Manning roughness coefficient was increased to 0.03 (Eartch channel-weedy) to dissipate the energy at the Baffles and drops. The scour was estimated assuming that the valley cross section does not tolerate the high water velocities. The model was undertaken with some details of networks of the reaches until the observed effect on the subsequent inundation maps was considered as shown in the program outputs. The depths conforming to the maximum discharge which HEC-HMS computed at the distinct cross-sections and accomplished interpolations along the reaches were computed by HEC-RAS. Fig. 5 shows longitudinal projection of water surface for the valley and also it can be noted the inundated areas estimates for different frequencies.

As noted before, the scour at bridge piers which happened for the old bridge was the main factor for the failure. So, it was recommended to check the safety of the proposed bridge against scouting. Scour depth was estimated using HEC-RAS, the results obtained show scour depths against the flood of 100 y equals to 5.7 m for peir (1) and 5.6 m for pier (2). Fig. 6 shows cross-section in the bridge after scour occurring. This means that all piers foundations for the proposed bridge should be deeper than estimated scour depths to ensure the bridge safety and its stability against the flow of 100 y frequency. On the other hand, the water velocity was estimated to be 6.3 m/s where it is somewhat high, so we may add more baffles to reach the allowable water velocities. Another alternative solution may be proposed

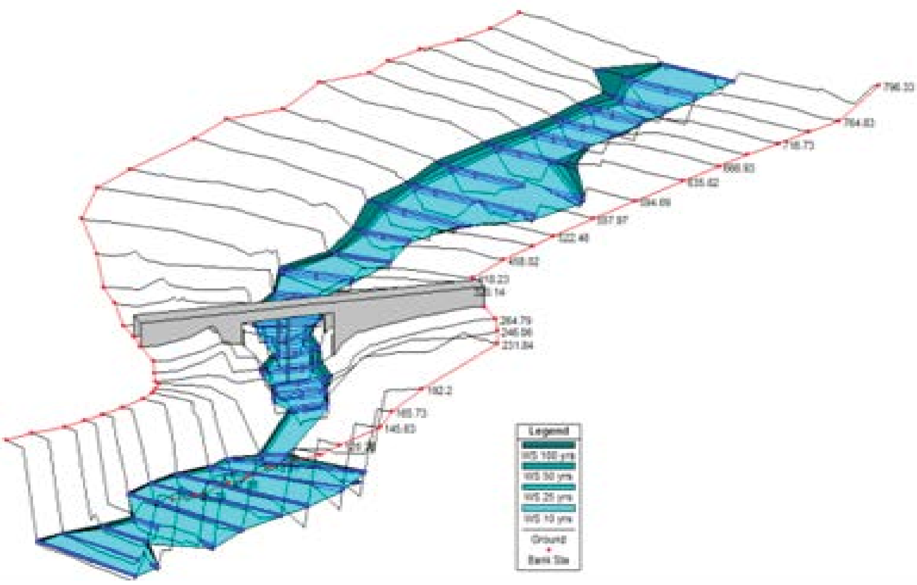

Fig. 5. Longitude projection of water surface for the Wadi.

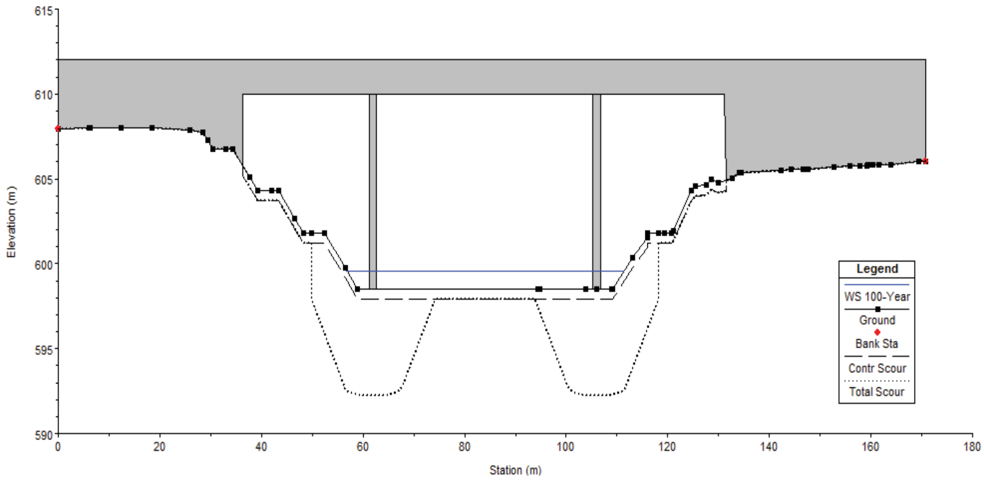

Fig. 6. Cross-section in the bridge after scour occurring.

by altering the cross section of the valley at the upstream and downstream of the bridge to make sure that there is no hydraulic interference between the water section and the pier locations, as well as avoiding the high water velocities.

Other proposed mitigation measure is protecting bridge from scouring impacts which may include strengthening and enforcement of Wadi bed around bridge piers and abutments by pouring of large aggregates and stones with bed soil and lateral sides.

It was shown from the results that the collapse of the bridge was due to deep scour at bridge piers below foundations as a result of high flow velocity and soil type of Wadi bed. For that reason, it was proposed to check the design of the proposed bridge against scour using 100 y flood frequency, as well as strengthening the Wadi bed.

5. Conclusions

This paper provided a basis for a flood-damage analysis of one of the vulnerable areas in Riyadh (Al-Thumama Bridge) which was subjected to severe flood-related damage. The current research demonstrated estimates of the expected flows beneath the bridge and suggests the appropriate hydraulic section and to investigates the resulted scour depths at the bridge piers due to the expected flows. This scour depth should be taken into account in bridge design to ensue not occurring any failure for the proposed bridge constructed across the Wadi. The methodology included the help of relevant programs (i.e., WMS, HEC-HMS and HEC-RAS). The study has shown the effect of flooding on the chosen site of the area involved in working simulations for the dimensions of potential flow of each frequency and the limits of growth and the extent of harm to humans and surrounding facilities, taking into account the urban development within the boundaries of the drainage basin. The value of the weighted curve number was estimated based on the urban development and land-use changes. The hydraulic modelling was done by HEC-RAS to determine the hydraulic characteristics for different sections to include the water levels, flow velocity and the expected scour depth at the bridge piers. Another parameter was considered in the hydraulic modelling which is the Manning roughness coefficient, which was increased to 0.03 to dissipate the energy at the Baffles and drops. The study has shown significant values of the scour depths at the bridge piers due to the high water velocities under the bridge which happened during the storm event. This problem may lead to the bridge collapse if those values of the scour depths did not take into account during the bridge design.

So the study recommended taking into account the expected scour depth which obtained from the hydraulic modelling which guides the designer to use deep foundations at the piers of the bridge. Also, it is recommended to use some accessories or devices in the stilling basin to dissipate the energy at the downstream of the valley. Also, it is recommended to strengthen the soil type of the bed to match it with the calibrated value of the roughness coefficient used in the modelling to reduce the flow velocity and hence dissipate the high kinetic energy which causing much scour.

Acknowledgments

The authors extend their sincere appreciations to the Ministry of Transportation, Riyadh, Saudi Arabia for their valuable information regarding to that study. Special thanks also to the reviewers for their suggestions and improvement of the manuscript.

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Desalination and Water Treatment
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doi: 10.5004/dwt.2022.28231

263 (2022) 204–206
July

Groundwater in the Arab region: making the invisible visible

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ABSTRACT

The Arab region is one of the most water scarce regions in the world with 19 states below the water scarcity threshold including 13 states below the absolute water scarcity. Groundwater is heavily relied upon and it is the primary source of freshwater in more than 11 Arab States, yet the invisible and complex character of groundwater being underground and out of sight has not given it the due attention it deserves. Hence, this report explores the importance of groundwater and the challenges it is facing, with the aim of bolstering its status to a strategic resource for the Arab region.

Amid the water scarcity situation, limited renewable groundwater resources continue to be exploited at an unsustainable rate, exceeding the natural recharge rates. Excessive use of groundwater, especially by the agricultural sector combined with low efficiency, has led to the decline in groundwater storage in more than two thirds of the Arab region, where the area of decline has doubled in 2018–2019 compared to 2002. In some countries over 88% of all irrigation water comes from groundwater compared to a global average of just over 37%. Moreover, it is projected that by 2050, available groundwater per capita will have decreased by more than half since the beginning of the century and 17 Arab States, accounting for 79% of the total population, will be below the absolute water scarcity threshold.

In addition to their excessive use, groundwater resources are also threatened by anthropogenic pollution sources, from agricultural and industrial practices and from sea water intrusion in coastal cities. The deterioration in the quality of groundwater resources, both due to overexploitation and pollution is aggravating the problem of water scarcity. For example, in Beirut, seawater intrusion has shifted inland between 500 and 1,200 m from 1970 reference point. In Gaza, only 25% of wastewater is treated due the lack of proper wastewater collection and treatment infrastructure, which is further complicated by the occupation that has restricted access to natural resources.

This is alarming knowing that groundwater is central to achieving the Sustainable Development Goals (SDGs) and targets adopted in the 2030 Agenda for Sustainable Development in the region. It is directly linked to SDG6 and central to achieving many other SDGs such as SDG2 for ending hunger. It is also an important component of climate change adaptation, having a high buffer capacity against drought. Accordingly, the projected impacts of climate change on water resources in the region, will further increase dependency on groundwater at a time when groundwater recharge is also projected to decrease, necessitating conjunctive management of surface water and groundwater. The impacts of climate change on groundwater at the aquifer level is showcased by ESCWA on the Beni-Amir aquifer, Morocco and the Eocene aquifer, Palestine. Results from the study on Beni-Amir aquifer indicate that the water table is expected to decrease 10 to 25 m (RCP4.5 and RCP8.5, respectively) by end of century, resulting in partial depletion of resources in the top three layers of the aquifer system, particularly in the northern Beni-Amir area. In the case of Palestine, the results on the Eocene aquifer showed that in the 2041–2060 horizon, the average precipitation is expected to decrease in all scenarios between 3% and 12%, whereas the recharge in 5 out of 6 precipitation scenarios showed a reduction by 12%–16%. Consequently, with no decrease in the aquifer pumping, the water levels in all scenarios will drop.

The declining availability of groundwater resources due to increased consumption, development demands, inefficient use and climate change should prompt Arab States to explore innovative and integrated governance frameworks to improve groundwater resources management and

Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

ensure equitable access for current and future generations to this strategic resource. Groundwater governance has been historically weak in the Arab region, characterized by fragmented legislations and policies, limited funding, lack of coordination and lack of data and knowledge. More recent evaluation of the management of groundwater resources through the SDG indicator 6.5.1 reporting mechanisms on the degree of implementation of IWRM has unfortunately reinforced some of the main challenges listed above in the Arab region mainly in terms of lack of implementation of management tools and proper financing. In response to the lack or fragmentation of groundwater management policies, ESCWA developed regional groundwater abstraction management guidelines offering a unified approach to deal with uncontrolled groundwater exploitation and use.

Groundwater governance is further complicated by transboundary aquifers. In fact, all countries, except for Comoros, share at least one aquifer with their neighboring countries. These transboundary aquifers cover almost 58% of the Arab region's total area. Some of these aquifers are directly connected to surface-water hydrological systems and should also be conjunctively managed. Other transboundary aquifers contain fossil groundwater reserves requiring specialized legal, policy and management frameworks that consider their non-renewable character. The status of regional transboundary water cooperation is captured in a recent regional report prepared by ESCWA on the progress on SDG indicator 6.5.2 in the Arab region for the year 2021. The report revealed the challenges faced by the Arab states that hinder the establishment of well-developed cooperation frameworks which are mainly linked to lack of knowledge and data exchange and financial constraints. However, there are encouraging signs where cooperation on transboundary aquifers has progressed, including a Joint Authority for the Nubian sandstone Aquifer, a cooperation framework for the Senegalo-Mauritanian Aquifer, a signed agreement for the Saq-Ram Aquifer, and a consultation mechanism on the North Western Sahar Aquifer System. These cooperation agreements should be maintained and further developed by holding regular meetings, coordinating objectives and management plans, and regularly exchanging data and information. Regional knowledge exchange around these agreements should be enforced.

Advances in technologies provide an opportunity to fill the data and information gap that hinders the management of groundwater. Integrated remote sensing data offer a solution to assess the groundwater status. In addition, Managed Aquifer Recharge (MAR) is one of the most important solutions to consider for securing water supply and for improving groundwater quality where it is deteriorating. MAR is already used in more than 44 sites across the Arab region. Technologies can assist in selection of where MAR can be a potential solution for the region and for improving the water security.

Furthermore, in response to the need for availing more data and information on groundwater and improving access to such data as established through the reporting on SDG indicators 6.5.1 and 6.5.2, ESCWA will be initiating an Arab Groundwater Digital Knowledge Platform. This platform aims to increase access to regional knowledge and information on groundwater resources through a dedicated digital interactive platform.

Finally, the relation of groundwater to water scarcity, human activity, transboundary water cooperation, climate change, and water governance is highlighted in the following key findings.

1. Groundwater and water scarcity

- Action by countries has not been able to address the groundwater challenges yet, which underscores the need for immediate action on several fronts including socio-economic, environmental, and governmental.
- The use of integrated tools such as remote sensing data and in-situ data offers a great opportunity for adequate groundwater monitoring leading to improved management.
- Managed Aquifer Recharge is one the most promising approaches in the Arab region to alleviate water scarcity impacts and improve water security.

2. Groundwater and human activity

- Management of groundwater must extend beyond water only into a coherent cross-sectoral governance approach.
- Food security is largely dependent on groundwater in many Arab countries. This necessitates improved efficiency and productivity through coherent management of water and agriculture sectors benefiting from enhanced use of technologies.

3. Transboundary groundwater

- There are encouraging signs where cooperation arrangements in the region on groundwater have progressed.
- Transfer of experience and knowledge from regional groundwater cooperation arrangements are essential to accelerate progress at the full regional scale.
- Leveraging innovative approaches and technologies can help fill the information and knowledge gap.

4. Climate change and groundwater

- While it is well recognized that protecting and preserving groundwater contributes to increasing society resilience to climate change, there is still insufficient action recognizing and acknowledging this role for groundwater.
- In the face of projected climate variability in terms of availability and reliability of surface water and precipitation, groundwater can be used as a reliable buffer resource to offset climatic variability however its management has to be integrated across sectors such as water and agriculture with conjunctive management of surface water and groundwater.

5. Groundwater governance

- Good groundwater management requires good information based on sufficient and reliable data with the needed investment to produce useful knowledge to guide decision makers thus enabling informed decisions to be made and stakeholders behavior to adapt.
- ESCWA proposed regional groundwater abstraction management guidelines offer a unified approach to tackling overexploitation.

The importance of groundwater for the Arab region's water security under a changing climate demands improved governance through innovative management approaches, enhanced use of technologies and dedicated funding for better understanding of the resource and heightened regional cooperation.

The above-mentioned findings are discussed in more details in the forthcoming ESCWA Water Development Report 9.

Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28232

263 (2022) 207–213
July

Using electricity consumption as a tool for groundwater abstraction in Abu Dhabi Emirate farms, UAE

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Received 28 February 2022; Accepted 7 May 2022

ABSTRACT

Farm irrigation for agricultural crops such as vegetables, palm trees for date production, and Rhodes grass for camel fodder, currently (2019) is the largest use of groundwater in Abu Dhabi Emirate. Each farmer was permitted to drill two wells within the farm boundary for irrigation groundwater supply [1]. In practice, many farms have more than two wells because farmers drill new wells to replace dry or low-yielding wells, because of the belief that more wells increase the amount of groundwater available to the farm, and because there is no enforcement of the two-well rule. Because the farms are closely spaced in regular grids that extend over large areas, well interference can be substantial in and around the farming districts, and groundwater-level declines can be large. At present there are more than 24,000 farms in Abu Dhabi Emirate, consuming about 2,100 million m^3 of groundwater from more than 54,000 abstraction wells. Farm area in Abu Dhabi Emirate increased from 35,000 ha in 1996 to 120,000 ha in 2006, with most of the increase occurring in Al Ain region. The typical citizen farm was a 183-m by 183-m plot of leveled land surrounded by a concrete and block wall and date palm, fodders and vegetables were the primary crops. All of these have no water flow meters to measure the real abstraction. To estimate the groundwater abstraction, groundwater wells electric use records for 2011 to 2018 were used to estimate groundwater use at selected pilot farms in Al Ain region. The high correlation between the amount of irrigation groundwater produced and the amount of electricity consumed at the studied farms offered the possibility of using farm electric records to estimate historical and current groundwater abstraction in farming districts that have substantial concentrations of farms. The compiled records begin in 2011 and includes historical meter readings for about 20,000 farms, forests, and rural wells, comprising about 940,000 total readings. The data was filtered to extract only data for farms that were constructed as typical citizen farms with the combination of date palm and grass crops similar to the mixed farms previously studied and for which irrigation efficiency was estimated. Electric use for these farms was estimated on an annual basis for 2011–2018 for each of 9 farming districts in the pilot project. More than 900,000 farm electric meter readings were collected and analyses during this study. Based on a previous investigation that showed groundwater use and electric use, it has been found that trends were linear at mixed palm and grass farms and that the ratios of the trends yielded an average irrigation efficiency of 0.77 m^3/kWh. During the 8-y period of records, total annual groundwater uses for farms irrigation in the 9 farming districts pilot project increased from 581 to 743 Mm^3, with about 28% increase in groundwater use.

Keywords: Groundwater use; Water demand; Irrigation; Electrical use

Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

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1. Introduction

Abu Dhabi Emirate, one of the seven Emirates which comprise the United Arab Emirates (UAE), occupies an area of 67,340 km^2, or about 80% of the total area of UAE as shown in Fig. 1. The Emirate has an arid climate with less than 100 mm/y average rainfall, a very high evaporation rate (2–3 m/y), a low groundwater recharge rate (<4% of total annual water used) and no reliable, perennial surface water resources. Furthermore, it is a downstream water user and shares trans-boundary water resources along common borders with Saudi Arabia and the Sultanate of Oman, 350 and 280 km in length respectively. Historically, all the Emirate's water requirements were met solely from groundwater obtained from shallow hand dug wells and the traditional Falaj system, comprising man–made channels used to collect groundwater, spring water and surface water and transport it, by gravity, to a demand area. Since the entire Emirate's Aflaj are now dry, a system of borehole support has been developed over the last 5–10 y. Over the last two to three decades, however, rapid economic development, coupled with sharp population increases and the development of a large agricultural sector, substantially supported from government subsidies, has meant an increasing reliance on unconventional water resources, such as desalination, and also the development of alternative conventional water supply measures, such as recharge dams, storage dams, recharge wells, interception of groundwater losses, re-use of wastewater and water transfers.

The Emirate occurs in the subtropical arid climatic zone and is exposed to oceanic effects of the Arabian Gulf and Indian Ocean. Rainfall is erratic and unreliable. Orographic effects are clearly seen on the rainfall distribution. The Al Hajar mountains in neighboring Oman, which reach elevations in excess of 2,000 m.a.m.s.l, generate high rainfall incidents, especially in the winter months, which provide for the runoff to Wadis which cross over the border into Abu Dhabi Emirate. Within Abu Dhabi, this high elevation rain occurs only at Jebel Hafeet, which, at an elevation of 1,163 m (a.m.s.l), is the highest point in Abu Dhabi Emirate and the only high mountain massif within the Emirate. Mean annual rainfall within Abu Dhabi Emirate varies from 46 mm at Jebel Dhanna in the Western Region to 119 mm at Al Wigan, south of Al Ain, in the Eastern Region. The mean annual rainfall at Al Ain 1971–1994 is 96.4 mm with a maximum of 303 mm/y. The mean annual precipitation for Abu Dhabi Island is 87 mm with a maximum of 227 mm/y. Groundwater, albeit mostly brackish and saline in quality still provides around 80% of all water used in the Emirate [2]. No natural, perennial surface water resources exist within the Emirate, apart from the spring at Ain Al Fayda and it is therefore important to understand the various hydrologic processes and hydrogeological settings which control the extremely valuable groundwater resources.

The GWRP [3] and GWAP [4] have used different methods to calculate the groundwater in storage in the Emirate, but both have ultimately calculated average saturated aquifer thickness and specific yield to estimate stored volumes. The volume of fresh groundwater calculated differs by only 8%. It is not possible to compare the saline and brackish groundwater calculations, since different thresholds have been used to define this water quality. The GWRP calculated a total groundwater reserve of 253 km^3 (7% fresh and 93% brackish) as shown in Fig. 2 and the GWAP total estimate of 640 km^3 (79.4% saline) is much larger since groundwater of salinity of up to 100,000 mg/L TDS was included, whereas the GWRP included groundwater with less than 15,000 mg/L TDS. The most striking feature of both estimates is that the amount of fresh groundwater remaining in storage is very small, ranging from 2.6% to 7% of the total. According to the GWAP assessment more than three-quarters (12.5 km^3) of the fresh water in storage occurs in the Liwa lens and only about 4 km^3 in the Eastern region.

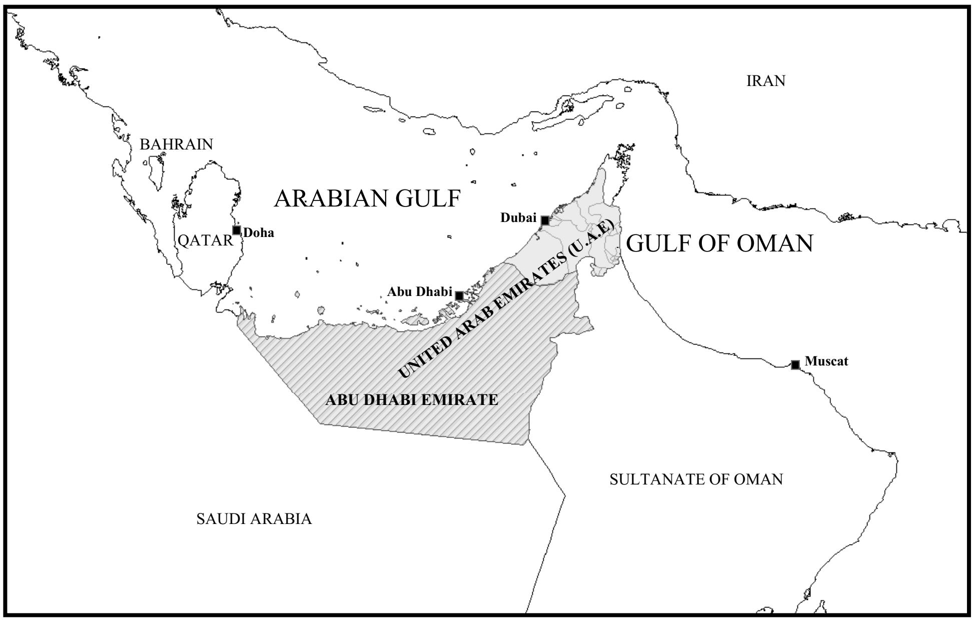
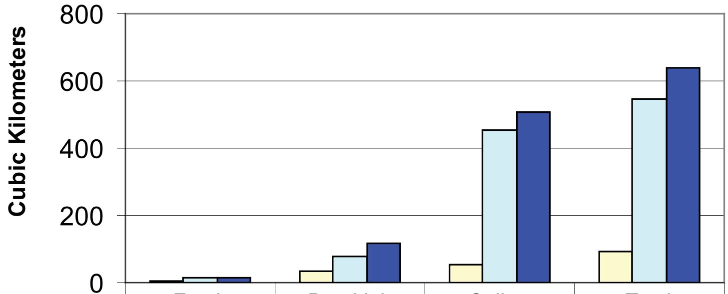


Fig. 1. Location of Abu Dhabi Emirate, United Arab Emirates.



	Fresh	Brackish	Saline	Total
Eastern Region	4	35.9	53.3	93.2
Western Region	12.5	79.9	455.3	547.7
Total	16.5	115.8	508.6	640.9

Groundwater Type

Fig. 2. Groundwater reserve aquifer systems.

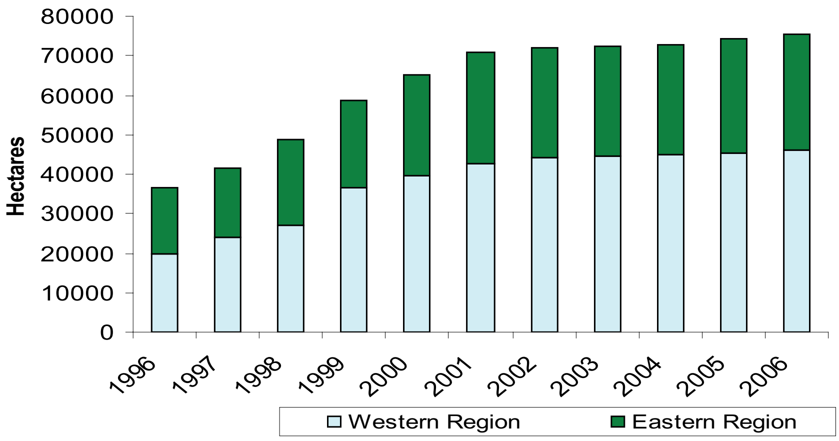


Fig. 3. Expansions of agriculture farms (1996–2006).

According to the GWRP assessment, at current groundwater abstraction rates, it is projected that the fresh and brackish groundwater resources will be depleted in 50 y.

It is estimated that the annual groundwater abstraction is about 2,100 million m^3. At present groundwater is utilized for irrigation by agriculture sector (83%), forestry (12%) and amenity plantation and road verges (4%) and industrial sectors (1%). Groundwater not used for domestic water supply since 2009 due to the deterioration of groundwater quality which is not in compliance with potable water quality guidelines and standers [5]. The estimated groundwater uses in agriculture sector is about 85% (1,750 million m^3/y). By the end of 2019, there were about 24,250 farms, occupying around 75,500 ha and a small number of large, state fodder (government) farms occupying about 17,000 ha [6] in addition to more than 320 afforested areas, amenity plantations. Fig. 3 shows the expansion in agriculture due to large government support. Citizen's farms are typically 2–3 ha in size and each has two drilled wells at opposite corners of the plot. A well supported system of subsidies promotes agricultural expansion to the tune of 3,000 new farms each year, although expansion is currently restricted due to exhaustion of groundwater supplies. The major limitations on agricultural development are lack of groundwater resources and high groundwater salinity used in irrigation. Close proximity of wells results in well interference effects and unrestricted irrigation causes extreme cones of depression as shown in Fig. 4 resulting in a deterioration in salinities, which are usually low brackish to high brackish to begin with.

At present there are no water flow meters to measure the real abstraction in agriculture sector. To estimate the groundwater abstraction, groundwater wells electric use records for 2011–2018 were used to estimate groundwater use at selected pilot farms in Al Ain region. The high correlation between the amount of irrigation groundwater produced and the amount of electricity consumed at the studied farms offered the possibility of using farm electric records to estimate historical and current groundwater abstraction in farming districts that have substantial concentrations of farms. The compiled records begin in 2011 and includes historical meter readings for about 20,000 farms, forests, and rural wells, comprising about 940,000 total readings. The high correlation between the amount of irrigation water produced and the amount of electricity consumed at the studied farms offered the possibility

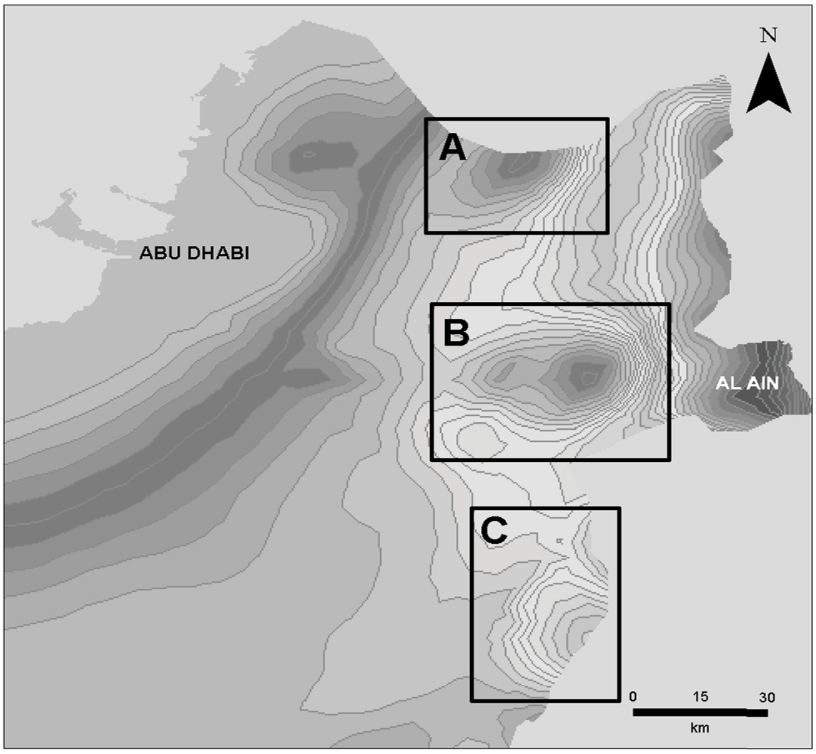


Fig. 4. Groundwater cones of depression (January 2019).

of using citizen farm electric records to estimate historical and current water use in farming districts that have substantial concentrations of citizen farms.

2. Using electric use records for groundwater estimation

At Al Ain region (east of Abu Dhabi) The massive farm construction program from the mid-1990s to the mid-2000s increased the number of mixed palm and grass farms from a few hundred to more than 7,000 in 9 farming districts (Al Aushush, Nahel North, Nahel South, Al Ankah, Al Dhahira East, Al Dhahira West, Al Ageer, Al Wagan North, and Al Wagan South). Al Ain Distribution Company (AADC) digital farm electric use records for 2004 to 2009 were used to estimate groundwater abstraction at these farms based on a previous investigation that showed groundwater use and electric use trends were linear at mixed palm and grass farms. A multi-year monitoring program of groundwater use and associated electric use at 14 selected farms started in June 2006. The general locations of the monitored farms are between Al Ain and Al Hayer, between Al Hayer and Nahel, west of Al Ain in Al Ankah, and south of Al Ain in Al Dhahira as shown in Fig. 5. The study concentrated on three farms devoted entirely to the production of date palm trees (palm farms), and 10 farms devoted to the production of date palms and grass fodder for animals (mixed palm and grass farms), and one farm devoted primarily to the production of roses. The three palm farms, as with many palm farms, are not constructed in the style of a typical citizen farm. However, because they are devoted to a single crop and because the total number of trees was fixed, they are ideal farms to study. By February 2010, the three palm farms had been monitored for a sufficient period to assess water use for palm trees [7]. By January 2011, the 10 mixed palm and grass farms and the rose farm had been monitored for a sufficient period to assess water use for mixed palm and grass farms.

Data from two of the ten mixed farms were not analyzed because it was later determined that these farms were receiving water from wells that were located outside of the farm and operated by a different electrical circuit. For palm farms, the average long-term groundwater use rate was 0.156 m^3/d/tree (156 L/d/tree) and the average long-term electric-use rate was 0.37 kWh/d/tree. This measured water-use rate compares favorably with published estimated palm tree water-use requirements of 112 to 314 L/d/tree [8] determined from research conducted in Saudi Arabia. The average irrigation efficiency was 0.49 m^3/kWh [9]. For mixed palm and grass farms, average total farm long-term water use was 354 m^3/d with a standard deviation of 218 m^3/d. Water use for grass only was estimated by subtracting total tree water-use (using the palm farm data analysis) from total irrigation water use [10]. The average long-term grass water use for mixed farms was 207 m^3/d/ha with a standard deviation of 110 m^3/d/ha. On average, water use for grass was 86% of total irrigation water use at mixed farms. Average long-term farm electric use at mixed farms was 536 kWh/d with a standard deviation of 377 kWh/d. Average irrigation efficiency was 0.77 m^3/kWh with standard deviation of 0.23 m^3/kWh. The average farm groundwater uses in the Al Aushush farming district increased from 225 m^3/d in 2004 to 250 m^3/d in 2009, with the number of farms for

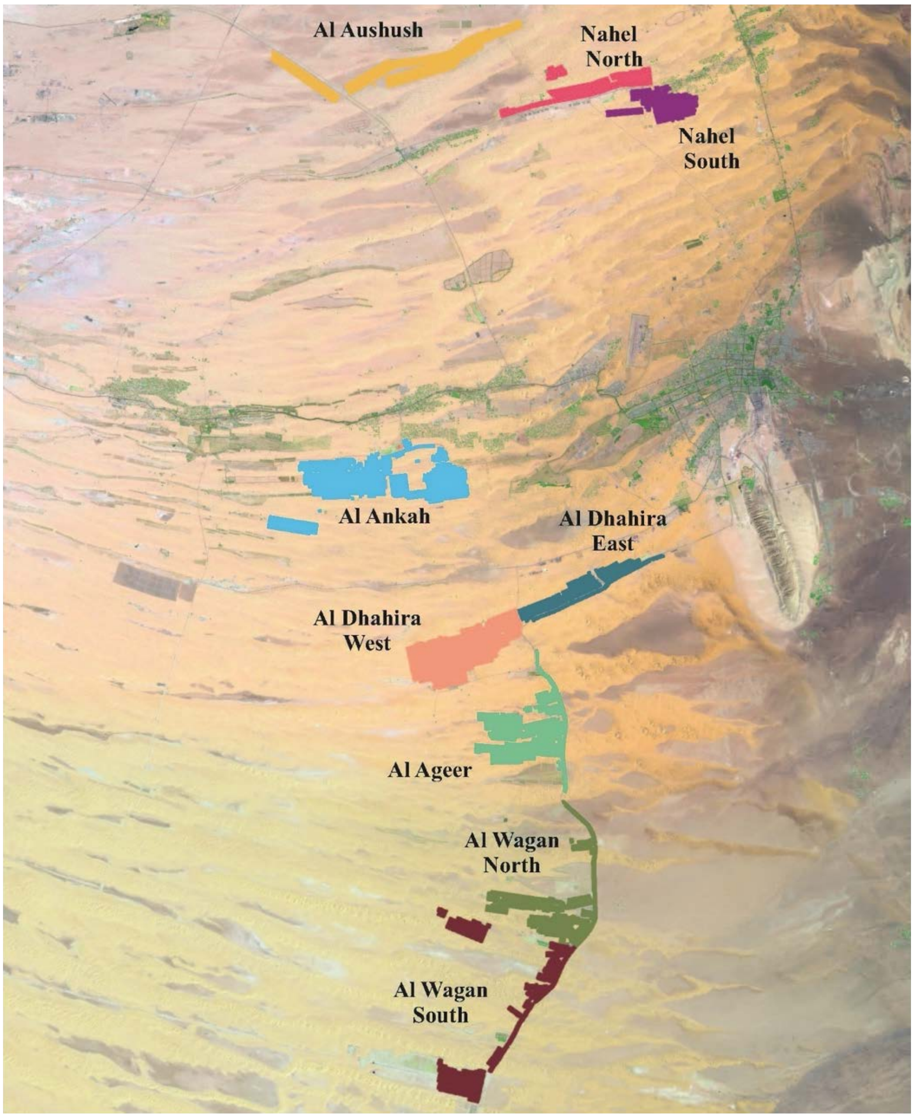


Fig. 5. Location of 9 farming districts for which electric meter readings were analyzed.

which electric meter reading data was available increasing from 810 to 915 during the same period. From 2004 to 2009, the percentage of farms using between about 150 and 350 m^3/d of irrigation water increased from 72% to 79%, with most of the increase occurring from 2004 to 2005. This probably was caused by the abrupt increase in new farms in late 2004 and early 2005 [11]. The percentage of farms using less than 150 m^3/d declined from about 20% in 2004 to about 10% in 2009. Total farm district groundwater uses in 2009 was 229,000 m^3/d or 83.7 Mm^3/y, which was a 26% increase over the annual 2004 groundwater use as shown in Table 1. Fig. 6 shows the annual groundwater use by farms in each farming district.

3. Results and outcomes

The 3-y study of 10 citizen farms in eastern Abu Dhabi Emirate that focused on the production of date palms and grass fodder for animals concluded that groundwater use and electric use generally exhibited linear trends in time. Because of this relationship, it was possible to determine average farm irrigation efficiency (0.77 m^3/kWh) as the ratio of total amount of irrigation water distributed to crops to total farm electric use, and it was possible to use compiled farm electric records to estimate historical and current water use in farming districts that have substantial concentrations of citizen farms. Farm electric-use records obtained from the Al Ain Distribution Company (AADC) were used to estimate water use in 9 farming districts (Al Aushush, Nahel North, Nahel South, Al Ankah, Al Dhahira East, Al Dhahira West, Al Ageer, Al Wagan North, and Al Wagan South) during the period for which digital electric-use data was available (2004–2009). The growth history of each farming district was determined by extrapolating the slope of first linear segment of each farms electric-meter reading data backwards in time to the predicted time of the zero reading. All of the districts exhibited similar growth trends, with growth at 2 farming districts being fairly constant from

Table 1
Results of groundwater use analysis for all farming districts

Farms	Year					
	2004	2005	2006	2007	2008	2009
Al Aushush						
Number of farms	810	908	917	921	926	915
Average use (m^3/d/farm)	225	234	246	247	246	250
Minimum use (m^3/d/farm)	1	1	10	10	5	2
Maximum use (m^3/d/farm)	651	620	620	620	622	738
Standard deviation (m^3/d)	97	87	84	84	88	88
Total daily use (m^3)	182,000	213,000	225,000	227,000	228,000	229,000
Total annual use (Mm^3)	66.6	77.8	82.4	83	83.2	83.7
Al Nahel North						
Number of farms	366	385	393	395	397	392
Average use (m^3/d/farm)	178	177	179	183	184	190
Minimum use (m^3/d/farm)	13	1	13	1	2	3
Maximum use (m^3/d/farm)	663	556	556	556	557	691
Standard deviation (m^3/d)	93	89	90	92	94	99
Total daily use (m^3)	65,000	68,000	70,000	72,000	73,000	74,000
Total annual use (Mm^3)	23.8	24.9	25.6	26.4	26.7	27.2
Al Nahel South						
Number of farms	318	338	358	327	307	289
Average use (m^3/d/farm)	142	125	119	119	118	121
Minimum use (m^3/d/farm)	8	2	1	1	4	1
Maximum use (m^3/d/farm)	757	624	624	624	626	624
Standard deviation (m^3/d)	95	87	82	84	85	85
Total daily use (m^3)	45,000	42,000	42,000	39,000	36,000	35,000
Total annual use (Mm^3)	16.5	15.5	15.5	14.2	13.3	12.8
Al Ankah South						
Number of farms	1,032	1,304	1,352	1,357	1,346	1,327
Average use (m^3/d/farm)	286	283	302	304	310	315
Minimum use (m^3/d/farm)	1	1	3	7	2	5
Maximum use (m^3/d/farm)	976	974	974	974	976	974
Standard deviation (m^3/d)	127	116	112	112	111	109
Total daily use (m^3)	295,000	369,000	408,000	413,000	417,000	418,000
Total annual use (Mm^3)	107.9	134.7	149.2	150.7	152.4	152.7
Al Dhahira East						
Number of farms	386	391	462	467	469	475
Average use (m^3/d/farm)	292	291	277	302	309	312
Minimum use (m^3/d/farm)	1	1	9	9	7	5
Maximum use (m^3/d/farm)	703	701	878	933	936	952
Standard deviation (m^3/d)	145	145	143	149	151	158
Total daily use (m^3)	113,000	114,000	128,000	141,000	145,000	148,000
Total annual use (Mm^3)	41.1	41.6	46.8	51.6	52.9	54.1

early 1990 to 2006, one farming district showing slightly increased growth from the late 1990s to 2006, and 6 farming districts showing rapid growth from the late 1990s to 2006. The 8 farming districts showing the most rapid overall growth also exhibited abrupt smaller increases in numbers of farms around 2004 to 2006, and all farming districts show nearly flat growth from 2006 to 2009 [12].

Average groundwater uses per farm at the Al Aushush farming district (about 1,200 electric meters) increased from 225 to 250 m^3/d from 2004 to 2009, with total farm-district

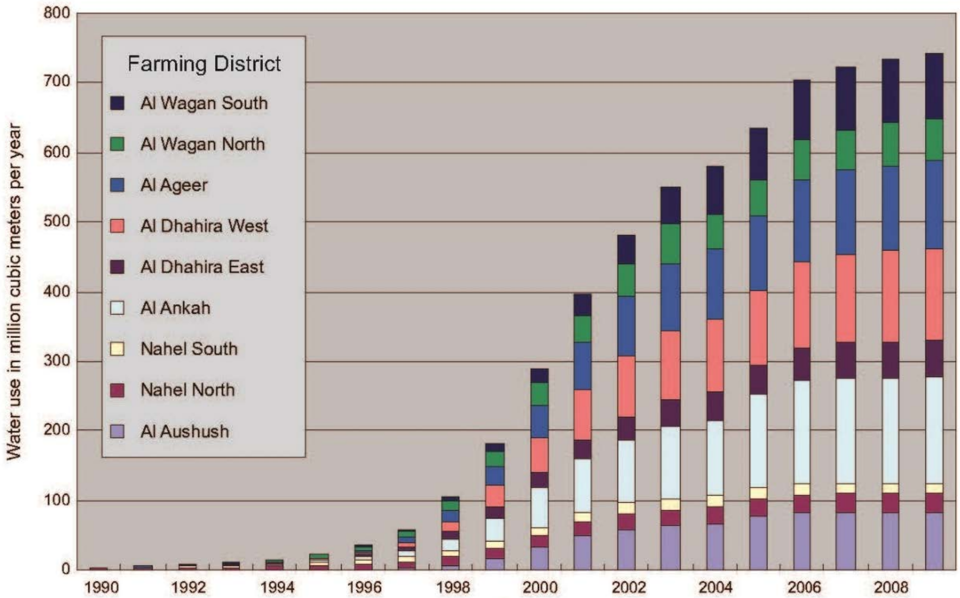


Fig. 6. Annual water use by citizen farms in each farming district.

water use increasing 26% to 83.7 Mm^3/y from 2004 to 2009. Average groundwater uses per farm at the Nahel North farming district (about 700 electric meters) increased from 178 to 190 m^3/d from 2004 to 2009, with total farm-district water use increasing 14% to 27.2 Mm^3/y from 2004 to 2009. Average groundwater uses per farm at the Nahel South farming district (about 700 electric meters) decreased from 142 to 121 m^3/d from 2004 to 2009, with total farm-district water use decreasing 22% to 12.8 Mm^3/y from 2004 to 2009. Average groundwater uses per farm at the Al Ankah farming district (about 1,600 electric meters) increased from 286 to 315 m^3/d from 2004 to 2009, with total farm district water use increasing 42% to 152.7 Mm^3/y from 2004 to 2009. Average groundwater uses per farm at the Al Dhahira East farming district (about 500 electric meters) increased from 292 to 312 m^3/d from 2004 to 2009, with total farm-district water use increasing 25% to 54.1 Mm^3/y from 2004 to 2009. Average groundwater uses per farm at the Al Dhahira West farming district (about 1,200 electric meters) increased from 296 to 332 m^3/d from 2004 to 2009, with total farm-district water use increasing 27% to 131.1 Mm^3/y from 2004 to 2009. Average groundwater uses per farm at the Al Ageer farming district (about 1,150 electric meters) increased from 319 to 346 m^3/d from 2004 to 2009, with total farm district groundwater use increasing 22% to 125.5 Mm^3/y from 2004 to 2009. Average groundwater uses per farm at the Al Wagan North farming district (about 900 electric meters) increased from 272 to 296 m^3/d from 2004 to 2009, with total farm district groundwater use increasing 28% to 61.7 Mm^3/y from 2004 to 2009. Average groundwater uses per farm at the Al Wagan South farming district (about 900 electric meters) increased from 295 to 321 m^3/d from 2004 to 2009, with total farm district groundwater use increasing 34% to 94.3 Mm^3/y from 2004 to 2009. Total annual groundwater uses for citizen farms in the 9 farming districts during the 6-y study period increased from 581 Mm^3/y in 2004 to 743 Mm^3/y in 2009.

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Desalination and Water Treatment
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doi: 10.5004/dwt.2022.28233

263 (2022) 214–219
July

A numerical approach for the evaluation of sustainable yield of shared aquifer basins: a case study from the Mediterranean Countries

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Received 28 February 2022; Accepted 28 April 2022

ABSTRACT

The aim of this research is to illustrate that developing steady-state models for shared aquifer basins will provide an opportunity to better manage these shared aquifers by realizing the transboundary fluxes between sharing countries. This study addresses a case study in the Eastern Mediterranean Countries. The addressed case study is a source of high level of disputes between sharing countries with regards of water rights. Therefore, this study provides an important methodology to evaluate the sustainable yield of the shared aquifers in order to help develop optimum utilization plans especially for domestic and agricultural uses. An understanding of the regional scale hydrogeological processes and assessing their impact on the aquifer basins will lead to a significant improvement in the determination of the sustainable yield of the shared aquifer basins. A numerical model (GMS-MODFLOW) was developed for the shared aquifer addressed in this study which is the Western Aquifer Basin (WAB) in Eastern Mediterranean Countries. The model was calibrated using historic and recent data. The sustainable yield of the WAB has been considered as the calibrated long-term discharge of the main springs (Timasah and Ras Al-Ain) of the aquifer basin before its development. The results of the study show that the steady-state sustainable yield of WAB was 357.9 Mm^3/y, respectively.

Keywords: Steady-state flow model; Sharing countries; Utilization plans; Springs discharge

1. Introduction

The aim of current research is to assess the sustainable yield of shared aquifer basins within their hydrogeological boundaries using numerical modelling as the main approach. This current research mainly utilizes the results of a research project conducted by Newcastle University on the Western Aquifer Basin (WAB) in the Eastern Mediterranean Countries [1]. The numerical modelling approach was also used to estimate the sustainable yield of other shared aquifers in the Arabian Gulf Countries [2]. In the context of this paper, the term sustainable yield is referred to that percentage of the volume of aquifer annual recharge that can be extracted from the aquifer through means of pumping wells without causing severe drop in the water levels and without causing severe deterioration in its water quality [1]. The determination of the sustainable yield for shared aquifer basins can help develop realistic and reasonable future groundwater utilization plans in one sharing country without causing harm to other sharing countries. This is normally achieved if the hydrological regime of regional/shared aquifers is understood and is well conceptualization. Also, such studies improve and strengthen databases of all sharing countries with regards to deterioration in water quality and drawdowns in the water levels of shared aquifer basins. These studies normally illustrate to all sharing countries that technical cooperation and holistic management of shared aquifer

Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

basins is the best way to face challenges of droughts created by climate changes. Managing shared aquifer basins without holistic approach can lead to more difficult consequences. Examples of such shared aquifers are known worldwide and the Middle East [3–5]. In reality, most sharing countries face legal issues and conflicts related to the development of shared aquifer basins due to over exploitation of their part in the shared resource of water [4–7]. Hydrogeological assessments can predict the likely impacts of different groundwater exploitation scenarios, but they are unable to determine the best fit conditions [4–7]. The most important factor that affect the management of shared groundwater resources or aquifer basins is the recharge from rainfall. Basically, if the shared aquifers are not renewable on annual recharge basis, then the determination of the sustainable yield is of no importance. Pumping the shared aquifer basins by one or two sharing countries beyond their renewable capacity will create a lot of conflict and tension between the sharing countries [4]. It is not always the case that the shared aquifer basins yield freshwater as the case for the Eastern Mediterranean Countries, brackish water (with total dissolved solids of less than 10,000 mg/L) are also very important to the Arabian Gulf Countries where these sources are vital for agricultural use [8,9]. In these countries, brackish water can be used also for mixing purposes with desalinated water to convert the mixture to be suitable for domestic use [8,9]. It should be emphasized that the estimation of the sustainable yield of shared aquifer basins requires reasonable approximation to the cross-boundary fluxes. This requires information on the regional hydrogeology and recharge of the shared aquifer basins.

The study area of this research is the Western Aquifer Basin (WAB) in the Eastern Mediterranean region (Fig. 1). The study area of WAB is around 6,035 km^2 with 29% within the lands of West Bank and Gaza and 71% in Historical Palestine. The hydrogeological set-up of the two aquifer basins is provided in later sections of this paper.

Fig. 1 shows a number of shared groundwater aquifer basins in the Eastern Mediterranean countries. The current research, concentrates on the Western Aquifer Basin (WAB). The WAB basin has two aquifer units as shown in the geological cross-section of Fig. 2.

The two aquifer units as indicated clearly in Fig. 2 are the Upper Aquifer (UA) and the Lower Aquifer (LA). The UA has larger outcrop area than the LA, and confined conditions exist where the aquifers dip below the recent sediments. The karstified carbonate rocks of limestone and dolomites of the UA and LA persists within the West Bank and extends beneath the Mediterranean Sea. Numerous lineaments have been identified and some of these are likely to represent discontinuities that affect the hydraulic integrity of the dividing aquiclude. The groundwater divide is roughly north–south, groundwater flows east to the Jordan Valley, and west towards the Mediterranean Sea. The WAB has two prominent spring complexes (called Ras El-Ain and Timsah, Fig 3) in the discharge area for the karstic aquifer. The two complexes have similar water levels. The water quality of the springs is good. This implies that flow paths were long enough to prevent serious pollution from fertilizers.

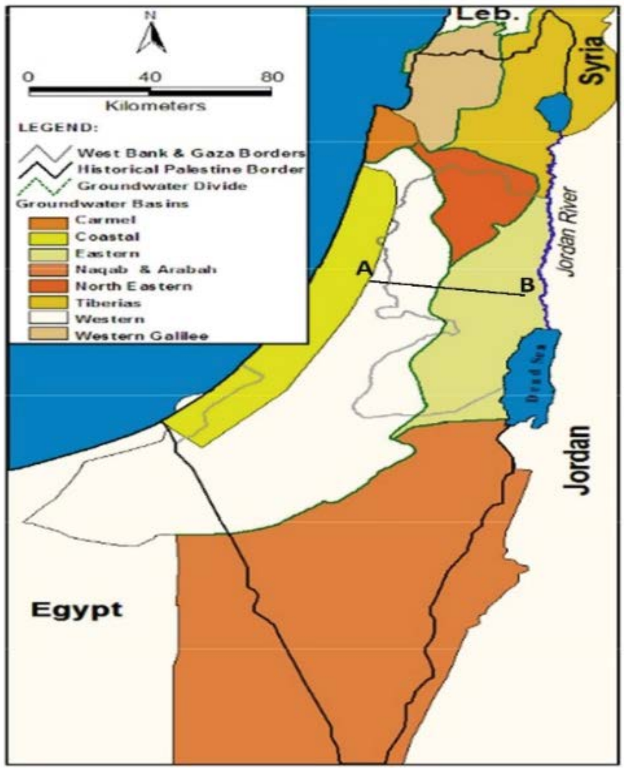


Fig. 1. Location map of the WAB study area WAB is in white color.

2. Methodology

2.1. Software and data

This research adopted a numerical approach (using the MODFLOW-GMS software) for WAB aquifer. This approach required detailed information and data on the geometry of the aquifers and their hydraulic properties. The geometry of aquifers was collected from many geological cross sections together with seismic data to determine the thickness of all encountered geological formations over the entire domain of the aquifer basin. The hydraulic properties of aquifers were collected from many pumping tests carried out at the pumping wells with observation or monitoring wells. Although this type of data exists but difficulties were encountered. In this sense, there is an uncertainty about the hydraulic properties of the aquifer but with a successful calibration process of these parameters the uncertainty has been reduced.

2.2. Conceptual and steady-state model of WAB

The aquifer system of WAB includes 3 layers: Upper Aquifer (UA), aquitard (Yatta) and Lower Aquifer (LA) as seen in the geological cross section (Fig. 2). The grid was constructed with a fine zone, in areas with high stresses, such as the regions located with wells and springs. Then the input data were assigned from the conceptual model to the cells of the grid. The size of the model cells is not the same for model area. The cell area varies between 0.25 km^2 around the main springs (Al Timsah and Ras El-Ein springs) to 4 km^2 far away from them which is the largest

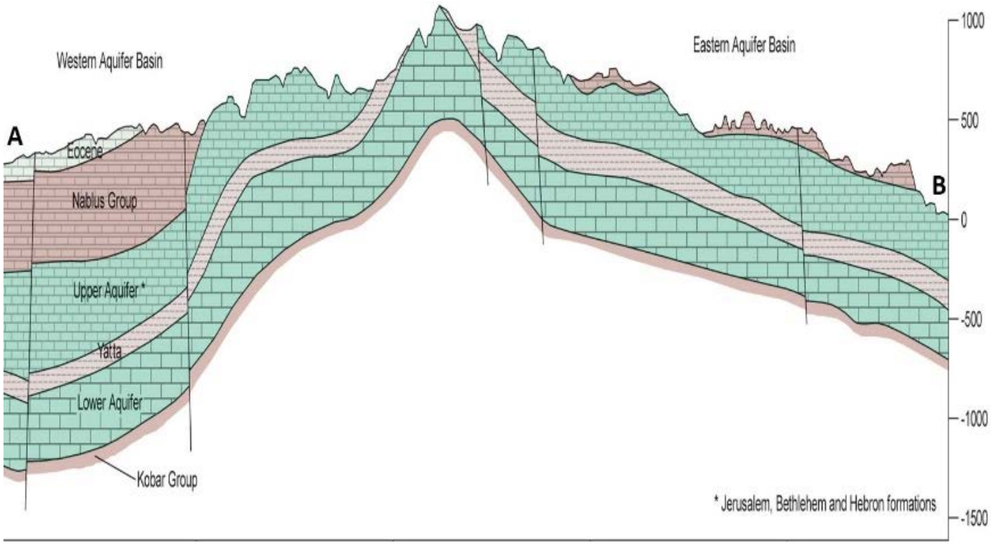


Fig. 2. Geological cross-section AB shown in Fig. 2 of the West Bank aquifer of Eastern Mediterranean Region.
Source: SUSMAQ, 2001, 2003 [10,11].

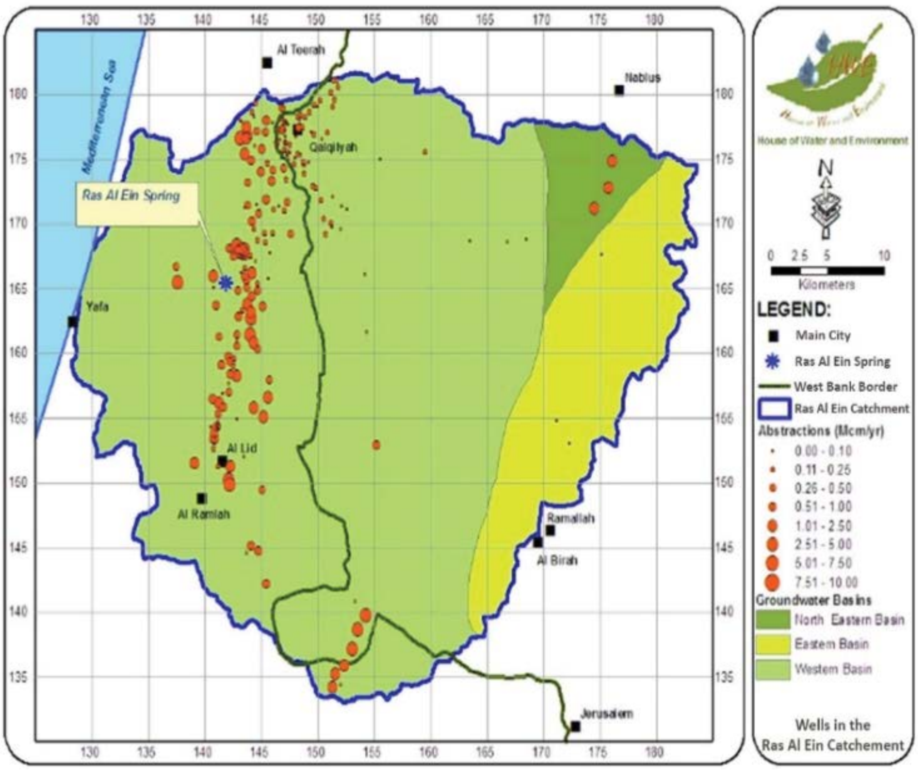


Fig. 3. Location of the main spring (Ras Al-Ain) in the WAB showing heavy pumping around it.

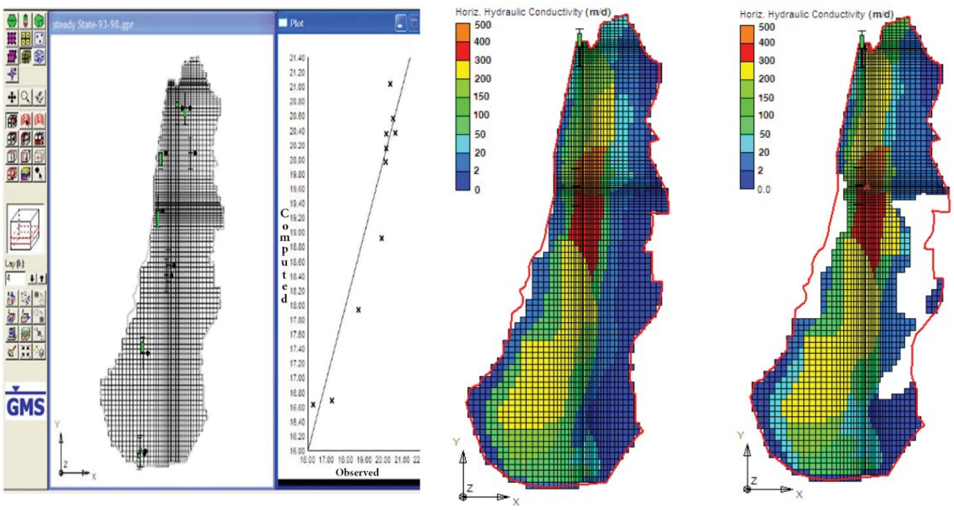
cell area used in this study. The WAB hydraulic boundaries were difficult to determine because the structural of the basin is complex with many faults and anticlines. No-flow boundaries were considered where erosion occurs and the aquifers were permanently above the water levels (and thus dry) or the regions with considerable changes in hydraulic properties that inhibit lateral flow. No-flow boundaries where assigned at groundwater divides near the high anticlines at the recharge zones (the eastern boundary of WAB). In addition, the litho-facies changes between the WAB and the Mediterranean constitute a no-flow boundary. Additionally, most of the southern boundary was considered as a no-flow boundary, since the permeability is very low (a barrier) compared to the rest of the aquifer area. Timsah and Ras El-Ein springs were considered a general head boundary. The recharge estimation of WAB is complex due to the complexity of its hydrogeology and structural geology [12]. However, the determination of the recharge volumes for the entire basin is very important to understand the sustainable yield of the basin. To enable recharge calculation on a physical basis considering aquifer outcrops, a distributed object-oriented recharge model was developed and tested by the British Geological Survey (BGS) [13]. An object-oriented approach was chosen to enable a range of recharge mechanisms to be incorporated easily into the model. Recharge is calculated at a node, which is held on a grid, which enables to consider a distributed recharge estimate. Four types of recharge node were used in this study: soil moisture balance method, wetting threshold, urban recharge process and irrigation losses.

In addition to these mechanisms, runoff routing to wadis and subsequent infiltration was also incorporated in the model. The values obtained from the BGS recharge model was used as an input data for the calibration process. After assigning initial recharge values from BGS recharge model [13] and hydraulic conductivity values (obtained from many pumping tests) [10–13] to the model cells, it was possible to adjust these values (calibration process) so that the computed results of water level and spring discharge match the observed ones. According to data availability in WAB, a set of target observation wells were chosen for calibration of the model. The calibrated results show (Fig. 4) clearly that the low permeability areas for both LA and UA are at the eastern recharge zone, the contact of the aquifer with the Mediterranean Sea and in the south region.

3. Discussion and results

The simulation results about the WAB model (Fig. 5) show that the movement of the groundwater flow moves towards the two major spring in the north (Timsah Spring) and in the middle (Ras Al-Ain Spring). Tables 1 and 2 represent the recharges from different components to WAB and spring discharges of WAB.

It is clear that the calibrated recharge of WAB is 357.9 Mm^3/y equals the measured spring complex discharges at 355.8 Mm^3/y with a relative error less than 1%. Thus, the steady-state modelling approach yields the sustainable yield of the WAB at 357.9 Mm^3/y. The Ras Al-Ain spring emerges from both the LA and the UA as they are connected hydraulically near the spring complex. The spring was subjected to heavy pumping (around 220 Mm^3/y) around it as seen in Fig. 5. Operating these wells has almost dried these springs in 1991 [15] and led to the change in groundwater flow direction towards the springs. Fig. 5 shows the direction of groundwater flow prior to the pumping by groundwater wells. When the winter season of the 1991/1992 brought rainfall with a huge amount of a few orders of the annual rainfall, the water levels of WAB raised to high levels of 50 y back causing Ras Al-Ain and



(a) (b) (c) (d)

Fig. 4. Location of observation wells (a), water level calibration (b), permeability calibration of LA (c) and UA (d) of WAB.

Table 1
Steady-state calibrated WAB recharge (Mm^3/y) from different components according to aquifer units [11]

Aquifer unit	From rainfall	From rainfall runoff	From wastewater runoff	From water supply leakage	From seawater intrusion	Subtotal
UA	244.92	16.99	1.55	5.47	3.6	272.53
Yatta	21.1	1.45	0.02	0.25		22.82
LA	55.4	3.75	0.29	0.71		60.15
Sub-total	321.42	22.19	1.86	6.43	3.6	**355.5**

Table 2
Steady-state calibrated spring discharges (Mm³/y) from before utilization of WAB [11]

Spring complex	Observed discharge (Mm³/y)	Modelled discharge (Mm³/y)	Relative error
Al-Timsah	101.3	100.9	0.4%
Ras El-Ein	254.5	257	0.9%
Total	**355.8**	**357.9**	**0.6%**

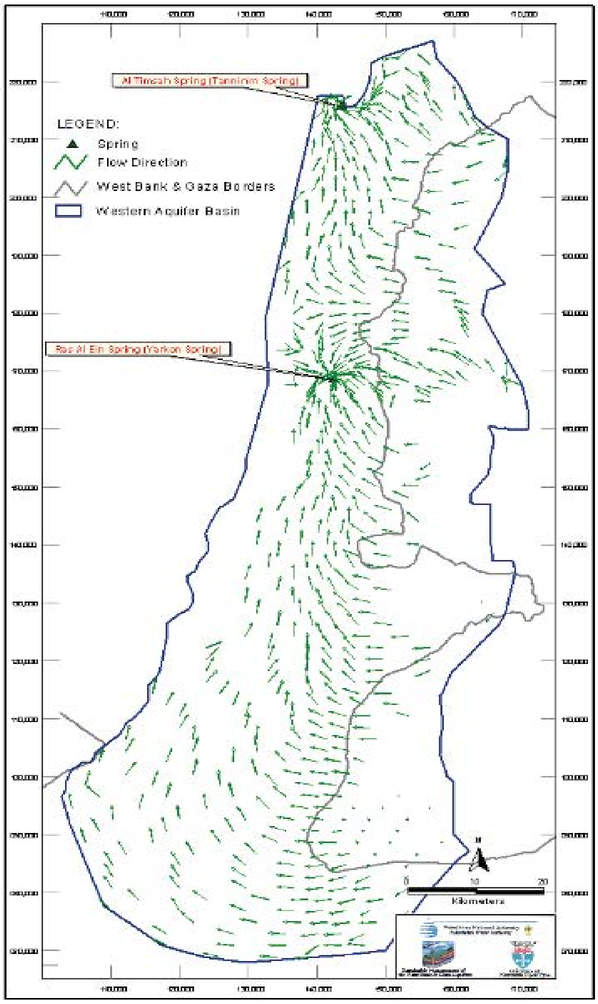


Fig. 5. Directions of groundwater flow of WAB before utilization (putting pumping wells into operation).

Timsah springs to discharge water again. The spring complex is located in a strong karstic system in both the UA and LA [15].

Although this study discussed the sustainable yield of WAB but in reality the shared aquifer basin is pumped beyond its sustainable yield capacity. This act creates a legal dispute of how these shared water resources should be managed with an agreement of all involved sharing countries. This type of agreement should be developed according to the international law of shared international aquifers.

4. Conclusion

The sustainable yield of shared regional aquifers was estimated in this study by utilizing the developed and calibrated steady-state numerical groundwater flow models. The MODFLOW-GMS software packages was used to estimate the sustainable yield for WAB. The sustainable yield of the calibrated steady-state numerical model for WAB was determined to be 357.9 Mm³/y. The sustainable yield was estimated by developing a calibrated steady-state water budget of WAB. This paper calls for the international law to be applied in order to manage internationally shared aquifer basins.

Acknowledgements

The author would like to extend his appreciation to the support of the management of the Kuwait Institute for Scientific Research (KISR) in carrying out this research. The author would also like to express his thanks to the Water Research Center of KISR and Newcastle University (UK) that made a number of relevant documents available for this study.

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Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28234

263 (2022) 220–229
July

Understanding saline water dynamics in coastal aquifers using sand tank experiment and numerical modeling

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Received 28 February 2022; Accepted 1 May 2022

ABSTRACT

A better understanding of seawater intrusion (SWI) problem in coastal aquifers is important for a perspicacious management of groundwater resources. SWI is affected by various hydrogeological and hydrological parameters such as: hydraulic conductivity (K_{sat}) of the aquifer, abstraction rate, recharge rate, density of seawater, etc. The objective of this paper is to explore saline water dynamics in an unconfined aquifer under different hydraulic gradients and under managed aquifer recharge (MAR) by using sand tank experiments and numerical simulations using SEAWAT code. Also, the efficiency of MAR in countering SWI malady was explored under different values of K_{sat} by using SEAWAT code. Numerical modeling is an effective tool to investigate the effect of K_{sat} on seawater dynamics. Modeling is cheaper and required less time as compared to the sand tank experiment. The sand tank experiment showed that the retreat rate of the saline water interface is always higher than the intrusion rate. As the hydraulic gradient across the sand tank increases, the saline water interface recedes further in the seaward direction. Injection of 1,060 cm^3 freshwater into a well located at the toe of a saline water interface caused its retreat seaward by 40%. The calibrated model was used to simulate the effect of aquifer's hydraulic conductivity on the dynamics of saline water under MAR. The results show that MAR practiced in highly conductive aquifers was less effective in combatting SWI because the injected water discharges rapidly from the aquifer. A small water table mound develops when MAR is practiced in a highly conductive porous medium and hence there is only a small effect in controlling SWI. In contrast, a low aquifer's hydraulic conductivity slows down water flow, develops a higher water table mound and thus induces a significant effect on controlling SWI. Therefore, optimizing MAR requires close consideration of geological settings and hydrological conditions to ensure high efficiency of MAR in mitigation of salinized aquifer.

Keywords: Managed aquifer recharge; Injection wells; Seawater intrusion; Sand tank experiment; SEAWAT

1. Introduction

Groundwater is the main source of freshwater in arid regions that are characterized by limited water resources due to the low rate of precipitation. More stresses are exerted on coastal groundwater aquifers due to expansion of freshwater demand by municipalities, industries, agriculture, aggravated by the population growth [1,2]. Management of coastal aquifers is of high importance to sustain its usability for water supply. One of the main threats to degradation

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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

of water quality in coastal aquifers is seawater intrusion (SWI). SWI is the invasion of saline water into coastal aquifers [3,4]. The difference between freshwater and saline water specific gravity induces the ingression of the seawater into the aquifers [5]. SWI is classified into two types which are active and passive. Active SWI occurs when the hydraulic gradient in the aquifer is reversed to be in the landward direction whereas passive SWI occurs, when the hydraulic gradient is oriented seaward but of small value that is not enough to control SWI [6–8]. In our study presented here, we consider the case of passive SWI. In many coastal aquifers (especially, in arid regions), SWI is accelerated by over-abstraction of fresh groundwater and limited natural recharge. In fact, mismanagement of coastal aquifers accelerates the deterioration of the groundwater. The rate at which SWI occurs in a coastal aquifer depends on the abstraction rate, depth and intervals of the screens of abstraction wells, the concentration of salts in groundwater, and the hydraulic gradient among other factors [9]. Other hydrological parameters that affect the rate of SWI are K_{sat} of the geological formation of the aquifer, aquifer's geometry, density ratio (seawater/freshwater), and boundary conditions [10]. SWI is also affected by sea-level rise due to climate change, or in some areas due to land subsidence [8,11,12]. Tidal fluctuation may affect the scale of intrusion within the intertidal zone [13,14]. SWI can be controlled by implementation of physical barriers such as subsurface dams, cut-off walls, and mixed physical barriers [15,16], as well as hydraulic barriers such as negative (abstraction well), positive (injection well), and mixed barriers (abstraction and injection wells) [5]. Also, SWI can decelerate by using managed aquifer recharge (MAR), controlling the abstraction rate [17] and pumping from the transition zone [18]. MAR is shown to manage and protect coastal aquifers and slow down the SWI rate [19,20]. SWI was studied by sand tank experiments [2,9,21–29], analytical modeling [10,28,30–35] and numerical modeling [24,25,27,36,37]. The objective of this paper is twofold:

- Study the impact of different hydraulic gradients and MAR (by injection wells) on the dynamics of the saline water interface by using sand tank experiment.
- Numerically study the impact of K_{sat} on the efficiency of MAR in countering SWI problem.

2. Laboratory methods

2.1. Details of the experimental set-up

The sand tank utilized in this experiment was designed and fabricated using 2 mm thick transparent acrylic sheets. It is a rectangular parallelepiped with dimensions 100 cm long, 60 cm height and 15 cm wide (Fig. 1). The sand tank design considered the following aspects: the hydraulic gradient, the boundary conditions, the way the tank will be packed with soil and easiness of parameters measurement and data collection. The tank was packed using the wet-packing method where water is first added to the tank, followed with placing the selected sand material to avoid occurrence of a trapped air [2,26]. An artificial white coarse sand was used as a porous medium. The physical and hydrological properties of the sand were estimated in the lab. The grain diameter is 0.6 mm, the porosity (n) is 0.45 and K_{sat} is 4.5 cm/min. The tank is designed to have a water compartment at the left side to represent the upstream boundary (of freshwater), and another compartment at the downstream boundary (right side of the tank) to represent the seawater boundary. The two compartments are equipped with control valves that allow the selection of different hydraulic gradients across the tank corresponding to different runs. The inner walls of the compartments and the bottom boundary of the tank are lined with fine mesh to hold the packed soil and prevent colmation of drain valves. Two tanks of fifty-gallon capacity connected to the sand tank to supply both freshwater and artificially made saline water. The water is injected into the sand tank using two pumps (WP-7000: AC 220–240 V, 105 W, 50/60 Hz,). Liquid flow controller (Model: DFC15, DIGITEN) was used to measure and control the flow rate and to know the volume of both saline water and freshwater supplied into the sand tank during the experiment. The discharging water across both boundaries was measured during the experiment. The density of freshwater used during the experiments is 1.000 g/cm^3 and that for the saline water is 1.045 g/cm^3 (the salt's concentration is 50 g/L). To reach this concentration of saline water, around 14,000 g of table salt was dissolved in 180 L of freshwater.

The rate of intrusion and the length of saline water interface during all runs were measured by rulers (Fig. 1)

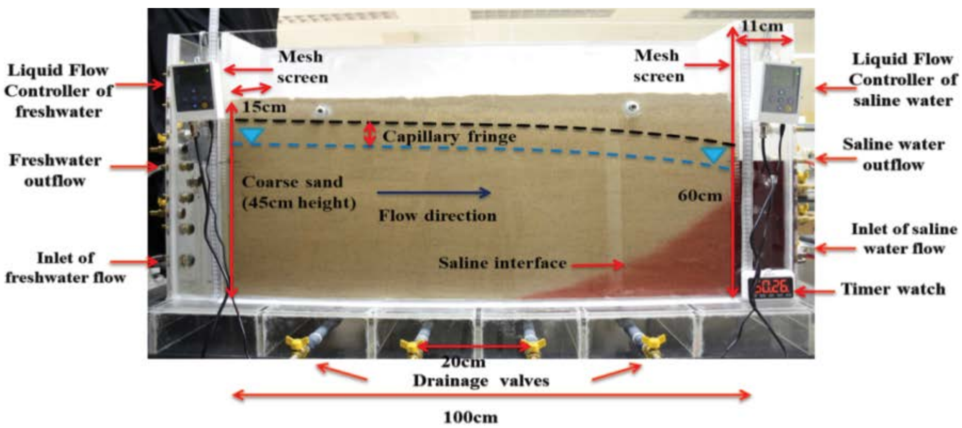


Fig. 1. Design of the sand tank.

and analysis of photos taken by a digital camera. The saline water was colored with Red Food Dye to easily visualize the movement of the saline water interface in the sand tank.

2.2. Procedure of different hydraulic gradient experiment

Different hydraulic gradients (i) were used to investigate the dynamics of the saline water interface. The interface advances and retreats backwards to the right compartment in Fig. 1. This oscillating behavior of the interface was measured using rulers fixed along the bottom side of the tank and along the vertical seawater boundary. The saline water interface toe (X_{toe}) position, depth to the interface at x = 0 (the coastline) (z_w), the discharge zone (DZ), and the seepage face (SF) were recorded during all runs. The inflow rate of freshwater into the tank was measured (using a flow rate controller) to be about 2.5 L/min while saline water supplied into the tank at the rate of 1.5 L/min. The experiments run until the system reach steady-state conditions at which the saline water interface stabilizes. The results were compared when the system reaches steady-state. The system considered reaching steady-state when (X_{toe}) position does not change with time. The parameters for all runs in this experiment are summarized in Table 1.

2.3. Procedure of injection well experiment

One injection well was fixed at the middle of the sand tank (50 cm from the saline water compartment) and at 42 cm depth from the top of the porous medium. The diameter of an injection well was 2 cm. The injection freshwater was colored with a blue food dye. Also, the level of the water table was monitored and measured using water level sensors. The injection started when the X_{toe} reached 50 cm from the seawater boundary. In addition, the areas cleaned from the saline water for all laboratory sand-tank experiments were calculated using Mathematica5 program. Also, the pore volume of area cleaned from saline water was calculated by Eq. (1) [38]. The injected volume of freshwater needed to reduce the salinity of a certain area of the aquifer that is contaminated by saline water was also evaluated.

$$\text{Pore volume} = \begin{pmatrix} \text{Vertical cross section area} \\ \times \text{Length of the tank} \end{pmatrix} \times \text{porosity} \quad (1)$$

2.4. Numerical modeling approach

MAR laboratory experiment was simulated using the SEAWAT code (MODFLOW Processing Pro version 8.0.31, Simcore software [39]). This code was run for steady-state conditions. The conceptual model used is presented in Fig. 2. The dimensions of modeled domain are x = 100 cm and y = 30 cm. The modeled domain was discretized with a grid size of Δy and Δx = 1 cm based on grid sensitivity analysis [40]. We assigned constant heads for both saline and freshwater boundaries and assigned a no-flow boundary for the bottom of the rectangle in Fig. 2. The parameters used in

Table 1
Parameters used for different hydraulic gradient experiment

No. of runs	Constant head of freshwater (h_f) (cm)	Constant head of saline water (h_s) (cm)	i = (dh/dl)	Inflow rate of freshwater (L/min)	Inflow rate of saline water (L/min)	Concentration of inlet saline water (g/L)
1	23	22.6	0.004	2.5	1.5	50
2	23	20.6	0.024	2.5	1.5	50
3	30.5	29.7	0.008	2.5	1.5	50
4	30.5	27.5	0.03	2.5	1.5	50
5	30.4	27.8	0.026	2.5	1.5	50
6	34	27.8	0.062	2.5	1.5	50

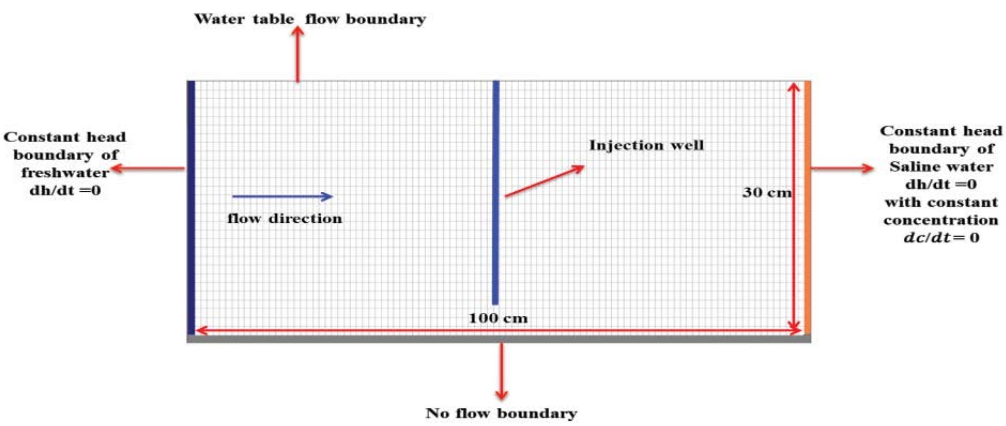


Fig. 2. Sketch of conceptual model for SEAWAT simulations.

simulations are presented in Table 2. Trial and error method was used for calibration. After calibration, SEAWAT was used to simulate our sand tank experiment, and to explore the impact of K_{sat} on the dynamics of saline water interface under MAR. Numerical modeling is a good tool to explore variation of parameters. Simulations are much cheaper compared with physical experiments. There are less associated efforts and sources of uncertainty, which are inevitable in physical experiments, for example, during packing and unpacking of porous media. Selected iso-concentric lines (isochlors) were plotted and used for comparison purposes.

3. Results and discussion

3.1. Dynamics of saline water interface under different hydraulic gradients

The effect of the hydraulic gradient (i) on the dynamics of the saline water interface was investigated. Fig. 3a presents the results of Run 1 for i = 0.004. The (h_f) and (h_s) were kept at 23 and 22.6 cm, respectively. In this run, during the first 5 min, X_{toe} advanced 6 cm upstream. Then the rate at which the saline water interface migrated in the tank towards the freshwater compartment was 1.4 cm/min. The rate decelerated with time is 0.1 cm/min (Fig. 4a). In average, the saline water interface intruded with the rate of (0.134 cm/min) during the 530 min of the experiment before reaching steady-state (Fig. 4a). The total inflow of freshwater into the tank during this experiment (until the steady-state condition reached, 530 min) was 600 L (600,000 cm^3) and 350 L (350,000 cm^3) of saline water intruded. The X_{toe} reached almost the upstream boundary. The z_w was 19.5 cm, DZ was 5.5 cm, and SF was 4.5 cm (Fig. 3a). During this run, the saline water contaminated about 7,590.4 cm^3 of the aquifer volume (the total aquifer volume in the tank considering 23 cm depth and 15 cm inner width for the porosity of 0.45 is 15,525 cm^3). The metered freshwater discharge (q_{out}) (at steady-state) through the coastal boundary was 1.5 L/min (1,500 cm^3/min) (Fig. 5) with concentration of 48 g/L. In Run 2 (Fig. 3b), i was 0.024 and the retreat of the saline water interface from its position in Run 1 (99 cm upstream the coastal boundary) was monitored and evaluated. The h_f and h_s were set to 23 and 20.6 cm, respectively. The interface receded back (right part in Fig. 3b) at an average rate of 0.33 cm/min during the first 245 min. The interface stabilized (reached steady state) after 245 min (Fig. 4b) and X_{toe} was at 11 cm from the coastal boundary. The changed values of z_w, DZ, and SF are shown in Fig. 3b. Setting i to 0.024 caused a retreat of the interface by about 88 cm. During this run, a total volume of inflowing freshwater into the tank across the upstream boundary measured as 520 L (520,000 cm^3) while the intruded saline water through the coastal boundary was 300 L (300,000 cm^3). The aquifer pore volume occupied by saline water was 380.3 cm^3 which is equivalent to 5% only of the aquifer volume. We found that a total inflow of 520 L (520,000 cm^3) of freshwater cleaned about 1,068.17 cm^2 of salinized area of the aquifer which is equivalent to 7,210.2 cm^3 of the pore volume. The q_{out} (at steady-state) through the seawater boundary was 1.5 L/min and the concentration of the discharged water was 46 g/L (Fig. 5).

In the third run, the hydraulic gradient was reduced again to allow intrusion but under the hydraulic gradient higher than that used in Run 1. The new i is 0.008 (h_f and

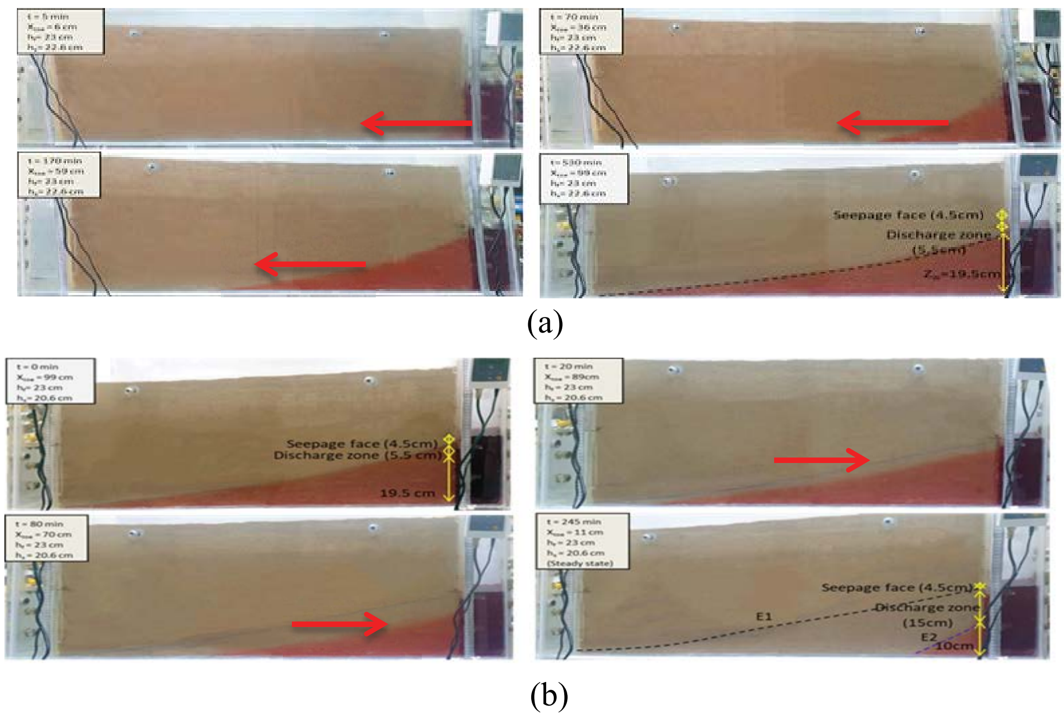


Fig. 3. Photos for (a) Run 1: SWI at selected times (5, 70, 170, and 530 min) for i of 0.004 and (b) Run 2: seawater retreat at selected times (0, 20, 80, and 245 min) for i of 0.024 when i was reset to 0.024 instead of 0.004.

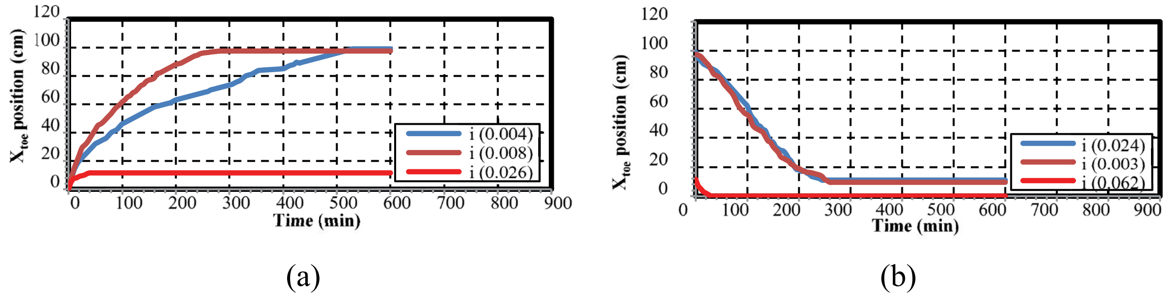


Fig. 4. Summary of the effect of i in saline water intrusion over time considering X_{toe}: (a) saline water intrusion and (b) saline water retreat.

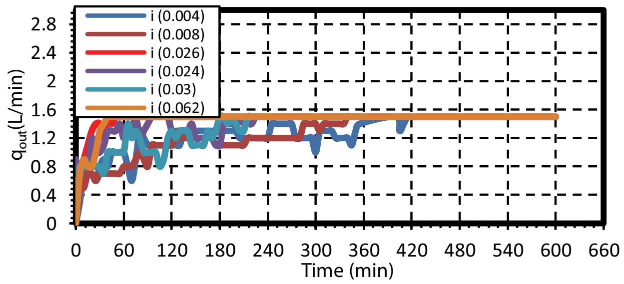


Fig. 5. Freshwater discharge q_{out} through seawater boundary.

h_s set to 30.5 and 29.7 cm, respectively). The ingression of the saline water interface is presented in Fig. 6a. The saline water interface moved faster at the beginning with a rate of 1.4 cm/min during the first 10 min (X_{toe} reached 14 cm inland). Then, the rate gradually decreased to 0.002 cm/min (Fig. 4a). The saline water interface intruded forwards with an average rate of 0.1051 cm/min during 285 min after which the system stabilized when the X_{toe} was at 97.5 cm. During this run, a total of 590 L (590,000 cm^3) of freshwater flow into the tank from the upstream boundary while an amount of 330 L (330,000 cm^3) was the inflow to the tank from the seawater boundary. The corresponding values of z_w, DZ and SF were 25.5, 5, and 6 cm, respectively (Fig. 6a). The salinized aquifer volume under i = 0.008 is 7,527.5 cm^3 which is almost similar to that of Run 1 for gradient of 0.004 (7,590 cm^3) and 20 times more than that for gradient of 0.024. The q_{out} via the seawater boundary at steady state was similar to that measured for i = 0.024 (1.5 L/min) with the concentration of the discharged water of 47.8 g/L (Fig. 5). Fig. 6b shows the results of Run 4 for i = 0.03 (h_f and h_s were 30.5 and 27.5 cm, respectively). The values of h_f and h_s are selected based on the pre-existing control valves. Analyses of the data are presented in Fig. 4b, shows that the saline water interface receded back with an average rate of 0.1214 cm/min during the first 260 min after which the flow reached steady state. The X_{toe} was measured to be at 9.5 cm from the coastal boundary. The z_w, and SF decreased to 10 and 3 cm, respectively, and DZ increased to 17.5 cm (Fig. 6b). For the X_{toe} to retreat by 88 cm (from where it was at i = 0.008) to the steady-state at i = 0.03, around 500 L (500,000 cm^3) of freshwater flushed the tank over the 260 min. However; an inflow of 230 L (230,000 cm^3) of saline water only entered the aquifer through the coastal boundary. In general, as i increases the SWI decreases as the freshwater flow acts against the landward ingression of the interface. This is in fact agreeing with the findings in the literature.

Fig. 7a shows Run 5 with i = 0.026 (h_f and h_s are 30.4 and 27.8 cm, respectively). The saline water interface intruded over a distance of 11.5 cm with an average rate of (0.0321 cm/min) over a period of 40 min at which the system reached an equilibrium state (Fig. 4a). Also, z_w, DZ and SF were found to be 11, 17.5, and 3 cm, respectively, Fig. 7a. The occupied volume by saline water was 440.7 cm^3. When the equilibrium state reached in Run 5, the hydraulic gradient in the tank during Run 6 increased to 0.062 (the h_f and h_s were 34 and 27.8 cm, respectively). As a result, the interface retreated towards the saline water compartment with an average rate of 0.1516 cm/min over 25 min. The saline water flushed out completely from the system after 25 min (Figs. 4b and 7b). About 35 L (35,000 cm^3) of freshwater flushed out through the tank and resulted in cleaning out 440.7 cm^3 of salinized aquifer volume. The flow rate q_{out} for all runs at steady-state was practically the same (1.5 L/min). However, the concentration of discharging water varied, depending on the i value. For Runs 5 and 6, q_{out} is presented in Fig. 5 and the concentration of outflowing water was 46 and 40 g/L, respectively.

The results in Fig. 4a and b show that the retreat rate of the interface is always faster than the intrusion rate. This finding is similar to what is found by experiments of Goswami and Clement [24] and analytical solution by Rathore et al. [10]. From the curve in Fig. 8, it seems that the relation between i values and the X_{toe} is not simply linear. It seems that there is a threshold value of i beyond which the change in the position is not really significant. This means that after certain i value, the induced effect on the position of the interface is negligible. As that, flushing out the aquifer with a larger volume of freshwater will be just a waste.

3.2. Experimenting with the dynamics of saline water interface under MAR injection well

The injection well located at 50 cm from seawater boundary (Run 7). Injection of 1.06 L (1,060 cm^3) of freshwater causes retreat of the X_{toe} in the seaward direction by 20 cm (X_{toe} reached 30 cm from the seawater boundary (retreated by 40%)). The shape of the saline water interface

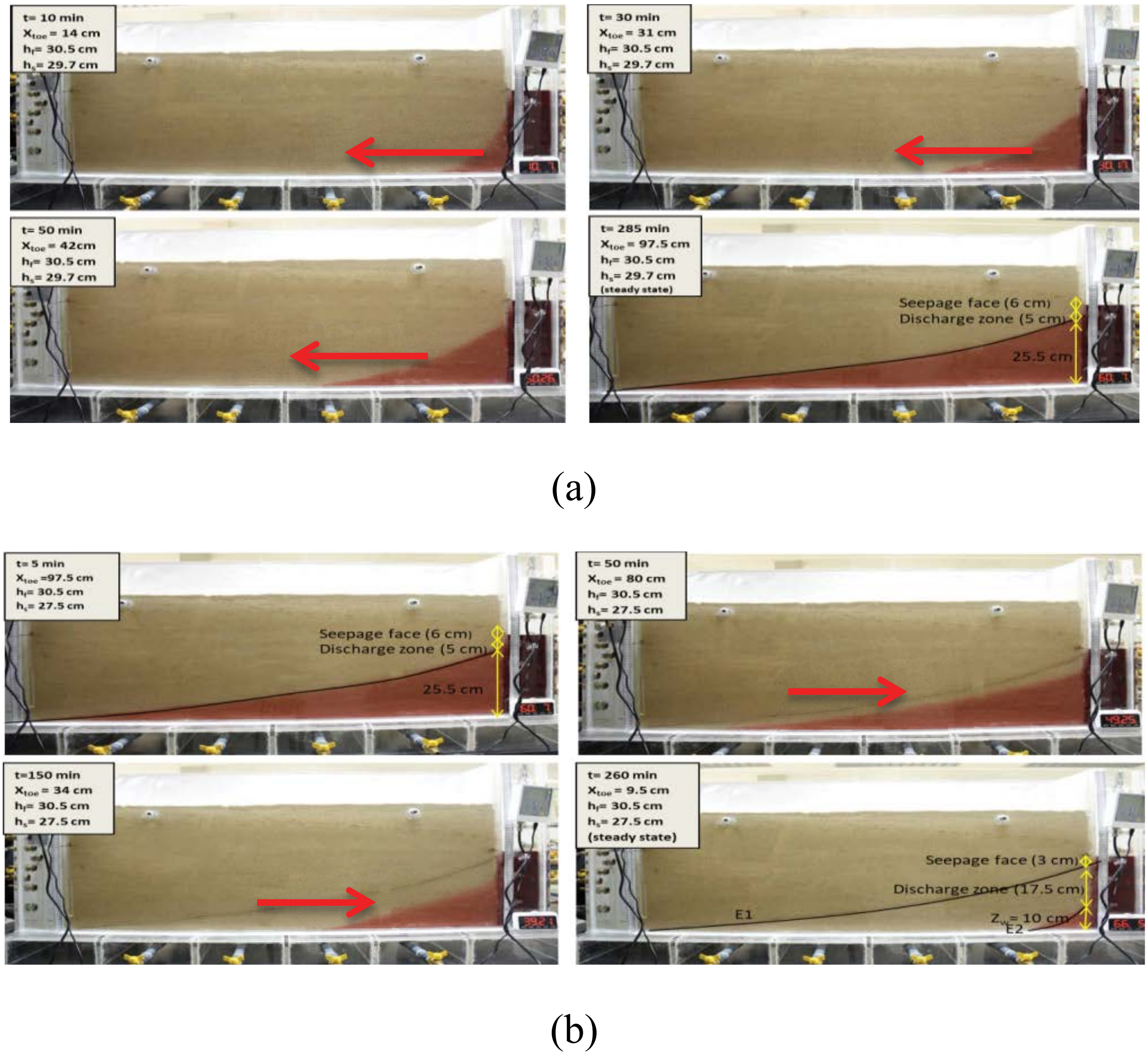


Fig. 6. Photos for (a) Run 3: SWI at selected times (10, 30, 50 and 285 min) under *i* of 0.008 and (b) Run 4: seawater retreat at selected times (5, 50,150 and 260 min) under *i* of 0.03 when was reset to 0.03 instead of 0.008.

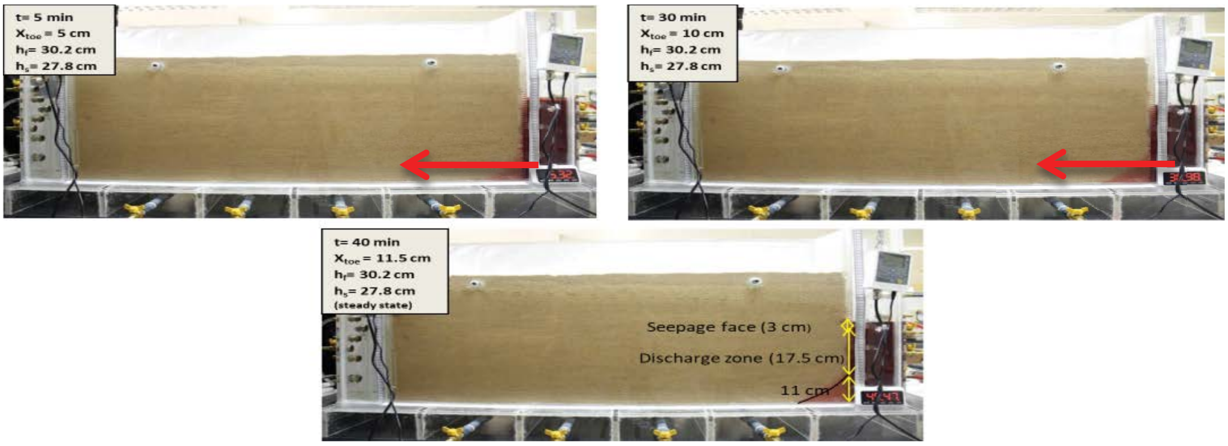
Table 2
SEAWAT parameters for the base case run

Parameter	Value	Parameter	Value
Hydraulic head at freshwater boundary	23.0 (cm)	Courant number	0.5 (–)
Hydraulic head at saline water boundary	22.6 (cm)	Longitudinal dispersivity	0.1 (cm)
K_{sat}	4.5 (cm/min)	Diffusion coefficient	0.5 cm^2/min
Effective porosity	0.45 (–)	Seawater concentration	50 (g/L)

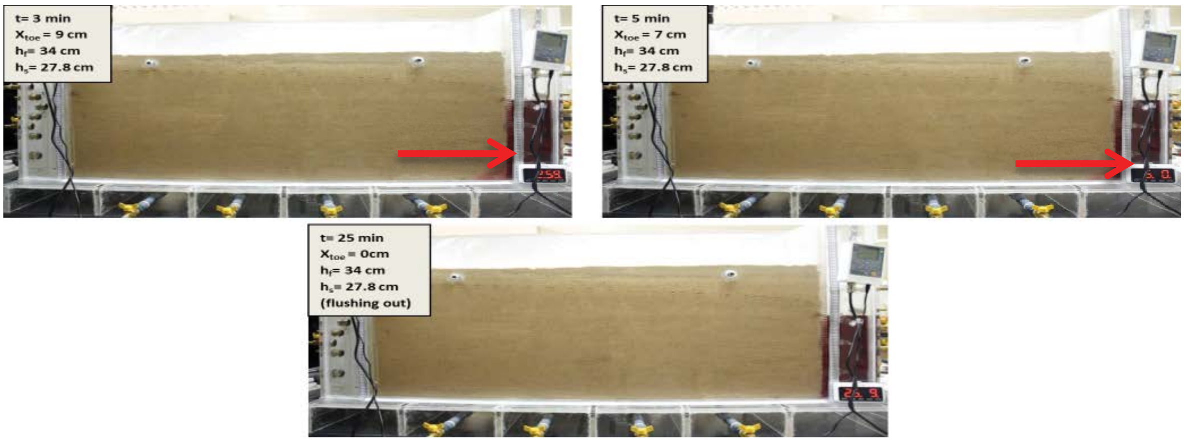
is affected by the MAR. The X_{toe} is at 30 cm, z_w of 17.5 cm and the thickness of the interface at 25 cm from the coastal boundary (z_x) is 7.5 cm (Fig. 9a and b). The salinized area before injection was found to be 479.652 cm^2. Injection of around 1.06 L of freshwater cleaned around 173.60 cm^2 of this salinized zone. The pore volume of the cleaned area is calculated as 1,171.8 cm^3.

3.3. Numerical simulation to investigate the effect of the hydraulic conductivity of the aquifer on SWI

Steady state calibration of the developed model was performed (for the experimental Run 7 discussed above). A good agreement between the results obtained from the numerical simulations and the sand tank experiment was



(a)



(b)

Fig. 7. Photos for (a) Run 5: SWI at selected times (5, 30 and 40 min) under *i* of 0.026 and (b) Run 6: seawater retreat at selected times (3, 5 and 25 min) under *i* of 0.062 when *i* reset to 0.062 instead of 0.026.

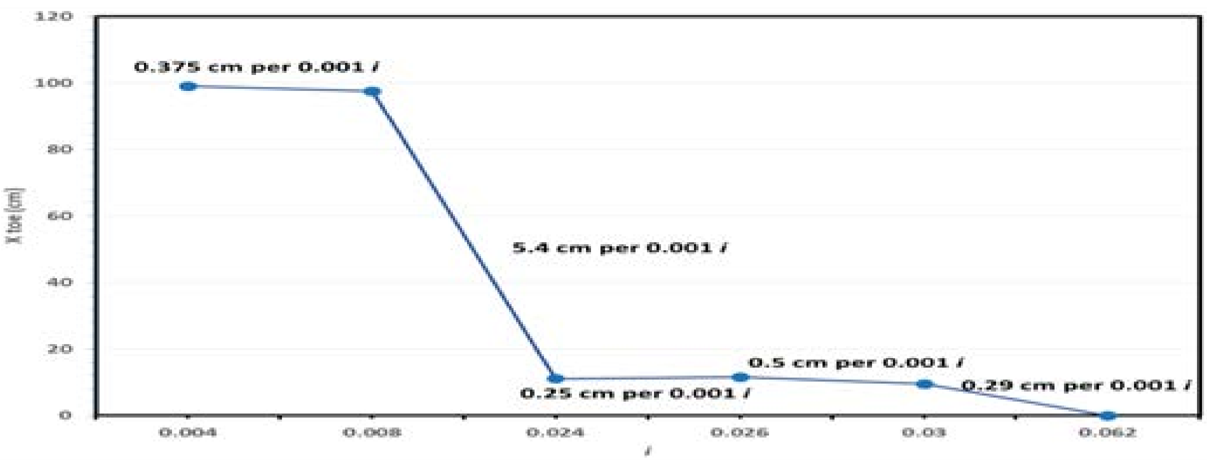


Fig. 8. Position X_{toe} under different *i*.

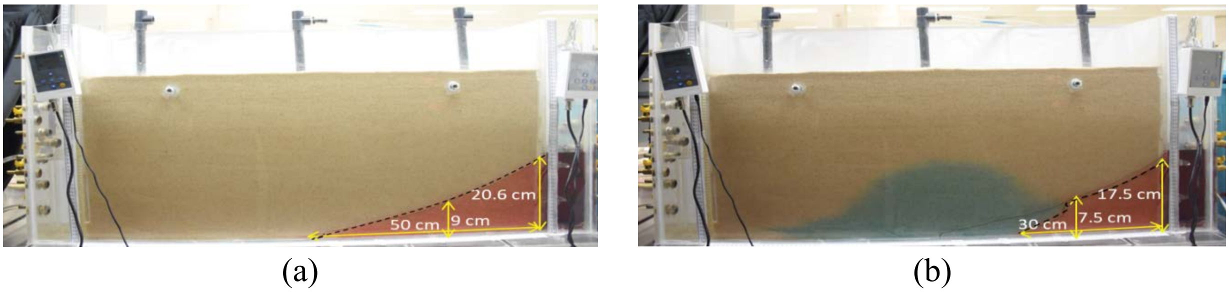


Fig. 9. Saline water interface: (a) before injection and (b) during injection (after 15 min since commencement of injection).

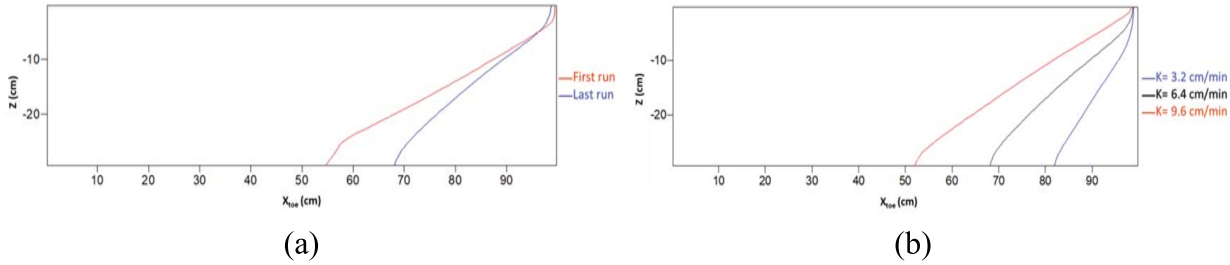


Fig. 10. (a) X_{toe} position modeled as 70% isochlor (during injection) for the first and final calibration and (b) 70% isochlor under different values of K during injection.

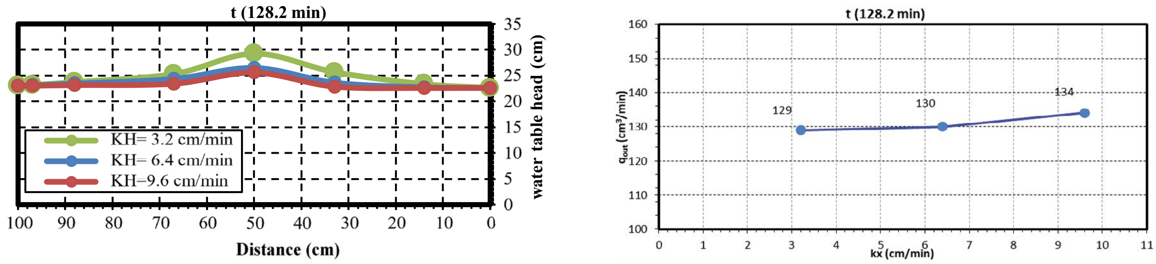


Fig. 11. (a) Water table height for different K_{sat} values and (b) simulated q_{out} volume for the simulations for different K_{sat}.

found for the following parameter set (porosity = 0.56, K_{sat} 6.4 cm/min, the initial longitudinal dispersivity ($\propto_L$) = 2.5 cm and the diffusion coefficient = 0.007 cm²/min). Under injection, X_{toe} retreated from 50 to 31 cm from the seawater boundary (retreated by 38%) (Fig. 10a) which is very close to X_{toe} during the sand tank experiment (Fig. 9b). High permeability of the aquifer caused a high rate of SWI that agrees with Abdoulhalik and Ahmed [41]. The calibrated model was used to investigate the impact of K_{sat} on the dynamics of the interface under the injection at the toe position. The K_{sat} values of 3.2, 6.4, and 9.6 cm/min, were examined. X_{toe} prior to injection was 50 cm. First, during injection of 1,060 cm³ under K_{sat} value of 6.4 cm/min, the X_{toe} of the selected 70% isochlor retreated by 19 cm seawards. Then, K_{sat} was increased to 9.6 cm/min, and X_{toe} receded backward by only 2 cm. However, when K_{sat} value decreased to 3.2 cm/min, the X_{toe} retreated by 32 cm (from 50 to 18 cm, by 64%) (Fig. 10b). The height of the water table mound was larger under a smaller K_{sat} value (Fig. 11a). Analysis of the water budget in the numerical simulations showed that injection into a low permeable material resulted in less discharge of water outside the tank (Fig. 11b). Hence, the developed water table mound was high and induced more effect on the interface (the interface retreats further seawards). In general, the simulations illustrated that K_{sat} is one of the key factors for MAR to induce significant effect in controlling SWI.

4. Conclusion

This paper presents the results of sand tank experiments and numerical modeling to investigate the dynamics of SWI in a coastal aquifer under MAR activities for different hydraulic properties of the aquifer. The feasibility of MAR in SWI mitigation was assessed and the rate of interface retreatment was found faster than the rate of its advancement. The sand tank experiment illustrates the importance of the gradient i in controlling SWI. SEAWAT simulations manifested that low aquifer's hydraulic conductivity increases the effectiveness of MAR in controlling SWI. If MAR practiced in highly conductive porous medium, the impact of the injection on controlling SWI is low. This is because of a rapid discharge of injected water out of the aquifer. In very permeable aquifers, the height of the developed water table mound is relatively small that limits induced piezometric heads needed for a seaward push of the saline water interface. Sand tank experiments and numerical modeling should be extended to consider heterogeneous aquifers and other hydrological drivers, like the abstraction rate of groundwater, and parameters of tidal fluctuations at the sea boundary.

Acknowledgements

The first author acknowledges the assistance of the administration of Sultan Qaboos University (SQU) in awarding her a full MSc scholarship. The authors would like to further extend acknowledgement to the financial support provided by SQU through internal grant IG/AGR/SWAE/19/01 and the support of the Research Group DR/RG/17.

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Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2022.28235

263 (2022) 230–247
July

Artificial recharge via injection wells for salinity ingress control of Salalah plain aquifer, Sultanate of Oman

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Received 28 February 2022; Accepted 1 May 2022

ABSTRACT

Seawater intrusion (SWI) has been considered one of the most widespread environmental problems that deeply threatened the quality and sustainability of fresh groundwater resources along coastal aquifer in Salalah. The main objective of this study is to determine the results of the same investigation conducted in 2008 by the same author with the results of the current actual transient scenario for the same period of years 2006–2020. The developed 3D flow showed that the wedge of the SWI in 2020 could possibly be tracked up to 2 km and less than 500 m from the shoreline under the predictive scenario and current actual transient scenario, respectively under constant underflow. The findings of the modeling simulation explained that the maximum path lines of the injection fluids were able to reach the abstraction wells located more than 1.2 km southward of the injection bores in one year travel time under the current actual transient scenario under constant underflow. In 2020 the injection of municipal treated effluents was found to be effective in pushing back the SWI zone front by more than 1.2 km under the current actual transient scenario compares to less than 500 m under predictive scenario under constant underflow, especially at the middle of the injection boreholes of the aquifer. This study revealed that the application and simulation of the method helped increase the groundwater levels and decrease the salinity total dissolved solids levels along the vicinity of the injection line.

Keywords: Salalah plain aquifer; Seawater intrusion; 3D groundwater modeling simulation; Injection boreholes; Artificial groundwater recharge; Municipal treated effluents

1. Introduction

Salalah, the capital of Dhofar Governorate is a city located in southern Oman about 1,000 km from Muscat the capital. It is situated along the coast of the Arabian Sea and is considered the second-largest city in the Sultanate of Oman. In the 2020 Omani census, the population of Salalah reached 331,949 people. The increase in population gives an impression of the progressive development in the region. The issuance of new laws and regulations has encouraged both local and international companies to increase the local economy in Salalah. With this case, there is also an increase in the water demand for municipal, commercial, agricultural, and industrial sectors.

The main Salalah saturated aquifer layers are the upper alluvium layer of the quaternary age and the second layer of fractured limestone, and the third saturated layer is marly limestone, deposited in the tertiary age. As early as 2013, the tertiary aquifer was the main source of water supply for all. Looking back in 1992, the status of the aquifer was constant, but in 2005 there was a discrepancy in groundwater quality in most of the agriculture strips. It was found out that the quality of drinking water did not meet the standards set by the Omani Standards [1]. Studies and investigations were conducted resulting to the heavy withdrawal of large quantities of groundwater from the Salalah aquifer and its effect on saltwater intrusion in Salalah plain aquifer [2–4].

Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

The results of the investigations became the most widespread environmental problems that deeply threaten the quality and sustainability of fresh groundwater resources along coastal aquifers [5]. Even the neighboring countries are experiencing similar problems and are implementing appropriate management strategies to control the impacts of intrusion problems considering acceptable limits of economic and environmental costs [6]. Similar to what is happening in Salalah, groundwater levels are declining across its plain aquifer as there are currently daily withdrawals from about 1,500 boreholes exceeding the rate of the natural water recharge. The application of method conducted by Shammas [7], about using artificial groundwater recharge that is municipal treated effluents (MTEs), found effective to control the continuously declining groundwater levels at Salalah plain aquifer.

In the past, the entire city likely depended on the karstic coastal plain aquifer for all domestic, and industrial purposes [8]. Pumping from Salalah and Saada wellfields were used for potable water usage for Salalah City. The traditional agricultural farms were utilizing 31.2 Mm^3/y. Garziz farm wells were pumping 10.61 Mm^3/y for the cultivation of Rhodes grass. With the situation, Salalah coastal aquifer started to suffer saline intrusion [3].

From 2013 seawater desalination facility owned by Sembcorp Salalah Independent Water and Power Plant Company (IWPP) is utilizing reverse osmosis technology and produces 25.2 Mm^3/y of water [9]. Pumping from Salalah and Saada wellfields were simulated during predictive scenario at 23.75 Mm^3 in 2020, whereas at current actual transient scenario both wellfields pumped only 10.6 Mm^3 in 2020. So, the abstraction from Salalah and Saada wellfields were reduced by almost 60% in 2020 as reverse osmosis technology facility compensated the balance in potable water demand. The second desalination plant based on reverse osmosis technology is owned by Dhofar Desalination Company and started its operation in mid of 2021 at a maximum capacity of 120,000 m^3/d, and the production depends on the demand. The plant is located at a coastal site adjacent to the existing Sembcorp IWPP in the Dhofar Region.

The unconfined layer in the upper portion of the aquifer is the quaternary Wadi alluvium where the traditional farms are utilizing 31.2 Mm^3/y for the main yielding zone as its groundwater depth is less than 10 m [10]. So, the net agricultural demand is modeled in this study at 46 Mm^3/y for the predictive scenario [3,11] and along the current transient actual scenario.

Due to the high groundwater consumption at 10.61 Mm^3/y before the year 2012 to irrigate Rhodes grass, and low economic returns of Rhodes grass [2,10], the government decided to convert three-quarters of Garziz farm area to residential areas as illustrated in Fig. 2. Presently, almost 75% of the former Garziz farm area has been converted to residential uses. Garziz farm which is owned by Dhofar Cattle Feed Company is illustrated in Fig. 2.

Simulation modeling of the impact of the reduction in groundwater recharge originating from the horizontal precipitation from the mountain indicated that the reduction of the tree cover would result in a significant impact on the aquifer sustainability [12]. The availability of the underflow recharge happens on annual basis operations intended for the mountains of the region and Salalah coastal plain, but the situations were threatened by the annual reduction of horizontal precipitation.

In places near the sea this phenomenon seawater intrusion (SWI) always happens as in the case of the Salalah coastal zone [13], because more than 1,500 wells were drilled to get groundwater for their houses and farms, the reason why SWI began to seep into the Salalah groundwater aquifer since 1993 [1,3,14,15].

Salalah central sewage treatment plant started its operation in 2003 providing 20,000 m^3/d treatment of municipal sewage until the tertiary stage and ended up with a chlorination process prior to the effluent output stage [3] and [16]. Fig. 2 illustrates the data of pumping rates utilized by both Garziz and Ministry of Agriculture and Fisheries of the Sultanate of Oman farms from the Salalah plain aquifer.

To halt salinity in the Salalah aquifer, Shammas [7] recommended the relocation of Garziz farm since they were accumulating 10.61 Mm^3/y pumps from those 13 wells for Rhodes grass cultivation since 2012. Presently, there are only 3 active pumping wells after the government decided to stop the operation of 10 wells to pump groundwater for Rhodes grass irrigation at approx. 2.26 Mm^3/y. This means that from 2012 to present, there is approx. 77% blocked pumps monitored and recorded at Garziz farm.

The present application of simulation is a sequel of the study and investigation conducted by Shammas [7], presented, and published by the same author, and proved that the injection method is effective in halting SWI. The present study assessed and measured once more the efficacy of the artificial recharge utilizing groundwater modeling in two scenarios. In the Sultanate of Oman, the volume of wastewater has been increasing rapidly in the last 30 years due to the increase in freshwater use for all domestic, industrial, and commercial purposes. Treated wastewater and sludge, which is a by-product of this treatment, can be resources under certain circumstances [17]. Related to this, the produced MTEs were able to meet the regulatory limits set by the Omani Standards except for some: nitrate, *Escherichia coli*, and the total suspended solids. Furthermore, it should be noted that the performance of Salalah and Darsait Sewage Treatment Plant can be classified as the best compared to the other four sewage treatment plants (STPs) studied in Oman as mentioned by the study of Baawain et al. [16].

A 3D flow and solute advection transport model were developed to assess the effectiveness of the proposed recharge scheme and tracked the solute transport with respect to the modern method/technique being utilized nowadays. The flow predicted the wedge along the saline intrusion and tracked up from the shoreline with the injection and without the injection for the period 2006 to 2020, respectively. The study simulated the predictive scenario vs. the real situation scenario in terms of water and salinity levels for the period 2006–2020. It was investigated and proven that the MTEs had increased the water levels at the vicinity of the injection line added to that, reducing the influence of saline inflows from the coastal areas. The former study Shammas [7] prediction is the act of forecasting what will happen in the future. Such actions manifested by the author were anchored by the prediction models that aim to quantify the effectiveness of the future based on a

Fig. 1. Location map of Garziz farm converted to residential areas. https://www.google.com/maps/search/garziz+farm/@17.0392622,54.1267529,3800m/data=!3m1!1e3

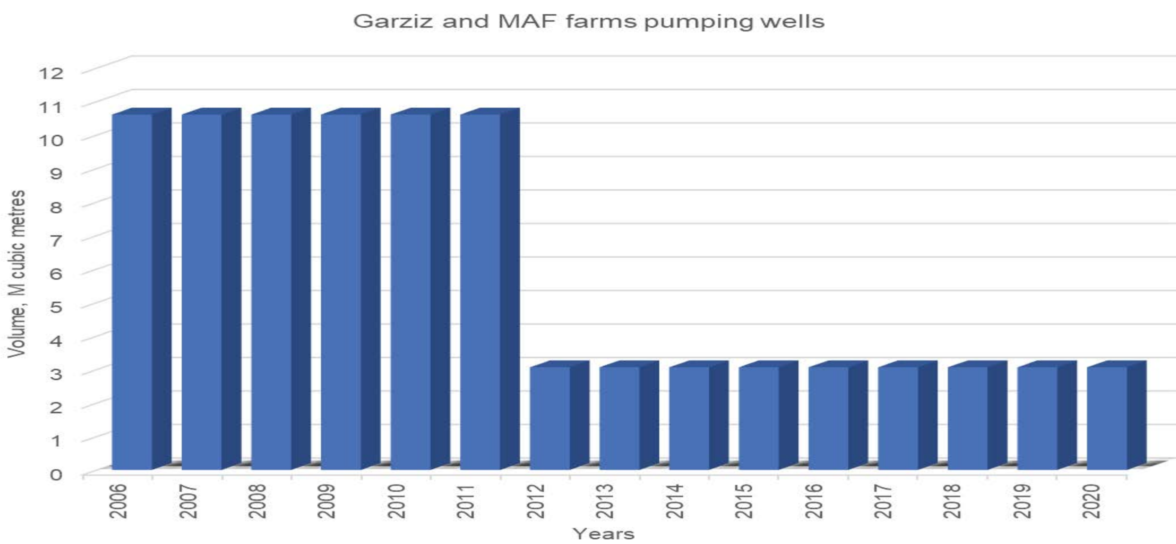

Fig. 2. Pumping rates of Garziz and Ministry of Agriculture and Fisheries of the Sultanate of Oman farms from Salalah plain aquifer.

set of predictors. Model scenarios are developed, validated, and updated to give importance to the effectiveness and sustainability of the artificial recharge. There is an urgent need for the best groundwater management technique to be used to combat the salinity. It is also prime and proper to investigate the plain aquifer hydrogeology flow system to determine if the artificial infiltration scheme is effective. It has been visualized by the investigator that the actual condition of the aquifer system and the prediction for the groundwater situation will be harmoniously balanced to halt SWI due to present and future abstraction simulation.

1.2. Salalah coastal aquifer

The plain aquifer is generally brackish, except for those areas where freshwater occurs in the central plain (<1,500 mg/L) and along the piedmont [18]. The main characteristics of this aquifer include saturated thickness typically 60–70 m with a maximum of about 120 m; very high transmission ranging from 1,000 to 200,000 m^3/d; high permeability associated with karstic features; and, hydraulic conductivity ranging between three orders of magnitude, from 10s to 1,000 s m/d. The natural annual recharge of the coastal well is approximately 50 MCM/y [10], with approximately 7.15 MCM/y of treated wastewater as reflected on Table 1. Groundwater table levels are constant in the plains area, ranging from 10 m above mean sea level near the mountain front to sea level near the coast. Given the unusually high transmission, groundwater level trends showed enough rising and declining trends as depletion in freshwater storage is rapidly replaced by adjacent brackish or seawater inflow. Given the experiences of salinity in Salalah plain with high vulnerability to SWI, wastewater treatment and injection project was established in 2003 [7].

In Salalah, coasts is about 20,000 m^3 of MTEs are injected daily to halt saline intrusion. Injection of MTEs into 40 boreholes is ongoing and still extended to a longitudinal distance of 12 km, considered a routine to discourage seawater intrusion. Table 1 displays the rate of artificial recharge conducted to treat effluents as revealed by Salalah Sewage Treatment Plant.

Table 1 reveals the variations of the injected volume of MTEs being injected from 2003 up to 2020. Such discrepancies were attributed to other transactions of agencies involved in the proceedings.

1.3. Objectives of the study

This follow-up investigation wanted to expose ground modeling scenarios utilized and developed by the author for salinity ingress of Salalah coastal aquifers towards sustainable groundwater through-flow [7,11,13], with the following objectives:

- To determine and compare the results of the predictive modeling scenario conducted in 2008 by the author is in harmony with the results of the current actual transient scenario for the same period of years 2006–2020.
- To apply MODFLOW, MT3DMS, and PMPATH numerical codes for the modeling simulation of artificial recharge via injection wells in the Salalah coastal aquifer.

Table 1
The artificial recharge rates of MTEs

Year conducted	Through flow to wells (million m^3)
2003	2
2004	2.43
2005	4.95
2006	1.74
2007	2.35
2008	2.54
2009	2.58
2010	2.42
2011	2.54
2012	2.6
2013	1.76
2014	1.6
2015	2.05
2016	4.56
2017	6.66
2018	2.27
2019	5.32
2020	7.15

- To study the efficacy of the artificial groundwater recharge by MTEs on halting SWI in the Salalah coastal aquifer.

1.4. The problem

The primary aquifers in terms of agricultural and municipal utilization are the shallow coastal aquifers that receive modern recharge from the mountain flowage, direct recharge from intense precipitation events, and indirect recharge through riverbeds infiltration [18]. One of the main challenges in coastal aquifers is how to provide the short-term water demand through abstraction from the coastal aquifers while maintaining their long-term water balance. Increased extraction of groundwater and reduction of flow towards the coast of Salalah has caused the saltwater interface to move inland. Apparently, the water increases due to the unbalanced allocation of water in the aquifers. In this situation, seawater intrusion is expected to increase causing serious problems to Salalah's domestic, industrial, and agricultural purposes. There was a pond injection project proposed before by Shammas [3] to combat this alarming situation way back in 1998, but due to permeable aquifer conditions, well injection was preferred, and the injection scheme had started in April 2003 [7].

However, the injection process continued with the 9.38 Mm^3 being injected till the end of 2005. This was found not sufficient to balance the Salalah aquifer [10]. Since there is a strong need for agricultural expansion beyond traditionally cultivated coastal plains, the situation led to the increased utilization of the aquifer. Presently, the region is experiencing desertification due to overgrazing in the Jabal area along the Dhofar mountains. Knowingly, this vast vegetation is important to recharge the underground reserves since this is supporting the water position in the Salalah plain [12]. There is a strong need for the implementation of policies that will protect the groundwater of Jabal as it contributes 98% of the Salalah aquifer recharge [12]. A policy to stop desertification in the Dhofar Region is very essential to protect the remains of the Jabal's unique biodiversity and to enhance the groundwater recharge for the Salalah aquifer [12].

In addition, it is essential to enhance the vegetation coverage at Jabal. The application of reforestation programs are possible measures to sustain the remaining natural rangelands. Tree planting should be given full attention to increasing fog water interception since this will benefit grassland production and increase groundwater recharge of the Salalah aquifer [12]. The importance of implementing fog water collection is crucial in this situation. This is the foremost reason why the author was prompted to conduct a follow-up investigation on the water levels and cross-check the effectiveness of artificial recharge set and discussed in the previous results and findings with comparison to the current actual results during the same time. The present investigation deals with the concrete balance between aquifer recharge and abstraction presented in two modflows and solute transport scenarios.

1.5. Review of the pilot scheme for the injection of treated wastewater

Salalah Central Sewage Treatment Plant (STP) started its operation in 2003 for the purpose of receiving and treating 20,000 m^3/d of Salalah's wastewater [7]. STP expansion of sewage influents treatment with a maximum of 50,000 m^3/d had been completed in 2018. The current amount of the MTEs that are being injected is about 40% of the total MTEs were injected into constructed boreholes situated parallel to Salalah coastline that extends until Al Muntazah Street and reduced from 90% of the MTEs that were being injected before [7]. The remaining balance has been discharged to Raysut Cement Factory, Bir Bint Ahmed Farm, and other related stakeholders. Injection of MTEs was started in the city of Salalah in 2003 through pipelines with 40 injection boreholes and 40 observation bores located along the coastal zone in distances of 1.5 to 2 km from the shoreline [7]. The injection bores are located 300 m apart from each other starting from west to east along the Salalah coastal agricultural strip [7] to monitor the groundwater levels and quality pertaining to total dissolved solids (TDS).

1.6. Importance of periodic modeling method for the MTEs in Salalah plain aquifer

In the last study of the effectiveness of the injection method, several salient ideas came up that triggered the author to continue what he started to halt SWI in the coastal aquifer. Groundwater depletion has become a critical issue that threatened water supplies for farmers and other users that resulted to rapidly progressing saltwater intrusion. Artificial groundwater recharge from then till present is the most direct way to address groundwater depletion with recycled water through injection well. The injection method stabilized the water levels and even reduced the SWI along the injection scope [7]. Artificial recharge was utilized to raise groundwater levels, prevent SWI, supplement water supplies, and remain in long-term storage for future use or drought mitigation [19]. The abstraction from the aquifer has been controlled and the quality of the water has been maintained according to Omani Standards OS 08/2012. The data gathered supported the results of the modeling scenarios that prompted the increase of water levels [7]. The injection method would not be effective unless there was controlled pumping of artificial water coming from both eastern and western parts of the coastal areas. The injection well with MTEs located in the central part of the Salalah coast was more effective than the central plain of Salalah due to higher permeability that supported the flushing and transporting of the underflow combined with the injected fluids towards the coast [7].

1.7. MTEs of water as an efficient measure to control SWI in Salalah aquifer

Groundwater recharge with MTEs is an attractive option for many reasons. It is more publicly acceptable than direct potable reuse because of the psychological value of the environmental buffer. Several analyses had been conducted

Fig. 3. (a) Collection tank of treated wastewater is located in Raysut area of Salalah City. (b) The injection borehole (in yellow color) serves as an observation well located along Salalah coastal plain (Fig. 3a and b after [7]).

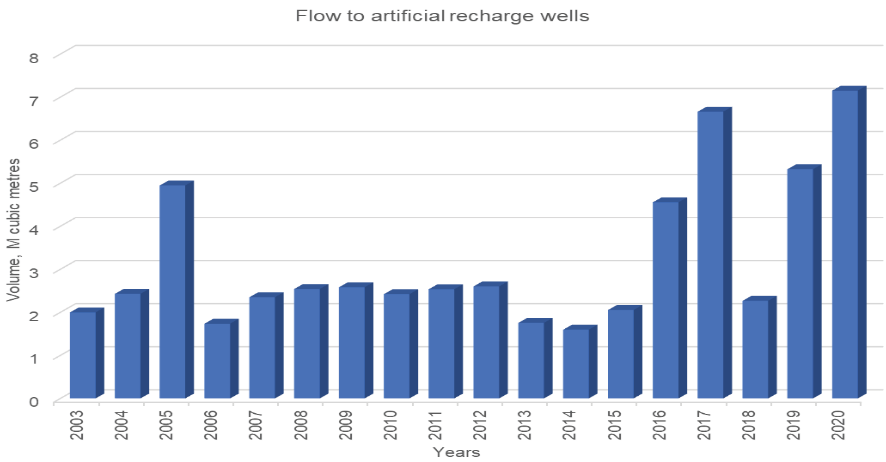

Fig. 4. Artificial recharge rates of MTEs from the Salalah Central STP.

to determine the positive potential of utilizing artificial recharge in the repulsion of SWI by means of experimental, analytical, periodic, predictive, and numerical modeling. Expounding on these scenarios are the piloting of several surface reservoirs to alter recharge systems like lakes, canals, and other spreading recharge possible to recharge unconfined aquifer systems through infiltration of collected water [20]. Illustrated in Fig. 4 are the artificial recharge rates of MTEs from the Salalah Central STP.

Similar to the findings of the study on the effects of a large dam in the retardation of SWI in Al Khoud, Muscat Oman, conducted by Abdalla and Al-Rawahi [21] it was found out that the artificial recharge of water is an efficient measure to control SWI and elevate the groundwater levels. By transporting river water to inner lakes through a pre-constructed canal, an integrated methodology for the future sustainability of the flow system had been developed. The study of Shammas [7] & Abdalla and Al-Rawahi [21] identified that the cost of providing high quality or desalinated water for recharging purposes is a challenge that the recharge barriers are facing. This strong notion prompted the author to monitor completely on placing renewable sources of water, such as MTEs as the sources of recharge for seawater intrusion mitigation. The utilization of MTEs for common utility sectors or artificial storage in subsurface layers could sustain the water demands and protect the system against SWI in Salalah coastal aquifer [7].

1.8. MTEs direct injection procedure

Salalah Sanitary Drainage Services Company (SSDSco) utilizes a biological treatment system, known as an activated sludge process, to achieve tertiary treatment. The quantities of MTEs projected in the investigation of Shammas [7], which are available for reuse is about 6.6, 8.6, and 10 MCM for 2006, 2015, and 2020, respectively. These quantities are sufficient to irrigate between 273, 356 and 414 Ha, respectively, of net water demand 24,170 m^3/ha/y as assumed by Geo-Resources Consultancy [4]. Whereas the actual MTEs injected were about 1.7, 2, and 7 MCM for 2006, 2015, and 2020, respectively (Fig. 4). Direct injection has been found effective in which recycled municipal wastewater has undergone tertiary treatment. They are injected directly into the groundwater aquifer via injection wells [7]. The water is then mixed with the groundwater and remains in the groundwater aquifer until it is pumped out for use. During the operation, the injection wells directly prevent SWI by acting as a hydraulic barrier. To form a hydraulic barrier, injection wells are lined up along the divide between saltwater and freshwater, and the injected freshwater takes up the space that the saltwater would otherwise encroach on. Shammas [7] investigation proves that direct injection of MTEs entails injecting high-quality MTEs into a confined groundwater aquifer.

Currently, Dhofar Municipality is utilizing 9,000 m^3/d (3.3 m^3/y) of the MTEs for irrigation of green landscapes at Salalah City. The use of MTEs on amenity plantings and water conservation measures are also considered appropriate instead of pumping this quantity directly from the Salalah aquifer.

2. Materials and method

A modeling scheme of 3D flow groundwater simulation model using MODFLOW [22] was utilized in this study under constant underflow. Solute transport predictive modeling was carried out in Salalah plain aquifer using MT3DMS [23] under constant underflow representing a mass transport simulation model and PMPATH was used for the advection transport. Predictive simulation and current actual transient simulation of the aquifer were carried out for the 2006–2020 years under constant underflow to predict the behavior of the aquifer under the injecting MTEs method. The baseline scenario assumes that underflow is constant through the predictive and current actual transient period.

The underflow was derived from the developed numerical groundwater flow modeling and calibration with hydraulic heads of 1992. The underflow from the Jabal was derived from the developed steady-state flow model at 50 Mm^3 [12].

The main argument of the present investigation is to determine whether the results of the predictive modeling scenario conducted in 2008 are congruent to the results of the current actual transient scenario for the same period of years 2006–2020. In the present study, both the predictive scenario and the actual/current transient scenario were modeled and simulated during the same period of 2006–2020 years under constant underflow. In this paper, the Salalah plain aquifer has been divided into three saturated layers [7]. The first layer was allocated for irrigation of coastal agricultural farms, the second layer for Garziz farm and Salalah wellfield wells. The direct injection of MTEs at 48 m depth below ground surface is taking place in the coastal agricultural zone, which has direct contact with the third layer of the same aquifer that is pumping from far inland area for potable water especially Saada wellfield which is located at distance almost 11 km inland from injection bores.

3. Results and discussions

The results of the predictive scenarios in the previous investigation of Shammas [7] are presented, discussed, and compared accordingly with the results of the current actual transient scenarios. The advection transport model predicted that in 2020 the maximum path lines of the injection fluids would reach the abstraction wells that are located approximately 1 km, southward of the injection bores in a year's travel time. The developed flow showed that the wedge of the SWI in 2020 would be tracked up to 2 km and less than 500 m from the shoreline under the predictive scenario and current actual transient scenario, respectively under constant underflow, especially at the middle of the injection boreholes of the aquifer.

3.1. Potentiometric heads result under constant underflow

Currently (2020) the injection method is effective in pushing back the saline zone front by 1 km. towards the sea. The investigation of the application of the injection method helped increase the water levels and reduced groundwater salinity (TDS) at the vicinity of the injection bores. The schematic figures below explained the results of the predictive modeling scenarios. In Fig. 5, water levels at 0.5 m amsl reached Garziz farm site approx. 4 km inland. The water levels at the coastal agriculture strip which is located between 500 m and 2 km distance from the shoreline are less than 0.5 m amsl.

In Fig. 6, the water levels in 2005 during the current transient model were illustrated. This shows that water levels at 0.5 m amsl reached Garziz farm site at approx. 5 km inland. The water levels at the coastal agriculture strip are less than 0.4 m amsl. At the east and west of the coastal agricultural strip the water levels were recorded at levels little more than 0 m amsl.

Meanwhile, in Fig. 7, the water levels in 2005 during the current transient model has been presented and compared. It shows that the water levels at 0.5 m amsl reached Garziz farm site at approx. 5 km inland. The water levels at the coastal agriculture strip are less than 0.4 m amsl. At the east and west of the coastal agricultural strip the water levels were recorded at levels little more than 0 m amsl.

In Fig. 8, the water levels at 0.5 m amsl reached areas behind Garziz farm site at approx. 5 km inland. The water levels at the coastal agriculture are less than 0.2 m amsl as shown below.

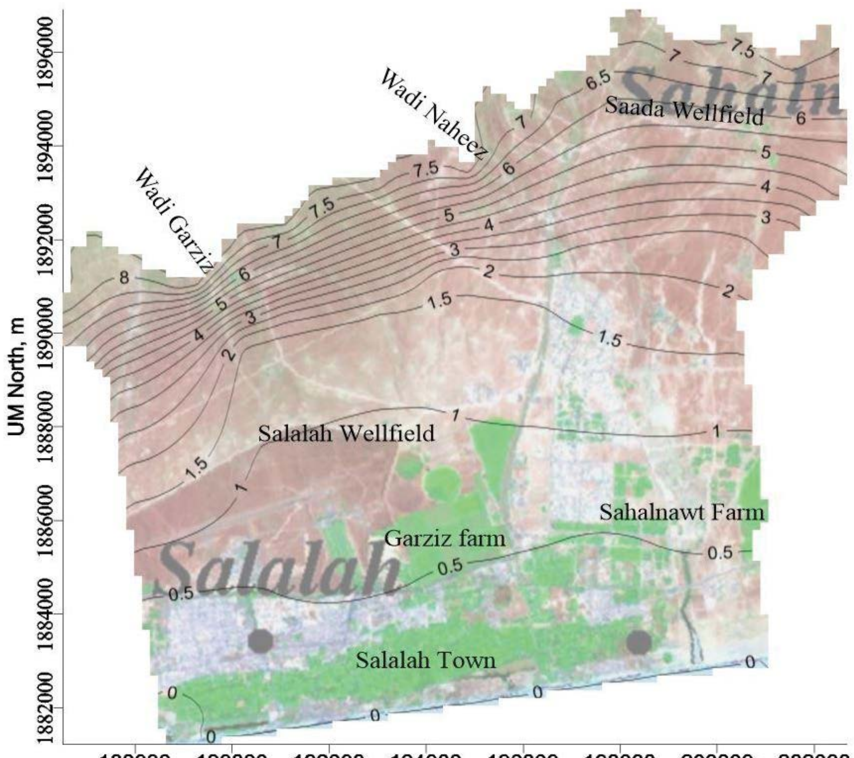

Fig. 5. Schematic diagram of water levels (m) with injection period 8-year 2000, current transient scenario.

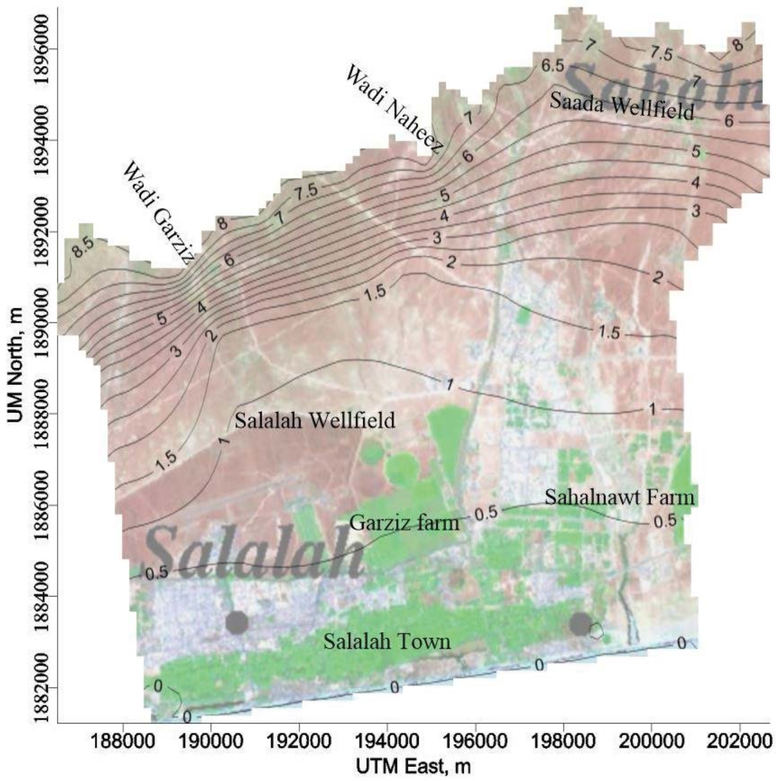

Fig. 6. Schematic diagram of water levels (m) with injection period 13-year 2005, current transient scenario.

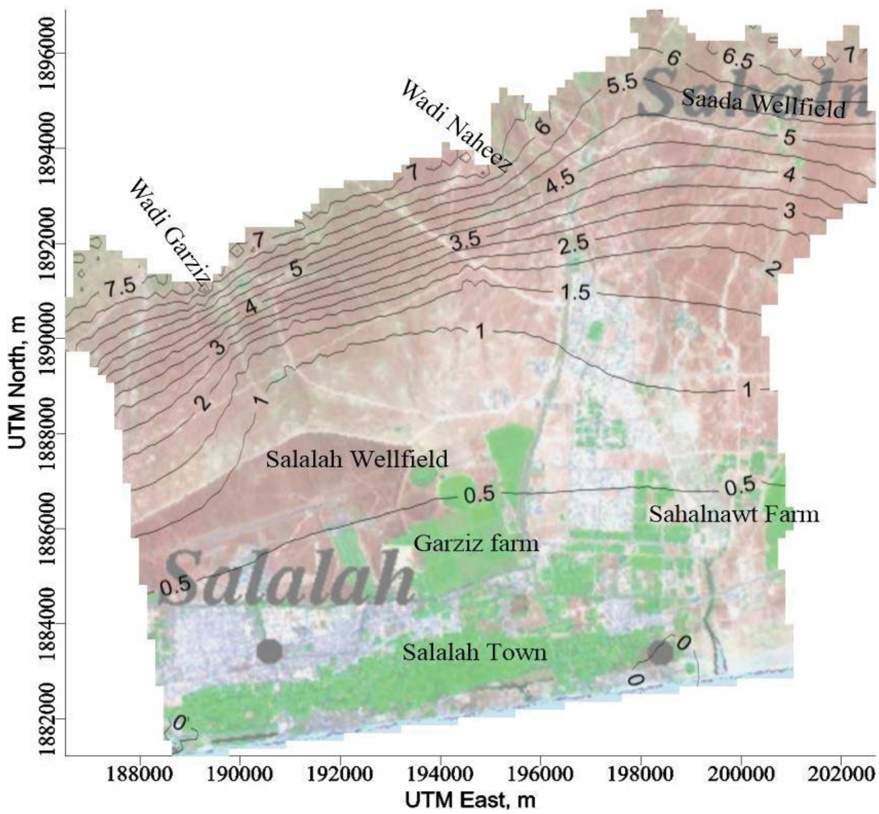

Fig. 7. Schematic diagram of water levels (m) with injection period 18-year 2010 with injection, predictive scenario.

Fig. 8 illustrates the water levels in 2010 during the current transient period. This explains that the water levels at 0.5 m amsl reached areas far behind Garziz farm site and reached Salalah wellfield areas at approx. 6 km inland. The water levels at the center of the coastal agriculture strip are less than 0.1 m amsl. At the east and west of the coastal agricultural strip, the water levels were recorded at 0 m amsl.

Fig. 9 shows the water levels in 2015 during the predictive transient. Fig. 9 explains that the water levels at 0.5 m amsl reached areas far inland and reached Salalah wellfield areas at approx. 7 km inland. The water levels at the center of the coastal agriculture strip are less than 0.1 m amsl. At the east and west of the coastal agricultural strip, the water levels were recorded at 0 m amsl.

Moreover, the above illustration, Fig. 10 illustrates the water levels in 2015 during the current transient period. It explains that the water levels at 0.5 m amsl reached Garziz farm site, at approx. 5 km inland. The water levels at the center of the coastal agriculture strip are less than 0.5 m amsl. At the east and west of the coastal agricultural strip, the water levels were recorded at 0 m amsl. To compare the predictive scenario with the current transient scenario during this period, it has been found that the water levels increased in the current transient scenario as compared with the predictive scenario during the same period. The results were compared based on the results of groundwater pumping reduction from the Salalah wellfield and Garziz farms.

Fig. 11 shows the water levels in 2020 during the predictive transient. Fig. 11 explains that the water levels at 0.5 m amsl reached areas far inland behind Salalah wellfield areas at approx. 8 km inland. The water levels at the center of the coastal agriculture strip are less than 0.05 m amsl. At the east and west of the coastal agricultural strip, the water levels were recorded at 0 m amsl.

The water levels in 2020 during the current transient period have been taken too and compared as shown in Fig. 12 where the water levels at 0.5 m amsl reached the areas under Garziz farm site, at approx. 4 km inland. The water levels at the center of the coastal agriculture strip are less than 0.5 m amsl. At the east and west of the coastal agricultural strip, the water levels were recorded at 0.02 m amsl. To compare the predictive scenario with the current transient scenario in this periodic modeling, it was revealed that the results of water levels had increased in the current transient scenario as compared with the predictive scenario during the same period. The comparison has been elicited by means of groundwater pumping reduction from Salalah wellfield and Garziz farm.

3.2. Solute transport results under constant underflow

Fig. 13 shows that the salinity levels (TDS, mg/L) located at the center of the coastal agricultural strip of Salalah City accumulates 2,000 mg/L whereas along the eastern and western parts of the city, the TDS level exceeds 4,000 mg/L. This clearly explains that there was seawater intrusion as proven by the 10,000 mg/L excess in the majority areas of Salalah City with distances of 500 m from the base shoreline.

In Fig. 14 the salinity levels (TDS, mg/L) located at the center of the coastal agricultural strip of Salalah City is

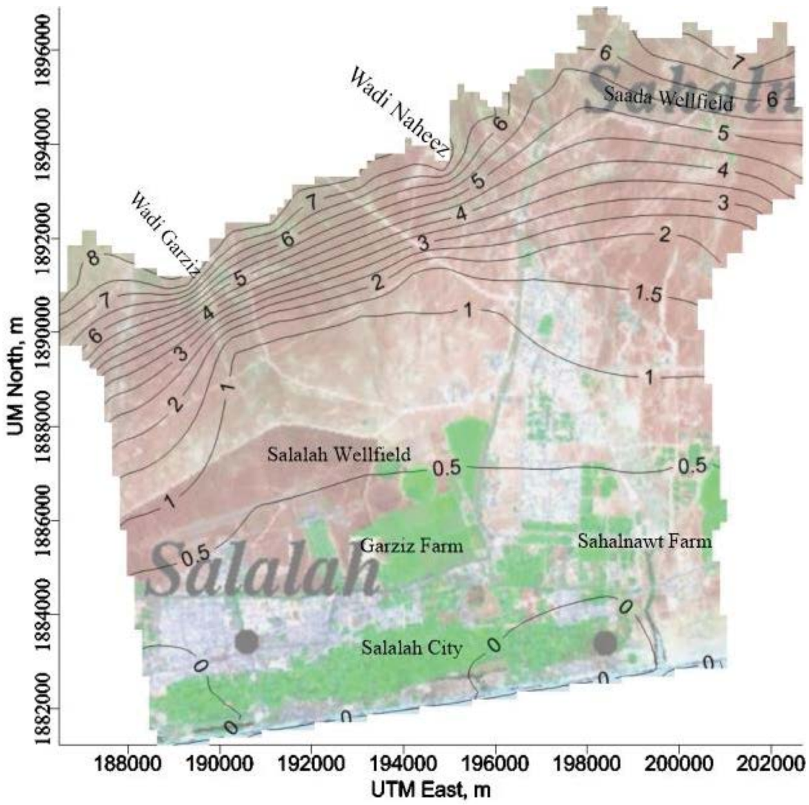

Fig. 8. Schematic diagram of water levels (m) with injection period 18-year 2010, current transient model.

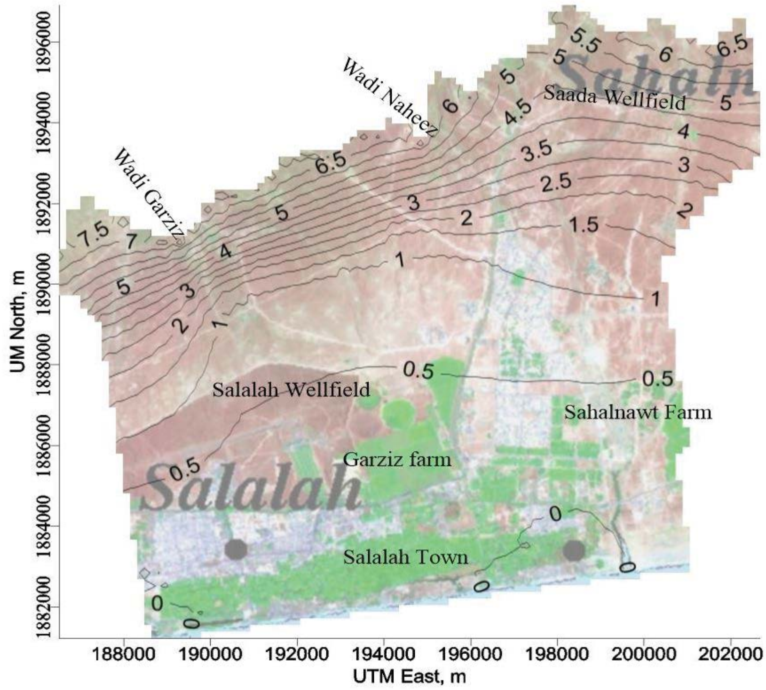

Fig. 9. Schematic diagram of WL baseline sc a p23 – 2015 with injection, predictive scenario.

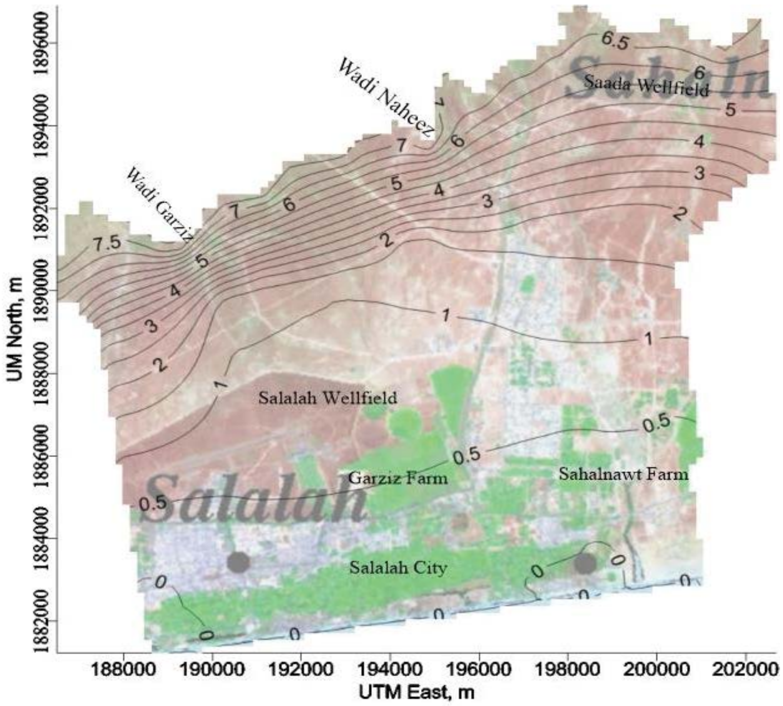

Fig. 10. Schematic diagram of water levels (m) with injection in layer 1 period 23 – year 2015, current transient scenario.

slightly higher than 2,000 mg/L that was accumulated in Fig. 13. It is clearly seen that along the eastern and western parts of the strip is an excess of 5,000 mg/L TDS. Seawater intrusion is obvious, and TDS exceeded 10,000 mg/L in most of the areas at distances 500 m from the shoreline.

In Fig. 15 the salinity levels (TDS, mg/L) at the center of the coastal agricultural strip (Salalah City) are within 2,000 mg/L whereas at the east and west parts of this strip, the TDS exceeded 4,000 mg/L. Similarly, there is a presence of seawater intrusion since the level of TDS exceeded

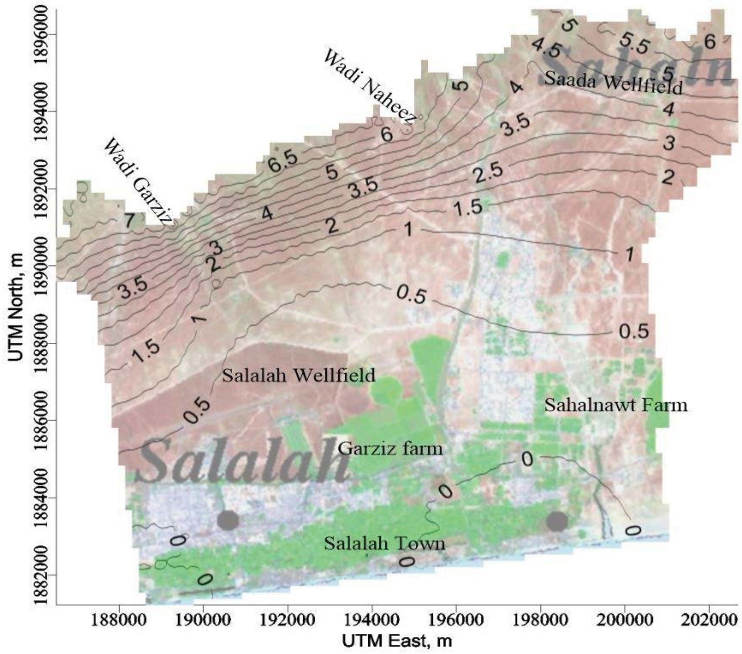

Fig. 11. Schematic diagram of water levels (m) period 28 – year 2020 with injection, predictive scenario.

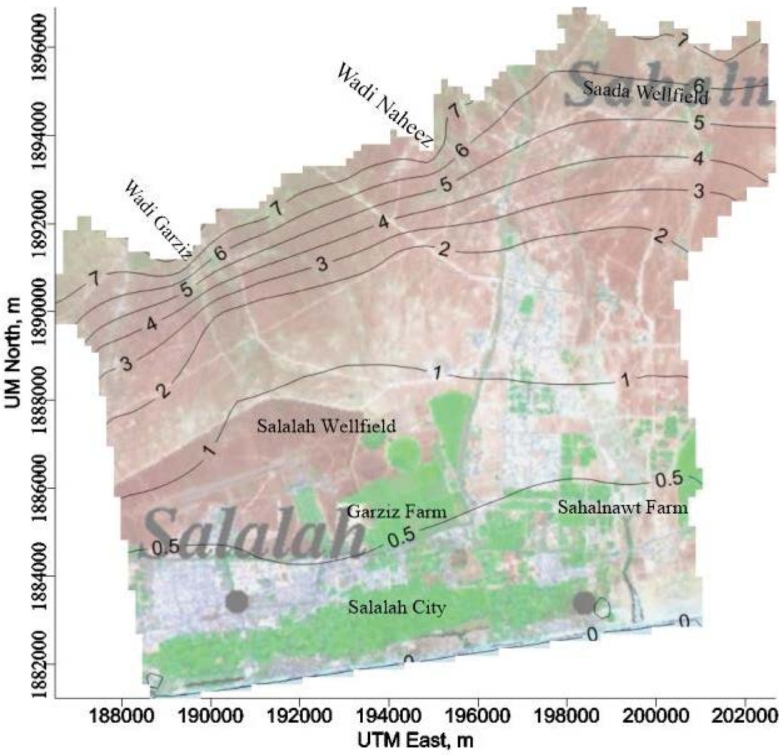

Fig. 12. Schematic diagram of water levels (m) with injection at year 2020, current transient scenario.

10,000 mg/L in most of the areas of Salalah City with distances 500 m from the shoreline.

In Fig. 16 the salinity levels (TDS, mg/L) which were found located at the center of the coastal agricultural strip in Salalah City is within 2,000 mg/L while on the eastern and western parts of the of the strip, the TDS exceeded 4,000 mg/L. This clearly implies the ingress of seawater intrusion as it exceeds 10,000 mg/L in most areas with distances 500 m from the shoreline. This figure shows that the TDS levels reached 2,000 mg/L at along the injection route

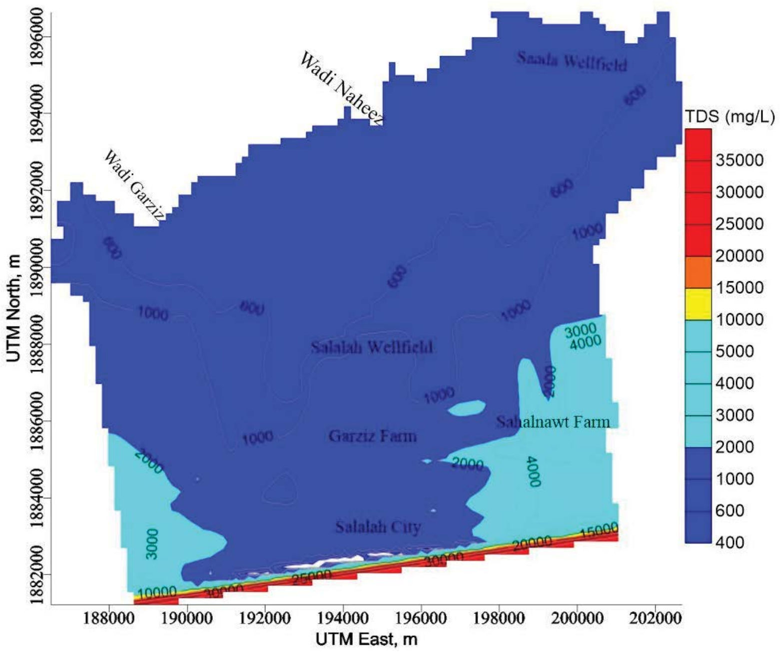

Fig. 13. Schematic diagram of TDS (mg/L) with injection in the year 2000, current transient scenario.

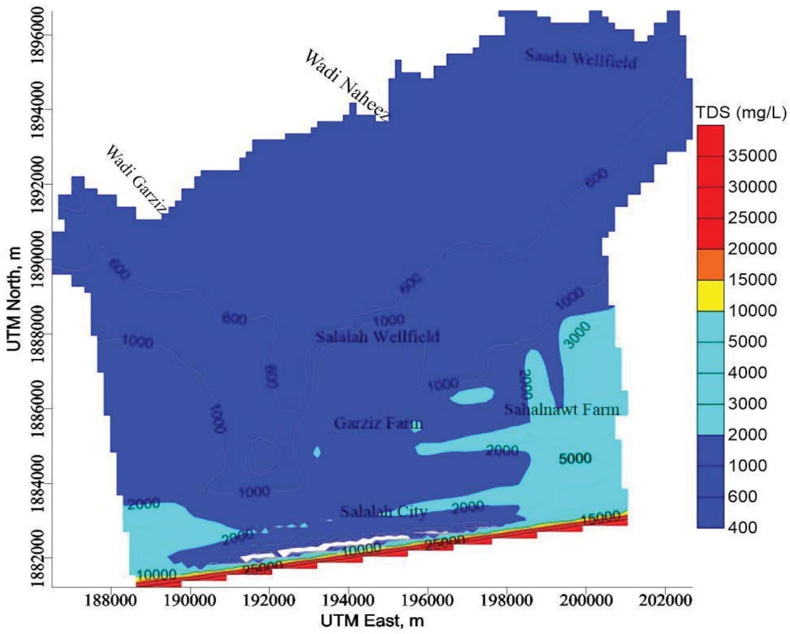

Fig. 14. Schematic diagram of TDS (mg/L) with injection in the year 2005, current transient scenario.

lines which are located at 1.5 km from the shoreline, which means that the injection by MTEs pushes back the saline intrusion.

Meanwhile, Fig. 17 explains that the salinity levels (TDS, mg/L) located at the center of the coastal agricultural strip of Salalah City is within 2,000 mg/L. It has been found also that along the eastern and western parts of this strip, the TDS exceeded 4,000 mg/L. This is another implication of the presence of SWI since the level exceeds 10,000 mg/L at most of the areas at distances 500 m from the shoreline. This figure shows that the TDS levels reached 3,000 mg/L along the injection route lines which are located at 1.5 km from the shoreline, which means that the injection by MTEs pushes back the saline intrusion.

In Fig. 18 the salinity levels (TDS, mg/L) located at the center of the coastal agricultural strip (Salalah City) is within 2,000 mg/L whereas, at eastern and western parts of this strip, the TDS exceeded 3,000 mg/L. Seawater intrusion

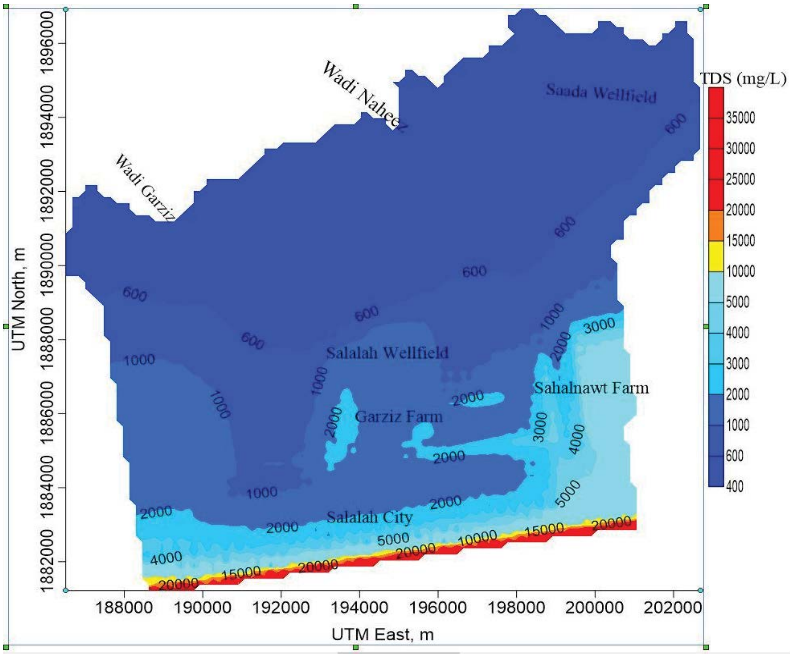

Fig. 15. Schematic diagram of TDS (mg/L) with injection in the year 2010, predictive scenario.

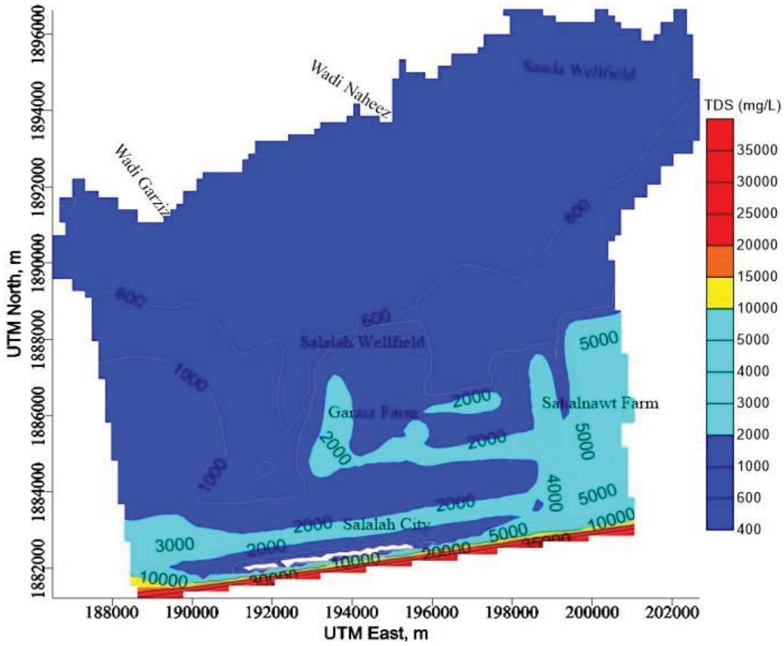

Fig. 16. Schematic diagram of TDS (mg/L) with injection in the year 2010, current transient scenario.

is obvious and TDS exceeded 10,000 mg/L at most of the areas at distances 500 m from the shoreline. This figure shows that the TDS levels reached 2,000 mg/L at along the injection route lines which are located at 1.5 km from the shoreline, which means that the injection by MTEs pushes back the saline intrusion.

To compare the predictive scenario vs. the current transient scenario, the solute transport modeling shows that salinity results decreased during the current transient scenario as compared to the predictive scenario during the same periods. These resulted to groundwater pumping reduction from Salalah wellfield and Garziz farms.

The salinity levels (TDS, mg/L) in Fig. 19 located at the center of the coastal agricultural strip (Salalah City) is within 3,000 mg/L while along the eastern and western parts, the TDS exceeded 4,000 mg/L. Seawater intrusion is obvious and TDS exceeded 10,000 mg/L at most of the areas inland at distances 500 m from the shoreline. This figure

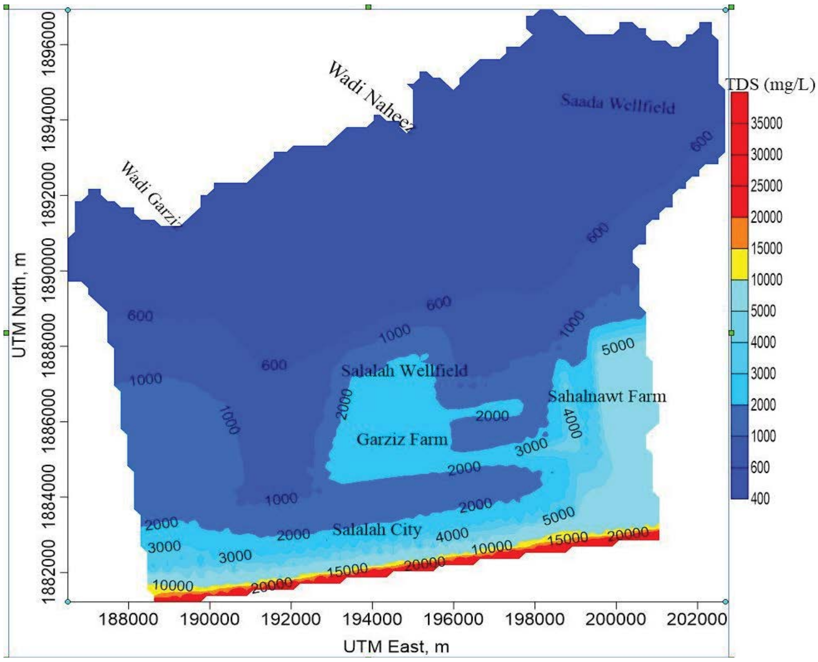

Fig. 17. Schematic diagram of TDS (mg/L) with injection in the year 2015, predictive scenario.

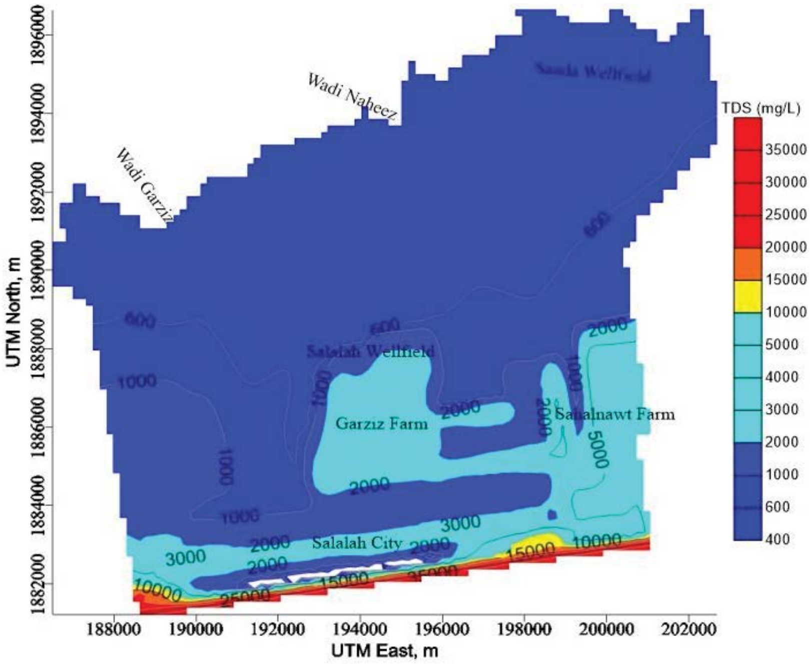

Fig. 18. Schematic diagram of TDS (mg/L) with injection in the year 2015, current transient scenario.

shows that the TDS levels reached 3,000 mg/L at areas along the injection route lines which is located at 1.5 km from the shoreline, which means that the injection by MTEs pushes back the saline intrusion.

In Fig. 20 the salinity levels (TDS, mg/L) located at the center of the coastal agricultural strip (Salalah City) is within 2,000 mg/L whereas, at east and west parts of this strip, the TDS exceeded 3,000 mg/L. Seawater intrusion is obvious and TDS exceeded 10,000 mg/L at most of the areas at distances 500 m from the shoreline. This figure shows that the TDS levels reached 2,000 mg/L at areas along the injection route lines which is located at 1.5 km from the shoreline, which means that the injection by MTEs pushes back the saline intrusion.

To compare the predictive scenario with the current transient scenario at this period, the solute transport levels show that salinity results were decreased in the current transient scenario as compared with the predictive scenario

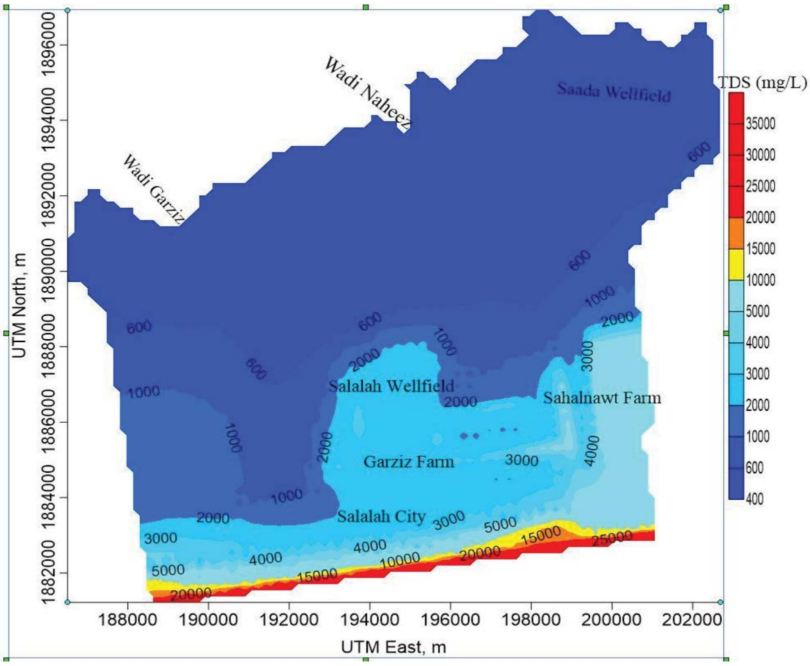

Fig. 19. Schematic diagram of TDS (mg/L) with injection in the year 2020, predictive scenario.

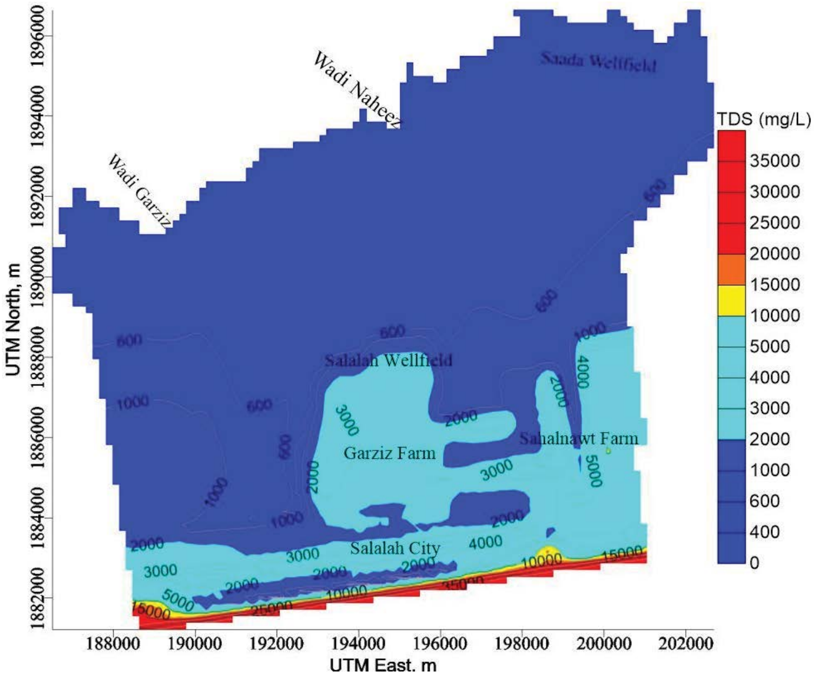

Fig. 20. Schematic diagram of TDS (mg/L) with injection in the year 2020, current transient scenario.

during the same period as a result of groundwater pumping reduction from the Salalah wellfield and Garziz farm.

3.3. Advection transport results under constant underflow

Fig. 21 shows the effectiveness of the injection method in combating SWI in 2020 under predictive scenario as revealed with no-management interference compared to Fig. 22 under current transient scenario with management interference. In Fig. 21, the solute transport of the injected MTEs could travel almost 500 m downstream in just one year by using PMPATH (advection transport) compared to the current transient scenario (Fig. 22), where the path lines could travel more than 1.2 km downstream of the injection lines in about one year.

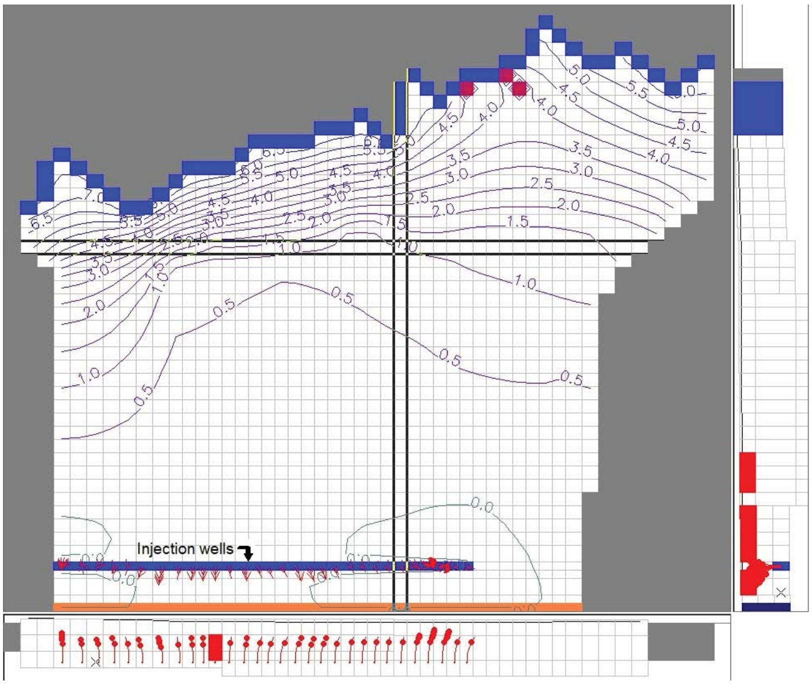

Fig. 21. PMPATH results of one-year simulation time, with the injection in 2020, predictive scenario.

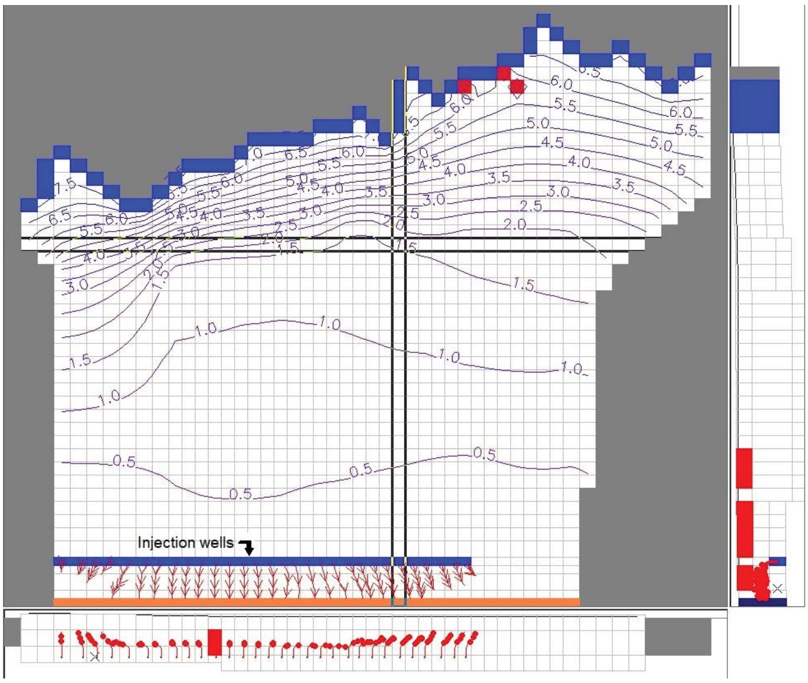

Fig. 22. PMPATH results of one-year simulation time, with the injection in 2020, current transient scenario.

3.4. Conclusion and recommendations

The injection scheme of the MTEs in the Salalah plain aquifer stabilized the water levels and reduced the salinity (TDS) along the injection lines. The abstraction from the aquifer has been able to manage about 77% of pumping rates of the wells that are operating at Garziz farm considerably blocked since 2012 until the present. In addition, the abstraction from the Salalah wellfield was reduced by more than 60% in 2020 as reverse osmosis technology facility started to operate concurrently producing 25.2 Mm^3/y of water since the year 2013.

From the results of the investigation conducted by Shammas [7] and the present investigation also conducted by Shammas, it has been found that the direct injection method conducted along the eastern and western edges of the Salalah coastal aquifer was found less successful as compared to the injection procedure conducted in the middle of the injection boreholes of the aquifer. Those manifestations were attributed to the slow movement of underflow recharges in the edges of the aquifer along with the fast movement of saline intrusion. To compare the predictive scenario with the current actual transient scenario, the solute transport shows that TDS results decreased in current transient scenario as compared with predictive scenario during the same period. Such manifestations could be attributed to the decrease of groundwater pumping that was being held from the Salalah wellfield and Garziz farm.

The following are strongly recommended for the sustainable management of the coastal aquifer:

- Since it was observed that there was weak subsurface flow, this study recommends refraining from injection procedures, instead, to allocate the rate of injection among other boreholes.
- It was observed, too that the middle boreholes of the coastal aquifer are found to be significantly effective for direct injection.
- Similar to the 2008 recommendation of the author, Garziz farm should be relocated since they are pumping 8 Mm^3/y from 13 wells for the cultivation of Rhodes grass. Since 2012, 10 wells were closed in Garziz farm, which means only 3 wells remain pumping groundwater at almost approx. 2.26 Mm^3/y. The implication that 77% of the pumping rates were blocked from 2012 to the present would definitely be helpful to the coastal aquifer.
- The expansion of the STP also took place and the central STP currently (2020) treats more than 50,000 m^3/d effluents to a tertiary level, of which only 40% of MTEs outputs were used (2020) for artificial recharge.
- Increase the injection rates by at least 80% of the total MTEs outputs daily. This study recommends reusing more than 80% of MTEs into injection bores. These processes can be considered as an effective integrated water resource management method for Salalah coastal aquifer.
- The quality and quantity of the MTEs, the depth of the injection bores, cost, and the source of providing the high quality of MTEs are the factors that should be taken into consideration in constructing an artificial recharge system.
- It is a fact that utilizing desalinated seawater is costly, thus, the application of MTEs can be alternate reliable water management having low cost but higher environmental benefits.

Acknowledgments

The author expresses his appreciation of thanks to the Proprietor & CEO of AAE for funding this research study.

List of notation

SWI	—	Seawater intrusion
MECA	—	Ministry of Environment and Climate Affairs
PAEW	—	Public Authority for Electricity and Water
DCFC	—	Dhofar Cattle Feed Company
DGEWRDG	—	Directorate General of Environment and Water Resources in Dhofar Governorate, MRMEWR
DWR	—	Department of Water Resources Affairs in the DGEWRDG
EC	—	Electrical conductivity
FAO	—	Food and Agriculture Organisation of the United Nations
GDP	—	Gross domestic product
GIS	—	Global information system
MTEs	—	Municipal treated effluents
m amsl	—	Metres above mean sea level
mg/L	—	Milligrams per litre
mm/d	—	Millimetres per day
Mm^3	—	Million cubic metres
μS/cm	—	Micro Siemens/cm, a measure of electrical conductivity (EC)
MAF	—	Ministry of Agriculture and Fisheries of the Sultanate of Oman
MRMEWR	—	Ministry of Regional Municipalities, Environment and Water Resources of the Sultanate of Oman
MWR	—	(Former) Ministry of Water Resources of the Sultanate of Oman
NWD	—	Net water demand
NWI	—	National wells inventory
PCDESR	—	Planning Committee for Development and Environment of the Southern Region, Sultanate of Oman
PD-GIS	—	Planning Department-Geographic Information System Section for MRMEWR
SSDSCo	—	Salalah Sanitary Drainage Services Company
STP	—	Sewage treatment plant
TDS	—	Total dissolved solids
Ha	—	Hectare
MCM	—	Million cubic metres
Jabal	—	Mountain
IWPP	—	Independent water and power plant
OS	—	Omani Standards

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Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2022.28236

263 (2022) 248–256
July

Equilibrium states of groundwater chemistry in coastal region of Kuwait

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Received 28 February 2022; Accepted 17 May 2022

ABSTRACT

Groundwater samples were collected along the coastal region of Kuwait to determine the geochemical nature of the ions and their thermodynamic states. The state of thermodynamic equilibrium predicts the nature of the reaction in the aquifer. The geochemical nature was determined by standard plots and ion ratios. The geochemical results of the groundwater samples were then studied with stability plots for silicate and carbonate equilibrium and later they were compared with the saturation states with the aid of geochemical model (PHREEQC). The samples reflect higher electrical conductivity values with greater values of Na and Cl ranging from brackish to hypersaline nature. The silicate stability plots with respect to major cations reflect that the samples were stable with respect to K-feldspar and kaolinite composition. The carbonate stability plots reflect the stability of the composition predominantly with respect to calcite and dolomite fields. Subsequently, the saturation states of silicates and the carbonate minerals were determined by using PHREEQC. The saturation index values indicate these samples were consistent with the observations made by plotting in the stability plots with minor variations. Though lithology plays a critical role the minor variations were mainly due to the consideration of temperature and the impact of the associated ionic species in the model. The variations were more significant in the carbonate mineral saturation as carbonates react and attain saturation faster than the silicate minerals. The study also infers that the "Common Ion Effect" governs the saturation of these carbonate minerals. Hence, the study reveals the fact that the carbonate minerals are more saturated than the silicate minerals in the groundwater and it is mainly governed by the lithology of the associated ions.

Keywords: Hydrogeochemistry; Stability plots; Saturation states; PHREEQC

1. Introduction

Coastal groundwater is a fragile environment acting as a buffer between a fresh and saline aquatic water bodies. In general coastal groundwater is brackish to saline in nature, especially in arid regions. In certain regions they are hyper-saline to acidic hyper saline in nature [1,2]. The geochemical nature of the coastal groundwater are generally affected by numerous factors like coastal land use [3–5], seawater intrusion [6,7], variation in the inflow of the river water [8], Submarine groundwater discharge [9,10], tidal influx [11,12], backwaters, lagoon and other coastal surface water bodies [13]. In a multi-layered aquifer system the shallow aquifers are predominantly saline in nature [14,15]. The variation in lithology also governs the geochemistry of the coastal waters [16]. The brackish groundwater of the arid region is utilized for the various domestic and industrial purposes [17–19]. The geochemical variation in these waters may affect the utility. The normal variation in temperature triggers the change in pH apart from the nature of the host rock interaction and anthropogenic factors [20]. This change affects the thermodynamic states of ions and thereby alters their mobility and availability for reaction [21,22]. There are several computer aided programs like SOLMINQ, PHREEQC, WATEQ4F, EQNR3, etc., to determine the thermodynamic states of water. They calculate

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the ionic strength and the saturation states of water with respect to definite pressure, temperature, and concentration. Further, the shift in equilibrium governs the concentration of the resultant water and thereby changes in the state of equilibrium. Such hypothetical conditions by varying the temperature or external conditions can be simulated to understand the possible geochemical nature. The software CHIDAM and WATCLAST can plot the thermodynamic states for silicate minerals with respect to cations and silica in groundwater [23,24]. Coastal groundwater of Kuwait vary spatially with respect to their interaction with lithology, open sea, bay, and anthropogenic activities along the shore [14,19,25]. Drastic variation of temperature is observed in Kuwait with extremely hot summers and cold winters, which would affect the thermodynamic states of water seasonally thereby changing the water quality and the ions available of reaction. Hence this study aims to understand the thermodynamic equilibrium states and their variations with respect to temperature. The spatial variation of the saturation states were also been determined in this study.

2. Study area

Two major aquifers in Kuwait are the potential groundwater sources, the younger Kuwait group aquifer (KGA) deposited in the continental environment and the older Dammam Formation formed in the marine conditions. The Kuwait group aquifer is composed of the Ghar (predominantly represented by calcretised sandstone) and Fars (fossiliferous limestone and evaporites) formations deposited during Miocene, followed by the Dibdibbah (predominantly of gravelly coarse sand) formation formed during Pleistocene and then by recent sediments [26]. Dibdibba fromation serves as the prominent aquifer in KGA, followed by Fars aquitard then by Ghar formation. The KGA has a thickness of ~400 m in the north east and ~150 m in the south-western part of Kuwait. The piezometric surface varies from zero to 90 m with respect to the sea level, from the southwest to the coastal region respectively. The transmissivity varies from 10 to 200 $m^2\ d^{-1}$, near the Bay and north eastern region respectively, with saturated thickness varying between 0 and 400 m. The Dammam Formation of Eocene is separated from the overlying KGA by a major unconformity. The Dammam Formation has a thickness varying between ~280 and 150 m, piezometric level ranging from a few meters to ~90 m with respect to the sea level [27]. The transmissivity varies due to the karstic nature of the formation and it's found to be higher in the south-western and southern part of Kuwait [28].

3. Methodology and analysis

Groundwater samples were collected from 20 shallow bore wells along the coastal region of Kuwait (Fig. 1). The coastal region represents the open sea and the Bay. The groundwater samples were collected after well purging, before purging the screened interval of the well, the static water level of the well was measured. The pH, temperature, electrical conductivity (EC), dissolved oxygen (DO), and oxidation–reduction potential (Eh) were measured in the field. The aim of measuring these parameters on-site was to ensure that purging would extract a sufficient quantity of water allowing representative groundwater sample to collect; and to provide on-site measurements of unstable parameters such as temperature and to compare with laboratory measurements to validate changes due to holding time and transport. The groundwater and seawater samples collected were analyzed using ion chromatography for major cations and anions (Na, K, Ca, Mg, Cl, and SO_4) (Method No. 4110); nutrients (NO_3, NH_3, PO_4) and silicate (H_4SiO_4) have been analyzed using a discrete analyser (Method No. 4130). Trace metals were analyzed using the Agilent 5100 ICP-OES Model equipment using the USPEA 200.7 procedure. These laboratory analyses were conducted in the Water Research Center's (WRC's) laboratory at KISR according to the procedures explained in the Standard Methods for the Examination of Water and Wastewater, 22nd edition. The silicate stability plots for Ca, Mg, Na and K were plotted using CHIDAM software [23] and the simulations by varying temperatures were determined by PHREEQC [29]. Saturation states of the minerals were obtained by determining the ratio between the ionic activity product and solution constant. Further variation in the composition of each groundwater sample was simulated for a range of temperatures between 19°C to 28°C. The saturation states, variation in pH, ionic strength and groundwater composition were recorded.

4. Results

The geochemical results show variation in groundwater composition, the maximum, minimum and the average composition of the groundwater samples are presented in Table 1. Greater variation in salinity was noted, the samples range from brackish to hypersaline and to acidic hyper salinity. The pH varies from acidic to alkaline conditions. Higher concentration of Cl was observed, followed by SO_4, HCO_3 and H_4SiO_4, but greater variation was observed with respect to Cl and SO_4 ions. Similarly, Na was observed to be predominant in cations followed by Ca, Mg and K. Range of variation was observed to be higher in all the cations. The concentration of ions governs the formation of saturation states apart from the environmental variables like temperature and pressure.

Kaolinite composition is achieved by the interaction of H_4SiO_4 with $Al(OH)_3$, initially, $Al(OH)_3$ referred as gibbsite and dissolved silica derived by the dissolution of feldspar at a definite pH. Subsequently with the further dissolution of feldspar enhances the Al in groundwater along with the dissolved silica concentration. Thus the colloidal association of the derived ions results in the compositional stability with kaolinite [30].

$$KAlSi_3O_8 + 8H_2O = Al(OH)_3 + K^+ + OH^- + 3H_4SiO_4 \quad (1)$$

$$KAlSi_3O_8 + 4Al(OH)_3 + H_2O = 3Al_2Si_2O_5(OH)_4 + 2K^+ + 2(OH)^- \quad (2)$$

Breakdown of single feldspar releases K_2O and Na_2O in 1:1 ratio to SiO_2·CaO is released in 1:2 ratios to SiO_2.

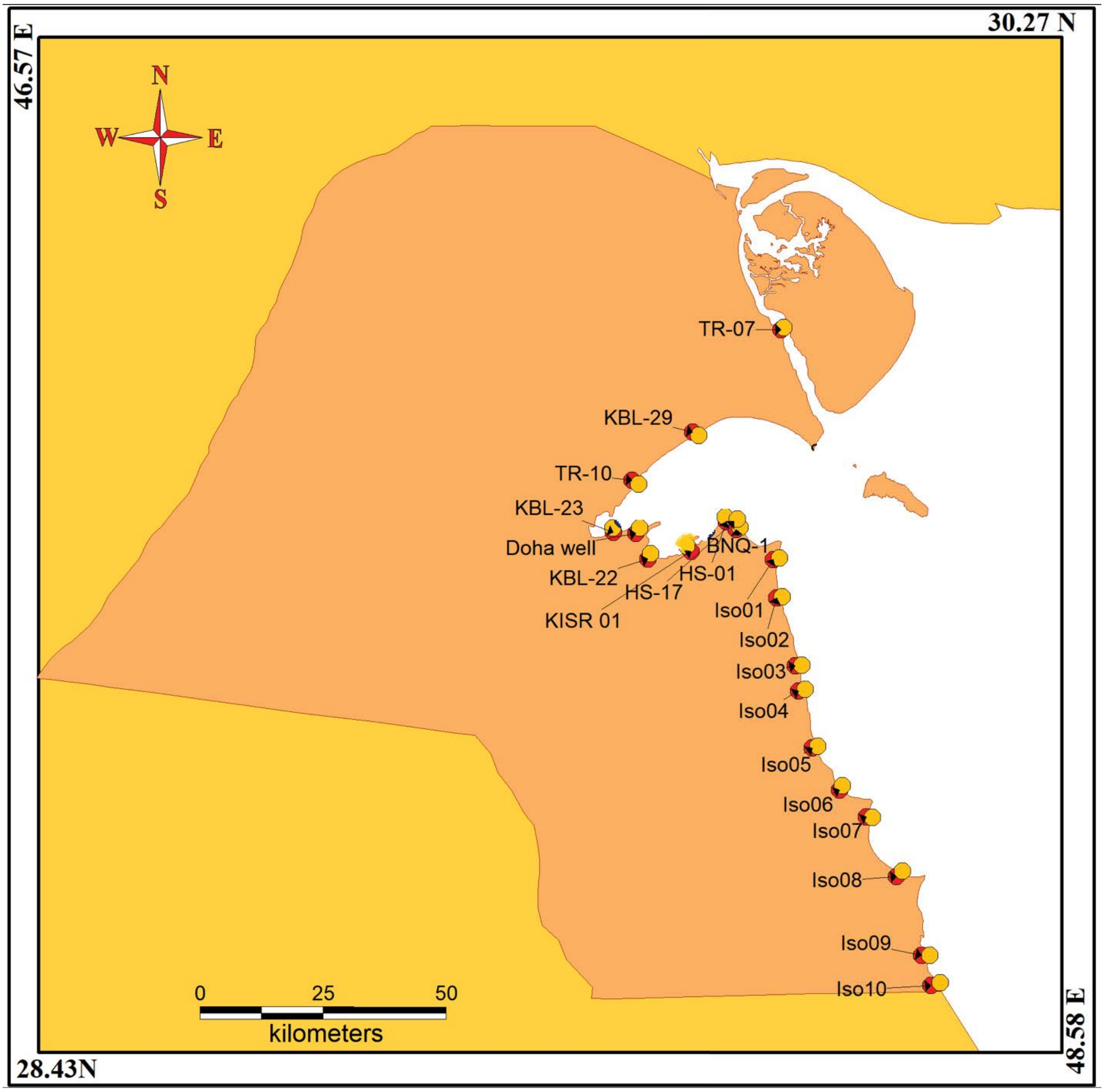

Fig. 1. Location of the groundwater samples collected for the study along the coastal region of Kuwait. All samples were collected from Kuwait group aquifer wells with depth less than 60 m.

Hence in water with biotite and feldspar, K_2O, Na_2O and CaO will be released into the groundwater. SiO_2 will be partly removed and partly fixed [31]. H_4SiO_4 obtained by the dissolution of feldspar is utilized for the formation of kaolinite from gibbsite. During this process, the migration of the groundwater composition is observed along the gibbsite–kaolinite interface. The composition is noted along the boundary until all the gibbsite is exhausted due to the reaction with silica and Al. Thus from then on the composition is observed to migrate to kaolinite stability field. Similarly, the composition is observed along the muscovite–kaolinite boundary till the stable kaolinite is exhausted by reacting with K, and Al derived from the dissolution.

$$3KAlSi_3O_8 + 14H_2O = KAlSi_3O_{10}\left(OH\right)_2 + 2K^+ + 2\left(OH\right)^- + 6H_4SiO_4 \quad (3)$$

The samples in the sodium stability plot falls in the kaolinite stability field. As dissolution of feldspars continues the value of $Si(OH)_4$ and $[Na^+]/[H^+]$ increases from gibbsite and the composition migrates to kaolinite field. The potassium stability plot indicates incongruent dissolution of K-feldspar stable with kaolinite. The variation of ion result in shift of kaolinite to K-feldspar (Fig. 2). The plots for Ca^{2+} shows representation in kaolinite field. In magnesium

Table 1
Maximum, minimum and average concentration of groundwater samples collected along the coast

Parameter	Unit	Groundwater (n = 20)		
		Min.	Max.	Average
EC	µS/cm	1,273	97,840	35,257
pH		7.06	8.26	7.48
HCO_3	mg/L	52	263	142
Na	mg/L	19	21,063	6,745
K	mg/L	4	864	256
Ca	mg/L	30	2,643	952
Mg	mg/L	2	2,279	781
SO_4	mg/L	31	4,272	2,930
Cl	mg/L	29	47,208	14,238
F	mg/L	0.07	4.97	2.77
H_4SiO_4	mg/L	1.50	44.23	15.14
NO_3	mg/L	0.00	617.49	82.79
TDS	mg/L	182	78,600	26,362

plot, samples were observed along the boundary of kaolinite–chlorite field. The solubility of silica and the variation of Mg^{2+} ions result in the change in compositional stability from kaolinite to chlorite (Fig. 2).

Almost all the groundwater samples collected adjacent to the coast fall in the albite stability field due to the higher concentration of Na. Subsequently, the samples with relatively lesser concentration of Na fall in the Na-montmorillonite field (Fig. 2). It is inferred from the ionic ratio that the Na concentration is higher than the Ca in groundwater. Thus, the sodic feldspar field exhibit a predominant display of the samples. The carbonate stability system is generally derived by relating the activity ratios of Ca and Mg to logpCO_2. The major carbonate minerals are aragonite, calcite ($CaCO_3$), dolomite ($Ca,Mg(CO_3)$) and magnesite ($MgCO_3$). The vertical distribution of the field is between the two carbonate end members calcite and magnesite representing the regions with higher and lower Ca/Mg ratio respectively. Dolomite is intermediate between these two end members, the logpCO_2 indicate variation along the horizontal direction considering the stability fields of brucite ($Mg(OH)_2$) and carbonates (Fig. 2). The atmospheric logpCO_2 value is designated as –3.75 [32], all the groundwater samples were noted to have a higher logpCO_2 ranging from –2.8 to –1.8, this is mainly due to the fact that they represent a closed system with lesser atmospheric interaction [33]. All the samples plot in the dolomite field due to the predominance of both Ca and Mg in the samples (Fig. 2). The trend indicates movement of composition of samples from calcite to hydromangesite, with respect to changes in logpCO_2 values.

4.1. Temperature simulations

The pH-REdoxEQuilibirum Code (PHREEQC) was adopted to simulate the groundwater composition by varying the sample temperatures from 19°C to 28°C. The selected outputs of the simulation was considered for the study like, pH, ionic strength, saturation index of predominant sulfate (anhydrite-SI_{An}; gypsum-SI_{Gy}) and carbonate minerals (aragonite-SI_A, calcite-SI_C, dolomite-SI_D, magnesite-SI_{Mg}), halite (SI_{Ha}), forms of silica (quartz-SI_{Qtz}, silica amorphus-SI_{Sio2}, chalcedony-SI_{Chal}), clinoenstatite (SI_{CE}) and forsterite (SI_{Fo}) minerals were considered.

The order of saturation states regarding the minerals considered are as follows:

$SI_D > SI_C > SI_{Ar} > SI_{Mg} > SI_{Qtz} > SI_{Chal} > SI_{Gy} > SI_{An} > SI_{Sio2} > SI_{CE} > SI_{Ha} > SI_{Fo}$

The state of saturation with regard to sulphate, carbonate and silicates show the following order:

Sulphate minerals: $SI_{Gy} > SI_{An}$

Carbonate minerals: $SI_D > SI_C > SI_{Ar} > SI_{Mg}$

Silica minerals: $SI_{Qtz} > SI_{Chal} > SI_{Sio2}$

Fe silicates: $SI_{CE} > SI_{Fo}$

The trend of saturation were observed to be the same in all samples except for the SI of carbonates which varied in samples 10, 13, 14, 16, 17 and 20 (Table 2). These samples located along the southern flanks of the bay reflected higher saturation states of magnesite than the calcite and aragonite. The trend of variation in these saturation states were simulated from 19°C to 28°C. The data reveals that the saturation states of carbonate minerals, halite, and Fe-silicates increases with temperature. The decrease of saturation states was observed for different forms of silica, gypsum, pH and ionic strength of the samples. Anhydrite was observed to be sensitive with respect to temperature as most of the samples showed a decrease in saturation from 21°C–24°C (Table 2). The SI_C and SI_{Ar} (calcium carbonates) show similar behaviour in most of the samples with an increase in saturation state with increase in temperature, but certain location HS-01, KBL-23 and TR-07 show a decrease in saturation with increase in temperature. These samples have pH values >7.5 and Mg >850 mg/L. This condition favors the available HCO_3 and Ca to combine with Mg and form Ca, Mg carbonates (dolomite and magnesite) when temperature increases. The formation of this mineral is governed by the selected association of Ca to HCO_3 than to SO_4 at certain temperature. This is mainly due to the phenomenon referred as "Common Ion Effect". This temperature depends on the composition of the groundwater and the atmospheric pressure. The temperature simulation study also reveals that a decrease in pH is observed with increase in temperature and this process changes the availability of HCO_3 in groundwater and thus its capacity to associate with ions to become saturated.

4.2. Spatial variation of saturation index

The saturation states of the minerals considered were compared to sampling location in the study area (Fig. 3).

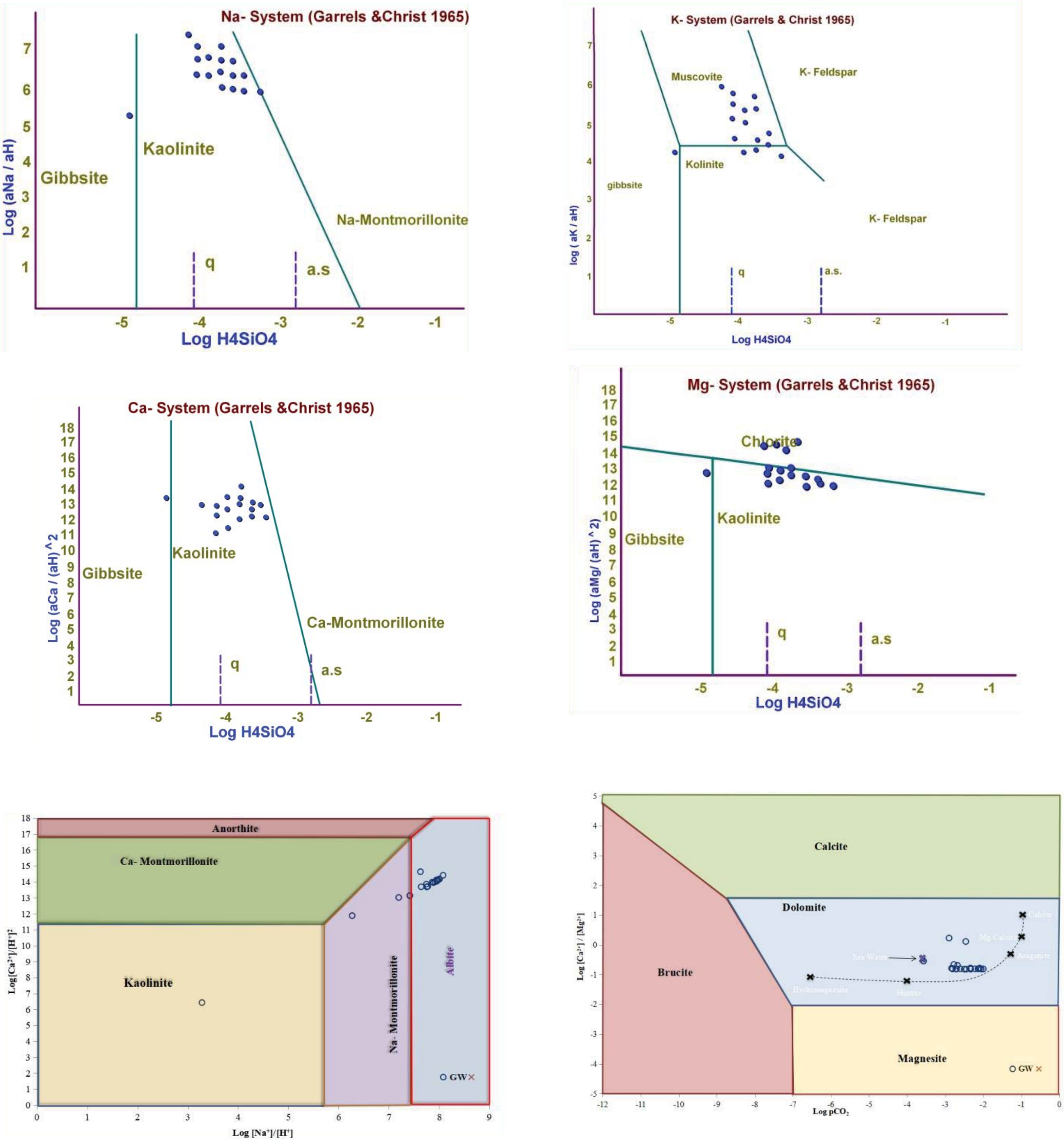

Fig. 2. Thermodynamic states of the groundwater samples observed in the different stability plots group aquifer wells with depth less than 60 m.

The trend of the saturation states predominantly remains the same. The SI_{Mg} is nearly saturated in all the samples located in the coast adjacent to the open sea. The coastal samples adjacent to the southern part of the bay show under saturation of magnesite. Further, the SI_{An} shows under saturation in the coastal samples adjacent to the bay but samples adjacent to the open sea show near saturation. This variation is mainly due to variation in the groundwater composition [19,23,25]. Though the trend of the saturation states of minerals remain the same minor variations are observed at specific locations due to the compositional variability in the groundwater.

4.3. Common ion effect

The composition of groundwater play a major role in determining the saturation states of minerals. As the availability of ions play a significant role in saturation

Table 2
Summary of the trend of saturation states of minerals obtained by simulating the temperature variation from 19°C to 28°C though PHREEQC model

Sam	pH	IS	Sulphate		Carbonates				Hal	Silica			Silicate	
			Anh	Gyp	Ara	Cal	Dol	Mag		Qtz	Si	Cha	CE	Fo
Iso 01	↓	↓	25(	↓	↑	↑	↑	↑	↓	↓	↓	↓	↑	↑
Iso 02	↓	↓	21(	↓	↑	↑	↑	↑	↓	↓	↓	↓	↑	↑
Iso 03	↓	↓	21(	↓	↑	↑	↑	↑	↓	↓	↓	↓	↑	↑
Iso 04	↓	↓	21(	↓	↑	↑	↑	↑	↓	↓	↓	↓	↑	↑
Iso 05	↓	↓	23(	↓	↑	↑	↑	↑	↓	↓	↓	↓	↑	↑
Iso06	↓	↓	22(	↓	↑	↑	↑	↑	↓	↓	↓	↓	↑	↑
Iso 07	↓	↓	23(	↓	↑	↑	↑	↑	↓	↓	↓	↓	↑	↑
Iso 08	↓	↓	26(	↓	↑	↑	↑	↑	↓	↓	↓	↓	↑	↑
Iso 09	↓	↓	23(	↓	↑	↑	↑	↑	↓	↓	↓	↓	↑	↑
Iso 10	↓	↓	23(	↓	↑	↑	↑	↑	↓	↓	↓	↓	↑	↑
BNQ-1	↓	↓	21(	↓	↑	↑	↑	↑	↓	↓	↓	↓	↑	↑
HS-17	↓	↓	23(	↓	↑	↑	↑	↑	↓	↓	↓	↓	↑	↑
HS-01	↓	↓	24(	↓	↓	↓	↑	↑	↓	↓	↓	↓	↑	↑
KISR 01	↓	↓	↑	↓	↑	↑	↑	↑	↓	↓	↓	↓	↑	↑
KBL -22	↓	↓	21(	↓	↑	↑	↑	↑	↓	↓	↓	↓	↑	↑
Doha well	↓	↓	25(	↓	↑	↑	↑	↑	↓	↓	↓	↓	↑	↑
KBL-23	↓	↓	26(	↓	↓	↓	↑	↑	↓	↓	↓	↓	↑	↑
TR-10	↓	↓	24(	↓	↑	↑	↑	↑	↓	↓	↓	↓	↑	↑
KBL-29	↓	↓	21(	↓	↑	↑	↑	↑	↓	↓	↓	↓	↑	↑
TR-07	↓	↓	26(	↓	↓	↓	↑	↑	↓	↓	↓	↓	↑	↑

Blue indicates the decrease of saturation with increase in temperature and the ochre indicates the vice versa. The "24(" indicates the decrease and increase of saturation sates with the adjacent value reflects the temperature with lowest value of anhydrite saturation.

states, Ca and HCO_3 are the common ion for the carbonate minerals (calcite, aragonite and dolomite). Ca is the common ion for both the carbonate and the sulphate minerals considered. The exponential variation was noted in SI dolomite and anhydrite. Hence, it is observed that there is a decrease in the saturation states of the carbonate minerals, when there is an increase of sulfate mineral saturation, due to the dual role of "Ca" a common ion. Though the greater concentration of certain ions like $SO_{4,}$ Na and Cl are observed their saturation states are not obtained due to the solution composition, availability of other ions and the pressure (P) – temperature (T) conditions. The variation of saturation index of gypsum and anhydrite in saline conditions were attempted in the $CaSO_4$-NaCl-H_2O system by (1955) [34] and the study concluded that the mineral transition temperature is decreased by the enhancement of groundwater salinity. The equilibrium temperature of gypsum–anhydrite in NaCl solution was estimated by [35], their transformation in saline aqueous solution was determined by [36]. Laboratory studies were reported with regard to $CaSO_4$ system [37] and $CaSO_4$-Na_2SO_4-H_2O system by [38]. The transformation of gypsum to anhydrite was studies by (1937) [39] in $CaSO_4$-H_3PO_4-H_2O the system, with the interplay of MgCl and NaCl. The study inferred that anhydrite and gypsum cannot co-exist in Na_2SO_4 waters. The $CaSO_4$-H_2SO_4-H_2O system shows that simultaneous precipitation of both the salts anhydrite and gypsum do not alter their field of stability [40] studied the $CaSO_4$-NaCl-H_2O system and concluded that a minimum value of 0.75 is required for the activity of brine water to form the calcium sulfate deposits. The activity of brine water with $CaSO_4$ varies between 0.90 and 0.96 for a change in temperature of 25°C to 70°C. Similarly, it is to be noted that the silica at lower temperatures is comparatively more saturated with quartz, silica and chalcedony. At higher temperatures, the clinoenstatite and forsterite show an increase in saturation. There is a decrease in pH with temperature, as the silica dissolution is favoured in alkali environment [41,42]. Later the dissolved silica is associated with cation to form clinoenstatites and forsterite. Hence it is inferred that the variation in temperature governs the pH and the dissolution of minerals.

5. Conclusion

The study on the thermodynamic states of groundwater samples show that the coastal groundwater are predominantly stable with the kaolinite field as reflected by the silicate stability plots. The saturation index of the minerals observed in the study are in the following order, $SI_D > SI_C > SI_{Ar} > SI_{Mg} > SI_{Qtz} > SI_{Chal} > SI_{Gy} > SI_{An} > SI_{Sio2} > SI_{CE} > SI_{Ha} > SI_{Fo}$. The temperature simulation from 19°C to 28°C, shows an increase in saturation sates with temperature in clinoenstatite, forsterite, dolomite, magnesite minerals. Except for three samples the saturation index of calcite and aragonite were observed to increase with temperature. The anomaly

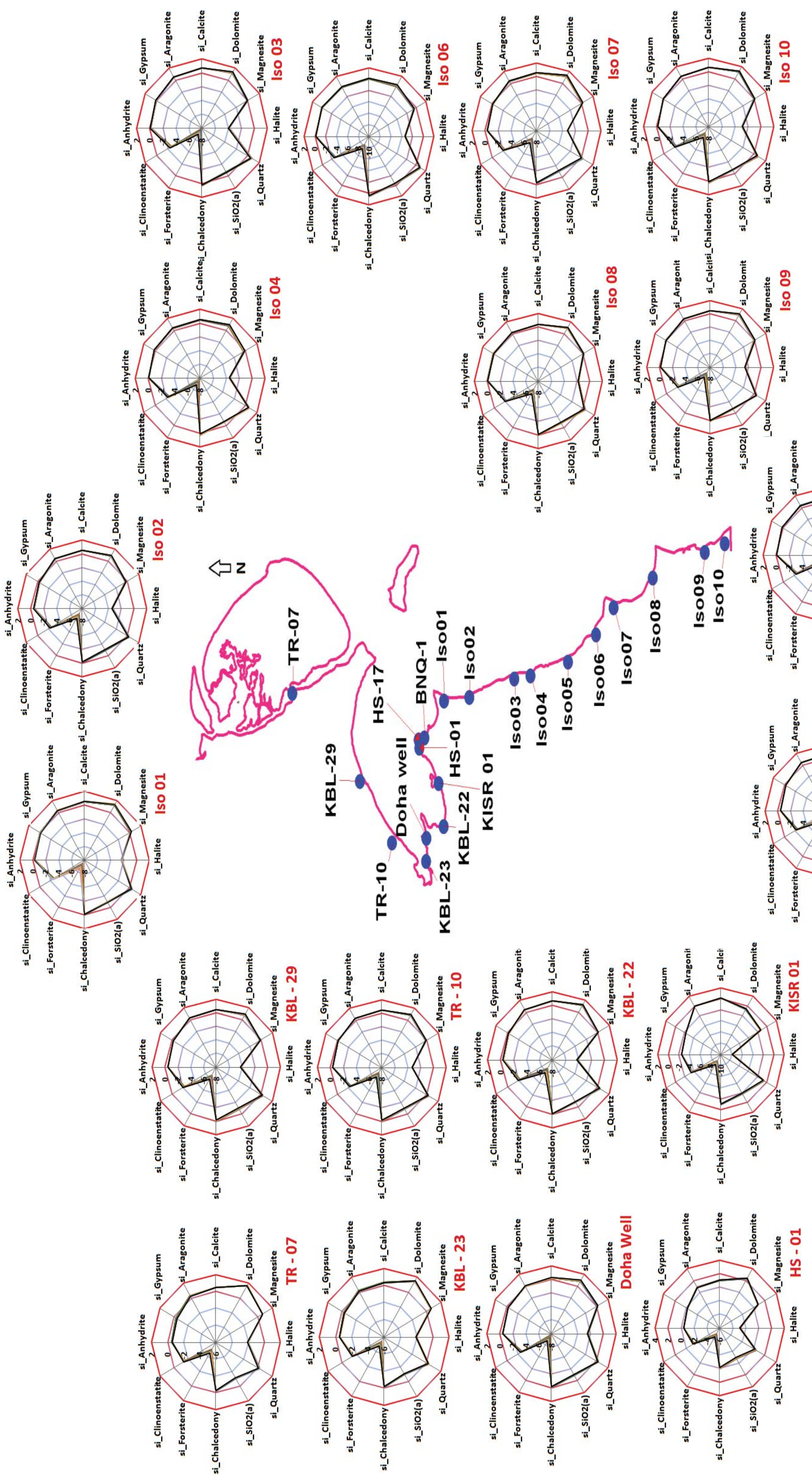

Fig. 3. Sampling location of the groundwater samples collected in the study area and their spatial variation in saturation states of the minerals considered for study.

was due to the pH and Mg concentration in these samples. pH, ionic strength, saturation index of gypsum and silica decreased with increase in temperature. Anhydrite showed a mixed behaviour with most of the low saturation states observed around 21°C–24°C. Ca being the common ion for both the carbonate and the sulphate minerals, tend to be more associated with the Ca, Mg carbonates like dolomite and magnesite. The saturation states are governed by the availability of ions and the P-T conditions. The anhydrite and gypsum saturation states are also inferred to be affected by the salinity, presence of H_2S and the pH of the groundwater. The spatial variation of the saturation indices show that the samples adjacent to the open sea are more saturated than the samples adjacent to the bay, especially with respect to anhydrite. Though higher concentration of certain ions are observed in the samples they do not tend to saturate either due to the non-availability of the associated ions or due to P-T conditions. This study provides a key understanding on the nature of water to form precipitates or scales on the pipe line either during the extraction or during transportation when there is a variation in temperature.

Acknowledgement

The authors would like to acknowledge WRC, and the KISR management for the encouragement and support. The authors would also like to thanks KFAS for the financial support for study through the project WM067C.

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Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28237

263 (2022) 257–264
July

Monitoring of inorganic and organic pollutants in the desalinated water from thermal desalination plants

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Received 28 February 2022; Accepted 28 April 2022

ABSTRACT

Monitoring of inorganic and organic pollutants in the produced water from Saline Water Conversion Corporation (SWCC) seawater desalination plants was carried out over 20 y on the eastern coast and 8 y on the western coast of the Kingdom of Saudi Arabia. Water samples from SWCC plants were analyzed with an emphasis on toxic elements such as mercury, arsenic, lead, cadmium, selenium, chromium, and toxic disinfection by-products (DBPs) such as trihalomethanes (THMs) arising due to chlorination. Considering the Saudi Arabian Standards Organization (SASO) and World Health Organization (WHO) guidelines for drinking water, results show compliance with all the values for the components analyzed and found to be under the SASO and WHO regulations. Over the 20 y of the study, elevated THM concentrations were found for all plants located on the Arabian Gulf in the years 2001–2003, and elevated arsenic concentrations for the same plants in 2007. The fact that these increased levels were reported for all plants on the Arabian Gulf suggest they arise from systemic environmental effects impacting this restricted body of water.

Keywords: Toxic elements, Drinking water, Desalinated water, Heavy metals, Disinfection by-products, Saline Water Conversion Corporation

1. Introduction

Saudi Arabia is an arid country with limited fresh water resources. The major source of drinking water in the Kingdom of Saudi Arabia is desalination of seawater. The Saline Water Conversion Corporation (SWCC), a government agency responsible for producing desalinated water in the Kingdom, operates approximately 30 desalination plants along the coast of Red Sea and Arabian Gulf with a combined production capacity of close to 6 million m^3/d. Multi-stage flash (MSF) plants contribute the major share of the water being produced in the Kingdom, followed by reverse osmosis (RO), and multi-effect distillation (MED).

Providing safe and good quality drinking water is the highest priority of SWCC. Water produced by SWCC plants are regularly monitored for the water quality in compliance with national and international regulations, particularly for toxic heavy metals such as Hg, Se, Pb, As, Cd, Cr and toxic disinfection by-products (DBPs) such as THMs (trihalomethanes) arising from sea water chlorination (Table 1). SWCC's Desalination Technologies Research Institute (DTRI) has been entrusted with monitoring water

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quality control and has previously reported results of this ongoing monitoring, but no updates have appeared for several decades [1–4]. THMs have been reported at concentration of up to 90 μg/L in Arabian Gulf seawater near thermal desalination plant brine discharge points [5] and up to approximately 20 μg/L in similar environments in the Red Sea [6], the physical process of desalination means that they very much less concentrated in the produced water. Le Roux et al. [6] reported total THM concentration ≥ 0.38 μg/L in MSF distillate from a desalination plant located on the Red Sea.

2. Experimental methods

2.1. Sampling

Initially the sampling was done on monthly basis for only the plants located in the Eastern province (i.e., Jubail, Khobar and Khafji); from 2011 it was extended to all SWCC thermal plants on a bi-monthly basis. The collection of samples was carried out by DTRI staff in coordination with personnel at the respective desalination plants.

2.2. Analytical methods

2.2.1. Heavy metals

For the determination of heavy metals, samples were collected in polypropylene bottles. Their pH was set at 1.0 with the addition of a few drops of AR grade nitric acid.

Analyses were performed by Perkin Elmer Atomic Absorption Spectrometer-400 (AAS-400) with hydride generation for Hg, Se, and As. For the remaining metals (Cd, Cr, Pb) a Perkin Elmer (AAS-800) spectrometer with Graphite Tube Atomizer (GTA) was used [7].

2.2.2. Total trihalomethanes (TTHMs) analysis by GC/MS

According to the Standard Methods all samples were analyzed based on the described procedures in American Public Health Association (APHA) Standard Methods [7]. Based on the direct aqueous injection, an Agilent 5890 series, gas chromatography (GC) high performance quadrupole mass spectrometer (GC-MS) using a Purge and Trap technique was used for the identification and quantification of THMs.

The GC oven temperature was programmed from 40°C (4 min) to 140°C at 8°C/min. Other GCMS parameters were as follows:

- Column: J and W-DB5, 60 m × 0.25 mm × 0.25 μm thickness; Carrier gas: Helium at 1.2 ml/min.
- Injector temperature: 300°C;
- SIM mode (ions selected: 83, 85, 127, 129, 171 and 173); MS Quad. temperature: 150°C; MS source temp.

3. Results and discussion

The study assessed the concentrations of the toxic elements such as mercury (Hg), arsenic (As), lead (Pb), cadmium (Cd), selenium (Se), chromium (Cr) and toxic disinfection by-products (DBPs) such as THMs (trihalomethanes) arising due to sea water chlorination for a period of 20 y in the Eastern and 8 y in the Western provinces. Data are presented in Tables 2–15. Table 1 shows permissible limits according

Table 1
Relevant SASO limits for unbottled drinking water (2009), WHO limits for drinking water (2008), the detection limits of toxic elements and THMs, and previously reported values in desalination product water

Year	Cd (ppb)	Cr (ppb)	Se (ppb)	Pb (ppb)	Hg (ppb)	As (ppb)	TTHM*	$CHCl_3$ (ppb)	$CHBrCl_2$ (ppb)	$CHBr_2Cl$ (ppb)	$CHBr_3$ (ppb)
SASO Limit	3	50	10	10	1	10	Note 1	200	60	100	100
WHO Limit	3	50	10	10	1	10		300	60	100	100
Detection limit	0.002	0.004	0.030	0.050	0.009	0.030		0.03	0.05	0.05	0.10
Mayan Kutty et al. [1] (MAX)	1.0–1.3	ND	0.52–0.67	ND	0.3–2.8	0.77–1.8					
Gao et al. [10] MED	0.02		ND	0.01	ND	1.4					
Gao et al. [10] RO	ND		0.1	ND	0.01	ND					
Le Roux et al. [6] MSF									0.15	0.12	0.11
Le Roux et al. [6] RO										0.07	19.05

Note 1: TTHM*: The sum of the ratio of each to its respective guideline value should not exceed 1, as per the function:

$$\frac{C_{\text{bromoform}}}{\text{GV}_{\text{bromoform}}}+\frac{C_{\text{DBCM}}}{\text{GV}_{\text{DBCM}}}+\frac{C_{\text{BDCM}}}{\text{GV}_{\text{BDCM}}}+\frac{C_{\text{chloroform}}}{\text{GV}_{\text{chloroform}}}\leq 1$$

where *C*: concentration; GV: guideline value; BDCM: bromodichloromethane ($CHBrCl_2$); DBCM: dibromochloromethane ($CHBr_2Cl$).

Table 2
Occurrence of heavy metals and disinfection by-products in desalinated water of Khobar MSF Plant

Year	Cd (ppb)	Cr (ppb)	Se (ppb)	Pb (ppb)	Hg (ppb)	As (ppb)	TTHM (ppb)	$CHCl_3$ (ppb)	$CHBrCl_2$ (ppb)	$CHBr_2Cl$ (ppb)	$CHBr_3$ (ppb)
1989 [3]	<0.002	<0.004	<0.03	<0.05	<0.009–0.25	<0.03–0.47	<3.50/5.29	<0.01/0.04	0.18/0.20	<0.01/0.10	3.30/4.95
1990 [3]	<0.002	<0.004	<0.03–0.37	<0.05	<0.009	<0.03					
1991 [3]	<0.002	<0.004	<0.03	<0.05	<0.009	1.2–5.6					
1992 [3]	<0.002	<0.004	<0.03	<0.05	<0.009–0.3	<0.03–1.24					
1993 [3]	<0.002	<0.004	<0.03–0.60	<0.05	<0.009–0.3	<0.03–1.8					
1994 [3]	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03–0.70					
1998	0.2–0.3	0.3	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
1999	0.1–1.59	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2000	<0.002–0.1	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2001	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<7.8	<0.03	0.31	0.48	1.0–7.0
2002	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<4.1	<0.03	<0.05	0.3–0.5	1.0–3.5
2003	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<2.7	<0.03	<0.05	<0.05	2.0–2.6
2004	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2005	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2006	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2007	<0.002	<0.004	<0.03	<0.05	<0.009	0.1–0.2	<0.23	<0.03	<0.05	<0.05	<0.10
2008	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2009	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2010	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2011	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2012	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2013	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	2.0–10
2014	<1	<1	NA	<1	<1	<1	<0.23	<0.03	<5	<5	<5
2015	NA	NA	NA	NA	<1	<1	<0.23	<0.03	<5	<5	<5
2016	NA	NA	NA	NA	<1	<1	<0.23	<0.03	<5	<5	<5
2017	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA
2018	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA

NA = not analysed

to the Saudi Arabian Standards Organization (SASO) and World Health Organization (WHO) [8,9] and results previously obtained from MSF, MED, and RO desalination plants [1,6,10].

The data from the Tables 2–4 for the plants located in the Eastern Province (Khobar, Khafji and Jubail) showed that for the entirety of the study period the six toxic elements studied were either below the detection level (Table 1) or present in very low concentrations in the desalinated water. Average values for all the six elements analyzed were found to be well below the Saudi Arabian Standards Organization (SASO) and World Health Organization (WHO) permissible limits [8,9].

Traces of Cd were observed in desalinated water during the years 1998 and 1999 in Khobar (0.1–1.59 ppb) and in 1999 in Khafji (0.2–0.24 ppb). The origin of these elevated levels of Cd are not known.

Traces of As were observed during the same year (2007) in the samples of all three plants (Khobar, Khafji and Jubail). These observations are consistent with some activity of contamination with As in the source water during these periods in the Arabian Gulf, as it is highly unlikely that contamination associated with corrosion of metallic components of the MSF plants (for example) would coincidentally occur at all three plants. As the Arabian Gulf is a relatively shallow body of water with restricted connections to the Indian Ocean, it is more sensitive to events that could increase As levels systemically: significant extractive industries are located in and around the Arabic Gulf, and it receives relatively large volumes of freshwater discharge from the Tigris–Euphrates–Karun watershed.

Chlorination of seawater containing organics results in the formation of disinfection by-products (DBPs) that are known to have adverse health effects [11,12]. The major DBPs are trihalomethanes (THMs), viz. chloroform ($CHCl_3$), bromodichloromethane ($CHBrCl_2$), dibromochloromethane ($CHBr_2Cl$) and bromoform ($CHBr_3$) [11]. At most times no THMs could be detected, despite the fact that significant concentrations are expected to be produced in the discharged brine Elevated levels of THMs (though well within the acceptable limits) were found for all plants sampled on the Arabian Gulf in 2001–2002 and for two out of three plants sampled on the Arabian Gulf in 2003. It was found that bromoform was the predominant species formed, but

Table 3
Occurrence of heavy metals and disinfection by-products in desalinated water of Jubail MSF Plant

Year	Cd (ppb)	Cr (ppb)	Se (ppb)	Pb (ppb)	Hg (ppb)	As (ppb)	TTHM (ppb)	$CHCl_3$ (ppb)	$CHBrCl_2$ (ppb)	$CHBr_2Cl$ (ppb)	$CHBr_3$ (ppb)
1989 [3]	<0.002–1.1	<0.004	<0.03–1.1	<0.05–1.2	<0.009	<0.03–0.50	>0.09/>0.40	0.05/0.08	0.02/0.13	0.01/0.08	0.01/0.13
1990 [3]	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03–0.60					
1991 [3]	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03					
1992 [3]	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03–0.49					
1993 [3]	<0.002–1.3	<0.004	<0.030–0.52	<0.05	<0.009	<0.03–0.77					
1994 [3]	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03–0.5					
1998	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
1999	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2000	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2001	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<7.1	<0.03	<0.05	<0.05	1.0–7.0
2002	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.6	<0.03	<0.05	<0.05	0.2–0.5
2003	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2004	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2005	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2006	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2007	<0.002	<0.004	0.1–0.2	<0.05	<0.009	0.08–0.09	<0.23	<0.03	<0.05	<0.05	<0.10
2008	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2009	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2010	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2011	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2012	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2013	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2014	<1	<1	NA	<1	<1	<1	<0.23	<0.03	<5	<5	<5
2015	NA	NA	NA	NA	<1	<1	<0.23	<0.03	<5	<5	<5
2016	NA	NA	NA	NA	<1	<1	<0.23	<0.03	<5	<5	<5
2017	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA
2018	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA

NA = not analysed

Table 4
Occurrence of heavy metals and disinfection by-products in desalinated water of Khafji MSF Plant

Year	Cd (ppb)	Cr (ppb)	Se (ppb)	Pb (ppb)	Hg (ppb)	As (ppb)	TTHM (ppb)	$CHCl_3$ (ppb)	$CHBrCl_2$ (ppb)	$CHBr_2Cl$ (ppb)	$CHBr_3$ (ppb)
1989 [3]	<0.002	<0.004	<0.03	<0.03–0.58	<0.009	NA	<1.10/<0.97	<0.01	0.12/0.01	<0.01/0.01	0.96/0.94
1990 [3]	NA	NA	NA	NA	NA	NA					
1991 [3]	NA	NA	NA	NA	NA	NA					
1992 [3]	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03–0.60					
1993 [3]	<0.002–1.0	<0.004	<0.03–0.67	<0.05	<0.009–2.8	<0.03–1.3					
1994 [3]	<0.002	<0.004	<0.03	<0.05	<0.009–0.6	<0.03–0.5					
1998	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
1999	0.22–0.24	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2000	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2001	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<1.1	<0.03	<0.05	<0.05	0.8–1.0
2002	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<1.1	<0.03	<0.05	<0.05	0.3– 1.0
2003	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.9	<0.03	<0.05	<0.05	0.3– 0.8
2004	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2005	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2006	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10

(Continued)

Table 4

Year	Cd (ppb)	Cr (ppb)	Se (ppb)	Pb (ppb)	Hg (ppb)	As (ppb)	TTHM (ppb)	$CHCl_3$ (ppb)	$CHBrCl_2$ (ppb)	$CHBr_2Cl$ (ppb)	$CHBr_3$ (ppb)
2007	<0.002	<0.004	<0.03	<0.05	<0.009	0.02–0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2008	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2009	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2010	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2011	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2012	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2013	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2014	<1	<1	NA	<1	<1	<1	<0.23	<0.03	<5	<5	<5
2015	NA	NA	NA	NA	<1	<1	<0.23	<0.03	<5	<5	<5
2016	NA	NA	NA	NA	<1	<1	<0.23	<0.03	<5	<5	<5
2017	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA
2018	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA

NA = not analysed

Table 5
Occurrence of heavy metals and disinfection by-products in desalinated water of Jeddah MSF Plant

Year	Cd (ppb)	Cr (ppb)	Se (ppb)	Pb (ppb)	Hg (ppb)	As (ppb)	TTHM (ppb)	$CHCl_3$ (ppb)	$CHBrCl_2$ (ppb)	$CHBr_2Cl$ (ppb)	$CHBr_3$ (ppb)
2011	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2012	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2013	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2014	<1	<1	NA	<1	<1	<1	<0.23	<0.03	<5	<5	<5
2015	NA	NA	NA	NA	<1	<1	<0.23	<0.03	<5	<5	<5
2016	NA	NA	NA	NA	<1	<1	<0.23	<0.03	<5	<5	<5
2017	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA
2018	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA

NA = not analysed

Table 6
Occurrence of heavy metals and disinfection by-products in desalinated water of Shoibah MSF Plant

Year	Cd (ppb)	Cr (ppb)	Se (ppb)	Pb (ppb)	Hg (ppb)	As (ppb)	TTHM (ppb)	$CHCl_3$ (ppb)	$CHBrCl_2$ (ppb)	$CHBr_2Cl$ (ppb)	$CHBr_3$ (ppb)
2011	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2012	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2013	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2014	<1	<1	NA	<1	<1	<1	<0.23	<0.03	<5	<5	<5
2015	NA	NA	NA	NA	<1	<1	<0.23	<0.03	<5	<5	<5
2016	NA	NA	NA	NA	<1	<1	<0.23	<0.03	<5	<5	<5
2017	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA
2018	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA

NA = not analysed

at levels well below the regulated SASO and WHO values. Again, the similar result across three plants is consistent with a systemic event affecting the entire Arabian Gulf. In an earlier study, Mayan Kutty et al. [2] reported a similar clustering of elevated Hg results from these three plants on the Arabian Gulf in 1994, with the timing of the measurements consistent with a body of contaminated water apparently moving from north to south. It should be noted that overall, significantly higher levels of heavy metal contamination were measured in this earlier study than in the current work, perhaps unsurprisingly considering the unusually large amounts of pollutants generated in the Arabian Gulf as a result of armed conflict between 1984 and 1991.

For all the plants sampled in the Red Sea region, the concentration of the six target elements and the DBPs of interest were found to be below the detection level

Table 7
Occurrence of heavy metals and disinfection by-products in desalinated water of Yanbu MSF Plant

Year	Cd (ppb)	Cr (ppb)	Se (ppb)	Pb (ppb)	Hg (ppb)	As (ppb)	TTHM (ppb)	$CHCl_3$ (ppb)	$CHBrCl_2$ (ppb)	$CHBr_2Cl$ (ppb)	$CHBr_3$ (ppb)
2011	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2012	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2013	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2014	<1	<1	NA	<1	<1	<1	≤1	<0.03	<5	<5	<5
2015	NA	NA	NA	NA	<1	<1	≤1	<0.03	<5	<5	<5
2016	NA	NA	NA	NA	<1	<1	≤1	<0.03	<5	<5	<5
2017	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA
2018	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA

NA = not analysed

Table 8
Occurrence of heavy metals and disinfection by-products in desalinated water of Shuqaiq MSF Plant

Year	Cd (ppb)	Cr (ppb)	Se (ppb)	Pb (ppb)	Hg (ppb)	As (ppb)	TTHM (ppb)	$CHCl_3$ (ppb)	$CHBrCl_2$ (ppb)	$CHBr_2Cl$ (ppb)	$CHBr_3$ (ppb)
2011	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2012	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2013	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2014	<1	<1	NA	<1	<1	<1	≤1	<0.03	<5	<5	<5
2015	NA	NA	NA	NA	<1	<1	≤1	<0.03	<5	<5	<5
2016	NA	NA	NA	NA	<1	<1	≤1	<0.03	<5	<5	<5
2017	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA
2018	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA

NA = not analysed

Table 9
Occurrence of heavy metals and disinfection by-products in desalinated water of Azizia MED Plant

Year	Cd (ppb)	Cr (ppb)	Se (ppb)	Pb (ppb)	Hg (ppb)	As (ppb)	TTHM (ppb)	$CHCl_3$ (ppb)	$CHBrCl_2$ (ppb)	$CHBr_2Cl$ (ppb)	$CHBr_3$ (ppb)
2011	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2012	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2013	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2014	<1	<1	NA	<1	<1	<1	≤1	<0.03	<5	<5	<5
2015	NA	NA	NA	NA	<1	<1	≤1	<0.03	<5	<5	<5
2016	NA	NA	NA	NA	<1	<1	≤1	<0.03	<5	<5	<5
2017	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA
2018	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA

NA = not analysed

Table 10
Occurrence of heavy metals and disinfection by-products in desalinated water of Wajeh MED Plant

Year	Cd (ppb)	Cr (ppb)	Se (ppb)	Pb (ppb)	Hg (ppb)	As (ppb)	TTHM (ppb)	$CHCl_3$ (ppb)	$CHBrCl_2$ (ppb)	$CHBr_2Cl$ (ppb)	$CHBr_3$ (ppb)
2011	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2012	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2013	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2014	<1	<1	NA	<1	<1	<1	≤1	<0.03	<5	<5	<5
2015	NA	NA	NA	NA	<1	<1	≤1	<0.03	<5	<5	<5
2016	NA	NA	NA	NA	<1	<1	≤1	<0.03	<5	<5	<5
2017	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA
2018	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA

NA = not analysed

Table 11
Occurrence of heavy metals and disinfection by-products in desalinated water of Farasan MED Plant

Year	Cd (ppb)	Cr (ppb)	Se (ppb)	Pb (ppb)	Hg (ppb)	As (ppb)	TTHM (ppb)	$CHCl_3$ (ppb)	$CHBrCl_2$ (ppb)	$CHBr_2Cl$ (ppb)	$CHBr_3$ (ppb)
2011	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2012	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2013	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2014	<1	<1	NA	<1	<1	<1	≤1	<0.03	<5	<5	<5
2015	NA	NA	NA	NA	<1	<1	≤1	<0.03	<5	<5	<5
2016	NA	NA	NA	NA	<1	<1	≤1	<0.03	<5	<5	<5
2017	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA
2018	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA

NA = not analysed

Table 12
Occurrence of heavy metals and disinfection by-products in desalinated water of Laith MED Plant

Year	Cd (ppb)	Cr (ppb)	Se (ppb)	Pb (ppb)	Hg (ppb)	As (ppb)	TTHM (ppb)	$CHCl_3$ (ppb)	$CHBrCl_2$ (ppb)	$CHBr_2Cl$ (ppb)	$CHBr_3$ (ppb)
2011	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2012	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2013	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2014	<1	<1	NA	<1	<1	<1	≤1	<0.03	<5	<5	<5
2015	NA	NA	NA	NA	<1	<1	≤1	<0.03	<5	<5	<5
2016	NA	NA	NA	NA	<1	<1	≤1	<0.03	<5	<5	<5
2017	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA
2018	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA

NA = not analysed

Table 13
Occurrence of heavy metals and disinfection by-products in desalinated water of Qunfudah MED Plant

Year	Cd (ppb)	Cr (ppb)	Se (ppb)	Pb (ppb)	Hg (ppb)	As (ppb)	TTHM (ppb)	$CHCl_3$ (ppb)	$CHBrCl_2$ (ppb)	$CHBr_2Cl$ (ppb)	$CHBr_3$ (ppb)
2011	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2012	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2013	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2014	<1	<1	NA	<1	<1	<1	≤1	<0.03	<5	<5	<5
2015	NA	NA	NA	NA	<1	<1	≤1	<0.03	<5	<5	<5
2016	NA	NA	NA	NA	<1	<1	≤1	<0.03	<5	<5	<5
2017	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA
2018	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA

NA = not analysed

Table 14
Occurrence of heavy metals and disinfection by-products in desalinated water of Rabigh MED Plant

Year	Cd (ppb)	Cr (ppb)	Se (ppb)	Pb (ppb)	Hg (ppb)	As (ppb)	TTHM (ppb)	$CHCl_3$ (ppb)	$CHBrCl_2$ (ppb)	$CHBr_2Cl$ (ppb)	$CHBr_3$ (ppb)
2011	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2012	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2013	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2014	<1	<1	NA	<1	<1	<1	≤1	<0.03	<5	<5	<5
2015	NA	NA	NA	NA	<1	<1	≤1	<0.03	<5	<5	<5
2016	NA	NA	NA	NA	<1	<1	≤1	<0.03	<5	<5	<5
2017	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA
2018	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA

NA = not analysed

Table 15
Occurrence of heavy metals and disinfection by-products in desalinated water of Ummluj MED Plant

Year	Cd (ppb)	Cr (ppb)	Se (ppb)	Pb (ppb)	Hg (ppb)	As (ppb)	TTHM (ppb)	$CHCl_3$ (ppb)	$CHBrCl_2$ (ppb)	$CHBr_2Cl$ (ppb)	$CHBr_3$ (ppb)
2011	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2012	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2013	<0.002	<0.004	<0.03	<0.05	<0.009	<0.03	<0.23	<0.03	<0.05	<0.05	<0.10
2014	<1	<1	NA	<1	<1	<1	≤1	<0.03	<5	<5	<5
2015	NA	NA	NA	NA	<1	<1	≤1	<0.03	<5	<5	<5
2016	NA	NA	NA	NA	<1	<1	≤1	<0.03	<5	<5	<5
2017	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA
2018	<1	<1	NA	<1	<1	<1	NA	<0.03	NA	NA	NA

NA = not analysed

(Tables 5–15). For THMs, this is somewhat surprising, considering the values were significantly above the detection limit reported from MSF produce water from the Red Sea by La Roux et al. [6].

4. Conclusions

Routine Monitoring of six toxic elements (As, Hg, Pb, Cd, Se and Cr) in produced water from SWC thermal desalination plants on the Arabian Gulf for 20 y and the Red Sea for 8 y indicated that at all times the concentrations of all the elements were either not detectable or far below the SASO and WHO regulated values.

Chlorinated disinfection by-products (THMs) monitored in produced water were also found to be well below the regulated SASO and WHO values, with bromoform as the predominant species. This monitoring of the potential toxic contaminants over two decades indicates that the desalinated water produced by SWCC Plants has been safe for human consumption over the study period.

Episodes of elevated heavy metals did not appear to be connected to local pollution events, but with larger scale events affecting the entire Arabian Gulf.

While this program was limited to only six toxic metals and the main THMs, the current quality monitoring program within the SWCC monitors 18 metals along with DBPs and other organic materials, as required to monitor adherence to the SASO and WHO regulations, and will be reported on in a future publication.

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Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2022.28242

263 (2022) 265–266
July

Advancing water sustainability in Bahrain through water resource management knowledge platforms

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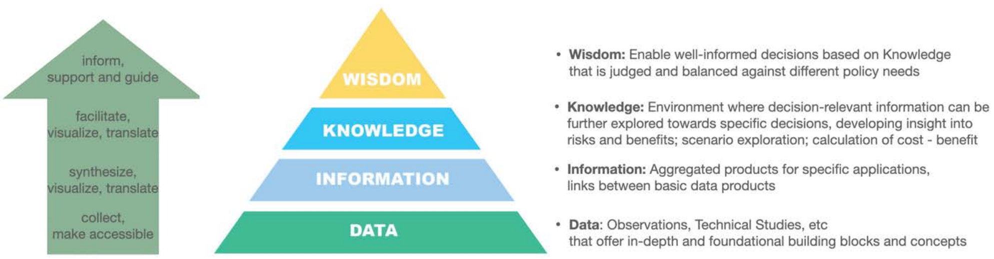
ABSTRACT

Water management poses a critical challenge for Bahrain, as demonstrated by the country's integrated water resources management SDG 6.1.5 scoring of 39/100 for 2020. However, the Kingdom is engaging progressive and proactive institutions, such as the Ministry of Oil of Bahrain (MOO), to respond to these challenges. MOO is working to implement a countrywide Integrated Water Resources Management (IWRM) program with the aim of building a resilient water sector for future development and climate change in the Kingdom of Bahrain. To this end MOO is hosting the Water Resources Management Unit (WRM) to implement this project. Through this activity, MOO has identified specific IWRM needs such as tool development and practical process support to address the country's sustainability goals. MOO/WRM and their partners are developing and implementing core building blocks for monitoring and analysis of water resources information, scenarios and alternatives, which should help guide their IWRM efforts. These tools and capabilities, strengthened by a targeted capacity-building program, will assist the Kingdom to improve water sector data information sharing, to open doors for improved public participation in IWRM dialogue, while actively identifying, designing, and evaluating the potential impacts of water management policies and projects.

Developing new IWRM plans at the country-level involves understanding assumptions regarding water demand projections as well as favored water supply and wastewater treatment options. However, such preconditions might not be the optimal balance between infrastructure and other strategies available to water resources planners and decision makers to optimize the potential impacts of various water resources management levers on quality potable water service provision, maximization of water reuse, and reduction of the environmental impacts of water production and wastewater discharge. The tools developed for WRF support should be flexible and extensible, in the case of Bahrain allowing for the analysis of key uncertainties such as climate change and



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Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

the costs of labor and energy inputs, as well as strategies such as artificial groundwater recharge, rainwater harvesting, and greywater reuse in new constructions.

Therefore, developing and implementing a comprehensive and flexible IWRM model that takes into account a variety of uncertainties, and both infrastructure and other strategies can be a constructive driver for identifying solutions that enhance the resilience of the country's water resources. The new WRM planning and analytical tools will be developed in an open data environment that can link water to energy, industry, health, environment and other sectors, and will include two allied Knowledge Platform elements, (1) a Decision Support System (DSS) based on the Water Evaluation and Planning (WEAP) model; and (2) a web-based Water and Climate Knowledge Platform (WCKP). Together, these will serve as quantitative modeling environments to assess water resource vulnerabilities and potential impacts of water management strategies.

Keywords: Water management; Water resources; Sustainability

Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28243

263 (2022) 267–281
July

Development of water information system for the Kingdom of Bahrain

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Received 28 February 2022; Accepted 8 May 2022

ABSTRACT

The creation of an effective water information system is essential for the formulation of sustainable water resources management, especially in countries where absolute water scarcity exists. This paper reflects on the experience of the Kingdom of Bahrain in developing the first part of its water information and management system – the Bahrain Water Resources Database (BWRDB). The prime objectives of the database are: (i) to provide a reliable, timely, up-to-date, standardized and internationally comparable water data and relevant information for knowledge sharing and dissemination; (ii) to support effective evidence-based decision and policy-making processes in water resources planning and management; and (iii) to provide water data and relevant information for tracking and reporting on progress against the sustainable development goal 6 targets and global indicators. The approach employed for the development of BWRDB is based on the globally accepted experiences in water information storage and management and data quality standards. The developed methodology includes three complementary phases: assessing data and information needs; data collection and quality control; and integration with GIS visualization tools and web-portal facilities. The third phase of the database development is yet to be implemented and will therefore not be covered in this paper. In its current version, the water information system is a simple MS Excel spreadsheet platform comprising 13 components, 31 sub-components and more than 440 statistical topics or variables covering a wide range of data on water resources and uses. It is, however, viewed as a work-in-progress project with ongoing development and improvement in scope and functionality. Being already put in practice, the BWRDB has played a key role and proved to be a valuable tool and a solid information base for serving the previously mentioned objectives. The paper concludes with a series of important next step actions, including strengthening the water data institutional framework by fostering inter-institutional coordination; and constantly upgrading and improving the database as more water data become available and needs for further software applications and evaluation processes arise.

Keywords: Water information system; Sustainable water management; Water data institutions; Water data monitoring system; Kingdom of Bahrain

1. Introduction

In arid regions, freshwater resources may at times be limited to the extent that demand for water can be met only by going beyond sustainable use [1]. Bahrain is not an exception, overexploitation from the available freshwater resources coupled with an inefficient use of water has exerted a major pressure on the water resources, leading to a significant environmental and socio-economic consequences. Over the last four decades, various measures and policy instruments to bring water demand into balance with supply and to ensure effective and sustainable water management have been implemented. These include institutional and legislative reforms and restructuring, supply augmentation through water reuse and desalinated water, and the introduction of numerous policy measures and interventions in the form of demand management instruments. However, the country still faces severe water scarcity. For example, in 2016, the country's level of water stress

Presented at the 14th Gulf Water Conference: Water in the GCC… Towards Economic Efficiency and Financial Sustainability, 13–15 February 2022, Riyadh, Saudi Arabia

1944-3994/1944-3986

reported at 138%[1] [2]. Furthermore, in spite of the endorsement of the National Water Strategy and its Implementation Plan (NWSIP) in 2018, the country still suffers from major water management and sustainability shortcomings.

Experiences from around the world demonstrate that sustainable water management can only be realised with a rigorous evidence-based decision making that in turn requires a solid and reliable water information base [3]. They also show that efficient water resources management cannot exist without effective access to and management of the necessary data and information [4]. However, when embarking on a task of the creation of an effective water information system, water resources planners and administrators are usually faced with the challenges of (i) how to organise existing water data and water-related information; (ii) how to manage the multiplicity of water data institutions and data delivery formats to ensure flexibility, efficiency, and comparability of datasets; (iii) how to organise the data sharing and information transfers between stakeholders and different data users; and (iv) how to set up and improve data access and processing capacity of the water information system [4].

Countries differ in their capability in developing water information systems depending on their financial ability, institutional arrangement, technical capacity and availability of supporting Information Technology (IT) infrastructure [3]. Obviously, countries with serious water problems such as the case with Bahrain will be the ones in vital need to develop effective water data management systems.

A substantial body of literature has been devoted to developing water information management systems [3,5–18]. In Bahrain, attempts to compile, store and manage water information in a systematic manner dated back to the 1940s of the last century when the Bahrain Petroleum Company (BAPCO) begun to compile large amounts of data and records on water wells and water levels and quality [19]. In 1980, Groundwater Development Consultants (GDC) produced and compiled much water information on these aspects together with additional data on the aquifers and aquitards hydraulic properties, including an extensive hydrogeological and hydrochemical mapping [20]. Prior to that date, in 1979, the Food and Agriculture Organisation of the United Nations (FAO) collected, stored and analysed large amounts of hydrometric, hydrogeological and hydrochemical information on Bahrain as part of an extensive regional study on the shared water resources in the Arabian Peninsula [21].

The country's computer-based efforts towards the development of water information systems commenced in 1985 with collaborative work between the then Water Resources Bureau and the Central Statistical Organisation; the resultant was the creation of a water information system known as Groundwater On-Line System (GWOS). The system comprises on-line computer facilities for nine files: water wells, water license, water meters, water abstraction, water salinity, water analysis, water levels, water codes, and reporting files. Collaborative work with the United Nations Development Programme (UNDP) in 1994 resulted in the establishment of a state-wide groundwater information system termed the Bahrain Groundwater Information System (BGWIS), with the United Nations' Groundwater for Windows (GWW) software being used as an application platform. The system contains one master file and numerous hydrogeological, hydrochemical and geometric main files, including files on thematic maps, graphics, and geological cross-sections [22,23]. In 1998, the Bahrain Centre for Studies and Research (BCSR) forwarded a proposal aimed to link this system to a hydrological geospatial platform – signified as Groundwater Resources Geographical Information System (GWRGIS) [24].

Al-Junaid developed a GIS-based tool for visualizing and handling water data on a sample of boreholes water quality data in the east of Bahrain using ArcView software with a customised graphical user interface [25]. A key conclusion from the thesis is that the developed database is capable of storing data in Excel spreadsheets format and generating visual displays of annual reports on water quality analysis and trends. In 2006, the Water Resources Directorate (WRD) presented a preliminary proposal for the establishment of a GIS-based digital groundwater information system with an end-user interface [26]. This was followed in 2009 by a more detailed project document [27] which integrates two initial proposals; namely, (1) establishment of a water information system; (2) upgrading the groundwater monitoring system; that proposal was also reviewed and evaluated by UNDP for potential technical assistance.

Schlumberger Water Services (SWS) [28] has submitted a document for the implementation of the proposed data management system called the National Integrated Water Resources Information System (NIWRIS). Concurrently, Ribeka presented another customised draft proposal – the Groundwater Information and Monitoring System (GWIM-System) – designed to upgrade the existing groundwater monitoring system and to integrate all the available water data and information into a groundwater information system [29]. Both proposals aimed at, although from slightly different perspectives, improving the existing water datasets by adopting advanced software solutions, including GIS-related software in the form of a groundwater data storage and management system. Unfortunately, none of these proposals has been materialised primarily due to financial constraints. Al-Thawadi [30] developed a relational database for boreholes data using MS Access platform. His database comprises five files, namely; well information, drilling information, full chemical analysis, water meters, and wells photos. The researcher concluded that it would be important to initiate more files such as observation wells network, well abstraction, geophysical logging and pumping tests at later stages to further assess the viability of the database.

This paper provides an overview of the development and organisation of the Bahrain Water Resources Database (BWRDB). The remainder of the paper falls into four sections. Section 2 provides the general background and rationale behind the development of the system. Section 3 describes the employed database development methodology. Section 4 covers the scope and structure of the BWRDB. The final section presents a summary and makes general recommendations as how to enhance and upgrade the BWRDB in terms of scope and functionality.

[1] More than 70% is considered to be very high stress.

2. Background and rationale

Rising demand for freshwater, coupled with increased volatility in global climate patterns means that robust and timely information to support decisions about allocating and managing water resources are more valuable than ever [31]. Integrated water resources management and the assessment and monitoring of water resources and their uses call for improved water statistics that are based on consistent concepts, definitions and terminology and are better integrated with economic, social and environmental statistics [32]. Such water data and related contextual information are also vital for tracking the progress on sustainable development goal 6 (SDG 6) of the Sustainable Development Agenda 2030 (SDGs), the goal that sets to "ensure water availability and sustainable management for all".

As pointed out in Section 1, a large amount of water datasets is available and somewhat easily accessible in Bahrain, but these are generally fragmented, incomplete and heterogenous. This simply calls for an action to organise and maintain these datasets into a consistent, more efficient, harmonised and internationally comparable water information system.

Specifically, the objectives of the BWRDB are:

- to set up a mechanism to organise and tie together water and water-related data and information into a reliable, systematic, consolidated, consistent, timely, and internationally comparable water storage and information system;
- to establish an efficient water data management strategy and analysis tools to support the rigorous evidence-based decision-making process in water resources planning and management;
- to promote good practice in data management and data sharing and information exchange among national institutions and regional and international organisations;
- to foster coordination and collaboration among the water data national institutions and stakeholders and between data producers and users;
- to enable statistical capacity development and to develop human resources capacities to enhance the quality and efficiency of the water data management and administration, and to improve national water data monitoring and reporting capabilities;
- to provide water data and relevant information to support tracking the country progress against SDG 6 targets and global indicators; and
- to meet the specific regional requirements set by the Gulf Cooperation Countries Unified Water Strategy and its Implementation Plan (GCC-UWSIP).

3. Methodology

The BWRDB methodology largely draws on experiences from various international organisations on the development of water data storage and information management systems. In particular, it has been basically built based on the following efforts and contributions: the United Nations Statistics Division (UNSD) and the United Nations Environment Programme (UNEP) Global Unified Water Questionnaire [33], the United Nations International Recommendations for Water Statistics UN/IRWS [32], the multi-purpose conceptual and statistical framework globally known as the Framework for the Development of Environment Statistics (FDES) [34], the FAO's Global Information System on Water and Agriculture – FAO/AQUASTAT [35], OECD/Eurostat Joint Questionnaire on Inland Waters – JQ-IW [36], the reading on International Environmental Statistics developed by the United Nations Economic Commission for Europe (UNECE) [37], the Organisation for Economic Co-operation and Development (OECD) environmental indicators [38], and the UNECE guidelines for the applications of environmental indicators [39].

It has also taken into consideration the International Standard Industrial Classification of all economic activities (ISIC) [40], the principles of the System of Environmental-Economic Accounting of Water (SEEA-Water) [41]. The methodological issues related to the tracking progress towards SDG 6 targets and global indicators are based on the definitions, rationale and methods of computation proposed by the UN agencies on water and sanitation-related indicators [42]. In addition, the country-specific conditions and regional requirements were fundamentally considered during the development of the database.

The developed BWRDB methodology is defined in three complementary phases:

- assessing data and information needs (the initial stage of the database development);
- data collection and quality control (the first implementation stage); and
- integrating and interfacing the generated data and information with a GIS-based platform and web-portal facilities (the second implementation stage).

3.1. Assessing data and information needs

Water data systems need to incorporate not only water data, but also other relevant data to fully serve the purpose of supporting water decisions [43]. Water data and relevant information originate from different sources and produced by diverse institutions and stakeholders at different levels of quality and spatiotemporal coverage using a variety of methods [4]. This phase of the database development includes identifying, prioritizing and assessing water data and information in terms of data sources,[2] data availability and accessibility, data topics, data providers and production procedures. The data and information needs assessment is summarised in Table 1. The assessment process has also touched upon the status of the existing national water data monitoring systems in terms of system design, spatial coverage, operating requirements, reliability of information, instrumentations and data analysis and report generation facilities.

Clearly, the table shows that water data and information required for the development of the water information system are very broad and complex, and dispersed independently over a variety of data producers with

[2] The term "data sources" is used here as defined by reference [32].

Table 1
Summary of the data and information needs assessment

Data sources	Data topics and variables	Data providers
Hydrological monitoring data: These are mainly *in-situ* monitoring data obtained from groundwater monitoring networks.	– *In-situ* observation of historical data on groundwater levels and quality. – Measured historical data on groundwater abstraction and sectoral groundwater use. – Data on the number of water meters installed.	Ministry of Works, Municipalities Affairs and Urban Planning (MoWMAUP) – Agriculture Engineering and Water Resources Directorate (AEWRD)
Administrative data: These types of data are broad in nature and are usually kept by the concerned authorities for administrative, water resources assessment and management purposes, long-term planning and data sharing and dissemination, including geospatial data, and off-line data on rules and regulation enforcement, water license conditions, etc.	– Hydrological data on boreholes logs, aquifer geometry, lithology, hydraulic properties, and geophysical logging. – Data on numbers of boreholes drilled, locations and ownership. – *Ex-situ* data on pumping tests, well yields and aquifer recharge. – Data on springs discharge, number of springs and locations. – Numbers and geospatial data on geographical locations and distribution of hydrological and monitoring data points. – Hydrologic measurements on springs flows and quality. – Topographic and contour maps on groundwater-related datasets. – Measured datasets on volume of wastewater flows and quality of wastewater produced, reused and discharged of to the environment, plants design capacities, sludge production, as well as data related to sanitation services infrastructures. – Measured datasets on quantity and quality of desalinated water produced, desalination plants design capacities and data and information on infrastructures related to drinking water services. – Number of establishments and employment in drinking water and sanitation services. – *Ex-situ* laboratory data on chemical and microbiological quality of drinking water and reused wastewater at end users' outlets. – Off-line data and information on water and sanitation regulations and laws, water use permits, water sales, water tariffs, etc.	– MoWMAUP – AEWRD. – MoWMAUP – Sanitary Engineering Planning and Projects Directorate (SEPPD) – MoWMAUP – Sanitary Engineering Operation & Maintenance Directorate (SEOMD) – Electricity and Water Authority (EWA) – Water Production Directorate (WPD) – EWA – Water Transmission Directorate (WTD) – Ministry of Health (MH) – Public Health Directorate (PHD)
Environmental monitoring data: Includes data collected from *in-situ* measuring points used for monitoring changes on ecosystems health and ambient water quality.	– Data on the state of environment and quality and health of aquatic ecosystems. – Amounts of sediments and nutrients load to receiving water. – Number and locations and distribution of the monitoring points (this may also be regarded as administrative data).	Supreme Council for Environment (SCE) – Environmental Policies and Planning Directorate (EPPD)

(Continued)

Table 1 Continued

Data sources	Data topics and variables	Data providers
Census and other economic and demographic surveys data: Census and surveys of households and establishments etc.	– Population censuses and population projections. – Percentage of the population connected to drinking water services. – Percentage of the population connected to sanitation services. – National accounts and other economic-related data. – Other demographic and socio-economic domains information.	– IGA – MoWMAUP – EWA
Agricultural data and surveys: Statistical and surveys-related data on agriculture variables, including geospatial data.	– Agricultural areas, crop patterns, crop yields and production, evapotranspiration, lands ownership, manpower in agriculture. – Geospatial data on soil patterns and characteristics, agricultural land areas, arable lands and other agriculture statistics. – Surveys on groundwater quality.	– MoWMAUP – AEWRD – MoWMAUP – Agriculture Statistics Department (ASD) – IGA
Meteorological monitoring data: *In-situ* data obtained from meteorological stations.	– *In-situ* observation and/or real-time data on various climatological parameters. – Numbers of meteorological stations and their geographical distribution (this may also be regarded as administrative data).	– Ministry of Transport and Communications (MTC) – Meteorological Directorate (MD) – Other private meteorological stations
Other environmental data: Various types of somewhat administrative and/or geospatial data and water-related information, provided by several institutions, stakeholders and private sectors.	– Land use patterns, land areas, land covers, biodiversity, etc. – Reported data on groundwater abstraction from private wells. – Data on industrial lands, industrial permits, industrial standard classification (ISIC), etc. – Bottled water imports and exports. Data on bottled water use. – Measured data on wastewater flows from private urban and industrial wastewater plants. Data on numbers of plants, establishments and employment characteristics. – Measured data on production from private desalination units. – Data on numbers of plants and employment characteristics.	– IGA – Survey and Land Registration Bureau (SLRB) – Topographic Survey Directorate (TSD) – Ministry of Industry, Commerce, and Tourism (MoICT) – Other stakeholders and private sectors who have their own wastewater treatment and/or desalination facilities
Research data: These are mainly supplementary or gaps fillings primarily of derived nature water data and related information provided by various academic institutions, research centers, consultancy studies, international and regional agencies.	– Supplementary hydrological, hydrometric and meteorological data from various consultancy and academic assessment studies and surveys. – Forecast products, outputs from predictive models, and inference data from remote sensing and other emerging technologies. – Specialised reports and databases of the regional and international organisations.	– Academic institutions – Research centers – Specialised consultant firms – International and regional organisations

numerous sources being used for their production and storage. Moreover, some institutions are having different departments in charge of producing, maintaining and managing water data. Our analysis has also shown that, although all the data producers are operating at the national level, the current institutional and legislative framework lacks the necessary inter-institutional coordination and legislative and institutional tools and procedures that organize and guide the processes of collection, harmonising, storing and dissemination of water data and relevant information. Apparently, the multiplicity of data providers and the absence of proper institutional coordination has led to the existing datasets being usually heterogeneous, incomplete and not comparable.

As a solution to this challenge, the so-called soft approach that focuses on collaboration and coordination arrangements among various water data institutions and other stakeholders were adopted. In this approach, parties formalize their working relationship in a written agreement setting out their respective roles and responsibilities and their commitment to assist one another [3]. Considering that the principal institutional reform for water resources management as a whole had been achieved through the establishment (1982) of the Water Resources Council (WRC)[3] and later by reactivation (2009) of this council with additional mandates and responsibilities, the developed approach appeared to be appropriate for fostering water data inter-institutional coordination.

The Information and eGovernment Authority (IGA) – who is the national statistical office and prime custodian of SDGs monitoring and reporting – took the leading role in coordinating this water data institutional arrangement. During the process, all the water data institutions were approached and several meetings were regularly held to explain the importance of having access to adequate water data and rational data production, and to ensure commitment and involvement of all institutions concerned with water data management. The core of this institutional arrangement is that water data and related information compiled by various data providers are to be coordinated and fed to IGA for data storing, knowledge sharing and dissemination at national, regional and international levels to ensure harmonisation, consistency and international comparability. At a later stage, it is foreseen that the WRC shall closely collaborate and coordinate with the IGA and play an important and supportive role in enhancing this institutional arrangement.

On the other hand, our assessment reveals that the national water data monitoring systems are inadequate and are gradually deteriorating with several shortcomings, including spatial coverage which is sparse and incomplete, common standards and guidelines are absent, groundwater quality monitoring is practically non-existent, in many cases advancement in IT is not incorporated, some water data monitoring points ceased to operate or being diminishing in numbers, and information generation and reporting capabilities are poor. This is another challenge that also needs to be considered and overcome from the institutional reform perspective.

3.2. Data collection and quality control

This phase of the database development involved designing and implementing of comprehensive data collection programme. This includes data and relevant information compilation, highlighting data gaps and limitations, data standardization and data verification and validation for quality assurance. The programme also entails the generation of information and indicators to support SDG 6 monitoring and to cater for the specific requirements of the GCC-UWSIP.

Most of the data topics and variables of interest were made readily available and accessible from various institutions and stakeholders (Table 1) with varying levels of temporal coverage. However, data gaps and limitations were inevitable as some data were not available, while other data were seemingly available but could not be attained due to several constraints. Data standardization was necessary to ensure consistency, comparability with the internationally accepted standards, including the definition of terms, metadata documentation, data formats and units of measurements and calculation rules and procedures. Data verification and validation to ensure quality assurance was achieved based on water data standards and expert checks and opinion substantiated by frequent meetings and consultations with the concerned personnel of the key stakeholders. The process involved checking for accuracy, data balancing, expected order of magnitude and extensive corrections for various datasets, primarily those related to groundwater abstraction and wastewater flows. However, some datasets are still in the process of being validated and updated.

The collected and verified water data and relevant information were then stored and maintained in MS Excel spreadsheet files. Subsequently, a rather straightforward two-digit components/sub-components and variables line coding system was developed for variable identification as will be explained in Section 4.

3.3. Integration database with GIS-based platform and web-portal facilities

This phase is concerned with integrating and interfacing the existing datasets with GIS visualisation tools and web-portal facilities using an advanced user interface such as Oracle, MS SQL Server, MySQL with thematic mapping and graphing facilities, appropriate modelling applications, and data storage in SQL database servers with the ability to perform complex spatial queries as well as a built-in-reporting tool in the form of a relational database. Data and information interoperability and registration of off-line data files that are normally only available in PDF and MS Word formats (i.e., some economic data, water rights and regulations and aquifer hydraulic properties files) would also be considered at this phase of the database development to

[3] A governmental body formed from the concerned ministries and authorities and headed by the Deputy Prime Minister. WRC is responsible for drawing the country's overall water policies and strategies; ensuring effective and efficient cooperation and coordination among the concerned authorities; setting up priorities for work plans and policy programmes; and following up and coordinating policies development and implementation.

enable transformation into a more readily usable format. As previously indicated, this phase represents the second implementation phase of the database methodological development that is currently under initial consideration and will therefore not be further covered in this paper.

4. Scope and structure of the BWRDB

In its current initial version, the BWRDB is a robust, simple and flexible metadata-driven MS Office Excel Spreadsheets data management system. It was originally developed as part of a consultancy agreement between the IGA and the author of this paper, and then incrementally upgraded and slightly aligned to address the specific requirements of the strategic objectives of the NWSIP 2018–2030 and the GCC-UWSIP 2015–2035 [44]. The scope of the BWRDB covers a wide range of water data and their uses as well as relevant information and indicators. The BWRDB organises these datasets in a simple manner into two Master Tables comprising 13 Main Tables[4] (Components), 31 Sub-components, and more than 440 statistical topics or variables. Master Table I: Water Variables (BWRDB_WVAR) contains 10 Components, and Master Table II: Supplementary Variables (BWRDB_SVAR) contains three Components. Fig. 1 shows the BWRDB interface, while the scope and structure of the database is diagrammatically illustrated in Fig. 2.

The first component brings together water data and statistics related to water resources inflows and outflows within the environment. Component 2 groups together statistics relevant to freshwater abstraction and use. Component 3 includes statistical topics on water supplied by the water supply industry and information on population served by drinking water services. Statistics and information relevant to wastewater generation and treatment classified by their type and levels of treatment are included in component 4. Component 5 provides supplementary datasets to those described in the previous component, including population sanitation coverage. Component 6 puts together water data and relevant statistics on water use efficiencies, costs and pricing and other water demand management aspects. This component is currently incomplete; development and categorization are still in progress[5].

The seventh component grouped the water quality data broken down by source, aquifers and levels of treatment. Data on groundwater levels, broken down by aquifers, are assembled in component 8,[6] while component 9 contains a variety of statistics and information on water infrastructure classified by water source and type of monitoring. Component 10 covers water data and statistics related to establishments and employment characteristics in water sectors. The physical and demographic and socio-economic domains related to water use and management are gathered and classified in component 11 (the first component in the Master File II). This component is also still being under continuous development. Component 12 groups together the available climatological parameters. The final component contains a set of economic and social variables and indicators. Efforts are underway to improve this component in terms of structure and inclusion of new variables and indicators.

Table 2 provides descriptions of the database components and sub-components along with their codes and data status and time span coverages. Further details regarding

[4] Each main table or component contains fields (Columns) and records (Rows). The fields describe the values (information) stored and the records are the variables or the categories of interest.

[5] At a later stage, this component shall host and register sub-components of some off-line files such as those related to water regulations and licensing.

[6] At a later stage, this component shall host sub-components related to the aquifer's hydraulic parameters.

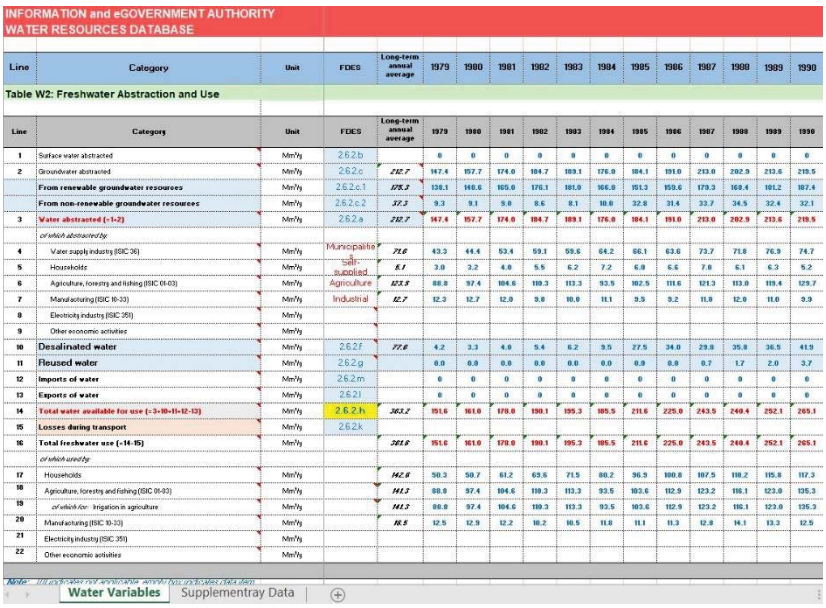

Fig. 1. BWRDB interface.

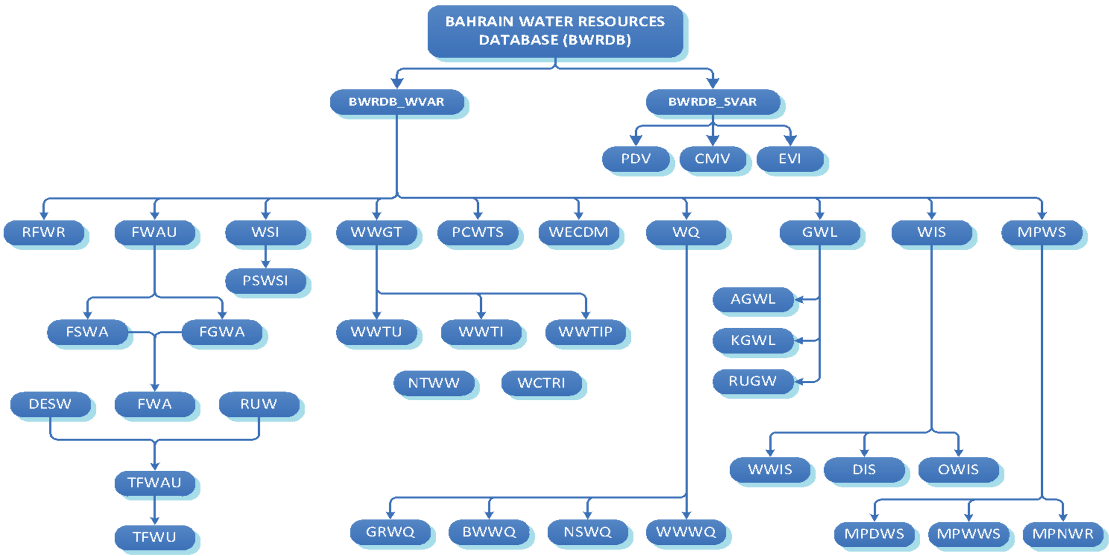

Fig. 2. Scope and structure of the BWRDB.

the structures of the BWRDB components and sub-components can be found in [44].

4.1. Setting variables codes

A rather straightforward two-digit component/sub-component coding system has been developed by assigning a code for each variable. The coding system simply combines the initial of the respective variable with its line and component numbers. A slightly distinctive coding setting was assigned to the variables describing the long-term annual averages, given their positioning in the tables.

To illustrate (Table 3), the variable freshwater abstracted by households (self-supplied) (FWAHH) is located in line (row) 5 of Component 2 "Freshwater Abstraction and Use" and is therefore coded FWAHH_02_05. Likewise, the variable wastewater treated in urban wastewater plants (WWTU) is located in line (row) 7 of Component 4 "Wastewater Generation and Treatment" and is therefore assigned the code WWTU_04_07. The examples given for the variables signifying the rainfall and net water supply by the water supply industry can be correspondingly explained.

The variable total dissolved solids concentration in the Sub-component 7.3 "Blended Water Quality" is coded WQTDS_7.3_04 because it is placed in line (row) 4 of Sub-component 7.3 of Component 7.0 Water Quality (WQ). According to [33], the long-term annual averages (LTAA) are to be computed as arithmetical means for datasets of not less than 30 y. Considering that LTAA is to be computed for most of the variables of interest, we have chosen to assume zero (00) line (row) for this variable, it is therefore coded differently. The coding FGWA_LTAA_00 signifies the variable initial of fresh groundwater abstraction (FGWA), its status as being LTAA and its arbitrary designated (00) line number.

The proposed coding system appears to be sensible and logical at this early stage of the database development, especially that, it clearly differentiates between similar variables such as water use by sectors, wastewater treated at various levels of treatment and most of the water quality parameters. One could argue, however, that this coding system implies some shortcomings; for example removal of an existing variable or creation of a new variable will necessitate recording of several other variables below. Furthermore, placing of the LTAA variables might pose a problem. Yet, it is believed that since the BWRDB is perceived to be as a work-in-progress, such coding problems could be easily overcome and improved in the next stages of the database development.

4.2. Examples for the database component

In Table 4, we present example data for component 2 "Freshwater Abstraction and Use" for the years 2008–2017. Fig. 3 shows the sub-components and statistical topic of this component. It should be noted here that the term freshwater abstraction and use is defined as follows [33]:

> Freshwater can be abstracted from surface waters (rivers, lakes etc.) and from groundwaters (through wells or springs). Water is abstracted by the public or private bodies whose main function is to provide water to the public (the water supply industry). It can also be directly abstracted by industries, farmers, households and others. The component asks for data on abstraction of freshwater, broken down according to the main activity of the water abstractor, as defined by the International Standard Industrial Classification of all economic activities (ISIC Rev. 4). The component covers the amount of water made available for use by abstraction, desalination, reuse and net imports. Total freshwater use equals total water available for use minus losses during transport. The component also covers the overall amount of water used by the main ISIC groupings.

The above definition implies that the terms "Water abstraction" and "Water use" are used here interchangeably,

Table 2
Database components/sub-components along with their codes and data status

Initial code	Component/sub-component/category	Remarks/data status and coverage
BWRDB_ WVAR	Bahrain Water Resources Database – Water Variables	Master Table I
Component 1.0: Renewable Freshwater Resources (RFWR)		
RFWR	Renewable Freshwater Resources	Sub-component 1.1.
Component 2.0: Freshwater Abstraction and Use (FWAU)		
FSWA	Fresh surface water abstracted	Sub-component 2.1. Not applicable to the Bahrain situation
FGWA	Fresh groundwater abstracted	Sub-component 2.2. Time-series records available for years 1979–2017. Data are disaggregated by sector in accordance with ISIC Rev.4
FGWR	Renewable fresh groundwater	Sub-component 2.2.1. Time-series records available for years 1979–2017. Data are disaggregated by sector in accordance with ISIC Rev.4
FGWNR	Non-renewable fresh groundwater	Sub-component 2.2.2. Time-series records available for years 1979–2017. Data are disaggregated by sector in accordance with ISIC Rev.4
FWA	Freshwater abstracted = FSWA + FGWA	Availability for years 1979–2017. Computed and disaggregated by abstraction by the water supply industry, and by sector in accordance with ISIC Rev.4
DESW	Desalinated water	Sub-component 2.3. Aggregated data, available for years 1979–2017
RUW	Reused water	Sub-component 2.4. Summed up data on treated sewage effluent. Availability for years 1982–2017
IOW	Imports of water	Excludes bottled water. Not applicable to the Bahrain situation
EOW	Exports of water	Not applicable to the Bahrain situation
TFWAU	Total freshwater available for use = FWA + DESW + RUW + IOW – EOW	Aggregated time series data available covering the years from 1979–2017
LDT	Losses during transport	Sub-component 2.5. Includes trans. losses only
TFWU	Total freshwater use = TFWAU – LDT	Time-series data available for years 1979–2017. Further computed and disaggregated by sector in accordance with ISIC Rev.4
Component 3.0: Water Supply Industry (WSI)		
WSI	Water supply industry	Sub-component 3.1. Data are available for years 1979–2017. Aggregated data, further disaggregated by sector in accordance with ISIC Rev.4
PSWSI	Population supplied by water supply industry	Sub-component 3.2. Total population served. Classification to urban and rural not applicable
Component 4.0: Wastewater Generation and Treatment (WWGT)		
WWG	Total wastewater generated	Sub-component 4.1. Not measured at present
WWC	Total wastewater collected	Sub-component 4.2. Availability for years 1982–2017
WWT	Total wastewater treated	Sub-component 4.3. Total aggregated data for years 1982–2017. Disaggregated by levels of treatment
WWTU	Wastewater treatment in urban plants	Sub-component 4.3.1. Aggregated total available for years 1982–2017. Data disaggregated by levels of treatment
WWTI	Wastewater treated in other (industrial) plants	Sub-component 4.3.2. Availability for years 1985–2017. Data disaggregated by levels of treatment
WWTIP	Wastewater treated in independent plants	Sub-component 4.3.3. Data available for one plant for years 2006–2016. Due to the small volume, data are included within urban plants
NTWW	Non-treated wastewater	Sub-component 4.4. Available only for some years
WCTRI	Wastewater collection, treatment, and reuse indicators	Sub-component 4.5. Data computed for years 2000–2016. Data for previous years not yet computed
Component 5.0: Population Connected to Wastewater Treatment (PCWCTS)		
PCWCS	Population connected to wastewater collection systems	Sub-component 5.1. Total population served. Classification into urban and rural does not apply to the Bahrain situation
PCWTS	Population connected to wastewater treatment systems	Sub-component 5.2. Total population served. Classification into urban and rural does not apply to the Bahrain situation

(Continued)

Table 2 Continued

Initial code	Component/sub-component/category	Remarks/data status and coverage
PNCWT	Population not connected to wastewater treatment	Sub-component 5.3.
Component 6.0: Water Use Efficiencies, Costs, and Demand Management (WECDM)		
WECDM	Water use efficiencies, costs, and demand management	Only a few data are available. The component is yet to be finalised in terms of data and possible sub-component classifications
Component 7.0: Water Quality (WQ)		
GRWQ	Groundwater water quality	Sub-component 7.1. Data are categorized by aquifers
AAWQ	Alat Limestone aquifer water quality	Sub-component 7.1.1. Time-series data available for years 2005–2017. Also available for specific years
KAWQ	Khobar aquifer water quality	Sub-component 7.1.2. Records are available for years 2005–2017. Also available for specific years
RUWQ	Rus – Umm Er Radhuma aquifer water quality	Sub-component 7.1.3. Time-series data available for years 2005–2017. Available for specific years
RJWQ	Ras Abu Jarjur Wellfield water quality	Sub-component 7.1.4. Time-series records are available for years 1985–2017
BWWQ	Blended water quality	Sub-component 7.3. Data are available for years 2005–2016
NSWQ	Natural spring water quality	Sub-component 7.4. Data are categorized by type of springs. Data are available only for specific years
LSWQ	Land springs water quality	Sub-component 7.4.1. Data are available only for specific years
OSWQ	Offshore springs water quality	Sub-component 7.4.2. Data are available only for specific years
WWWQ	Wastewater water quality	Sub-component 7.5. Data are classified as raw wastewater and levels of treatment. Data available up to the year 2017
RWWQ	Raw wastewater quality	Sub-component 7.5.1. Data are available for years 1996–2017
STWQ	Secondary treated wastewater quality	Sub-component 7.5.2. Data are available for years 1996–2017
TTWQ	Tertiary treated wastewater quality	Sub-component 7.5.3. Data are available for years 1996–2017
Component 8.0: Groundwater Levels (GWL)		
GWL	Groundwater levels	Data categorized by aquifers
AGWL	Alat Limestone groundwater levels	Sub-component 8.1. Time-series data available for years 2005–2017. Also available for some specific years
KGWL	Khobar groundwater levels	Sub-component 8.1. Time-series data are available for years 2005–2017. Also available for some specific years
RUGWL	Rus – Umm Er Radhuma groundwater levels	Sub-component 8.1. Time-series data available for years 2005–2017. Also available for some specific years
Component 9.0: Water Infrastructure (WIS)		
WIS	Water infrastructure	Data classified by type of water infrastructures
WWIS	Wastewater treatment infrastructure	Sub-component 9.1. Data are available up to the year 2016. Data computed and disaggregated by the required parameters. Many data gaps and limitations
DIS	Desalination infrastructure	Sub-component 9.2. Data are available up to the year 2016. Data computed and disaggregated by required parameters. Some data gaps
OWIS	Other water infrastructure	Sub-component 9.3. Data are available up to the year 2016. Data computed and disaggregated by required parameters. Many data gaps and limitations
Component 10.0: Manpower in the Water Sectors (MWS)		
MPWS	Establishments and manpower in the water sectors	Total employment and establishments in the water sector. Data classified by water sector (i.e., natural, desalination, wastewater)
MPDWS	Establishments and manpower in the desalination and water supply sector	Sub-component 10.1. Data available for years 2000, 2005, 2010, and 2015, but with some data gaps

(Continued)

Table 2 Continued

Initial code	Component/sub-component/category	Remarks/data status and coverage
MPWWS	Establishments and manpower in the wastewater and sanitation sector	Sub-component 10.2. Data available for years 2000, 2005, 2010, and 2015, but with some data gaps
MPNWR	Manpower in the natural water resources sector	Sub-component 10.3. Data available for years 2000, 2005, 2010, and 2015, but with some data gaps
BWRDB_ SVAR	Bahrain Water Resources Database – Supplementary Variables	Master Table II
Component 11.0: Physical and Demographic Variables (PDV)		
PDV	Physical and demographic variables	Not yet completed. It may be categorised into sub-components. Long time-series records available for most of the variables
Component 12.0: Climatic Variables (CMV)		
CMV	Climatic variables	Data are available for seven climatic variables for time span for years 1979–2017. Evaporation only for years 1983–2017. No time-series data for evapotranspiration
Component 13.0: Economic Variables and Indicators (EVI)		
EVI	Economic variables and indicators	Not yet completed but sufficient time-series records available for most of the variables. Shall host more subcomponents in the third development phase

Table 3
Coding system

Line	Variable	Variable code	Unit	LTAA	2015
5	Freshwater abstracted by households (self-supplied)	FWAHH_02_05	Mm^3/y		2.9
3	Net water supplied by water supply industry	NWSI_03_03	Mm^3/y		260.5
7	Wastewater treated in urban plants	WWTU_04_07	1,000 m^3/d		399.7
4	Total dissolved solids (blended water)	WQTDS_7.3_04	mg/L		246.0
12	Rainfall	CMVRAIN_12_01	mm		65.0
00	Long-term fresh groundwater abstraction	FGWA_LTAA_00	Mm^3/y		

Note: The figures in the last column represent the data values in their respective units of measurement.

meaning that water is abstracted from the environment and used in the economy [32]. It can be seen that the data are coherent, harmonised, standardized, internationally comparable, and are carefully aggregated (total water uses) and disaggregated (sectoral shares), well-checked for data balancing and order of magnitude to provide complete sets of water statistics. In addition, they have been reasonably coded and supported by standardized metadata. All the datasets are given in this component as annual averages expressed in volume per unit of time, million cubic metre per year (Mm^3/y). Apparently, however, data values in other components may be given in various units of measurements (i.e., as average annual values in other appropriate standard units of measurement, absolute annual values, in annual percentage terms, as estimated average values, etc.).

4.3. Putting BWRDB into practice

As mentioned in Section 1, Bahrain has approved its long-term NWS-IP 2018–2030 which is in line with the GCC-UWSIP 2015–2035 [45]. The country has also completed its baseline report for tracking progress towards SDG 6 monitoring [2,46]. These strategic activities relied almost entirely on water resources assessment, formulation of policy objectives and for tracking progress on SDG 6 targets global and regional indicators on the water data and relevant information as well as the derived national and global indicators made available and accessible from the BWRDB platform. In fact, the outcomes from these important projects gave proofs that these water data and relevant contextual information have significant elements and have highly contributed to the success of these projects.

5. Conclusions and recommendations

This paper has shared the experience of the Kingdom of Bahrain in developing and organising Phase 1 of its water information system. It has addressed some water data institutions and national data monitoring challenges facing the development of this system. In its current version,

Table 4
Example for database component: Component 2 "Freshwater Abstraction and Use"

Line	Category/Variable	Variable code	Unit	LTAA	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
1	Fresh surface water abstraction	FSWA_02_01	Mm^3/y		0	0	0	0	0	0	0	0	0	0
2	Fresh groundwater abstraction	FGWA_02_02	Mm^3/y		185.0	169.9	182.6	186.6	180.6	182.1	179.1	159.9	155.9	159.2
	- Renewable fresh groundwater	FGWR_02	Mm^3/y		127.1	112.4	123.2	127.3	132.4	134.2	130.5	112.6	107.3	103.8
	- Non-renewable fresh groundwater	FGWNR_02	Mm^3/y		57.9	57.5	59.4	59.3	48.2	47.9	47.1	47.3	48.6	55.4
3	Freshwater abstracted = FSWA_02_01 + FGWA_02_02	FWA_02_03	Mm^3/y		185.0	169.9	182.6	186.6	180.6	182.1	179.1	159.9	155.9	159.2
Of which abstracted by:														
4	Water supply industry (ISIC 36)	FWAWSI_02_04	Mm^3/y		72.8	59.4	64.6	72.4	63.8	60.9	57.3	35.2	33.3	41.2
5	Households (self-supply)	FWAHH_02_05	Mm^3/y		5.7	4.2	5.0	5.1	6.1	4.7	4.1	2.9	3.7	3.7
6	Agriculture, forestry, and fishing (ISIC 01-03)	FWAAG_02_06	Mm^3/y		90.0	87.7	94.9	91.1	91.3	97.4	98.4	103.9	102.5	97.7
7	Manufacturing (ISIC 10-33)	FWAMG_02_07	Mm^3/y		16.5	18.6	18.1	18.0	19.4	19.1	19.3	17.9	16.0	16.6
8	Electrical industry (ISIC 351)	FWAIN_02_08	Mm^3/y			Included within the manufacturing as available data do not permit further disaggregation by industrial type								
9	Other economic activities	FWAOEA_02_09	Mm^3/y			Included within the manufacturing as available data do not permit further disaggregation by industrial type								
10	Desalinated water	DESW_02_10	Mm^3/y		144.9	176.0	188.3	189.7	196.9	204.8	219.3	241.6	241.9	239.2
11	Reused water	RUW_02_11	Mm^3/y		40.4	38.9	36.2	38.3	37.5	33.1	32.3	30.6	37.4	39.5
12	Imports of water	IOW_02_12	Mm^3/y		0	0	0	0	0	0	0	0	0	0
13	Exports of water	EOF_02_13	Mm^3/y		0	0	0	0	0	0	0	0	0	0
14	Total freshwater available for use = FWA_02_03 + DESW_02_10 + RUW_02_11 + IOW_02_12 – EOF_02_13	TFWAU_02_14	Mm^3/y		370.3	384.8	407.1	414.6	415.0	420.0	430.7	432.1	435.2	437.9
15	Losses during transport	LDT_02_15	Mm^3/y		4.5	3.9	5.2	7.1	6.3	5.6	5.1	7.4	5.1	5.1
16	Brine flow at RAJDP	BFRAJ_02_16	Mm^3/y		12.5	11.6	12.6	12.9	9.1	9.2	10.3	8.9	10.3	9.7
17	Total freshwater use = TFWAU_02_14 – LDT_02_15 – BFRAJ_02_16	TFWU_02_17	Mm^3/y		353.3	369.3	389.3	394.6	399.6	405.2	415.3	415.8	419.8	423.1
Of which used by:														
18	Households	FWUHH_02_18	Mm^3/y		192.2	210.0	226.9	232.0	235.2	241.2	251.3	251.2	252.4	257.1
19	Agriculture, forestry, and fishing (ISIC 01-03)	FWUAG_02_19	Mm^3/y		139.2	135.0	138.0	138.0	138.4	138.2	138.0	140.3	144.5	142.1
	– Irrigated agriculture		Mm^3/y		139.2	135.0	138.0	138.0	138.4	138.2	138.0	140.3	144.5	142.1
20	Manufacturing (ISIC 10-33)	FWUMG_02_20	Mm^3/y		21.9	24.3	24.4	24.6	26.0	25.8	26.0	24.3	22.9	23.9
21	Electricity industry (ISIC 351)	FWUEI_02_21	Mm^3/y			Included within the manufacturing as available data do not permit further disaggregation by industrial type								
22	Other economic activities	FWUOEA_02_22	Mm^3/y			Included within the manufacturing as available data do not permit further disaggregation by industrial type								

Notes:
1. Zero values indicate data items not applicable.
2. Long term average (LTAA) values are not calculated in this table because of the limited data time span.
3. Brine flow at RAJDP is the brine flow rejected to the sea at the Ras Abu Jarjur Desalination Plant which uses non-renewable groundwater as feed water. This amount is to be deducted from the total water available for use because, although it is abstracted, it is not actually used. This variable reflects a country specific case (not shown in Fig. 3).

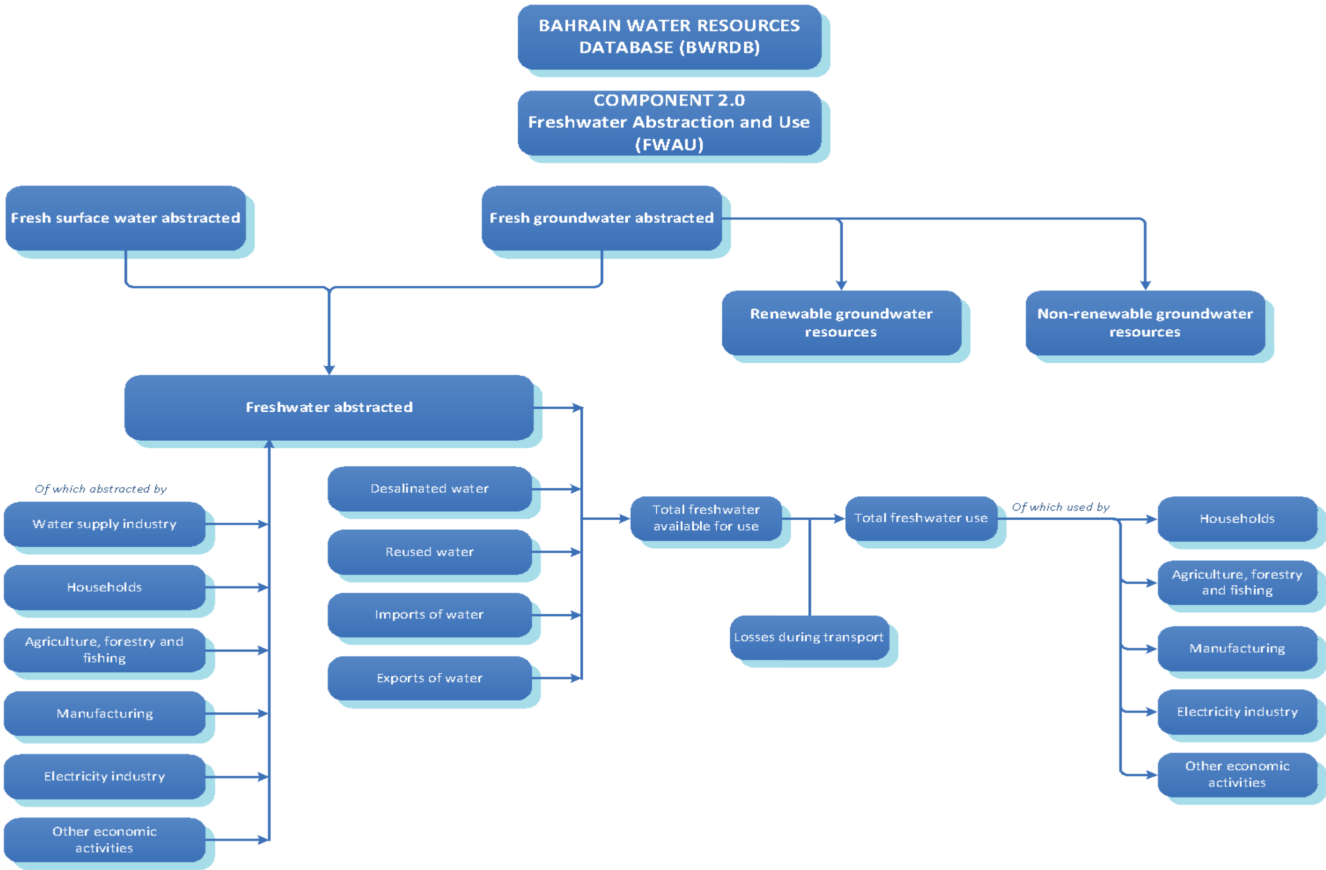

Fig. 3. Component 2 "Freshwater Abstraction and Use".

the BWRDB is a simple and flexible MS Excel platform comprising 13 components, 31 sub-components and more than 440 statistical topics covering a wide range of data and information on water resources and their uses. The BWRDB has basically been designed and structured to be a solid information base to inform sound decision making in water resources planning and management and to support monitoring of progress against SDG 6 global targets and indicators. Being already put in practice, the database gave sufficient proofs for serving and supporting the objectives of these strategic activities.

The paper has offered a number of important next steps actions for further improving the water information and data management system. It is necessary to strengthen the water data institutions by further fostering inter-institutional coordination and collaboration by formulating of a database administrator or inter-sectoral management team (technical steering committee) to be tasked with: (i) organising collaboration and coordination between institutions for more effective data sharing; (ii) specifying the different roles of the main actors and partners; (iii) defining the priorities and developing appropriate water data and information system procedures; (iv) setting up a protocol on the release of data and necessary security measures; (v) managing and controlling activities associated with the information system operation, performance, development, maintenance, data quality assurance and security enforcement; and (vi) improving human resources statistical capacities and implementing training in various database operations.

This committee may preferably be managed by the WRC to ensure better enforcement with close cooperation with the IGA. It is also crucial to improve the existing water data national monitoring systems in terms of data collection and quality control, and processing and reporting capabilities. Finally, great efforts are needed to constantly updating the database and integrating it with GIS-based visualization tools and geospatial data facilities, including mapping features, information-generation applications (modelling), statistical tools and web-portal services.

Acknowledgements

This paper is based on the author's consultancy contract with the Information and eGovernment Authority that then extended with the Arabian Gulf University, Kingdom of Bahrain. The author expresses his sincere thanks to these agencies for granting him permissions to publish this paper.

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doi: 10.5004/dwt.2022.28828

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