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ISBN 0-86689-078-5

Desalination Publications
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Balaban Desalination Publications

مؤتمر الخليج الخامس عشر للمياه
The 15th Gulf Water Conference

(2025) iii–viii
doi: 10.5004.dsal.2025.700093

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

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Preface

Over the past five decades, the GCC countries have witnessed an unprecedented and sustained economic and social transformation, which has been associated with one of the world's highest population and urbanization growth rates, coupled with rapidly changing lifestyles and consumption patterns. Such transformation has been associated with a rapid increase in sectoral water requirements that goes beyond their limited available freshwater resources.

Although the GCC countries are situated in one of the most water-scarce regions of the world with an extremely poor endowment of freshwater resources, they have done well in the provision of water supply to their populations primarily by relying on desalination technology, which is made possible by their strong economies and substantial financial and energy resources. Currently, a safe, affordable, and stable domestic water supply has been established in each country covering 100% of its population. However, municipal water supply systems are associated with substantial financial, economic, and environmental costs.

On the other hand, agricultural water demands, representing about 80% of the total water requirements in the GCC countries, have been met mainly by heavy groundwater abstraction, and to a lesser extent by treated municipal wastewater. However, a major concern is that the majority of these groundwater resources are non-renewable, are being extensively mined, and are rapidly depleting, while the remaining limited and renewable groundwater resources are being over-exploited beyond their replenishment rates, leading to their quality degradation due to saltwater intrusion.

In the past decades, to address the water sector challenges the GCC countries have been focusing on a supply-side management approach to meet the ever-increasing demands for water, manifested by the construction of desalination plants, dams, systems for groundwater abstraction, and reuse of treated wastewater. Recently, the countries have complemented this traditional approach by a demand-side management approach utilizing structural, sociopolitical, and economic policy tools to influence demand and achieve water use efficiency in the various consuming sectors.

Within the GCC countries' efforts to achieve effective water resources management, technology can play a major part as an enabler for both supply-side engineering measures and demand-side management and efficiency measures. The implementation of technology in the GCC countries' water management system has been more focused on the supply-side engineering measures and operation, and less on the demand and efficiency measures. Examples of these are technologies used to produce fresh and clean water (e.g., desalination and wastewater treatment technologies), and mathematical models that facilitate decision-making in the planning, management and optimal operation of water resources systems (e.g., simulation models for groundwater and surface water systems). The supply and demand systems can be better considered holistically both for longer-term planning and real-time operations facilitated by technology.

Recently, new generation of technologies, driven by the developments in information and communication technologies (ICTs), have been emerging providing powerful enabling tools for effective water management. Examples of these are smart water management technologies relying on ICTs to provide real-time, automated data to resolve water challenges, as well as for planning and operational purposes; e.g., SCADA in water supply, modern in-situ sensors and earth observation, improved metering and billing systems, or creation of "digital twins" of facilities/systems. Other examples include smart agriculture using sensors for data acquisition, transmission and presentation, and hydroinformatic systems which integrate numerical modeling and data science methods in a digital environment (typically GIS and cloud computing to facilitate data management, analytics, and visualization) that facilitate the conversion of data into information, subsequently into knowledge, and eventually management decisions.

As we stand on the brink of a technological revolution, i.e., the fourth industrial revolution, which will fundamentally alter and transform entire systems of production, management, and governance, it is expected that technology will have an impact on the entire water sector and its management-related activities. The current plethora of data coming from all types of devices together with the escalating increase in computer capacity is revolutionizing almost all sectors. The water sector system will not be an exception. For example, in the municipal water supply sector, combining the power of big data analytics, including Artificial Intelligence, with existing and future urban water infrastructure represents a significant untapped opportunity for the operation, maintenance, and rehabilitation of urban water infrastructure to achieve economic and environmental sustainability. Similarly, in agricultural water management, adopting smart water management systems, where sensors measure soil moisture in real-time and automatically irrigate the field without human intervention provide a major opportunity to enhance irrigation efficiency and optimize water use.

There will be a need for stocktaking of these modern innovations, explore their current adoption in the GCC countries, and explore policy, institutional, and technical facilitation of these technologies to improve overall water management and sustainability in the region. The advocated harnessing the potential of technologies in both the supply-side and demand-side management areas to achieve effective water management in the GCC countries. It promotes the exchange of experiences and discussion on the benefits, costs, risks, required human capacities, and barriers faced in their implementation.

The WSTA Fifteenth Gulf Water Conference is organized in Doha, State of Qatar during the period in collaboration April 28–30, 2024, in cooperation with Qatari General Electricity and Water Corporation (KAHRAMAA) and the GCC Secretariat General Secretariat (GCC SG). The conference is supported and scientifically endorsed by a number of international, regional, and local organizations, including: the United Nations Economic and Social Commission for Western Asia (UN-ESCWA), UNESCO Offices in Cairo and Doha, Food and Agriculture Organization (FAO), World Health Organization (WHO), Arab Organization for Agricultural Development (AOAD), International Center for Agricultural Research in the Dry Areas (ICARDA), International Center for Biosaline Agriculture (ICBA), International Water Management Institute (IWMI), International Desalination Association (IDA), Arab Water Utilities Association (ACWUA), Arabian Gulf University (AGU), Omani Water Society (OWS), European Desalination Society (EDS), and the Qatar Environment and Energy Research Institute (QEERI).

On behalf of the Conference Scientific Committee, I would like to thank all the authors and panelists from various parts of the world for joining us in our fifteenth Gulf Water Conference and for sharing their experience and innovative solutions in improving water sustainability and overcoming the water challenges in the arid GCC countries and Arab regions. I would like to express our sincere gratitude to the our esteemed and dedicated reviewers for their valuable time, expertise, and rigorous evaluation of the submitted papers.

Furthermore, we would like to express our thanks to Prof. Miriam Balaban for editing.

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

Conference Objectives

- Reviewing current and emerging technologies used in the various water sectors, improve their awareness, and identify their advantages, challenges, and limitations.
- Showing how the different technological means of implementation can promote the necessary transformative change in the water sectors.
- Presenting technological solutions implemented in the region and internationally to address water sector challenges.
- Discussing and highlighting the central role of investment in R&D in localizing and producing water sector technologies in the GCC countries to skate away from being just a market.
- Identifying the main barriers to the implementation of emerging technologies in the management of the water sector.
- Connecting water professionals to exchange experiences and best practice case studies in the GCC countries and other countries in the region on the use of technology in the water sector.

Conference Recommendations

1. Digitalization and the use of emerging technologies in the water sector

- Digitalization and emerging technologies have tremendous transformative potential for optimizing water management and enhancing its efficiency and resilience across the GCC countries. However, its employment and unlocking its potential in the water sector is considered slow due to a number of constraints and barriers that need to be addressed, which can be categorized into data, human capacity, modeling, infrastructure systems, and costs.
- There is a need to link water professionals and ICT professionals to overcome many of the constraints facing the employment of digitalization and emerging technologies in the water sector and coupling digitalization and cybersecurity in the water sector.
- It is important to incorporate emerging technologies and digitalization into academic and professional curricula related to the water sector to empower future generations of water professionals with advanced technological to address the pressing challenges facing water resources and contribute to a more sustainable future.

2. Sustainable Management of Desalination (localizing, mitigating impacts, and security)

- Desalination will continue to be the main water source in the water supply portfolio of the GCC and is expected to be increasing with time. Therefore, it is a strategic imperative to localize desalination in the region. Furthermore, it is also imperative to address desalination challenges in terms of energy efficiency, financial cost, and environmental impacts (i.e., air/GHGs emissions and desalination reject). Localization of the desalination industry in the region requires strategic planning and cooperation between policy makers, research centers and private sector to establish establishing an industrial ecosystem for desalination with active R&D as well as investment in innovative SMEs.
- Moreover, renewable and alternative energies represent a major opportunity for reducing emissions, and innovative technologies, including brine mineral extraction and electricity generation represents a potential solution for maximizing the benefit of desalination reject as well as reducing its impact on the marine environment.
- Desalination facilities, reliant on the quality of feed water, are vulnerable to oil spills as well as to other hazards in its feed seawater. A comprehensive oil spill management approach integrating advanced offshore cleanup, seawater intake, and onshore water pre-treatment processes is essential to robustly protect seawater quality and prevent desalination plant shutdowns.

3. Sustainable Management of Surface Water and Groundwater

- Recent climatological studies indicate increased frequency in extreme events of rainfalls in the region, which is attributed to global climate change, leading to less stationarity of historical climate data. It is important to maximize the utilization of the produced surface water and at the same time protect human life and infrastructure. Flooding risk maps and flood simulation based on Regional Circulation Models predictions represent an important activity in this regard. The natural drainage system of wadis to be re-identified and protected to reduce potential damage and to increase resilience of areas along wadi channel and downstream urbanized areas to flashflood hazards. An integrated approach that supports protection of cities and harvest part of the flashflood needs to be considered in the region.
- Groundwater, renewable and non-renewable, represents a major water source for all the GCC countries. Sustainability of non-renewable groundwater should be based on socio-economic criteria, while renewable groundwater will require plans for restoration. In addition to the demand management and conservation efforts, MAR represents a potential option for the supply side management, especially by surplus desalinated water and treated wastewater.
- Continuous and proactive monitoring, state of the art simulation modeling, and the existence of MIS are important components of groundwater resources and its management.

4. Maximizing Wastewater and Sludge Utilization

- To maximize the beneficial use of wastewater in treated wastewater reuse in agriculture, cooling, and energy generation, and energy and fertilizers production from sludge. A major push in this direction can be made by attracting private investors as part of the transition to circular economy of the water sector.
- Furthermore, decentralized wastewater systems have proven to be more efficient than the traditional centralized systems in terms of cost and operation. Establish a GCC network on energy conversion from wastewater.

5. Institutionalization of Water Safety Plans (WSP) and Sanitation Safety Plan (SSP)

Institutionalization and Implementing WSP and SSP, which are plans that are based on pro-active risk assessment and risk management approaches, present a major opportunity for ensuring safe management of water supply, protecting public health, maximizing health benefits of sanitation. Such plans need to be part of the performance criteria of the water supply and sanitation utilities.

6. Water Use and Management of the Municipal Water Sector

To enhance the water utilities participation in the provision of water supply and sanitation services to improve the quality of the service and reduce cost. However, this participation should be effectively regulated by a clear contract framework that is based on achievements. Moreover, benchmarking of water utilities (using the framework of Effectively Managed Utilities, EMU) is an important mechanism for achieving highest levels of performance and best practices within the country and between the GCC countries.

7. Water Use and Management of the Agricultural Sector

Digitalization of agriculture could be the next transformation in water management, and implementing emerging technologies (i.e., AI,RS, IoT, ..) has a major potential to increase water productivity and the contribution of the agricultural sector to food security. Innovative agricultural water management include: precision irrigation systems, smart irrigation, use of AI, use of analysis-ready remote sensing data platforms, integration with water management technologies and addressing climate change.

8. MIS in the Water Sector

A water MIS is an important component of the water management system to facilitate informed decision-making at various levels in the water sector, as well as policy formulation. It is important to establish a water MIS as a comprehensive framework that integrates data, information, and technologies to collect, process, analyze, and disseminate information related to water quantity, quality, usage, and availability.

9. Decarbonization of the Water Sector

The water sector has great potential in reducing GHGs emissions and contribute to the national commitments of carbon neutrality, especially in the municipal sector which depends mainly on the energy-intensive desalination. Technological solutions like Enhancing energy efficiency and increasing renewable energy, and demand management and efficiency solutions like reducing per capita water consumption and physical leakage represent the main area of work to reduce emissions.

10. Involvement of the GCC Research and Scientific Community in the International Decade of Science for Sustainable Development (IDSSD)

Encouraging the effective engagement of scientific and research institutions in the GCC under the umbrella of the UNESCO led "International Decade of Science for Sustainable Development" (IDSSD) to advance regional collaborative multidisciplinary innovative research initiatives in the water sector including all forms of knowledge within the realms of science, policy, and society.

The conference authorizes the Board of Directors of the Water Science and Technology Association to submit the conference recommendations to the Secretariat General of the Cooperation Council of 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 request WSTA to circulate the recommendations to relevant regional and national organizations and water-related forums.

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The 15th Gulf Water Conference

(2025) ix–xi
doi: 10.5004.dsal.2025.700112

WSTA 15th Gulf Water Conference
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ISBN 0-86689-078-5

Balaban Desalination Publications

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(2025) 1–2
doi: 10.5004.dsal.2025.700094

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Digitalization in water: Key to security in the realm of cyber insecurity risk in the Arab region

Hammou Laamrani

Economic Affairs Officer, Food and Environment Policies section, Climate Change and Natural Resource Sustainability Cluster, United Nations — Economic and Social Commission for Western Asia (UN-ESCWA), Lebanon
Email: hammou.laamrani@un.org

EXTENDED ABSTRACT

Over the last decade, the GCC countries and to a lesser extent, the rest of the Arab region has experienced a profound digital transformation, bringing the online population from 28.8% in 2012 to 70.3% in 2022, and the number of internet users to 327 million.

The transition to digital economies as reflected in countries' visions, and the growing trend in planning and building smart cities is reshaping all economic sectors in GCC. Indeed, AI alone is projected to impact the region's economies to the tune of $320 billion within the next decade.

This trend is promoting the growth of a digital economy by fostering innovation, entrepreneurship, and digital skills development. Initiatives such as startup accelerators, innovation hubs, and investment funds support the development of technology-driven industries and digital startups. However, this transition is not advancing equally across sectors, and digitalization in the water sector, though steadily growing remains relatively slower compared to its potential.

From a water security perspective, digitalization is rapidly adopted in urban water management and planning (smart metering and monitoring, data analytics and predictive maintenance, remote monitoring and control systems, integrated management systems, cloud computing and IoT integration ...). However, the transition to digitalization in agriculture that is the larger consumer of water resources and that constitutes a threat to non-renewable groundwater resources in GCC countries and in the Arab region in general is far slower. This is partly due to the existing digital divide and digital literacy between rural and urban contexts.

Many challenges are still facing the digitalization in water sector in the GCC and the region, require adequate policies and programmes:

1. Digital Divide: While urban centers in GCC countries are rapidly digitalizing, rural and remote areas may face challenges in accessing digital infrastructure and services. Addressing the digital divide requires targeted investments in expanding broadband connectivity, digital literacy programs, and inclusive digital development policies.
2. Skills Mismatch: Despite efforts to develop a digitally skilled workforce, there may still be a gap between the skills demanded by the digital economy and those possessed by the workforce. Continuous investment in education, training, and lifelong learning programs is essential to bridge this gap and ensure the workforce remains competitive in the digital age.
3. Integration and Interoperability: Achieving seamless integration and interoperability among digital systems and platforms remains a challenge, particularly in sectors with complex ecosystems such as healthcare, transportation, and finance. Standardization

ISBN 0-86689-078-5

efforts and interoperability frameworks are needed to facilitate data exchange, collaboration, and innovation across sectors.

4. Limited engagement of research and innovation: A search online shows that both RD and peer reviewed publications on digital tools and technologies in the water sector is limited and requires dedicated investments both by the public and private sectors. PPP investments could be a way to accelerate the innovation capacity for a grounded and secure digitalization in the water sector.

Besides the many remarkable opportunities digitalization implies in enhancing water sector resilience, sustainable management of water resources and water security, expanding the use of digital tools (AI, Blockchain, cloud computing and IoT integration IoT, Remote sensing and satellite imaging ...) comes with new emerging cyber security threats to water infrastructure and service delivery systems requiring a whole new approach to water security.

The rapid development in the cyber threat landscape has put GCC countries in front of a growing threat from potential cyberattacks, including ransomware, phishing, and malware attacks, targeting government institutions, critical infrastructure, businesses, and individuals. Governments in the GCC region have established national cybersecurity strategies and agencies tasked with enhancing cybersecurity capabilities, raising awareness, and coordinating responses to cyber threats.

Regulatory frameworks related to cybersecurity are being developed and strengthened to ensure the protection of critical infrastructure, personal data, and digital assets. Compliance requirements and cybersecurity standards are enforced to mitigate cyber risks. Collaboration between government agencies, private sector organizations, and academic institutions is essential for sharing threat intelligence, best practices, and resources to combat cyber threats effectively. Moreover, investments in cybersecurity education, training, and workforce development are crucial for building a skilled cybersecurity workforce capable of defending against evolving cyber threats and vulnerabilities. Investment in cybersecurity technologies such as intrusion detection systems, endpoint security solutions, encryption, and threat intelligence platforms to detect, prevent, and respond to cyberattacks are increasing in the GCC countries.

In conclusion, digitalization offers clear opportunities to GCC countries and the region efforts to make water sector sustainable, resilient and ensure water security, but effective cybersecurity measures are essential to mitigate cyber risks and safeguard the integrity, confidentiality, and availability of digital assets and critical infrastructure. Continual investment in cybersecurity capabilities, awareness, and collaboration is necessary to address the evolving cyber threat landscape effectively. This opens new avenues for GCC countries' cooperation, yet to be explored and research has a critical role to play in the multiple transitions needed for a more water secure future.

Keywords: Digitalization in water; Cyber security

Balaban Desalination Publications

مؤتمر الخليج الخامس عشر للمياه
The 15th Gulf Water Conference

(2025) 3–5
doi: 10.5004.dsal.2025.700095

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Deep neural networks application in environmental and water resources simulations

Mohammad Mahdi Rajabi

Faculty of Science, Technology and Medicine (FSTM), University of Luxembourg, Luxembourg
Email: mahdi.rajabi@uni.lu

EXTENDED ABSTRACT

Traditionally, environmental and water resources simulations (EWRS) have relied on physics-based analytical and numerical models. These models employ parameters that characterize the environmental systems, system state variables, and external forces as input into mathematical equations to predict future conditions of environmental systems and water resources. The effectiveness of these models is frequently limited due to the considerable computational resources and lengthy simulation times required for large-scale or repetitive simulations, and the partial comprehension or flawed mathematical representation of the physical processes that result in a mismatch between the predicted outcomes of the models and real-world observations at the field scale (Rajabi et al., 2023).

To address these challenges, there has been a shift towards employing data-driven models that incorporate machine learning (ML) techniques. Compared to traditional physics-based models, ML models are typically faster, simpler to develop, and require less detail information. Historically, a range of ML tools have been applied to develop data-driven models for EWRS, including random forests, support vector machines, polynomial chaos expansion, and tree-based regression models. Nevertheless, conventional ML methods often face difficulties when encountering infrequent, black swan cases within the dataset, struggle to adapt to new scenarios not included in their training data, may not effectively manage large volumes of data, and fall short in identifying the deep relationships and complex patterns among the parameters that affect outcomes. Deep neural networks (DNNs), a newer segment of ML, provide more flexibility and have shown to offer higher accuracy in predictions, particularly with extensive datasets (Samek et al., 2021). Their advanced learning capacities make DNNs a highly researched tool for EWRS, demonstrating significant promise over classical ML techniques.

Neural networks are computational models inspired by the human brain's structure, consisting of layers of interconnected nodes that process information using weighted connections and activation functions. They refine and optimize their internal parameters through a technique called backpropagation. DNNs build upon this foundation by incorporating multiple hidden layers between the input and output, enabling the extraction of progressively more abstract features from the data (Shen, 2018). In the context of EWRS, DNNs have found applications across various areas, including but not limited to flood prediction (Kao et al., 2020), hydrological modeling (Li et al., 2023), sediment transport modeling, water quality forecasting (Liu et al., 2019), weather prediction (Ren et al., 2021), groundwater modeling (Wang et al., 2022), water demand projection (Gil-Gamboa et al., 2024), and modeling changes in land use and land cover (Stoian et al., 2019), among others. DNNs have become increasingly popular in tasks requiring iterative simulations, such as Monte Carlo-based uncertainty analysis

ISBN 0-86689-078-5

and combined simulation-optimization, as well as near real-time forecasting.

DNNs come in various architectures, each optimized for specific data types and applications. Table 1 summarizes some prevalent DNN architectures along with their applications in EWRS. In recent years, the adoption of DNNs in EWRS has transitioned from primarily using deep feedforward neural networks to increasingly favoring convolutional neural networks (CNNs) and recurrent neural networks (RNNs), including long short-term memory (LSTM) networks, for their enhanced ability to model spatial and temporal patterns. Although graph neural networks (GNNs) and generative adversarial networks (GANs) are not as commonly employed, their adoption is on the rise. GNNs offer a valuable approach for analyzing unstructured data, whereas GANs are increasingly recognized for their ability to generate synthetic data. This progression underscores a wider movement towards adopting increasingly sophisticated DNN architectures to model the dynamics of EWRS. Concurrently, the utilization of DNNs in EWRS has undergone substantial development, transitioning from basic vector regression tasks to more sophisticated predictive modeling, including time series forecasting and both image-to-value and image-to-image regression. This advancement has been facilitated using CNNs and their combinations with RNNs, such as CNN-LSTMs, allowing for the efficient analysis of spatial and temporal data. More recently, attention has expanded to include processing point clouds collected via light detection and ranging (LiDAR) or similar technologies, employing advanced DNN architectures such as PointNet and various GNNs (Fang et al., 2024).

DNNs are commonly trained utilizing data obtained from physics-based simulations, positioning them not as replacements but as supplementary surrogates to conventional physics-based models (Rajabi et al., 2022). However, there is a gradual shift towards training DNNs with field data sourced from sensors or aerial imagery, expanding their applicability to phenomena that are inadequately understood and challenging to simulate using physics-based models. A relatively recent concept involves integrating residuals of physical equations into the loss function of DNNs. This approach, known as physics-informed or physics-constrained DNNs, utilizes physics-based losses either as a component of the objective function in backpropagation or as constraints. these physics-informed neural networks (PINNs) learn from both observational data and established physics principles, often creating a balance between the two to generate solutions that align with observations while remaining physically plausible. Compared to data-driven DNNs, PINNs also offer the advantage of requiring less data for training, as they leverage an additional source of information (Wang et al., 2022). The development of PINNs for EWRS represents an active area of research, as there is still much exploration to be done in various applications and issues such as convergence, computational efficiency, and determining the optimal balance between data-driven and physics-based components require further investigation.

Table 1
Examples of DNN architectures commonly used in environmental and water resources simulations

DNN architecture	Key features	Application examples
Feedforward neural networks (FFNNs)	Employs a straightforward architecture with layers connected in a feedforward manner. Commonly used for vector data.	Water demand forecasting (Gil-Gamboa et al., 2024).
Convolutional neural networks (CNNs)	Leverages convolutional layers for spatial hierarchy feature extraction. Go to option for image data and related tasks, such as image-to-image regression, image segmentation and image classification.	Forecasting contaminant and temperature distribution maps based on maps of material properties (Rajabi et al., 2022), Land cover prediction (Stoian et al., 2019).
Recurrent neural networks (RNNs)	Utilizes memory elements to process sequences and temporal dependencies.	Flood forecasting (Kao et al., 2020).
Hybrid CNN – Long- short-term memory (LSTM)	Developed for spatiotemporal data analysis.	Flowrate prediction in a watershed (Li et al., 2023).
Graph neural networks (GNNs)	Uses graph-based data representations for node and edge analysis. Compatible with point cloud and mesh-based data.	Groundwater level forecasting (Bai and Tahmasebi, 2023).
Generative adversarial networks (GANs)	Involves a dueling setup where one network generates data, and another evaluates it.	Generating synthetic weather data (Ji et al., 2024), Leak detection in water distribution networks (Rajabi et al., 2023).

Additional areas for future research encompass: (1) addressing the prevalent perception of DNNs as opaque black box tools by developing methodologies to improve their interpretability, thereby aiding stakeholders in understanding model predictions. (2) Developing DNNs capable of effectively capturing multi-scale interactions within environmental systems, enabling more comprehensive simulations of complex phenomena. (3) Addressing the scalability challenges associated with handling large-scale environmental datasets, including the exploration of scalable architectures and algorithms that can efficiently process and analyze vast amounts of data. (4) Investigating transfer learning approaches to leverage knowledge from related domains or datasets to enhance the performance of DNNs in environmental and water resource applications. (5) Exploring the integration of DNN-based predictive models into decision support systems for environmental management and planning, enabling stakeholders to make informed decisions based on the insights provided by DNNs.

Keywords: Data-driven models; Machine learning; Neural networks; Environmental simulations; Water resources modeling

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Balaban Desalination Publications

The 15th Gulf Water Conference

(2025) 6–9
doi: 10.5004.dsal.2025.700096

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Navigating water scarcity and supporting food security: market-based development of sustainable irrigation

Youssef Brouziyne*, Nafn Amdar, Makram Belhaj Fraj

International Water Management Institute (IWMI), MENA Office, Giza, Egypt
**email: youssef.brouziyne@cgiar.org*

EXTENDED ABSTRACT

Water scarcity in the Middle East and North Africa (MENA) region is a complex issue influenced by various factors such as climate change, population growth, urbanization, inefficient water management practices, and geopolitical tensions. This situation has significant implications for the irrigation sector in the MENA region, impacting agricultural productivity, food security, and socio-economic development. Some key implications are:

1. **Decreased Agricultural Productivity**. Water scarcity limits the availability of irrigation water for agriculture, leading to decreased crop yields and reduced agricultural productivity. Farmers may struggle to maintain their crops adequately irrigated, resulting in stunted growth, decreased fruit or grain production, and overall lower yields.
2. **Crop Losses and Economic Impact**. Insufficient irrigation water availability can result in crop losses, economic losses, and decreased income for farmers. Crop failures due to water scarcity can have severe consequences for rural livelihoods, exacerbating poverty and food insecurity in affected areas.
3. **Increased Water Stress**. Water scarcity exacerbates water stress in the irrigation sector, as farmers compete for limited water resources to irrigate their crops. This competition can lead to conflicts over water allocation, particularly in regions where water resources are shared among multiple users or countries.
4. **Salinization and Soil Degradation.** Water scarcity can exacerbate soil salinization and degradation in irrigated areas, particularly in arid and semi-arid regions. Limited water availability may result in improper irrigation practices, such as excessive groundwater pumping, leading to the accumulation of salts in the soil and reduced soil fertility.
5. **Shift in Irrigation Practices**. Water scarcity may necessitate a shift towards more water-efficient irrigation practices and technologies, such as drip irrigation, sprinkler irrigation, and precision agriculture. However, the adoption of these technologies may require significant investments in infrastructure and farmer training, which could pose challenges, particularly for small-scale farmers.
6. **Impact on Agricultural Diversity**. Water scarcity can influence the types of crops grown in irrigated areas, as farmers may prioritize crops that require less water or are more drought-resistant. This shift in crop choices can impact agricultural diversity and may have implications for food security and nutrition in the region.
7. **Dependency on Non-renewable Water Sources**. In some cases, water scarcity in the irrigation sector may lead to increased reliance on non-renewable

*Corresponding author

water sources, such as fossil groundwater reserves or desalinated water. However, the extraction and use of these non-renewable water sources can have environmental consequences, including groundwater depletion and energy consumption.

Interventions in the irrigation market ecosystem and innovations are crucial for empowering irrigation as an effective adaptation tool in the MENA region. By promoting water-use efficiency, sustainable resource management, resilience to climate change, economic development, environmental sustainability, and adaptation and mitigation, policymakers can help ensure the long-term viability of agriculture in water-stressed environments.

The International Water Management institute (IWMI) and its various partners worked with farmers and other stakeholders in the agricultural water value chain to mainstream inclusive irrigation innovation in the global south, including in MENA.

Case 1: Modernizing irrigation systems in the Nile Delta

In the Nile Delta of Egypt, irrigation systems have historically been crucial for supporting agricultural production in one of the most fertile regions of the country. The Nile River, with its annual inundation, has long served as the lifeblood of Egyptian agriculture, providing water for irrigation and replenishing soil nutrients. Traditional irrigation methods, such as basin irrigation and flood irrigation, have been practiced for centuries, harnessing the natural flow of the river to water crops. In recent decades, modern irrigation infrastructure, including canals, pumps, and water distribution networks, has been developed to enhance water management and increase agricultural productivity. Despite these advancements, challenges such as water scarcity, soil salinity, and the impact of climate change present ongoing concerns for irrigation systems in the Nile Delta, necessitating continued investment in sustainable water management practices and technological innovations to ensure the region's agricultural sustainability.

In 2019, the Government of Egypt started to implement a Nationwide Irrigation Modernization Program, which seeks to convert about 6 million feddans (2.4 million ha) of irrigated land from traditional surface to modern pressurized irrigation systems. Roughly, farm-level investments alone can easily amount to US$3–4.5 billion. These investments are expected to offer significant opportunities for improving the productivity and competitiveness of the agricultural sector. So far, the areas that use modern irrigation systems in Egypt account for 4.6 million feddans. The program is also expected to reduce farm-level water allocations, which could then be reallocated to other sectors including industries, domestic, and the environment. Within this context the International Water Management Institute (IWMI) provided the activity entitled "Egypt-Supporting MALR strategic objective to Modernize the On-Farm Irrigation Systems in Delta (EMFI)" under the Nile Delta Water Management Programme (NDWM), which is funded by the German Federal Ministry for Economic Cooperation and Development (BMZ) and implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). Under the NDWM, pilots of modern irrigation systems shall be installed in the two demonstration areas to contribute to improving the range of advice and services for smallholder farms on water-saving cultivation practices, initiating innovative measures and digital applications for efficient water use by smallholder farms, and strengthening the participation of civil society and women's groups in water use efficiency.

The project highlighted that solar-powered irrigation systems (SPIS) shall be engineered with multifaceted capabilities, incorporating photovoltaic panels for the capture of solar energy, inverters for the transformation of direct current to alternating current, and grid-tied controllers to facilitate interaction with the public electrical grid (feed in and usage). It also showed that a specialized adaptation shall be undertaken to manage both source water pumps and booster pumps, optimizing flow rates and hydraulic pressure to meet diverse irrigation requirements. To further extend its utility in agricultural settings, the system shall include smart controllers for both irrigation and fertigation, enabling precise, data-driven control over water and nutrient application rates. Accordingly, the business model is featured as a highly customized architecture that not only improves the system's operational efficiency but also offers an integrated solution for sustainable agriculture.

Based on these initial findings, the proposed customization of the market system is shown with all of its elements in Fig. 1.

Case 2: Taking drip irrigation to the next level in Jordan

In Jordan, irrigation systems play a critical role in sustaining agricultural production in a water-scarce environment. The country faces significant challenges due to its limited freshwater resources and increasing water demand. Traditional irrigation methods, such as flood irrigation, have been common historically but are gradually being replaced by more water-efficient technologies like drip and sprinkler irrigation. These modern irrigation systems help optimize water use by delivering water directly to the roots of plants, minimizing evaporation and runoff. Additionally, Jordan has implemented policies to promote sustainable irrigation practices, including water pricing mechanisms and subsidies for water-saving technologies. Despite these

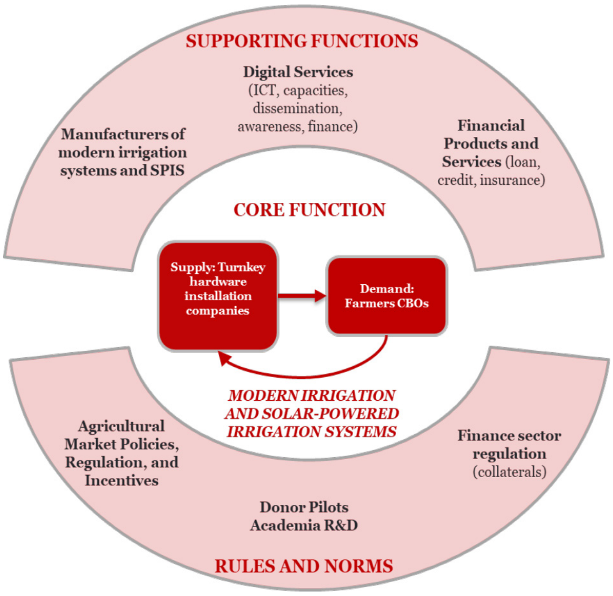

Fig. 1. Modern irrigation systems and solar-powered irrigation systems market diagram of core and supporting functions, and rules and norms that are key for the effective functioning of the market system for water/nutrient. Pesticides saving in agriculture.

efforts, water scarcity remains a pressing issue, and ongoing investments in irrigation infrastructure and management are essential to ensure the resilience and viability of agriculture in Jordan.

Jordan is an exceptional context for policy-makers and development agents to innovate and learn about water management policies and strategies. According to experts, with so few new options for fresh water, the country "will be center stage in showing how a semi-arid region deals with the devastating impacts of a warmer and drier regional climate.

Under the Water Innovation and Technologies (WIT) Program, The goal of the Market System Development (MSD) approach is to contribute to sustainable poverty reduction at scale. This is done through interventions that facilitate sustained changes in the behavior of market actors, and the functions and structures that shape the performance of market systems that matter to people living in poverty.

The WIT program is a five-year initiative implemented between March 2017 and July 2022 in Jordan. It was funded by the United States Agency for International Development (USAID). during the life of the program, the combined efforts of WIT partners, early adopters and farmers led to savings of approximately 24 MCM (in agriculture alone), exceeding the program's target for agriculture by more than 5 MCM. These savings were generated by approximately 200 farmers who optimized around 1,300 ha of farmland (Fig. 2).

To achieve these results, the WIT program explored how water-saving practices and technologies spread, which farmers adopt water-saving technologies and why, as well as technology adoption on farms as well as by different suppliers. Overall, the project identified the water saving market movement.

Overall, market-based development plays a critical role in driving irrigation innovation by enabling the incentivization of investment, promoting efficiency, enabling tailored solutions, facilitating scaling up, and ensuring sustainability. By harnessing market forces, policymakers, businesses, and entrepreneurs can unlock the full potential of irrigation innovation to address water scarcity, enhance agricultural productivity, and contribute to sustainable development.

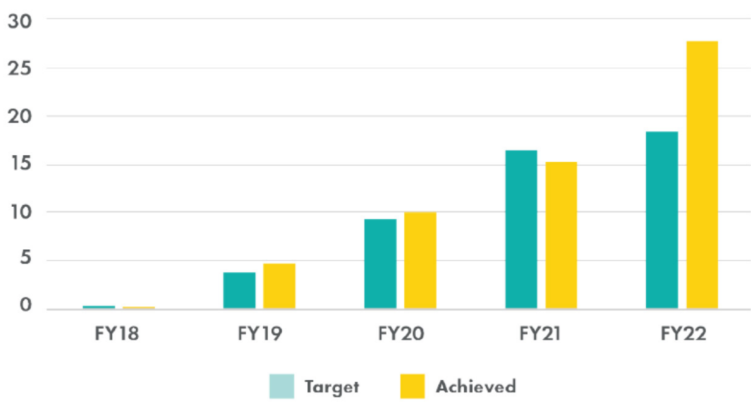

Fig. 2. Accumulated water savings in MCM per fiscal year, including both the agriculture and household components (24 and 4 MCM, respectively).

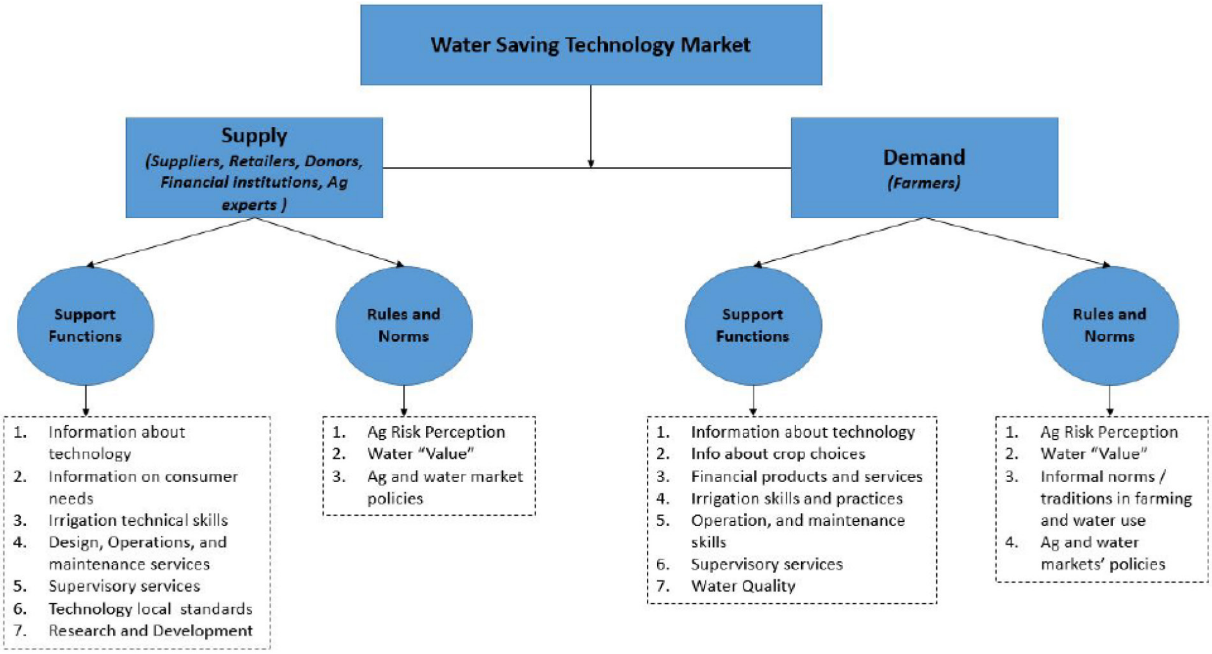

Fig. 3. Water saving technologies market components addressed in WIT.

Keywords: Market-systems; Modern irrigation; Farmer behavior; Irrigation technology

Balaban Desalination Publications

مؤتمر الخليج الخامس عشر للمياه
The 15th Gulf Water Conference

(2025) 10–11
doi: 10.5004.dsal.2025.700097

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

The role of the World Health Organization in drinking water, sanitation and hygiene, and updated publications

Rola Al-Emam

WASH, Occupational Health and Healthcare Waste Management, Climate Change, Health and Environment, Eastern Mediterranean Regional Office, World Health Organization (WHO/EMRO/CHE)
Tel. +962 6 5100676, Mobile +962 799726417, email: alemamr@who.int

EXTENDED ABSTRACT

Safe drinking water, sanitation and hygiene (WASH) are crucial to human health and wellbeing. Safe WASH is not only a prerequisite to health, but contributes to livelihoods, school attendance and dignity and helps to create resilient communities living in healthy environments.

Historically, the World Health Organization (WHO) work has included WASH components since the inception of the Organization in 1948. WHO has played a long-standing and significant role in promoting WASH as an objective and respected source of international guidelines, standards and normative information. The WHO vision for WASH is: *"To substantially improve health through the safe management of water, sanitation and hygiene services in all settings"*.

WASH is enshrined in the WHO constitution. WHO takes on board the need for progressive realization of the human rights to safe drinking water and sanitation, adopted by the UN General Assembly in July 2010. It has consistently issued health-based guidelines and good practice publications on WASH, which are designed to assist countries in developing national standards, informing regulations and establishing effective surveillance systems. For decades, WHO has monitored global and country access to water and sanitation. While the Organization has had various flagship priorities over the years, technical work on WASH issues has been a constant and is often included in broader initiatives.

WHO assists countries in improving policy, governance and monitoring towards the achievement of Sustainable Development Goals (SDG) beyond the WASH-focused SDG 6, e.g. SDG 3 on health and SDG 13 on climate change, which cannot be met without meaningful progress on Goal 6.

The WHO WASH 2018–2025 Strategy is underpinned by the following principles:

- Prioritize actions with the highest public health benefit;
- Strengthen health sector capacities in promoting safe WASH and taking up its public health oversight role in WASH, including effective outbreak response systems;
- Align with the SDGs, specifically targets relating to WASH, health, climate change and nutrition, as well as human rights principles;
- Employ the highest quality science including through collection, review and use of evidence about WASH impacts on health and a full range of practical experiences when developing norms and good practice procedures;
- Promote a contextual, incremental improvement approach when supporting countries to set national WASH standards and ambitious but achievable national targets;
- Capitalize on existing regional policy frameworks that promote WASH and stipulate national target setting;

ISBN 0-86689-078-5

- Stimulate sustainable change by strengthening government institutions and systems charged with implementation, oversight and regulation of WASH service delivery; and
- Engage with partners and positively influence partnerships to ensure health issues are considered and addressed by the WASH sector and to also ensure that WASH issues, notably in health care facilities, are addressed by the health sector as prerequisites to providing quality care.

Key WHO partners and stakeholders for WASH include Member States, practitioners, institutions for research and development, WASH partners, etc.

Some of WHO's priority intervention areas and recent publications are as follows:

- **Drinking-water quality and safety**: Guidelines for drinking-water quality (2022), Guidelines for drinking water quality: small water supplies and the Sanitary inspection packages (2024), the WHO/IWA updated Water Safety Plan manual (2023), Lead in drinking-water: Health risks, monitoring and corrective actions (2022), State of the world's drinking water: An urgent call to action to accelerate progress on ensuring safe drinking water for all (2022), Toxic cyanobacteria in water — 2nd edition (2021), Guidelines on recreational water quality: Volume 1 Coastal and fresh waters (2021), Domestic water quantity, service level and health (2020), Microplastics in drinking-water (2019), A guide to equitable water safety planning: Ensuring no one is left behind (2019), Management of radioactivity in drinking-water (2018).
- **Improving safety of sanitation and wastewater management**: WASH and health working together: a 'how-to' guide for neglected tropical disease programmes, second edition (2023), Sanitation safety planning — 2nd edition (2022), Global research agenda for improving the health safety and dignity of sanitation workers (2022), State of the world's sanitation: An urgent call to transform sanitation for better health, environments, economies and societies (2021), Guidelines on sanitation and health (2018), Guidelines for the safe use of wastewater, excreta and greywater — Volume 1 (2013). WHO is a member of the Climate Resilient Sanitation Coalition.
- **WASH in health care facilities (including healthcare waste management):** Progress on WASH in health care facilities 2000–2021: Special focus on WASH and infection prevention and control (2023), Water, sanitation, hygiene, waste and electricity services in health care facilities: progress on the fundamentals (2023), Energizing health: accelerating electricity access in healthcare facilities (2023), WASH FIT: A practical guide for improving quality of care through water, sanitation and hygiene in health care facilities. Second edition (2022), Global analysis of health care waste in the context of COVID-19 (2022), Overview of technologies for the treatment of infectious and sharp waste from health care facilities (2019), Safe management of wastes from health-care activities (2014) and the summary (2017).
- **Monitoring via the Global Analysis and Assessment of Sanitation and Drinking-Water (GLAAS), WHO/UNICEF Joint Monitoring Programme (JMP) and Burden of Disease**: Burden of disease attributable to unsafe drinking water, sanitation and hygiene: 2019 update (2023), Progress on household drinking-water, sanitation and hygiene 2000-2022: Special focus on gender (2023), Strong systems and sound investments: Evidence on and key insights into accelerating progress on sanitation, drinking-water and hygiene: GLAAS 2022 report, Progress on drinking-water, sanitation and hygiene in schools: 2000–2021 Data update (2022).
- **Integration of WASH with health and other programmes such as AMR, cholera, climate change and emergencies**: Technical brief on water, sanitation, hygiene (WASH) and wastewater management to prevent infections and reduce the spread of antimicrobial resistance (AMR) (2020), Safer water, better health (2019).

Despite the extensive technical support provided by WHO, populations are facing several challenges globally and in the Eastern Mediterranean Region. Emergencies are increasingly becoming more complex and affecting more populations than ever before. Climate change, natural disasters, and conflict are some of the few hurdles faced. Whether a natural disaster, a conflict, migration/refugee-related or a disease outbreak, and in many cases a combination of the above, WASH is an important element in both the provision of health care and reducing health risks during an emergency and in the future preparedness planning.

The keynote will mention some of the above WHO publications and will refer to the training session on Sanitation Safety Planning on Day 2 of the conference.
Keywords: WHO, Sanitation Safety Planning (SSP), Sanitation and health, Public health protection, Risk-based sanitation management and Incremental improvements in sanitation.

Keywords: WHO; Sanitation safety planning (SSP); Sanitation and health; Public health protection; Risk-based sanitation management; Incremental improvements in sanitation

Balaban Desalination Publications

The 15th Gulf Water Conference

(2025) 12
doi: 10.5004.dsal.2025.700098

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Addressing climate change risks on water and food security in the Arab Region

Vinay Nangia

Research Program Director – Soil, Water, and Agronomy, International Center for Agricultural Research in the Dry Areas (ICARDA), Rabat, Morocco, email: V.Nangia@cgiar.org

ABSTRACT

Water scarcity is increasing, especially in dry environments, such as in the Arab Region, with climate change and degradation of natural resources. About 41% of the Earth's land area is classified as dryland; wherein the farming system is characterized by low annual rainfall with much of it falling in the winter and spring. Agriculture, especially in the Middle East and North Africa (MENA) Region, is required to produce more food and welfare for rapidly increasing populations but with less freshwater resources. Conventional responses to this situation focus on increasing yields, improving irrigation efficiency, and managing demand. Here, it is argued that those strategies are either not working under current conditions or not anymore sufficient to cope with the daunting demand for more food in water scarce dryland regions. A paradigm shift in how we manage water is needed going into the future. The debate on how better to handle agricultural water allocation and use with increasing scarcity is being intensified over the last decade and is producing new transformative solutions. Climate-smart agricultural practices that require less water, can sustain climatic stresses, produce food with high nutritive values but require less water and energy to produce are the needs of the hour. ICARDA success stories from the Arab Region in these regards will be presented.

Keywords: Crop water productivity; Climate-smart agriculture; Drylands

ISBN 0-86689-078-5

Balaban Desalination Publications

مؤتمر الخليج الخامس عشر للمياه
The 15th Gulf Water Conference

(2025) 13–14
doi: 10.5004.dsal.2025.700099

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Water MIS for efficient integrated water resource management

Patrice Moix[a], Helmi Ana'am[b], Ayisha Alkhatri[c]*

[a]*Chief of Unit of Groundwater and Water Cooperation at HQ, UNESCO —Doha Office, Qatar*
email: p.moix@unesco.org
[b]*Representative from Ministry of Water and Environment, Yemen, email: helmi.anaam@gmail.com*
[c]*Ministry of Agricultural, Fisheries Resources and Water Resources, Sultanate of Oman*
email: Ayisha.ALkhatri@mafwr.gov.om

EXTENDED ABSTRACT

Background

Water is a critical resource essential for sustaining life, supporting ecosystems, and driving socio-economic development. Effective management of water resources is imperative to ensure their sustainable use, particularly in the face of growing global population and growing demands, climate change, and increasing water-related challenges. In this context, the deployment of Water Management Information Systems (MIS) has emerged as a pivotal tool to enhance the understanding, monitoring, and decision-making processes associated with water resources.

A Water MIS is a comprehensive framework that integrates data, information, and technologies to collect, process, analyze, and disseminate information related to water quantity, quality, usage, and availability. These systems leverage advancements in technology, including remote sensing, Geographic Information Systems (GIS), and real-time monitoring, to provide decision-makers with accurate and timely insights into water-related parameters.

The primary goal of a Water MIS is to facilitate informed decision-making at various levels, from local communities to national governments. By consolidating data from diverse sources, such as meteorological stations, river gauging stations, and satellite imagery, these systems enable a holistic view of water resources. Decision-makers can use this information to develop sustainable water policies, plan infrastructure projects, respond to emergencies, and address water-related challenges, including droughts, floods, and water pollution.

Water MIS not only enhances the technical aspects of water management but also contributes to the participatory and inclusive governance of water resources. Stakeholders, including communities, researchers, policymakers, and water resource managers, can access relevant and reliable information through user-friendly interfaces, fostering transparency and collaboration.

UNESCO, along with its extended water family network of Intergovernmental Hydrological Program, Category 2 Centers and UNESCO Chairs, recognizes the importance of Water MIS in achieving water security and sustainable development goals. Capacity building, knowledge exchange, and the promotion of best practices in implementing MIS are integral components with the strategic plan of the 9th phase of UNESCO intergovernmental Hydrological Programme (IHP-IX, 2022–2029: Science for Water Secured Word in a Chang-

*Corresponding author

ISBN 0-86689-078-5

ing Environment) to address water challenges. As the world grapples with the increasing complexities of water management, the continued development and utilization of Water MIS stand out as essential tools for navigating towards a water-secure and resilient future.

Objectives

UNESCO aims to bring together experts from around the world to discuss and advance the understanding and implementation of robust water management information systems.

The primary objectives include:

- Facilitate the exchange of experiences, best practices, and innovations in water management information systems among participating countries and organizations.
- Foster a dialogue among policymakers, researchers, and practitioners to develop and enhance policies that promote the integration of technology in water management for better decision-making.
- Provide a platform for showcasing technological innovations, tools, and methodologies that contribute to improved water data collection, analysis, and dissemination.

Keywords: Ecosystems; Climate change; Water demand; Water resources; Water challenges; MIS; GIS; Meteorological stations; UNESCO; Intergovernmental Hydrological Program

Balaban Desalination Publications

مؤتمر الخليج الخامس عشر للمياه
The 15th Gulf Water Conference

(2025) 15–16
doi: 10.5004.dsal.2025.700100

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Using technology to bridge the data gap for efficient management of agricultural water

Bert Coerver[a], Abdullah Barhy[b], Mohamed Abdallah[c]*

[a]*International Expert on Remote Sensing, FAO WaPOR Project, Land and Water Division, FAO Headquarters, FAO Regional Office for Near East and North Africa (RNE), email: Bert.Coerver@fao.org*
[b]*Geospatial Expert, Geospatial Unit, Land and Water Division, FAO Headquarters , email: Abdullah.Barhy@fao.org*
[c]*Programme Implementation Support Expert, Water Scarcity Initiative, FAO Regional Office for the Near East and North Africa, email: Mohamed.Abdallah@fao.org*

EXTENDED ABSTRACT

Background

Water scarcity represents a significant challenge to agricultural productivity and food security, particularly in the Near East and North Africa (NENA) region. Exacerbated by its arid and semi-arid climates, coupled with population growth, and changing climatic conditions, the demand for water in agriculture continues to rise despite the growing demands of other sectors, while water resources are becoming increasingly limited. In this context, data technologies, including Remote Sensing, Geographic Information Systems, Cloud Computing, Artificial Intelligence, among others, offer promising avenues for addressing water scarcity and agriculture-related issues.

Innovative solutions leveraging these technologies have emerged as crucial tools that provide valuable data and insights that contribute to monitoring of water use, assessment of crop yield and productivity, water requirements, and optimizing irrigation practices, and providing early warning, thereby enhancing water use efficiency and productivity in agriculture while considering the need of water in other sectors.

*Corresponding author

Overview and scope

Showcasing analysis-ready remote sensing data and geospatial portals utilization

The first segment of this session aims to showcase some FAO data resources and practical applications of remote sensing analysis-ready data, with a focus on cloud-based geospatial portals. By demonstrating how this data can be leveraged for a better understanding of land cover and land use, crop yield and productivity, water management and use, and land resources and evaluation, attendees will gain a deeper understanding of the potential of geospatial technology in addressing limited water resources availability and agriculture-related issues. The presentations will cover the following:

- **FAO water productivity open access portal presentation:** This presentation will showcase the FAO's Water Productivity Open Access Database (WaPOR), offering insights into remotely sensed derived Water Productivity data. The audience will be introduced to the portal's open-access data on water productivity in agriculture across various countries and regions. The portal gives access to a database that provides crucial geospatial information and analytics on water usage and productivity, facilitating assessments of

ISBN 0-86689-078-5

water use efficiency, identification of water stress areas, and the formulation of strategies for sustainable agricultural water management. The FAO WaPOR database emerges as a pivotal resource for tackling water-related agricultural challenges and promoting sustainable water management practices.

- **Land cover and land use/land evaluation and suitability presentation:** This presentation will showcase the efforts of the FAO in the assessment and mapping of land cover, cropland dynamics, and the utilization of the System for Earth Observation Data Access, Processing, and Analysis for Land Monitoring (SEPAL) platform. This includes demonstrating the capabilities of SEPAL in enhancing the understanding of land cover changes, crop monitoring, and land degradation assessment, as well as presenting the development of the Land Cover Legend Registry (LCLR) and Land Characterization System Software (LCHS) in collaboration with international partners, adhering to international standards. Additionally, the presentation will demonstrate the Global Agro-Ecological Zones (AEZ) database and modeling framework developed in collaboration between the FAO and the International Institute for Applied Systems Analysis (IIASA), highlighting how the GAEZ database supports sustainable agricultural development decision-making by outlining the suitability and production potentials of various crop types under specific input and management conditions.
- **Cloud-based geospatial tools for water and agriculture analyses presentation:** The final presentation aims to highlight the transformative potential of geospatial technology, cloud computing, and analysis-ready remote sensing datasets in addressing data gaps within the water and agriculture sectors. Attendees will explore how platforms, like google earth engine (GEE), integrating geospatial data and cloud computing infrastructure can efficiently process vast amounts of information, overcoming data scarcity and accessibility issues. Such platforms enable insights into agricultural water consumption, rainfall trends, crop health, and crop patterns, facilitating more informed decision-making and sustainable practices.

Panel discussion

Following the presentations, the technical session will facilitate a panel discussion and audience questions aimed at a deeper understanding of the explored themes and facilitate dialogue between experts and attendees. Leading the panel will be experts from FAO, offering diverse perspectives on harnessing remote sensing and geospatial technologies, alongside capacity development for sustainable agriculture and water management.

Expected outcomes

- *Enhanced understanding of FAO WaPOR data platform and capabilities:* Participants will gain deeper insights into the significance of FAO's Water Productivity Open Access Database (WaPOR) data and platform capabilities for addressing agricultural water productivity issues.
- *Increased awareness of FAO tools for land cover assessment and characterization:* Attendees will have an increased awareness of tools like the Land Cover Legend Registry (LCLR) and Land Characterization System Software (LCHS) supporting land cover assessment and characterization.
- *Advanced understanding of the use of SEPAL platform:* Participants will gain deeper knowledge of how SEPAL is utilized for assessing changes in land cover, monitoring crops, and evaluating land degradation.
- *Enhanced knowledge of the Global Agro-Ecological Zones (AEZ) database and platform:* Participants will gain a deeper understanding of how the GAEZ database supports sustainable agricultural development decision-making by illustrating the suitability and production potentials of different crop types under specific input and management conditions.
- *Increased familiarity with the use of cloud-based geospatial portals for water and agriculture related analyses:* Attendees will develop a deeper understanding of how geospatial platforms and analysis-ready data can be used to address challenges associated with water scarcity in agriculture.
- *Enriched Discussion and Knowledge Exchange:* Attendees and presenters will engage in a discussion that deepens their understanding of the topics presented.

Keywords: Water scarcity; Agricultural productivity; Sustainable water management; Water use efficiency; Crop mapping; Remote sensing; Geographic information systems (GIS); Cloud computing; Artificial intelligence (AI); Geospatial technology; Analysis-ready data; Google earth engine (GEE); FAO SEPAL; FAO WaPOR

Balaban Desalination Publications

(2025) 17
doi: 10.5004.dsal.2025.700101

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

De-carbonization pathways in the water sector in the GCC countries

Hind Al-Ali[a*], Mousa AlHajri[b], Mohammed AlAali[c]

Secretariat General of the Gulf Cooperation Council (GCC-SG) and WSTA
[a]*Ministry of Energy and Infrastructure, UAE, email: Hind.Alali@moenr.gov.ae*
[b]*Saline Water Conversion Cooperation (SWCC), KSA*
[c]*Electricity and Water Authority, Kingdom of Bahrain*

A special session in which national working papers from the GCC countries are presented to present their national vision, efforts, and experiences to reduce carbon emissions in the water sector to contribute to achieving carbon neutrality within the framework of the Paris Climate Change Agreement.

*Corresponding author

ISBN 0-86689-078-5

Balaban Desalination Publications

مؤتمر الخليج الخامس عشر للمياه
The 15th Gulf Water Conference

(2025) 18–21
doi: 10.5004.dsal.2025.700102

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Oil spill management to prevent catastrophic shutdown of desalination plants

Zhaoyang Liu

Senior Scientist, Water Center, Qatar Environment & Energy Research Institute (QEERI), Hamad Bin Khalifa University, Qatar Foundation, Qatar, email: zhliu@hbku.edu.qa

EXTENDED ABSTRACT

The combination of a growing global population and climate change has raised global concerns about the availability and safety of drinkable water. Seawater desalination is emerging as a low-cost, high-efficiency solution to coastal water constraint [1,2]. There are around 16,000 desalination plants in operation worldwide, spread over 177 countries, producing approximately 95 million m^3/d of fresh water. Nowadays, saltwater desalination technology is divided into two types: distillation and reverse osmosis [3]. Distillation desalination uses distillation units to convert seawater to steam and then condense it. Reverse osmosis desalination entails pressing new water via membranes. High-quality feed water is required for the efficient functioning of desalination units [4]. Pollutants that bypass the saltwater intake and pretreatment processes and enter the downstream desalination operations diminish heat transfer efficiency in thermal desalination facilities while fouling and destroying membranes in reverse osmosis desalination plants. As a result, the quality of the produced water deteriorates [5]. Intensive flushing and equipment cleaning frequently need a substantial plant closure [6,7].

The world's principal energy sources are oil and natural gas. Oil spills have emerged as one of the most important environmental concerns in recent years [9]. As seen in Fig. 1, there are various reasons of oil leaks. The majority of oil spills are caused by human error, but they can also be caused by fatigue loading, which occurs when fractures form in aging pipes as oil leaks. Furthermore, military actions related to regional wars and disputes have resulted in comparable instances [10]. Oil spills in the marine environment undergo a range of processes, including evaporation, dissolution, degradation, and emulsification [11]. Many types of oil can coexist in water, complicating oil spill cleanup [12]. Furthermore, waves and tides can exacerbate the problem by producing additional unanticipated oil motions. Seawater intake portals are often found in shallow water, which is heavily influenced by wave and tide activity. Currently, most oil spill response tactics focus on limiting

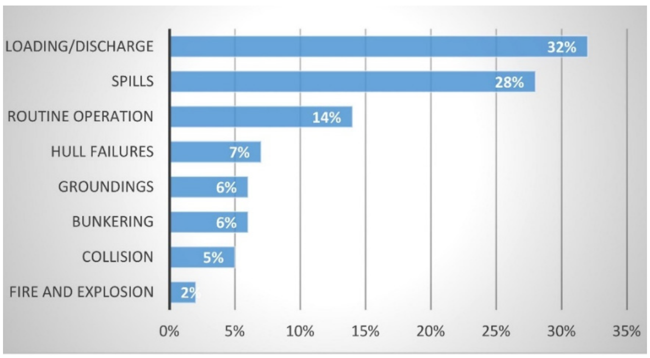

Fig. 1. Various causes of oil spills [8].

ISBN 0-86689-078-5

marine environment damage rather than desalination shutdown [13]. Desalination facilities usually use open surface seawater intake and conventional pretreatment, but these methods cannot handle significant seawater quality deterioration induced by accidental or planned oil spills [14]. For example, in 2001, more than 1300 t of fuel oil leaked from a sunk ship, forcing the closure of two desalination plants in the United Arab Emirates and causing water shortages [15]. In 2017, an aging pipe in Israel released approximately 100 m^3 of oil into the sea, resulting in an oil disaster that forced the closure of three desalination plants for 3 d [7].

The operation of desalination plants is highly dependent on feed water quality, which is controlled by a variety of parameters such as raw seawater quality, saltwater intake processes, and onshore pretreatment methodology [16,17]. Existing desalination facilities must be re-evaluated and redesigned with all of these aspects in mind in order to remove oil contaminants and ensure the quality of feed water during catastrophic oil

Table 1
Threat of oil spills to desalination plants in the Middle East

Countries	Causes	Consequences	Impact on human life
United Arab Emirates (UAE)	Diesel spilled from a damaged tanker (1997) A spreading oil slick from a sunken barge (1998) An oil slick reached the emirate's beaches from the sunken tanker Zainab (2001) Oil spill in the Arabian Gulf off the west coast of UAE reached the Al-Fujairah coast (March 2017) Oil spill after attacks on 4 oil tankers in UAE waters (2019) UAE oil spill causes 2 km of damage Thick layer of oil affected a major desalination plant at Fujairah (2013)	Shut down a water desalination plant and left Sharjah Emirate without water for a day Forced Emirates of Sharjah and Ajman to close two desalination plants Al Liyya water desalination plant was temporarily shut down to protect the inlets of the plant Fujairah oil spills caused by tankers illegally cleaning their holds Bunker spill from one of the four vessels attacked near Fujairah emirate. It affected a major desalination plant at Qidfa	SEVERE
Saudi Arabia	Oil spilled during Persian Gulf War (1991) Oil spills brought under control at Yanbu Port (2022)	Shut down a desalination plant that provides drinking water to millions of people. Authorities shut the desalting plant at Safaniya. Pollution caused by an oil leak in Jeddah.	SEVERE
Kuwait	Oil spilled from an offshore oilfield (2017)	Shut down the desalination plant for two days.	SEVERE
Egypt	Clean-up efforts in Egypt's Red Sea under way following oil spill (Aug 2022)	Jordan's official news agency Petra reported an oil spill at the berth of a container terminal in the port of Aqaba. Preliminary investigations determined that the spill had been caused by a docking ship in the area.	SEVERE
Yemen (2015–2022)	Very near miss The FSO Safer tanker had been rusting away off Yemen's coast since 2015. It threatened to release roughly four times the amount of crude oil spilled off Alaska in the Exxon Valdez disaster of 1989.		SEVERE

spills. This is critical to preventing desalination shutdowns and ensuring a continuous water supply. This article examines various oil/water separation technologies from the viewpoints of offshore oil spill cleanup, seawater intake, and onshore pretreatment. The benefits and drawbacks of each technology are discussed, as well as their applicability in various contexts. Due to the variety of oil types found in water, no single technology can remove all kinds of oil pollutants. Furthermore, because most oil spills occur by mistake and no one can foresee how badly, where, or when they would occur, a strong management plan to prevent desalination shutdown must take all of the aforementioned factors into account.

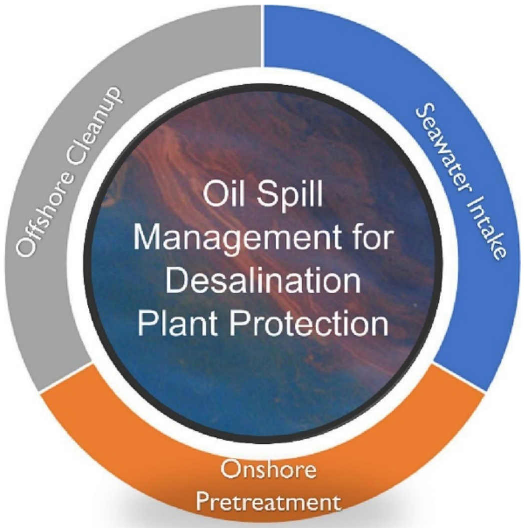

Fig. 2.

Seawater desalination is an important technology utilized to provide fresh water, but its safety is jeopardized by marine oil spill accidents. Historically, oil spills have caused entire shutdowns of desalination plants as well as serious disruptions in water supply. The functioning of desalination plants is sensitive to feed water quality, which is influenced by the following factors: (i) raw saltwater quality, (ii) seawater intake methods, and (iii) onshore pretreatment technology in desalination plants. As a result, this review paper thoroughly explores numerous oil-removal strategies from the perspectives of (1) offshore oil spill cleanup, (2) seawater intake, and (3) onshore pretreatment. A comprehensive strategy that incorporates all components is proposed to protect seawater quality and desalination facilities, with the goal of preventing desalination plant shutdown during oil spill situations [17].

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Balaban Desalination Publications

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(2025) 22–29
doi: 10.5004.dsal.2025.700028

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Fuel allocation in water and power cogeneration desalination plant

Ibrahim S. Al-Mutaz*, Meshari S. Aldalbahi

Chemical Engineering Dept., College of Engineering, King Saud University, PO Box 800, Riyadh 11421, Saudi Arabia
**email: almutaz@ksu.edu.sa*

ABSTRACT

Most large thermal desalination plants are combined with power generation, using energy that would otherwise be rejected by the environment. Energy is usually one of the largest operating costs and can vary appreciably with fuel value, plant configuration, and operating mode. In independent or privatized power and desalination plants, the Power and Water Purchase Agreement (PWPA) contains a method for allocating energy and other operating and capital costs between power and water. The method used is a key factor in the project payment structure. In this study, three methods were applied to calculate the fuel allocation: power to distillate ratio (PDR), heat value for potable water and exergy method. The most appropriate method was selected based on several general criteria that closely matched the operating conditions of the cogeneration plants. The recommended method has been applied in one of the Saline Water Conversion Corporation (SWCC) water and power cogeneration desalination plants to better identify the fuel distribution between water and power production. The design operating conditions were used to identify the appropriate methodology for the power-to-distillate ratio (PDR), heat value for potable water, and exergy. The accuracy of each methodology was determined and compared by applying it to a standardized plant and then implementing the appropriate methodology in one of the water and power cogeneration desalination plants.

Keywords: Thermal desalination; MSF; Water and power cogeneration; Fuel allocation; Power to distillate ratio

1. Introduction

Combined power and desalination plants are called cogeneration or dual-purpose plants. It has been a common practice to reduce energy consumption. All large Saudi MSF plants operate within the context of dual-purpose facilities for the simultaneous production of power and water [1]. A typical power plant produces steam at high pressure and temperature. The steam is expanded in the turbine to generate electrical energy. The desalination plant will use exhausted low-grade steam and hence share fuel consumption. The production ratios of these plants do not reflect the real demand for water and power.

The challenge faced by the cogeneration plants is to provide an operation that satisfies the diverse operational requirements imposed by power and water produc-

*Corresponding author

ISBN 0-86689-078-5

tion while retaining the inherent economic advantages of the cogeneration concept [2]. Energy intensity has a major contribution to fuel requirements which indicates there is room for potential efficiency improvements and fuel savings [3]. The maximum electric power is generated by the complete condensation of the high-pressure steam in the turbine [4]. Therefore, fuel is utilized for power generation. However, cogeneration is expected to result in cost savings, especially if fuel is well allocated within the cogeneration plant. Fuel allocation for power and desalination plants is a multi-objective task that requires the consideration of various factors, such as the water demand, the energy demand, the water quality, the energy efficiency, the capital cost and operating costs.

In the early work, a simple approach based on steam enthalpy and incorporating useful energy concept was proposed by Al-Sofi et al. [5] to account for the distribution of fuel cost between power and water production. In this method steam enthalpy requirements of either product (water or power) for both processes in single and co-production are compared. First law of thermodynamics with consideration of the cost factors was utilized to distribute fuel in dual-purpose boiler turbine generator (BTG)-MSF plants. The method is based on a formulation of an ideal point at which power and water products are equivalent. Also heat value for potable water produced from desalination of sea water was used to estimate the overall fuel efficiency of the system for fuel allocation to power and desalination and balancing the energy input against the output of power and desalination plants in the Water and Electricity Department (WED) of Abu Dhabi network, based on its own data [6]. Moreira et al. conducted an energy and economic analysis for a desalination plant using desalination cost as a parameter and performed sensitivity analyses to assess possible reductions in this cost. [7].

The work loss method and exergy method were utilized to allocate the fuel between the electrical power and desalinated water production [8]. Both methods focused on the discharging of steam to the MSF units instead of its expansion to the condensing turbine. An improved method for fuel cost apportionment of a combined power cum a desalination plant was proposed [9]. It was found that the conventional analysis for cogeneration systems has been hitherto the energetic (enthalpy) method, which is useful for efficiency evaluation purposes, but it may not be fully accurate for capturing the "quality of fuel energy" consumed by processes in producing two or more useful effects, e.g., electricity and water.

Exergy analysis can be used to identify irreversibility sources, or inefficiencies in a thermal power system. A rigorous thermodynamic approach based on the available energy (exergy) accounting method was employed to determine the design specific fuel energy consumption of each of the desalination and power plants [10]. This approach was applied to two operating dual purpose plants incorporating extraction (condensing) steam turbine cycles integrated with multistage flash (MSF) desalination plants. These plants were commissioned in the early eighties with power to water ratio 12.6 and 15.5 MW/migd. The study also included two operating backpressure steam turbine cycles integrated with MSF desalination plants with power to water ratio 5.2 and 7.8 MW/migd commissioned in 1983 and 2000, respectively.

An energetic approach based on input and outputs exergetic analysis was utilized to study the fuel allocation in a combined steam-injected gas turbine and thermal seawater desalination system [11]. They studied the fuel allocation in a combined steam-injected gas turbine (STIG) power generation and multi-effect thermal vapor compression (METVC) desalination system. They used seven methods namely, products energy method, products exergy method, power generation-favored method, heat-production-favored method, basic exergetic cost theory, functional approach and splitting factor method.

Osman et al. [12] proposed an energetic approach for cost estimation of a combined power and water system. They conducted a series of experiments to optimize the operational parameters of a boiler for the highest efficiency. To maximize the utilization of waste heat, Yang et al. found that a combined heat and water production system could easily provide improved water quality and economy with roughly equivalent energy efficiency [13]. Thermodynamic, economic, and environmental analyses were used to determine the optimal design and operation parameters and the exergy-based cost allocation for three power and desalination plants that use a multi-effect distillation with thermal vapor compression (MEDTVC) unit [14].

Iora et al. [15] reviewed the drawbacks of the conventional allocation methods such as incremental electricity-centered reference (IECR), incremental heat-centered reference (IHCR) and separate-productions reference (SPR), they proposed a slightly more elaborate, but self-consistent method whereby the allocation is adaptive and self-tuned to the local energy scenario by sharing the fuel savings on the basis of the average primary energy factors for electricity and heat in the given local area including the cogeneration facility of interest. They call it the self-tuned average-local-productions reference (STALPR) method. They finally show by means of a representative case study that the classical methods might provide unfair, distorted figures that become increasingly important as cogeneration gains higher fractions of the energy market in a given local area.

This work focused on the analysis of fuel allocation between water and power in cogeneration desalination plants, as fuel cost is the main shared component. The three approaches used in this study to determine the fuel allocation were power to distillate ratio (PDR), heat value for potable water and exergy method. Based on several factors that closely matched the operating parameters of the cogeneration plants, the most applicable approach was chosen. To determine the fuel distribution between the production of water and power more accurately, the suggested method was implemented in one of the desalination facilities of the Saline Water Conversion Corporation (SWCC).

2. Methods of fuel allocation in cogeneration desalination plant

The fuel consumption for a single-purpose power plant is readily obtained by dividing the power output (PO) by the heat rate (HR). The power output is the desired or expected electrical output of the plant in kilowatts (kW) or megawatts (MW). The heat rate is the amount of energy used by a power plant to generate one kWh of electricity. It is a technical specification for the plant. For cogeneration or dual-purpose plants that produce both power and water from the same source of energy, fuel allocation is necessary to distribute the fuel use between the two products.

Fuel allocation in the power to distillate ratio (PDR), heat value for potable water and exergy methods will be estimated using a simplified configuration of a cogeneration desalination plant shown in Fig. 1.

The actual power to distillate ratio in the plant is 61.2 kWh/kL. 8077 kg/h of natural gas is used with a lower heating value (LHV) of 50000 kJ/kg which makes the heat content of the fuel (H_f) as 112181.4 kJ/s (8077× 50000/3600). Steam heat content can be estimated by energy balance around the MSF unit, 79621185.6 kJ/h (22117 kJ/s).

The turbine load is 25 MW (25000 kJ/s). Heat utilization factor (K) for the desalination plant is 0.95. Recovery ratio of water output/makeup sea water is 0.10.

2.1. Power to distillate ratio (PDR) method

Power to distillate ratio (PDR) utilizes the first law of thermodynamics with consideration of the cost factors to distribute fuel in dual purpose desalination plants. The method is based on a formulation of an ideal point at which power and water products are equivalent. Heat value for potable water has been developed using a heat value for potable water produced from desalination of sea water [5]. It discusses the use of overall fuel efficiency of the system for fuel allocation to power and desalination and balancing the energy input against the output of power and desalination plants. Al-Sofi and Srouji [5] develop the following expression for the ideal power to distillate ratio (PDRci) in cogeneration (dual purpose) desalination plants.

$$\text{PDRci} = \frac{\left[0.5 \cdot \left(T_s - T_x\right) + 28\right]}{\text{GOR}} \quad (1)$$

where T_s is the turbine inlet steam temperature, T_x is the

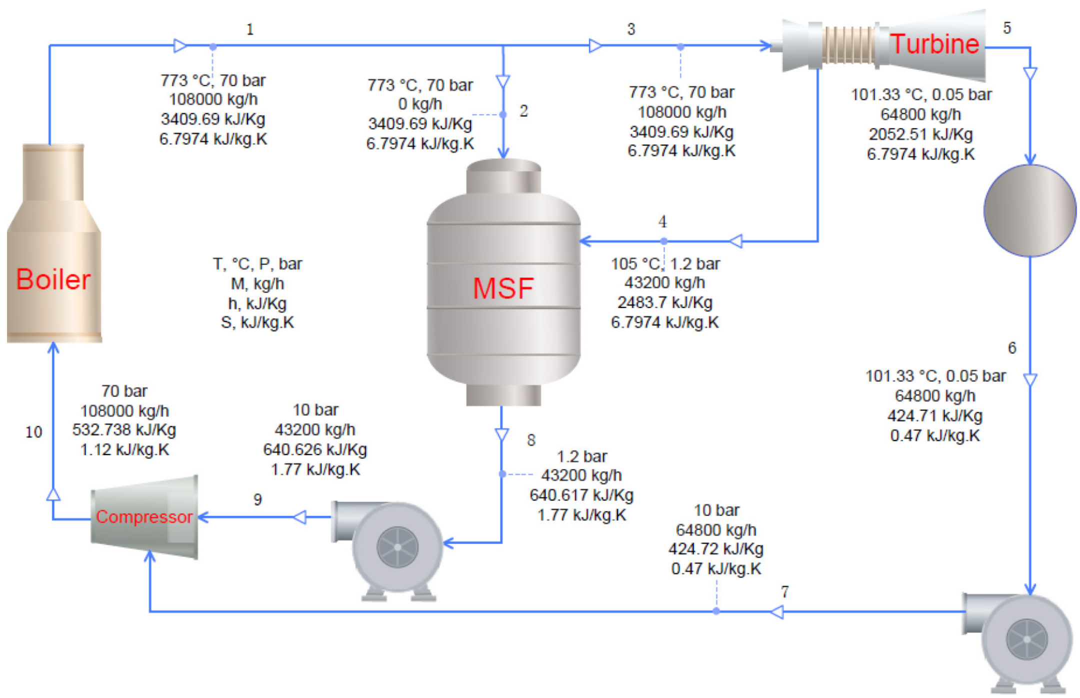

Fig. 1. Simplified flow diagram for a cogeneration desalination plant.

turbine outlet steam temperature and GOR is the gain output ratio which is defined as the ratio of the mass of distillate to the mass of the input steam.

An important ratio called delta (δ) and defined as the ratio of the actual power to distillate ratio and the ideal power to distillate ratio given in Eq. (2) can be used to characterize the cogeneration system. Delta (δ) will encompass two regions: Region I delta (δ) < 1.0; Region 2 delta (δ) > 1.0. Delta (δ) = 0 describes a turbine total bypass operation. Thus, delta (δ) exclusively between zero and one describes a back pressure turbine with some steam bypass to multistage flash (MSF) unit. On the other hand, delta (δ) > 1.0 describes the region for partially condensing boiler turbine generator (BTG). Formulation of equations describing these two regions is as follows:

$$\delta = \text{PDRca/PDRci} \tag{2}$$

Region 1 delta (δ) <1

The fuel fraction allocated to desalination is y_1 and the fuel fraction to power is z_1 as follows:

$$y_i = 1-(\delta)\cdot\left[1-\left(T_x / T_s\right)\right], \quad z_1 = 1-y \tag{3}$$

Region 2 delta (δ) ≥ 1

The fuel fraction allocated to desalination is y_2 and the fuel fraction to power is z_2 as follows:

$$y_2 = \left(\frac{1}{\delta}\right)\cdot\left(\frac{T_x}{T_s}\right), \quad z_2 = 1-y_2 \tag{4}$$

In case of applying power to distillate ratio (PDR) method, the result shows power to distillation is 45.47 kWh/kL.

Upon substituting values of the turbine inlet steam temperature (T_s = 773°C), the turbine outlet steam temperature (T_s = 101.33°C) and the gain output ratio (GOR = 345600/43200 = 8) into Eq. (1), the ideal power to distillate ratio (PDRci) equals 45.47 kWh/kL. Then according to Eq. (2) δ = 1.3 which falls into region 2. So, the fuel fraction allocated to power (z_2) is 90%, and the fuel fraction allocated to distillate (y_2) is 10%.

2.2. Heat value for potable water method

The heat value for potable water method utilizes the overall fuel efficiency of the system for fuel allocation to power and desalination and balancing the energy input against the output of power and desalination plants based on the specific plant data [6]. With the heat value for potable water method, power and desalination plants are evaluated and compared on an equal basis, i.e., under similar conditions of operational strategy; inputs and outputs, as to which plant gives better results overall, when water production and electrical power are combined or separated. The following procedure for estimating the fuel allocation by heat value for potable water method is outlined by Saeed [6].

If heat content of steam (H_s) is the heat needed by the desalination unit basically in the form of steam from a waste heat boiler, main boiler, or auxiliary boiler, then the specific heat consumption of desalination (SH_d) is:

$$SH_d = \frac{\Sigma H_s}{\Sigma W_p} = \frac{\text{heat constant of steam}}{\text{water production}} \tag{5}$$

If the recovery ratio (R) and the utilization factor (K) are known, then the heat value of desalinated water is given by:

$$HV_d = R_r \cdot SH_d \cdot K \tag{6}$$

Heat value of water (H_w) can be expressed as follows:

$$\Sigma H_w = \Sigma W_p \cdot HV_d \tag{7}$$

Knowing that the heat content of the fuel (H_f) is given as 112181.4 kJ/s. So, the ratio of water produced to total heat value of fuels (E_w) is:

$$E_w = \frac{\Sigma W_p \cdot HV_d}{\Sigma H_f} \tag{8}$$

and the overall thermal efficiency (E_f), then obtain:

$$E_f\,\% = \left[E_e + E_w\right]\cdot 100\% \tag{9}$$

$$1 = \frac{E_e}{E_f} + \frac{E_w}{E_f} \tag{10}$$

$$1 = F_e + F_w \tag{11}$$

where E_e is the ratio of power generated to total heat value of fuels, F_e is the fuel share for electricity generation and F_w is the fuel share for water production.

The respective fuel heat values to be allocated to the corresponding products are given by the following expression:

$$\Sigma H_f = \left(F_e \cdot \Sigma H_f\right) + \left(F_w \cdot \Sigma H_f\right) \tag{12}$$

where H_f is the total heat of fuel consumed for the power and desalination process, F_e and F_w are the fractions specifying the fuel shared by electricity and water, respectively. Upon substituting into Eqs. (5)–(12), the specific fuel energy consumption of desalination is 8% of fuel consumption and 92% of the fuel is shared by electricity as shown in Table 1.

Table 1
Fuel allocation based on heat value for potable water method

Water production (kg/h)	345600
Heat value of desalinated water (kJ/kg)	21.88
Heat value of water (kJ/s)	2101.11
E_w	0.02
E_p	0.22
The overall thermal efficiency (%)	24
F_w fractions specifying the fuel shared by water (%)	8
F_e fractions specifying the fuel shared by electricity (%)	92

2.3. Exergy method

The exergy analysis method is a tool for clearly distinguishing between the energy losses to the environment and the internal irreversibility of the process. Exergy is the theoretical limit to the work potential that can be extracted from a source or system in a given state when it interacts with a reference (environment) under constant conditions. Exergy defines the maximum capacity of a system to produce useful work when it transitions from a certain state to a final state that is in equilibrium with its environment. It uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics.

Exergy destruction is the measure of irreversibility, which is the cause of power losses. A system outputs the maximum possible work when it undergoes a reversible process from a certain initial state to the state of its environment (dead state). This represents useful work potential, energy, or availability.

Table 2 shows the enthalpy (h, kj/kg), entropy (S, kJ/kg.K), specific exergy (ψ, kJ/kg) and total exergy of (X, MW) of various streams of Fig. 1.

In order to calculate the total fuel consumption for the power and water production, the fuel energy allocated to common equipment has been considered the summation of the exergy losses in the boiler, feed water heaters, steam/air preheater, deaerator, and pumping power for common equipment, and distributed in a rational way between the power generation and water production. The fuel energy allocated to water production shall be the summation of the fuel energy assigned totally to water production and the portion of fuel energy consumption of common equipment allocated to water production, while the fuel energy allocated to power generation shall be the summation of the fuel energy assigned entirely to power generation and the portion of fuel energy consumption of common equipment allocated to power.

Energy allocated for power is the turbine and generator exergy consumption (5.541 MW), the condenser exergy consumption (4.634 MW) and the net power output (25 MW), equals 35.176 MW. While the energy allocated for water is the desalination plant exergy consumption (8.883 MW) and the product water exergy (0.255 MW), equals 9.138 MW. The common energy shared by power and water is the boiler exergy consumption (83.359 MW) and the other facilities (e.g. deaerator heaters, pumps exergy) consumption (0.001 MW), equals 83.360 MW.

So, the fuel allocation for power and water will be given by:

- Fuel allocation for power = energy allocation for power +((energy allocation for power/(energy allocation

Table 2
Properties of various streams of Fig. 1

Points	Temperature (°C)	P (bar)	M (kg/h)	h (kJ/kg)	S (kJ/kg.K)	ψ (kJ/kg)	X (MW)
1	773	70	108000	3409.69	6.797	1388.652	41.660
2	773	70	0	3409.69	6.797	1388.652	0
3	773	70	108000	3409.69	6.797	1388.652	41.660
4	105	1.2	43200	2483.70	6.797	462.662	5.552
5	101	0.05	64800	2052.51	6.797	31.4724	0.567
6	101	0.05	64800	424.71	0.470	289.237	5.206
7	180	10	64800	424.72	0.470	289.247	5.206
8	105	1.2	43200	640.617	1.770	117.744	1.413
9	180	10	43200	640.626	1.770	117.753	1.413
10	286	70	108000	532.737	1.120	203.565	6.107
Product	40	7.2	345600	167.93	0.570	2.6576	0.255

for power + energy allocation for water)) × common energy shared by power and water) = 101.345 MW.

- Fuel allocation for water = energy allocation for water +((energy allocation for water/(energy allocation for power + energy allocation for water)) × common energy shared by power and water) = 26.328 MW.
- Since the total exergy of the system is 118.912 MW, then the percentage of fuel allocation for power and water are 85% and 15%, respectively.

Table 3 shows a comparison between the percentage of fuel energy allocated to water using power to distillate ratio (PDR), heat value for potable water (HVW) and exergy methods applied to the simplified configuration of a cogeneration desalination plant shown on Figure (1). The comparison revealed that the exergy approach is to a large extent yielding comparable values in comparison with the other two approaches.

Table 3
Comparison of methods used to estimate % of fuel energy allocation to water

Method	PDR	HVW	Exergy
Fuel energy allocation to water	10	8	15
Fuel energy allocation to power	90	92	85

It is worth noting that these methods were developed through thermodynamic analysis. The power to distillate ratio (PDR) is quite independent because the approach is limited to conceptual thermodynamic basis and specific plant to calculate delta (δ). The heat value for potable water is simple to evaluate all the power and desalination plants and compare them on an equal basis under similar operating conditions. The determination of the K factor in using the heat value for potable water for various plants needs more studies on large amounts of data as to how this factor for the desalination unit will affect the overall efficiency of the power and desalination combined plants at certain conditions and locations.

3. Case study: SWCC plant

The exergy methodology will be applied to Al-Jubail Phase I desalination plant of the Saline Water Conversion Corporation (SWCC) to estimate calculate the fuel allocation between power and water.

Al-Jubail Phase I plant consists of 6 cogeneration units which are all fired by natural gas with heavy fuel oil (HFO) available as a reserve fuel. The schematic diagram of one 60 MW unit and 1000 m^3/h is shown in Fig. 2. This unit employs regenerative feed water heating system. Feed water heating is carried out in two stages of high-pressure heaters and low-pressure heaters along with one deaerating heat exchanger. Steam is superheated to 783 K and 87 bar in the steam generator and fed to the turbine. The turbine exhaust stream is sent to the desalination unit (MSF) and the condensate returns to the condensate return tank.

In order to calculate the fuel allocation in the exergy method, it is required to divide the cogeneration system into a number of subsystems which include the boiler, turbine, condenser, desalter and the other minor systems. An exergy balance was then carried out for each subsystem to determine the exergy destruction within the subsystem. The specific exergy and the total exergy rate associated with a fluid stream are calculated and summarized in Table 4 for all components present in the cogeneration cycle system.

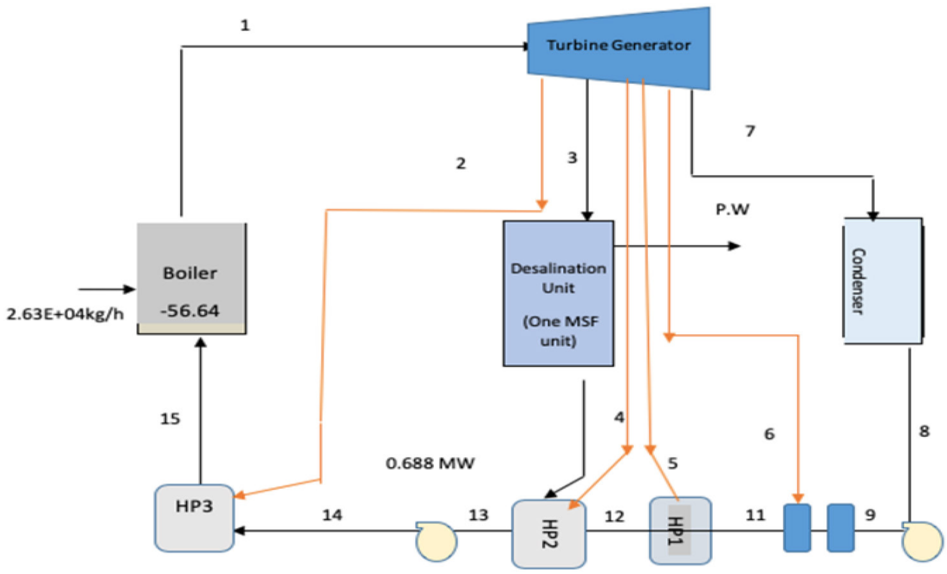

Fig. 2. Flow diagram for the design condition of Al-Jubail Phase I desalination plant.

Table 4
Operating condition of Al-Jubail Phase I desalination plant

Points	Temperature (°C)	*P* (bar)	*M* (kg/h)	*h* (kJ/kg)	*S* (kJ/kg.k)	ψ (kJ/kg)	*X* (MW)
1	510	87	281143.35	3415.995	6.712	1420.540	110.938
2	190	12.51	33360.35	2785.202	6.507	850.659	7.883
3	119	2	122469.93	2684.226	6.847	648.395	22.058
4	119	1.9	11413	2637.708	6.581	681.197	2.160
5	60	0.32	763	2510.519	6.728	510.205	0.108
6	250	25	295	2880.864	5.516	1241.777	0.102
7	42	0.082	106013.6	1976.759	6.314	99.852	2.940
8	42	0.082	113962.81	175.812	0.599	1.881	0.060
9	42	7.4	113962.81	176.132	0.599	2.201	0.070
10	45	7.4	113962.81	188.437	0.639	2.708	0.086
11	52	7.4	113962.81	217.697	0.730	4.862	0.154
12	57.55	7.2	113962.81	240.906	0.800	6.983	0.221
13	119	7.2	281206.09	499.535	1.517	52.047	4.066
14	120	129.5	284776.63	513.325	1.528	62.616	4.953
15	175.4	129.5	284776.63	742.910	2.095	123.235	9.748
16	54.5	0.85	5136.93	228.150	0.762	5.773	0.008
17	125.8	1.36	33360.35	528.471	1.590	59.219	0.549
Product water	40	3.6	948800	167.541	0.572	1.537	0.405
Desal condensate	119	10	122469.93	762.683	2.138	130.011	4.423

In order to quantify the exergy of a system, both the system and the surroundings must be specified. It is assumed that the intensive properties of the environment are not significantly changed by any process. The dead state is a state of a system in which it is at equilibrium with its surroundings, so the dead state temperature is determined at 25°C while the pressure is at 1 bar.

The fuel specific exergy is calculated as: $\psi_{\text{fuel}} = E_f \times \text{LHV}$, where $E_f = 1.06$ [16] is the exergy factor based on the lower heating value (LHV) [11]. In addition, the pump input power was calculated as $W_{\text{pump}} = m\ (H_{\text{out}} - H_{\text{in}})/\eta$, where $\eta = 0.95$, is the combined pump/motor efficiency.

It was found that the exergy destruction rate of the boiler is dominant over all other irreversibility in the cycle. It counts alone for 259 MW of exergy destruction in the plant, the exergy destruction in the turbine and desalination unit is 15.7 MW and 22.6 MW, respectively, while the total exergy destruction of the other components is only 8.4 MW as shown in Table 5.

It was also found that the fuel allocation for power generation is 74%, while that for water production is 26% at a power generation of 60 MW. The fuel allocation for power generation became 60% when the power generation is reduced to 30 MW, raising the fuel share for water production to 40%. Al-Jubail Phase I desalination plant is employing extraction condensing turbine, so it is expected that the percentage of fuel energy allocated to power of 74% is within the expected range between 70% to 85% [10]. Conversely for a plant which is designed within the context of back pressure steam turbines, the fuel energy allocated to power production ranges between 50.2% and 57% of the total boiler fuel energy [10].

Table 5
Exergy destruction of Al-Jubail components

Boiler	259.07	71.913
Turbine/generator	15.78	4.38
Desalination plant	22.63	6.28
Condenser	2.87	0.79
GC	0.034	0.009
HP #1	0.033	0.009
HP #2	2.73	0.76
Deaerator heaters	2.53	0.70
Pumps	0.189	0.053
Total exergy losses	305.90	84.912
Net power output	55	15.267
Product water exergy	0.40	0.11

Conclusions

Three methods for fuel allocation were reviewed: the power to distillate ratio (PDR), the heat value for potable water and the exergy method. The exergy method was found to offer better estimate of fuel allocation in co-generation (dual purpose) desalination plants. So, it is recommended to be used in desalination plants as a tool for pre-cost estimation of water production cost. This has become important especially with the expansion of the privatization sector.

The exergy destruction rate of the boiler, the turbine and the desalination unit were 259 MW, 15.7 MW and 22.6 MW, respectively. Clearly, the boiler is accountable for most of the exergy destruction in the plant, more than 71% of exergy destruction. It offers room for cost improvement, and it is recommended to be subjected to further studies.

It was observed that the fuel share for water production increases significantly when power generation is reduced. It is recommended to investigate effect of manipulating power production on the water production cost via the fuel allocation methods.

In future work, the fuel consumption of a single-purpose power plant producing only electric power will be compared with that of a cogeneration plant producing the same capacity.

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doi: 10.5004.dsal.2024.700057

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Solar-driven desalination in Saudi Arabia for a sustainable future

Raid Alrowais[1,*], D. Ybyraiymkul[2], M. Kum Ja[2], Kim Choon Ng[2]

[1]*Department of Civil Engineering, College of Engineering, Jouf University, Sakakah 72388, Saudi Arabia,*

[2]*Water Desalination and Reuse Center (WDRC), Biological and Environmental Science and Engineering Division (BESE), King Abdullah University of Science and Technology, Saudi Arabia*

ABSTRACT

All primary (fossil) energy sources available on planet Earth emanate from the Sun, namely its photosphere (at 5700 K) where useful solar irradiance is acquired either directly or indirectly on a receiver surface. The maximum potential of a solar receiver is gauged by either direct normal (DNI) or global (HGI) irradiance. The literature has widely reported three types of solar harvesters for the production of green electricity, namely (i) the stationary PV, (ii) the concentrated PV or CPV, and (iii) the CSP combined with thermal energy storage systems powering the power plants. Thus, depending on the PV materials and receiver designs, the solar systems could operate over a wide range of solar irradiance, ranging from 1 Sun to concentrations up to 1000 suns or more. Consequently, it is important to differentiate the inherent performance of these solar energy harvesters in terms of collectible energy efficiency. In the study of totally green desalination, all types of solar harvesters for electricity production will be utilized for powering the membrane-based seawater desalination plants. The water production efficacy from assorted PV and seawater reverse-osmosis plants will be compared and presented along with their estimated unit water production cost.

Keywords: Green desalination methods; Standard solar energy (SSE); Solar energy

1. Introduction

Amidst the increasing apprehensions about global warming [1–3], which are amplified by the extensive dependency on fossil fuels for worldwide energy supply [4–7], renewable energy sources emerge as the most promising and sustainable solutions. However, for these alternatives to meet global energy requirements, they must exhibit substantial potential and competitive capabilities relative to conventional energy sources [8–10]. Notably, solar energy surpasses all other available sources in energy potential and stands as capable of direct conversion into electricity through photovoltaic systems [11–13]. However, the challenges of implementing renewable solar systems are (i) the sinusoidal characteristics of solar irradiance availability, (ii) the intermittency caused by cloud cover, sand storms, etc., and (iii) the need for regular maintenance.

The Sun, being Earth's primary energy source, originates from its photosphere temperature of 5770 K, fuelling diverse solar energy systems. Designated as standard solar energy (SSE), this energy represents the Sun's highest observed temperature, establishing a foundational energy basis for terrestrial solar processes. Illustrated in Fig. 1 using classical thermodynamics is a representation of a heat engine operating between the

* Corresponding author.

Sun and Earth's ambient temperature, demonstrating the maximum achievable usable or Carnot work from this engine:

$$W_c = \frac{Q_{\text{SSE}}}{1 - \frac{T_a}{T_{\text{Sun}}}} \rightarrow W_c \approx Q_{\text{SSE}} \text{ as } T_{\text{Sun}} >> T_a \quad (1)$$

The study conducts a comparative examination of solar energy systems integrated into desalination plants. It investigates the efficacy, sustainability, and economic viability of different solar technologies when combined with desalination processes. The research assesses the performance of these integrated systems, considering factors such as energy yield, water production rates, environmental impact, and cost-effectiveness. By analyzing various system configurations and technologies, the study aims to determine the most efficient and sustainable approach for integrating solar power into desalination facilities. Its goal is to offer valuable insights for optimizing solar-based desalination plants to address future energy-water challenges.

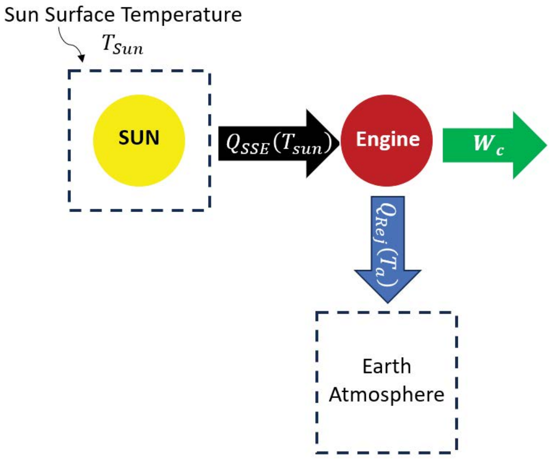

Fig. 1. An ideal heat engine operates from the Sun's photosphere to the Earth's surface, where Q_{SSE} is emitted as electromagnetic waves at T_{Sun}. The engine produces a maximum or Carnot work (W_C) while rejecting Q_{Rej} to ambient at T_a. As T_{Sun} = 5770 K, Q_{SSE} is considered the Standard Solar Energy (SSE) at T_{Sun}.

2. Solar-powered desalination Systems

To assess sustainable seawater desalination driven by solar energy, various configurations of hybrid solar desalination are being examined:

2.1. Case 1: Solar-powered membrane desalination using stationary photovoltaic (PV + SWRO)

This specific setup of solar PV + SWRO offers the advantage of straightforward installation and operation, which clarifies its prevalence as the preferred approach in sustainable PV systems, as illustrated in the schematic diagram in Fig. 2. All electricity generated by PV panels is utilized to operate the SWRO plant. In assessing the solar PV system's efficiency over an extended period, its performance is quantified using a metric known as the long-term rating (LTR), represented in terms of electrical energy. The LTR is essentially defined as the ratio of the annual valuable electricity delivered to the grid per unit aperture area of PV expressed as

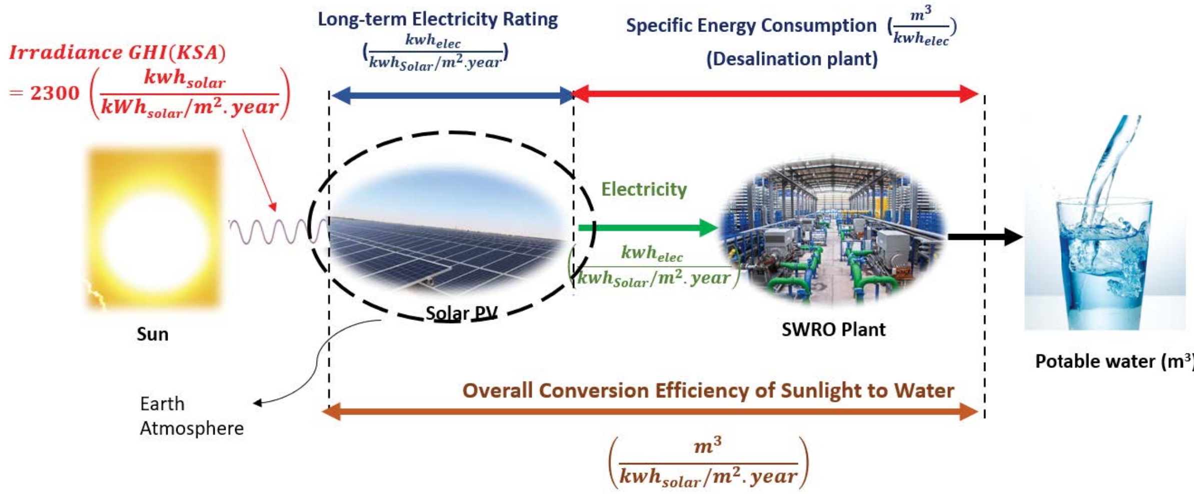

Fig. 2. Traditional solar photovoltaic (PV) technology is coupled with seawater reverse osmosis (SWRO) plants for water production. This setup evaluates three advantages: PV panel Long-Term Reliability (LTR), SWRO Specific Energy Consumption (SEC), and overall hybrid plant efficiency. LTR concerns the exergy and Second Law efficiencies of PV panels [15].

$kWh_{elec}/m^2/y$. Existing literature reports a specific energy consumption (SEC) range for SWRO plants spanning from 2.8 to 6 kWh_{elec}/m^3 of water produced. For the sake of comparison, an SEC value of 3.5 is adopted [14]. Despite the widespread use of solar PV plants today, it will later become evident that this method doesn't optimize energy efficiency in desalinated water production due to the absence of thermodynamic synergy between the integrated processes in sequence.

2.2. *Case 2: Membrane desalination using concentrated photovoltaic (CPV + SWRO)*

In this configuration, concentrated photovoltaic (CPV) technology is employed, utilizing a focusing lens such as a Fresnel lens or a contoured "parabola" along with a reflective hyperbolic surface, as illustrated in the schematic diagram in Fig. 3. This setup concentrates the incident solar radiation onto a homogenizer situated above a compact 3-junction solar cell, specifically multi-junction cells (MJC). CPV operates by intensifying beam radiation while redirecting diffuse irradiance back to the atmosphere. Its primary advantage lies in achieving a higher long-term rating (LTR), generating electricity at rates 2.5 to 3 times higher than observed in Case 1. However, the CPV concentrator necessitates precise 2-axis tracking mechanisms to effectively capture all direct beam irradiance onto the MJCs. The integration of the SWRO plant into CPV mirrors the conventional installation process seen in standard solar PV systems.

2.3. *Case 3: Hybrid thermal and membrane desalination using concentrated solar power (CSP + MED + SWRO)*

This hybrid arrangement integrates tower receiver-based Concentrated Solar Power (CSP), directing all incident beam irradiance onto a receiver situated at the tower, as illustrated in the schematic diagram in Fig. 4. The thermal energy collected at the tower receiver is then channeled into a circulating circuit of molten salt, enabling the storage or utilization of thermal energy to fuel a Rankine water-steam cycle. In this cycle, high enthalpy steam powers a turbine to generate electricity. Simultaneously, lower-pressure steam is extracted to fuel the multi-effect distillation (MED) plant, tasked with desalinating impaired seawater. While the MED plant does utilize some electricity, the surplus electricity produced by the turbine generator is directed toward powering the SWRO plant for increased potable water production. Similar figures of merit (FoM) are applied to evaluate the hybrid CSP plant, enabling comparison with the aforementioned two cases.

3. Results and discussion

Due to freshwater being scarce, a considerable amount of primary energy is used in the production of freshwater through desalination. Expanding on the concept of long-term rating as an authentic performance gauge and design factor, its application is further explored in forecasting water production, a critical necessity in Middle Eastern nations. Various desalination techniques, operated by three prevalent types of solar systems, are illustrated in Figs. 5 and 6.

Fig. 5 undertakes a comprehensive comparative analysis of PV, CPV, and CSP systems, focusing on their long-term ratings and employing exergy and second law efficiency principles. A crucial aspect to highlight is the variance in solar irradiance availability, notably maximal for the PV system, which can harness global radiations (both beam and diffuse). Conversely, CPV and CSP systems are restricted to utilizing beam

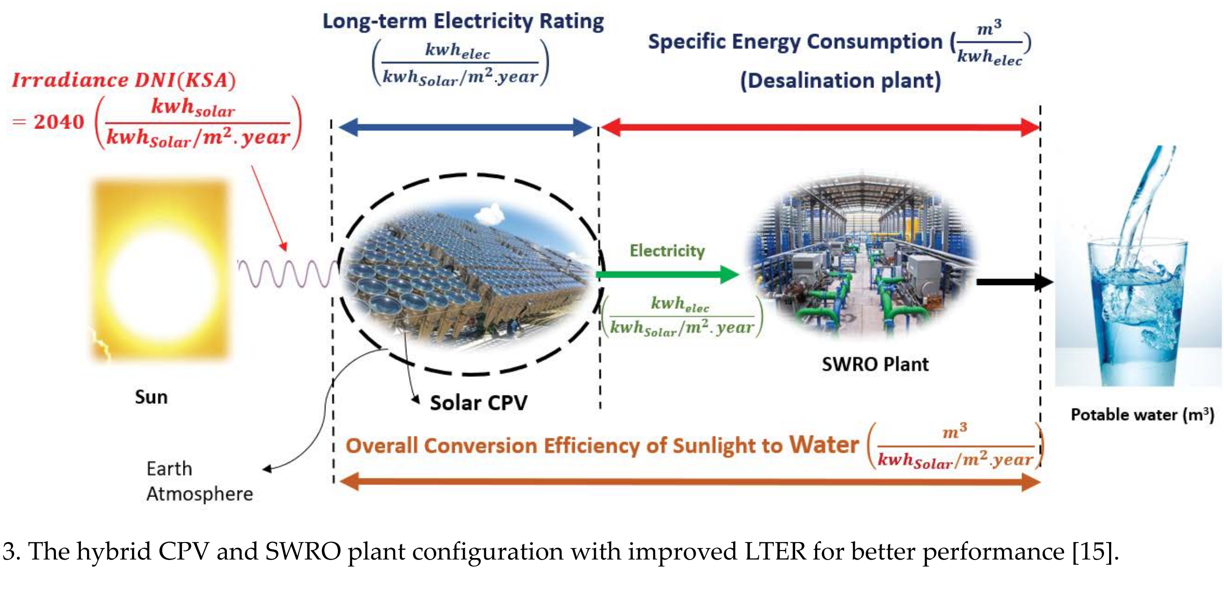

Fig. 3. The hybrid CPV and SWRO plant configuration with improved LTER for better performance [15].

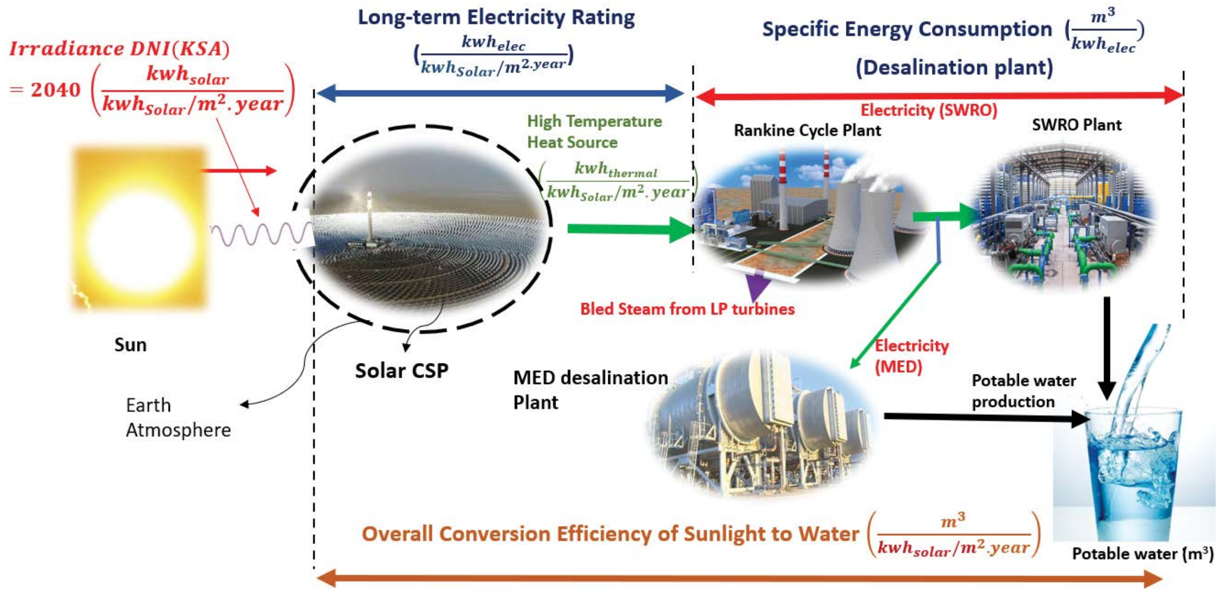

Fig. 4. The combined concentrated solar power (CSP) system involves a tower receiver equipped with multiple heliostats, the Rankine cycle featuring an electric generator, and both the multi-effect distillation (MED) and seawater reverse osmosis (SWRO) desalination facilities [15].

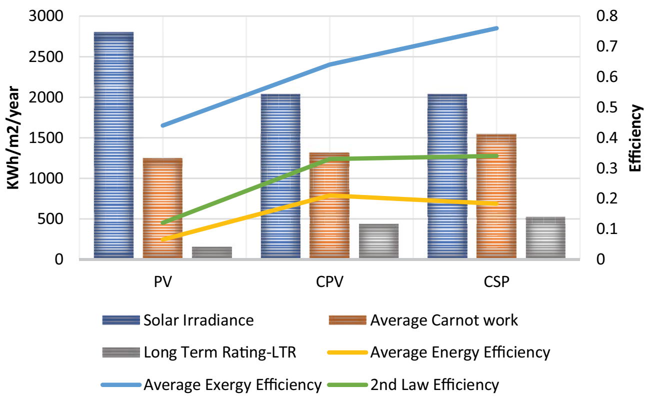

Fig. 5. A comparison of the performance capabilities among PV, CPV, and CSP systems.

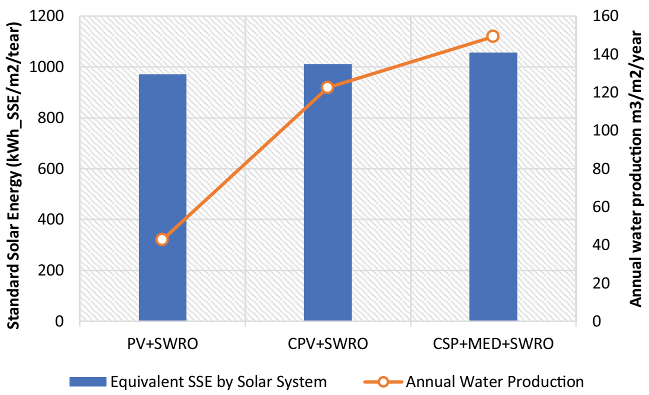

Fig. 6. Comparing various solar energy systems using a standardized measure of solar energy (SSE) to produce freshwater via different desalination methods.

radiations due to their reliance on optical concentrators. Despite PV's superior solar radiation availability, its long-term rating remains the least among the three systems. While CPV and CSP share identical solar radiation availability, their performance characteristics diverge notably. The CSP system showcases the highest average Carnot work, effectively managing thermal radiations [29], and exhibiting elevated exergy efficiency. Conversely, CPV, although not delivering the highest long-term rating or exergy efficiency, offers a straightforward method to directly convert solar energy into high-grade electrical energy, boasting the highest energy efficiency at 21%. Additionally, CPV demonstrates a nearly equivalent second law efficiency of 33%, closely aligned with CSP's 34%.

Fig. 6 provides a comparative evaluation of the solar energy systems discussed earlier, employing the equivalent standard solar energy (SSE) at the sun's surface as a benchmark for desalination technology. A similar pattern is observed in this graph, reflecting the efficiency of systems for water production. Concerning SSE equivalence, all three systems demonstrate nearly comparable performance levels. However, discernible differences emerge in water production metrics, with PV + SWRO showing the highest specific irradiance value per cubic meter of desalinated water produced, while CSP + MED + SWRO proves the most efficient with the lowest specific irradiance value per cubic meter. Consequently, CSP + MED + SWRO achieves a fourfold higher annual water production compared to the PV + SWRO system. Despite CPV + SWRO not presenting the most efficient water production technology, it offers a more straightforward configuration compared to CSP + MED + SWRO while maintaining a similar order of production metrics, as depicted in Fig. 3. This underscores how despite varying operational conditions and technologies, the long-term rating (LTR) and standard solar energy (SSE) serve as fundamental platforms for comparing solar energy systems in freshwater production via desalination.

4. Conclusion

The conventional efficiency-based rating for solar energy systems, like CPV at 26%, doesn't serve as an accurate design parameter due to solar energy intermittency and field condition variations. Long-term electrical ratings and average system efficiency, as in CPV at 20%, offer a more accurate system potential for plant designers, regardless of technology or operating conditions. Using the classical thermodynamics approach of a heat engine between the Sun and Earth's ambient temperature, standard solar energy (SSE) becomes a universal energy measure for various solar technologies despite their operation specifics. Despite PV having high solar radiation availability at 2490 kWh/m²/y, PV + SWRO showed the least efficiency with the highest consumption of standard solar energy per cubic meter of potable water, i.e., 6.49 kWh_SSE/m³. However, CPV + SWRO and CSP + MED + SWRO are more efficient in utilizing the SSE, at least twice as efficient as conventional PV, with 2.36 kWh_SSE/m³ and 2.99 kWh_SSE/m³, respectively. Despite the availability of diverse operational needs and technologies to date, whether thermal or electrical, yet the solar designers have opted to implement the least efficient solar design or system. The standard solar energy (SSE) approach, it allows a fair and objective energy efficiency comparison on a common SSE energy input platform that emanates from the surface of the sun.

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Balaban Desalination Publications

The 15th Gulf Water Conference

(2025) 35–39
doi: 10.5004.dsal.2025.700039

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Advanced GC-MS-SIM method for simultaneous determination of isphenol-A and phthalic acid esters (PAEs) in seawater

Mohammed Akkbik*, Ahmad Ali Ahmadi, Noora Al-Qahtani

Central Laboratories Unit, Office of VP for Research & Graduate Studies, Qatar University, Doha, Qatar
email: m.akkbik@qu.edu.qa

ABSTRACT

In response to environmental concerns and the need for precise analytical methods, a highly sophisticated gas chromatography-mass spectrometric (GC-MS) technique was developed for the simultaneous quantification of bisphenol-A (BPA) and three common phthalic acid esters (PAEs) in seawater samples. This novel method was meticulously designed to ascertain the total concentration of PAEs present in collected seawater samples, thus addressing environmental and health-related concerns in Qatar which is the main source of domestic water supply. The development of the extraction method for the determination of BPA, dibutyl phthalate (DBP), benzyl butyl phthalate (BBP), and bis(2-ethylhexyl) phthalate (DEHP) involved a comprehensive optimization process. Four crucial parameters, including the selection of the solvent, manipulation of physical conditions, and precise determination of the volume of acid, were meticulously refined. The extraction process was achieved through liquid-liquid extraction employing dichloromethane as the solvent. A 50 mL of seawater was previously adjusted to pH 4.0 with 50 μL of HCl (36-37%), then the mixture was manually shaken for 1 min with 2 mL of DCM. To further enhance precision, an ultrasonic water bath shaker was utilized for a precisely timed 30 min extraction period, all conducted at room temperature. Analytes, namely DBP, BPA, BBP, and DEHP, exhibited distinct and well-defined retention times of 10.2, 11.2, 11.9, and 12.7 min, respectively, within the chromatographic system. Our method demonstrates remarkable sensitivity, with instrument detection limits established at 0.09, 0.43, 0.33, and 0.93 μg/L for DBP, BPA, BBP, and DEHP, respectively. Furthermore, the calibration curve working ranges were thoughtfully determined to span from 2.5 μg/L to 250 μg/L for each of the target compounds. In assessing the precision of our method, relative standard deviation (RSD), indicating precision, consistently fell within the range of 0.87% to 11.10% for DBP, BPA, BBP, and DEHP. Additionally, recovery values spanning from 80.9% to 103.7% demonstrated the robustness and accuracy of our method across a range of sample matrices. In our comprehensive analysis of seawater samples, it was evident that the concentration levels of DBP, BPA, BBP, and DEHP remained well below the stringent standards established by the Environmental Protection Agency (EPA) for DEHP (6 μg/L) and the United States Environmental Protection Agency (USEPA) for PAEs (3.0 μg/L) in raw water. These results underscore the effectiveness and reliability of our advanced GC-MS method, which holds significant promise for environmental monitoring and health-related research.

Keywords: BPA; PAEs; Seawater; GC-MS-SIM

*Corresponding author

ISBN 0-86689-078-5

1. Introduction

Seawater is essential for drinking and plays a big role in areas with unique environmental and health challenges [1]. In Qatar, where there's not much freshwater, they mainly turn seawater into drinking water through a process called desalination [2]. Qatar has three primary desalination plants, one in Ras Abu Fontas south of Doha and two in Ras Laffan to meet the country's water supply needs. Seawater is the biggest water source on Earth and is becoming more important in places where there's not enough water. Marine plastic waste contains many organic pollutions such as BPA and PAEs that do not have a strong interaction with polymer chains and easily leach at stress conditions which are increase their potential threat to ecosystem and humans [2]. BPA is used primarily as a flame retardant and stabilizer in polyvinyl chloride, polycarbonate, rubber, and epoxy resins, while PAEs are used as plasticizers to produce polyvinyl chloride and polyethylene to improve their flexibility and transparency [3,4]. BPA and PAEs are classified as endocrine disruptor chemicals (EDC), which have carcinogenic toxicity at very low concentrations by mimicking estrogenic activity and may affect the health and reproduction systems of humans as well as wildlife [2–6]. In the sea, seawater is like a main storage for these harmful things, and that's a danger to sea life [1]. The problems of factories, more people, and the risk to coasts show why we need better ways to check if water is good [3,4]. The main point of this study is to find out for the first-time what plastic stuff is in the waters near Qatar. We're looking at three types of plastic stuff, BBP, DBP, DEHP, and also bisphenol A (BPA). The goal of this study to investigate concentration level of BPA and PAEs in Qatar marine according to recent published studies mentioned that the increasing rate of their use [5,6], and the scarce information regarding their presence in the marine environment using a very sensitive instrument like gas chromatography with mass spectrometry (GC-MS) to achieve this study.

2. Material and methods

2.1. Chemical and reagents

All chemicals and organic solvents were used at a HPLC grade. BPA and three PAEs analytical standards involve DBP, BBP, and DEHP used were purchased from Sigma-Aldrich (St. Louis, MO, USA). Solvents and reagents used for sample preparation was dichloromethane and hydrochloric acid (37%) (VWR, France) and sodium sulfate (Merck, Darmstadt, Germany). Reverse-osmosis ultrapure type quality water was obtained from from an Elga Purelab Ultra Analytic purification system (Elga, High Wycombe, UK).

2.2. Seawater sampling

Surface seawater samples were collected in three different locations-Qatar in May 2022; Ras Abu Fontas, Katara and Al Khor, three sampling points were taken per location.

2.3. Lquid–liquid extraction

The Environmental Protection Agency (EPA) explained a simple way to take out BPA and PAEs from seawater using a liquid-liquid extraction (LLE) method [7]. We made a few changes to that method. A 45 mL of seawater and put it in a 50 mL clean tube. Then, we mixed it with 2 mL of dichloromethane and added 50 µL of hydrochloric acid solution (36%). After mixing it by hand for 1 min, then a sonicator for 30 min and hold the mix in a centrifuge at 200 rpm for 5 min to separate it. Finally, 1 mL of organic phase part and put it in a clean tube with 100 mg of sodium sulfate to remove water drops, and then it will be ready for analysis by GC–MS.

2.4. Instrumental analysis

Analysis target compounds were carried out using an Agilent 6890N GC system (Agilent Technologies, Palo Alto, CA, USA) with a DB-5MS capillary column (30 m x 0.25 mm, 0.25 µm film thickness; Agilent, Santa Clara, CA, USA) equipped with an Agilent 5975B mass selective detector in electron impact mode (ionization energy set at 70 eV). The carrier gas was helium at a flow rate of 1.2 mL/min. Oven temperature was adjusted at 60°C for 1 min initially, and then increased to 300°C at 20°C/min. 3.0 µL volume samples were injected using hot-splitless injection mode, with the split closed for 0.7 min. Injector and detector temperatures were set at 250 and 280°C, respectively. Ion source temperature was set at 230°C and quantitative analysis was performed by SCAN mode and select ion monitoring (SIM) mode, the time for solvent delay was set to 8 min.

2.5. Validation of analytical method According to ICH

Validation of the analytical method was performed by assessment of the linearity, sensitivity, specificity and recovery according to ICH guidelines.

2.5.1. Linearity

A stock solution of BPA, DBP, BBP and DEHP at 10,000 µg/L was prepared in dichloromethane. Linearity was examined by automatic injections of standard mixture for over five different points in investigated ranges from low to high concentrations 2.5–250 µg/L in dichloromethane were prepared, and each concentration was repeated three times. The calibration curves were obtained by plotting the ratio of peak area vs. concentration between a specific m/z ions for (DBP, BPA, BBP, and DEHP).

2.5.2. Sensitivity

The instrumental response sensitivity is given by the slope of the calibration curve. Method with a large slope discriminates small differences in analyte contents. Limit of detection (LOD) and limit of quantitation (LOQ) were determined according to following equation:

$$\text{LOD or LOQ} = k \times B/S \quad (1)$$

where k is a constant (3 for LOD and 10 for LOQ), B is the standard deviation of the analytical signal, and S is the slope.

2.5.3. Specificity

Specificity of the analytical method was evaluated by peak purity curves through resolution factors (R_s), peak asymmetry factor (A_s) and number of theoretical plates (N). The resolution factor R_s was calculated based on Eq. (2):

$$R_s = (t_1 - t_2) / (W_2 + W_1) / 2 \quad (2)$$

where t_1 and t_2 are the retention times of the two components, W_1 and W_2 are the corresponding widths at the bases of the peaks obtained by extrapolating the relatively straight sides of the peaks to the baseline.

Asymmetry factor is a measure of peak tailing and was calculated based on Eq. (3):

$$A_s = b / a \quad (3)$$

where A_s is peak asymmetry factor, b is the distance from the point at peak midpoint to the trailing edge, and a is the distance from the leading.

Edge of peak to the midpoint (a and b were measured at 10% of peak height). The number of theoretical plates (N) was calculated using Eq. (4):

$$N = 16 \times (t_R/W_1)\ 2 \quad (4)$$

where N is the number of theoretical plates, t_R is retention time and W_1 is width at the bases of the peak.

2.5.4. Accuracy

The accuracy was evaluated through spiking and recovery testing. The recovery rate of PAEs at three different fortification levels 50, 200 and 500 µg/L was evaluated in order to assess the extraction efficiency of the proposed method using external standards addition.

2.5.5. Statistics

All GC-MS-SIM analysis were performed in three replicates. The results were expressed as mean (m) ± standard deviation (SD).

3. Results and discussion

Developed analytical method for PAEs were done firstly by the SCAN mode in order to determine retention time for each PAEs, then by the SIM mode for quantification. SIM quantitation ions of (DBP, BPA, BBP, and DEHP) are shown in Table 1.

3.1. Validation of analytical method

3.1.1. Linearity

The linearity of analytical method by GC-MS-SIM for PAEs (DBP, BPA, BBP and DEHP) was assessed by prepared five different concentrations in dichloromethane at 2.50, 10, 25, 100 and 250 µg/L with three replicates (n = 3) as shown in Fig. 1. The chromatographic responses were found to be linear over an analytical range of 2.50-250 µg/L, quite satisfactory and reproducible with time. The linear regression equation was calculated by the least squares method and summarized in Table 2.

The correlation coefficients were greater than ≥ 0.9994 with RSD ≤ 0.94 and R_s > 2.0 indicating a strong linear relationship between the variables. The results suggested that the developed GC-MS-SIM method has a linearity.

3.1.2. Sensitivity

LODs in this study for DBP, BPA, BBP and DEHP by GC-MS-SIM were lower — 0.09, 0.43, 0.33 and 0.93 µg/L,

Table 1
SIM quantitation ions for BPA, DBP, BBP and DEHP

Compound	Fragments (m/z)					
	M_W	R_t	1 (Quantitative)	2	3	4
DBP	278.34	10.09	149	150	76.1	223
BPA	228.29	11.18	213	119	228	85
BBP	312.36	11.93	149	91	206.1	104
DEHP	390.56	12.64	149	167	57.1	104

M_w: molecular weight (g/moL), R_t: retention time (min)

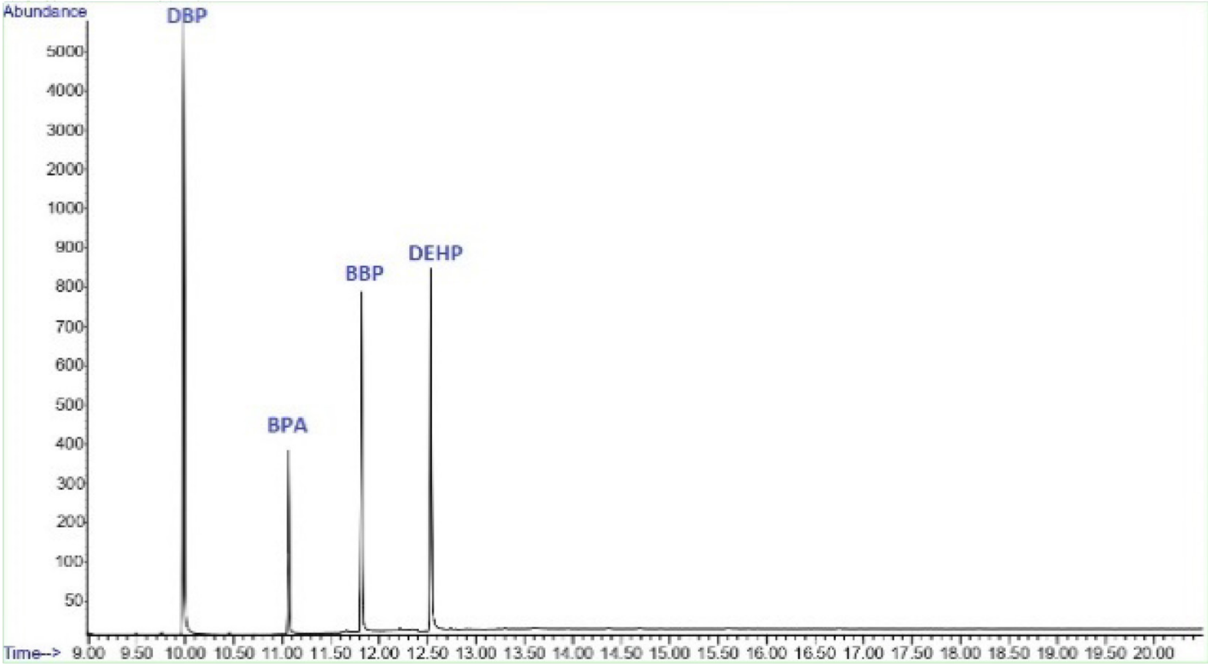

Fig. 1. Typical chromatogram of DBP, BPA, BBP and DEHP at 25 μg/L using GC-MS-SIM with spitless mode.

Table 2
Regression analysis of calibration curves for PAEs by proposed method

Compound	t_R (min)	Calibration equation	R^2	RSD	LOD	LOQ
DBP	10.1	$Y = 2978.8x – 10847$	0.9999	0.55	0.09	0.24
BPA	11.2	$Y = 724.67x – 26833$	0.9995	0.94	0.43	1.14
BBP	11.9	$Y = 1789.6x – 55768$	0.9996	0.81	0.33	0.92
DEHP	12.7	$Y = 3197x – 148431$	0.9994	0.60	0.93	2.65

R^2: correlation coefficient, RSD: relative standard deviation

respectively compared with previous publications. [8] reported that LODs of DBP, BBP and DEHP in wine were 150, 150 and 100 μg/L, respectively. [9] reported that LODs of DBP, BBP and DEHP in wine were 4 μg/L.

3.1.3. Recovery

The accuracy of method was performed to verify the effectiveness of the extraction step, and to exclude an incorrect quantification of DBP, BPA, BBP and DEHP. The accuracy was achieved using the technique of external standard addition at three spiked levels 5, 20 and 50 μg/L with three replicates ($n = 3$). The results are summarized in Table 3.

The recovery ranges in this study for DBP, BPA, BBP and DEHP (91.04–103.7, 80.90–96.59, 88.95–98.14 and 91.22–99.62%, respectively) are better than those

Table 3
Accuracy of developed method

Spiked level (μg/L)	Average recovery (% ± SD)			
	DBP	BPA	BBP	DEHP
5	94.04±3.4	80.90±8.2	98.14±6.1	99.62±5.7
20	91.04±2.9	96.18±5.7	90.28±4.8	91.22±4.4
50	103.7±2.9	96.59±5.5	88.95	97.82±3.5

SD: standard deviation

Table 4
Concentrations of DBP, BPA, BBP and DEHP (ng/L) in three different locations-Qatar

Location	DBP		BPA		BBP		DEHP	
	1	2	1	2	1	2	1	2
Ras Abu Fontas	5.90±0.01	5.84±0.01	1.86±0.01	1.00±0.01	1.1±0.02	1.22±0.03	7.1±0.02	7.22±0.03
Katara	24.37±0.01	24.55±0.02	3.72±0.02	6.16±0.02	6.22±0.01	6.04±0.01	16.22±0.06	16.04±0.06
Al Khor	17.77±0.02	17.69±0.02	14.72±0.01	12.91±0.01	2.05±0.02	2.24±0.01	32.45±0.07	32.90±0.05

reported by [9] for DBP, BBP and DEHP at spiked level 50–500 μg/L (88–96, 85–97 and 90–98, respectively), BBP and by [8] for DBP, BBP and DEHP at spiked level 100–500 μg/L (67–109, 71–100 and 69–90%, respectively). Thus, good recoveries with R.S.D lower than 8.2 were obtained for each of PAEs confirming that the developed method was accurate.

3.2. Real samples analysis

The developed method was successfully used to detect the concentrations of DBP, BPA, BBP and DEHP in collected coastal samples from different locations-Qatar in May 2022. The external standard method was employed for quantitative analysis of these compounds in seawater samples, and the results are displayed in Table 4. Total concentrations of these compounds in seawater were in the range of 15.0–67.7 ng/L, and the results in this study was in accordance with the results of the prior studies [9,10].

4. Conclusion

Our research provides an important role quality control studies of BPA, DBP, BBP and DEHP in marine environment of Qatar. The detection limit and the quantitation limit of in seawater samples were in range 0.009–0.093 μg/L. In addition, the present method showed good linearity and high correlation coefficients. In addition, the recoveries were 80.9–103.7% with good precision (n = 3, RSD: 2.9–8.9%) for seawater samples spiked at 50, 200 and 500 μg/L levels. This simple, accurate and highly sensitive method is expected to have potential applications in seawater samples. Generally, results confirmed that seawater in Qatar is safe.

Acknowledgment

The analysis by GC–MS was accomplished in the Central Laboratories unit, Qatar University. The contents herein are solely the responsibility of the author.

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مؤتمر الخليج الخامس عشر للمياه
The 15th Gulf Water Conference

(2024) 40–46
doi: 10.5004.dsal.2024.700032

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Oxide-activated carbon for seawater desalination using solar energy

Wafa A. Al Rawahi*, Amal S. Al Rahbi, Maryam S. Al Hashmi, Marwa Al Riyami, Hanadi Al Aameriya, Nada A. Al-Toubi, Riham A. Al-Nabhani

University of Technology and Applied Sciences, Applied Sciences Department, PO Box 74, Al-Khuwair, Postal Code 133, Al Khuwair Al Janubyyah St, Muscat, Oman, email: wafaaqib@hct.edu.om, wafa.alrawahi@utas.edu.om

A B S T R A C T

Desalination of seawater is an efficient process and a viable solution for water shortage problems. This process is consuming a large amount of energy. One of the latest possible solutions with less energy consumption is the use of activated carbon for the desalination process. Activated carbon can be produced using several materials including agricultural waste. In this work activated carbon was produced from palm tree trunks. The preparation of the activated carbon was done by two steps process. The first step was the pyrolysis for 2 h at 700°C under a nitrogen gas flow of 150 ml/min. The next step was the physiochemical activation using potassium hydroxide (1:1) under nitrogen and carbon dioxide gas flow of 150 m/min for 2 h. The prepared activated carbon was analyzed using Scanning Electron Microscopy (SEM) with Energy Dispersive X-ray (EDX) to study the surface area, the porosity, and the chemical composition. The application of the activated carbon in the desalination process was done by initially oxidizing the AC to use it for the reduction of the boiling point of the seawater followed by the desalination. This was supported by the use of a solar panel to provide the required energy for evaporation. The treated water was analyzed using inductively coupled plasma optical emission spectrometry (ICP-OES). The prepared activated carbon in this study was used to produce fresh water by the desalination of seawater based on an environmentally safe and lower energy cost method, which is a promising technique that can overcome the shortcomings of the current technologies.

Keywords: Activated carbon; Oxide-AC; Desalination; Solar energy

1. Introduction

Desalination has emerged as a critical solution for addressing water scarcity in Oman. The country's strategic plan envisions meeting 90% of its drinking water demand through the desalination of seawater (Abushammala et al., 2020). A variety of desalination technologies, including reverse osmosis, forward osmosis, multistage flash, and multiple-effect distillation, have been implemented in Oman. A study was conducted to understand the significance of seawater desalination in Oman, taking into account its social, economic, and environmental implications (Feroz et al., 2010). The study concluded that reverse osmosis is the most appropriate desalination technology for Oman, followed by forward osmosis, multistage flash, and multiple-effect distillation (Abushammala et al., 2020).

Activated carbon has received significant interest for its potential in desalination due to its exceptional adsorption capabilities and distinct microporous

* Corresponding author.

structure (Zhang et al., 2022). Researchers have examined its use in various desalination processes, such as solar desalination (Laxman et al., 2015) and seawater desalination. For example, a study conducted by Maddah (2020) explored the employment of coconut shell-activated carbon as a natural filter for desalinating seawater. The aim was to develop a cost-effective, eco-friendly, and energy-efficient desalination technique using natural materials (Maddah, 2020). The use of activated carbon in desalination offers significant and varied advantages. Research has demonstrated that super-activated carbon with ultra-high pore volume is particularly effective for capacitive desalination of brackish water (Zhang et al., 2022). In addition, activated carbon acts as an effective filtration medium in desalination, reducing solid buildup at the membrane site and decreasing energy requirements (Abushawish et al., 2023). This is due to its unique porosity and surface chemistry, making it an ideal component of the pretreatment process in desalination, where it collaborates with other materials like anthracite and sand to safeguard reverse osmosis filter membranes, ensuring uninterrupted operation and reduced energy consumption (Abushawish et al., 2023).

Activated carbon can be regenerated after desalination using several methods that restore its adsorption performance and enable its reuse. Some common regeneration methods are thermal regeneration, biological regeneration, wet oxidation, solvent regeneration, electrochemical regeneration, and autoregeneration (Ferrández-Gómez et al., 2021). Thermal regeneration involves heating the activated carbon to remove adsorbed organic matter, followed by cooling and activation using gases. Biological regeneration uses domesticated bacteria to digest organic matter. Wet oxidation treats the activated carbon with a wet oxidizing agent to remove adsorbed organic matter. Solvent regeneration uses a solvent to extract organic matter. Electrochemical regeneration uses an electrochemical process to regenerate the activated carbon (Ferrández-Gómez et al., 2021). These methods are conducted under specific conditions to ensure efficient removal of organic matter without compromising the carbon's structure or adsorption capacity. The autoregeneration system utilizes super-heated steam to regenerate activated carbon for water treatment filtration. The process entails generating steam at 400°C–600°C to clean the activated carbon surface, eliminating adsorbed organic matter and rejuvenating its adsorption capacity. The selection of regeneration methods depends on factors like the scale of treatment, the type of organic matter adsorbed, and the specific desalination process requirements (Thakur et al., 2021).

The objective of this study is to examine the production of potable water with reduced energy consumption through an environmentally sustainable method utilizing activated carbon derived from agricultural waste.

2. Material and method

2.1. Materials and chemicals

Concentrated sulfuric acid, nitric acid, hydrogen peroxide, hydrochloric acid 5%, ethanol, potassium chlorate, sodium nitrate, potassium permanganate, potassium hydroxide, cellulose, glacial acetic acid, acetic anhydrase, methanol, maleic acid, 1,4-Dioxen, acetone, nitrogen gas, carbon dioxide gas, activated carbon, heating mantle, magnetic stirrer, condenser, round bottom flask, adaptor, electrical balance, furnace, centrifuge, SEM, EDX, ICP-OES, carbolite reactor, solar panel, battery

2.2. Sample collection

The waste of palm tree leaf bases at the trunk was collected from a farm in the Al Dakhlia region in Oman for the preparation of activated carbon. The seawater sample was collected from Al-Gubrah Beach in Muscat city, on date 20th of February 2022 at coordinates 23.6054035 and 58.4095139 for the desalination process.

2.3. Activated carbon preparation

The collected waste of palm tree leaf bases at the trunk and dried for 24 h in the oven under 105°C. Then, it was ground to powder, and stored for further use. Pyrolysis is the first step of activated carbon preparation. In this process around 100 g of palm old leave base powder was used in each batch and it was placed in an electric furnace for carbonization at 700°C for 2 h (Carbolite reactor). This process of carbonization, was with a heating rate of approximately 10°C/min under a nitrogen (N_2) flow of 150 ml/min, reaching a temperature of 700°C over a duration of 2 h. Next, the saturated solution of potassium hydroxide was prepared and mixed with carbonized carbon at a ratio of 1:1. Then the solution was kept in the oven under 95°C overnight. The dried mixture was placed again in a horizontal tubular reactor and subjected to pyrolysis utilizing high-purity nitrogen with a flow rate of 150 ml/min until it reached the targeted temperature of 700°C. Subsequently, the nitrogen gas was replaced with CO_2, concluding the activation process within a span of 2 h. Next, the activated carbon was washed until the pH became neutral (Kyaw et al., 2021).

2.4. Oxide Activated carbon and supporting material

The Hummers method, used for graphene oxide creation according to Yin et al. (2016), was replicated for activated carbon oxide. Initially, 60 ml of H_2SO_4

(95%–98%, Aldrich) was chilled in a 250 ml beaker until <4°C. Then, a mix of 3.5 g $NaNO_3$ and 7 g activated carbon in H_2SO_4 was stirred for 2 h. A slow and careful addition of 21 g of $KMnO_4$ turned the solution dark green. After the removal of the ice bath 322 ml DDW altered it to brown after an hour of stirring at 35°C ± 2°C. The temperature was raised to 95°C ± 2°C for 30 min without stirring, followed by the addition of 70 ml H_2O_2, resulting in a bright yellow solution. Centrifugation, rinsing with 5% HCl, and DDW washes until pH 7 were conducted before ethanol (>99.5%, Aldrich) washing. Drying below 40°C for 24 h yielded the activated carbon oxide, analyzed using FT-IR, SEM, and EDX (Yin et al., 2016).

Methanol (2.55 ml) was used to dissolve malic acid, combined with cellulose triacetate (3.0 g), 1,4-dioxane (12.5 mL), acetone (4.3 mL), and activated carbon oxide (1.5 g) to create the support material. The malic acid-methanol solution was added to the mixture until a uniform gel formed. Afterward, it was cooled at 0.3°C for 24 h, followed by immersion in distilled deionized water for 4 h and subsequent annealing at 85°C in water for 15 min before storage in distilled deionized water (Nguyen et al., 2013).

2.5. Desalination process and set up

The solar desalination system comprises two tanks (Fig. 1). The smaller tank can be filled with seawater using a smart pump and contains a copper coil (12 V) that is immersed in the seawater. The copper coil is connected to a monitor and battery, which is connected to a solar panel, and a thermostat that regulates the water temperature. When the water reaches the desired temperature, the current stops. The larger tank collects the condensed water. At the top of the device, the condensed water flows down the slope of the lid and into the second tank, where it passes through a filter filled with O-AC. The energy consumed during the evaporation process was calculated over time, and the results were compared between seawater only and seawater with pellets.

3. Results and discussion

3.1. FTIR analysis

The Fourier transform infrared (FTIR) transmission spectra were obtained to investigate the surface functional groups present on activated carbon. It detects the presence of carbon atoms as well as other heteroatoms, such as hydrogen, oxygen, or nitrogen, which may be present in trace amounts. These heteroatoms can bond with the edges of the carbon layers, which in turn affects the surface chemistry of activated carbon and reveals the underlying carbon structure of the ACs. The FTIR spectra of activated carbon display bands at 1597 cm^{-1} and 1036–1382 cm^{-1}, which are attributed to the stretching vibrations of C=C in aromatic rings and C-O stretching vibrations, respectively. The FT-IR spectra of AC and OAC were analyzed to understand the oxidation mechanism. The results reveal that AC has no distinguishable adsorption peaks, while OAC shows functional groups such as –OH and C=O (Lee et al., 2021). This suggests that OAC has a more diverse range of oxygen functional groups following sulfuric acid oxidation, making it more hydrophilic and enhancing its adsorption capacity (Allwar, 2016).

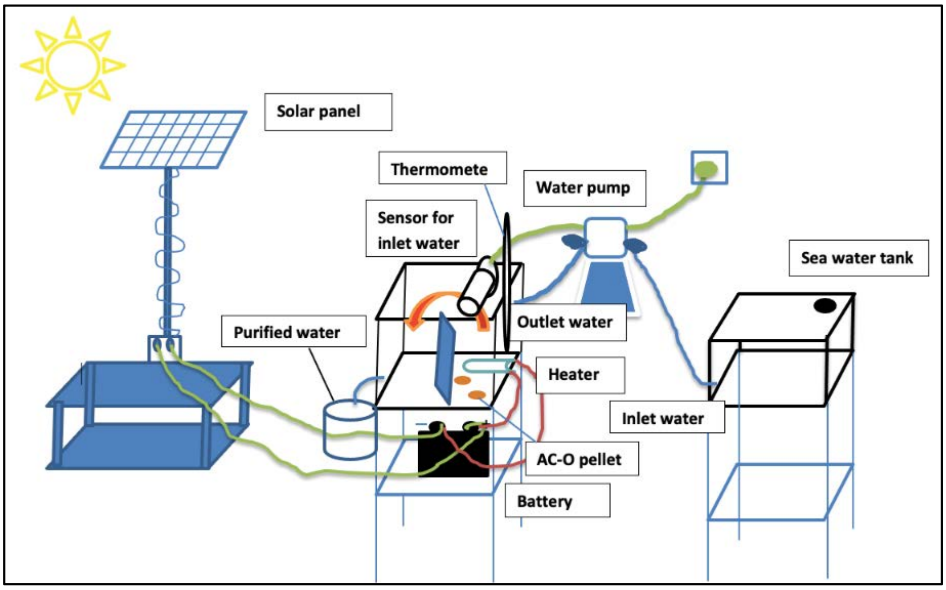

Fig. 1. Solar panel desalination set up.

3.2. Scanning Electron Microscopy (SEM) with Energy Dispersive X-Ray (EDX) characterization

Scanning Electron Microscopy (SEM) was carried out to study the morphology of the prepared activated carbon and the oxide activated carbon. As can be observed, the surface morphology of the activated carbon and oxide-activated carbon exhibits wrinkle structures and different pore sizes at various scales (Fig. 2). The prepared AC and AC-O have developed pores of different sizes and shapes that can adsorb metals from seawater. The pore development on their surfaces is attributed to the activation with KOH during carbonization, which left spaces after washing with distilled water. The images demonstrate the ability of the produced activated carbon to remove salts from seawater.

The chemical composition of the prepared activated carbon was analyzed using an Energy Dispersive X-ray spectrometer (EDXS), as illustrated in Fig. 3. Fig. 3a depicts the image of the activated carbon, and the activation process is evident, with the highest peak being for carbon at approximately 80%. The carbon atom accounts for the highest percentage at 79.8%, followed by oxygen at 15.4%. Other elements, such as Si, K, Al, Cl, and Mg, are present in small amounts (4.9%). These elements may originate from the initial waste and the activation process. Moreover, the pores visible in the image are a result of the activation with KOH. The prepared activated carbon was oxidized using a modified Hummers method. After oxidation of the activated carbon, it was characterized using (EDXS) and Fourier transform infrared spectroscopy (FTIR) to analyze the structural and chemical changes, respectively.

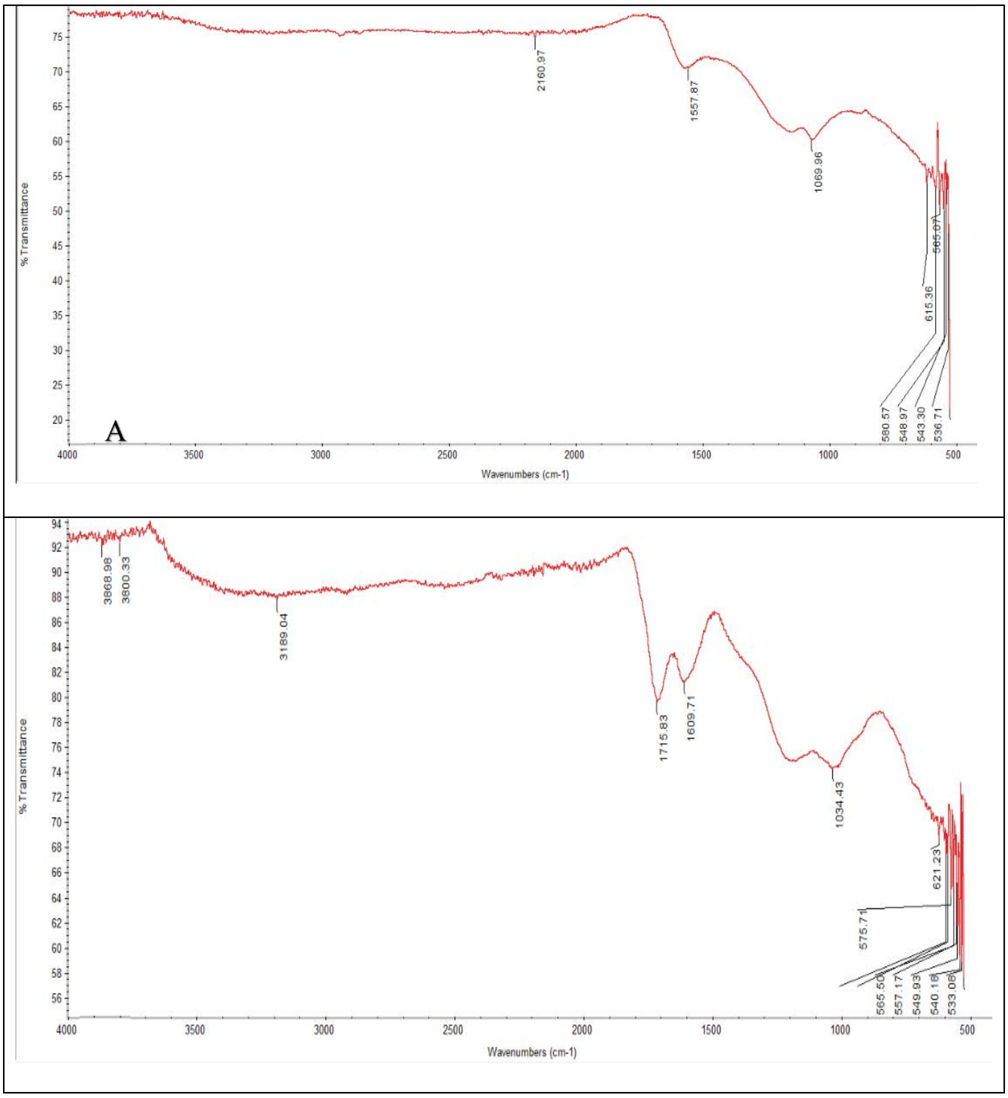

Fig. 2. SEM images (a-d) for AC and (e-h) for O-AC.

The EDXS patterns of the oxidized activated carbon are shown in Fig. 3, and the FTIR spectra are depicted in Fig. 4. These analyses provide insights into the structural and chemical modifications that occur during the oxidation process (27.6%), which can further enhance the adsorption capacity and performance of the activated carbon in removing metals from seawater. Due to the chemicals used such as H_2O_2, H_2SO_4, $NaNO_3$, and $KMnO_4$ this results in the oxidation process of activated carbon. Moreover, the figure shows that there is a presence of Si which is 18.4% which probably comes from the chemical used or the polymer. The SEM image in Fig. 2 shows pores in O-AC. These pores contain some metals (e.g. Na) from seawater which were held by these pores of the O-AC (Yin et al., 2016).

3.3. Examination of the boiling point of oxide-activated carbon by distillation process

A laboratory-scale experiment was conducted to investigate the effect of adding activated carbon (AC) and O-AC to the boiling point of seawater. The results showed that the boiling point of seawater alone was 100°C, while the boiling point of O-AC powder with seawater was 40.3°C, and the boiling point of O-AC pellets with seawater was 40°C. The flow rate of the desalination process was found to be faster in both O-AC powder (1.12 ml/min) and O-AC pellets (1.058 ml/min) compared to seawater alone (0.55 ml/min). These findings suggest that the desalination process with O-AC powder and seawater, as well as with O-AC pellets and seawater, is faster due to boiling at a lower temperature and shorter time with a larger volume than with seawater alone. This is because O-AC can store more energy during evaporation. The presence of hydroxyl groups on the surface of the activated oxide reduces the attractive interactions between the AC sheets and water molecules, affecting the arrangement of water molecules at the O-AC interface. As a result, the thermal energy storage capacity of the water system is higher than that of the O-AC system due to less energy desorption at the water-O-AC interface (Li et al., 2017).

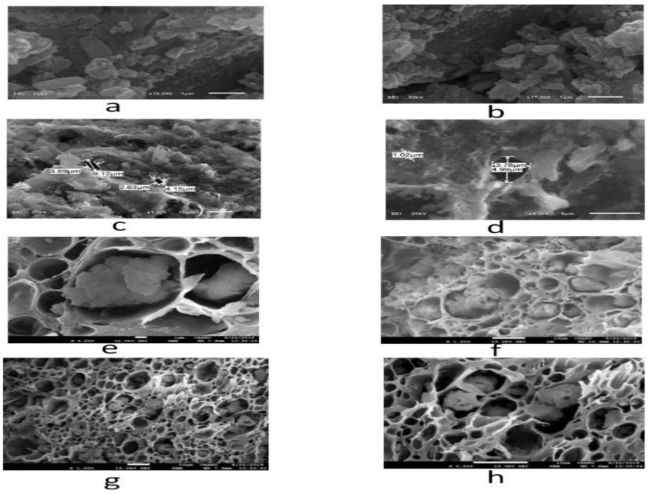

Fig. 3. EDXS characterisation of (a) AC and (b) O-AC.

3.4. Solar desalination of seawater with O-AC

Different methods have been developed to improve the desalination process with sustainable energy. One of the recent methods that has increased attention from different research fields is the use of activated carbon in desalination. In this project activated carbon was converted to oxide activated carbon. This is one of the novel technologies that can be used to accelerate the desalination process with less energy consumed and shorter time in the applications of activated carbon. It is prepared from recycled activated carbon from solid waste.

The solar desalination process was implemented to determine the energy required for evaporating seawater both with and without the addition of O-AC.

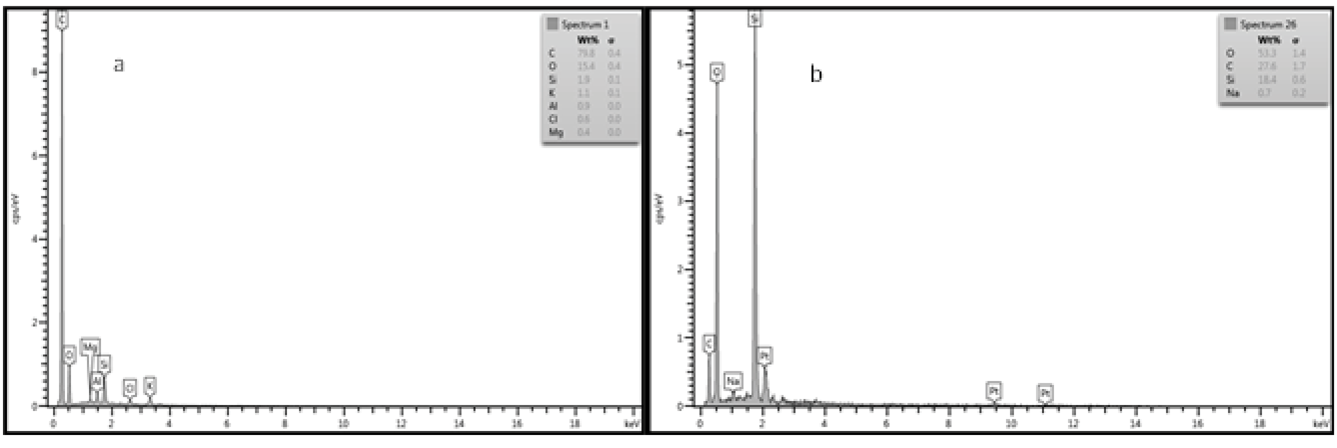

Fig. 4. FTIR of activated carbon (A) and oxide activated carbon (B).

The amount of voltage consumed during the desalination process was compared between the two scenarios, with and without the presence of O-AC. As shown in Fig. 2, in the absence of O-AC, the desalination process took a longer time (4.5 h), consumed more power (60 V), and produced a smaller amount of condensed water. In contrast, when O-AC was present, the process was faster (2.4 h), consumed less energy (40 V), and produced a larger amount of condensed water. This was attributed to the significant factor of O-AC, such as its porosity, which increased the surface area and enabled more energy to be absorbed, leading to a faster evaporation process (Chen et al., 2019). The principle behind this method is to decrease the boiling point of seawater to below 100°C. It is highly effective and practical, as it takes only 0.1 grams of activated carbon oxide to lower the temperature from 100°C to 40°C ± 4°C, making a significant difference that can be easily noticed by using a small amount of activated carbon oxide.

3.5. Elemental analysis results

Elemental analysis of sodium (Na), potassium (K), magnesium (Mg), and calcium (Ca) was conducted to assess the quality of desalinated water. According to Table 1, the concentration of these elements in seawater is significantly higher than the acceptable levels set by the World Health Organization (WHO). However, after adding O-AC and desalination with a solar panel, the amount of salt sharply decreased, resulting in the lowest elemental levels for sodium (5.77 ppm), potassium (0.79 ppm), magnesium (0.19 ppm), and calcium (0.45 ppm), which are all within the WHO's acceptable levels for drinking water. This demonstrates the effectiveness of the desalination method using O-AC compared to other methods. These results may be attributed to the higher efficiency of carbon due to its higher internal surface area (about 500–1500 m^2/g) and increased total pore volume. Carbon has its unique distribution of pore size, which can be classified into three types: macrospores (large), mesoporous (medium), and microspores (small). The prepared O-AC pellets show higher values for mesoporous, resulting in a larger surface area that supports the elimination of salts (Hussain et al., 2013).

Table 1
Elemental Concentrations (mg/L) of Standard World Health Organization (WHO) and desalinated seawater using ICP-OES instrument for seawater sample

Elements (mg/L)	Standard element based on the WHO	Seawater	Desalinated water with O-AC pellets (DS-WP)
Na	22.6	2392.43	5.77
K	3.4	948.58	0.79
Mg	7.5	701.0	0.19
Ca	17.2	2340.06	0.45

4. Conclusion

Desalination processes show that the oxide-activated carbon reduces the boiling point of seawater using less amount of energy. According to the experimental results, shows that oxide-activated carbon has the ability to reduce boiling point up to 40°C ± 4°C with collecting more amount of desalinated water from seawater. These are related to the characteristics of activated carbon, high porosity, and surface area, flexible adsorbents with a microporous structure, and a high degree of surface reactivity. The activated carbon is synthesized from the recycling of agricultural waste (palm waste), and the energy that is used to heat seawater for desalination is solar energy which can considered a renewable source and environmentally friendly

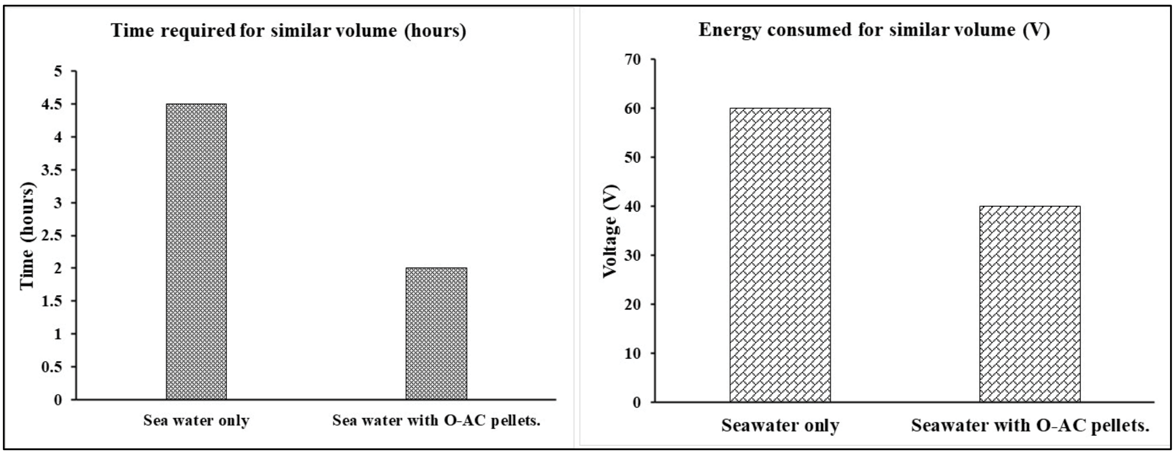

Fig. 5. Desalination process with and without oxide-activated carbon (O-AC).

source. The distilled water produced from desalination has high quality whereas it contains less amount of metals compared with WHO standards, so this desalinated water can be used in drinking, irrigation, industrial processes, and daily needs. To improve the quality and the amount of distilled water closed system of setup should be used to save heat and prevent the leakage of water vapored, also the coil material should be replaced with another that consumes less energy.

Acknowledgments:

The authors express their gratitude to the Applied Chemistry section instructors, Ministry of Higher Education and Innovation, for funding and providing the necessary facilities to conduct this research under grant number FURAB-2018. Furthermore, the authors acknowledge Nizwa University for their support in granting access to their facilities.

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Balaban Desalination Publications

مؤتمر الخليج الخامس عشر للمياه
The 15th Gulf Water Conference

(2024) 47–53
doi: 10.5004.dsal.2024.700073

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Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

An innovative approach to desalination and cooling using forward osmosis with thermal recovery and vapor absorption cycle

Hassan K. Abdulrahim*, Mansour Ahmad

Water Research Center (WRC), Kuwait Institute for Scientific Research (KISR), P.O. Box 24885, 13109 Safat, Kuwait, email: habdulrahim@kisr.edu.kw

ABSTRACT

Kuwait is facing an increasing demand for freshwater due to the country's limited natural water resources and hot, humid climate, which requires high levels of energy consumption. To address this challenge, a new system has been developed that integrates forward osmosis (FO) with thermal recovery and a vapor absorption cooling cycle. This system is unique because it utilizes low-grade heat sources, like solar energy or waste heat from power plants, to generate a cooling effect and drive the thermal recovery process of the FO desalination system. The FO process efficiently solves common desalination challenges like scaling, fouling, and precipitation, making it an ideal solution to manage extreme weather and water scarcity. Results of the study show that the proposed system is highly energy efficient, with a specific energy consumption of only 0.54 kWh/m^3 for desalination, which is remarkable in the realm of desalination technologies. Additionally, the system can produce 1300 m^3/d of desalinated water and a significant cooling effect of 500 refrigerant tons (RT) with a thermal energy input of 2550 kW. The system's innovative thermal recovery feature efficiently recaptures waste heat to increase the feed water temperature to the FO by 14°C, which significantly improves the performance of the FO system. This paper demonstrates that the proposed system is technically feasible and environmentally beneficial. This innovation has the potential to pave the way for a more sustainable and efficient approach to managing water resources and energy consumption, offering a promising solution to the pressing global issues of water scarcity and climate change. This system represents a significant step forward in sustainable energy and water management, and it holds great promise for future applications in similar climates worldwide.

Keywords: Combined cooling and desalination; Forward osmosis with thermal recovery; Vapor absorption cycle; Low-grade heat utilization

1. Introduction

Water scarcity and high ambient temperatures pose significant challenges in regions such as Kuwait and other Gulf Cooperating Council countries (GCC). Kuwait is a predominantly arid region with limited renewable water resources [1]. The average annual rainfall in Kuwait is a mere 10 cm, with an evaporation rate of 1.7 cm/d [2]. The groundwater in the country is predominantly saline or brackish, with total dissolved solids (TDS) ranging from 3000 to 9000 ppm [2]. The groundwater wells have a total installed capacity of approximately 145 million imperial gallons per day

* Corresponding author.

(MIGD), and the peak daily consumption reached 59.3 MIGD in the summer of 2019 [3].

Simultaneously, the ambient temperatures in Kuwait can soar up to 50 °C during summer, necessitating air conditioning in all buildings. These twin challenges of water scarcity and high temperatures need sustainable solutions to ensure the viability of life in Kuwait and other GCC countries. Water scarcity is currently addressed by desalinating seawater, which consumes substantial thermal and electrical energy and poses detrimental environmental impacts. Desalinated seawater accounts for 93% of potable water in Kuwait [4]. The high summer temperatures are managed using electrically driven A/C systems, which consume significant amounts of fossil fuels, such as natural gas (NG) and oil [5], to produce electricity. Despite possessing about 28% of the world's NG reserves, the GCC countries face a severe shortage of available NG to power their plants due to increasing consumption [5]. The demand for NG outstrips the region's gas exploration and production capabilities, necessitating imports [5].

Therefore, the GCC countries must explore sustainable primary energy sources such as solar thermal energy. Some countries have already started implementing solar air conditioning and district cooling technologies. The discussions on the challenges and potential of using solar energy for air conditioning can be found [6–8]. Solar energy is a promising solution for powering desalination plants and operating A/C systems, thereby replacing electricity and conserving primary energy sources such as N.G. or oil. Such a shift would reduce air pollution and greenhouse gas (GHG) emissions, contributing to global warming mitigation. Fig. 1 depicts various solar desalination configurations. As inferred from Fig. 1, each desalination technology can be paired with different solar energy systems, making it challenging to determine an optimal solar desalination system or derive general economic figures. Therefore, solar desalination must be evaluated on a case-by-case basis. The Kuwait Institute for Scientific Research, in collaboration with the Swiss Federal Institute of Technology and Atlantis Energy Ltd., Switzerland, designed and tested the first solar-operated, multi-stage flash (MSF) desalination plant [9]. The installation comprises a self-regulating MSF system that produces 100 m^3/d of freshwater using 220 m^2 line-concentrating collector arrays [9]. The solar power plant Kuwait 100 kWe (700 kWth) represents the world's first electro-thermal plant using high concentrating, point-focusing, parabolic dish collectors. The station was built near Kuwait City in the Sulaibiya desert and commenced experimental operations in early 1981. Reverse osmosis (RO) and MSF desalination plants are added to the power plant. The MSF plant produces 25 m^3/d of fresh water, while the RO plant produces 20 m^3/d of desalinated water [10]. Further information about the application of solar energy in desalination, its advantages, and economic aspects can be found [11–15].

Solar air conditioning, on the other hand, offers a practical solution for converting the intense summer heat in Kuwait and other GCC countries into cooling. It also contributes to environmental conservation by reducing air pollution and GHG emissions resulting from fossil fuel combustion in power plants. The primary benefits of solar air conditioning include reduced carbon dioxide emissions and significant alleviation of

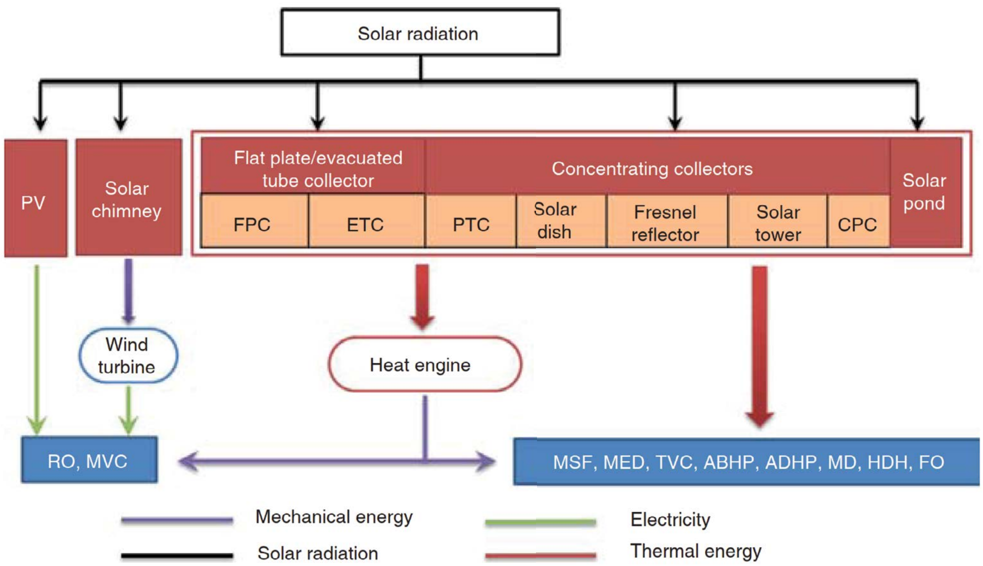

Fig. 1. Possible solar desalination arrangements [14].

the load on the power grid [16]. The demand for electricity for conventional air conditioning during the summer poses a significant concern. However, with solar air conditioning, the increase in cooling load requirements coincides with the highest solar intensity, rendering the GCC region an ideal candidate for solar air conditioning. Vapor absorption cycles (VAC), such as the ammonia-water or water-lithium bromide (H_2O-LiBr) absorption cycles, have long been utilized for refrigeration and air conditioning applications. The absorption cycle, a heat-driven device, can be used as a refrigerator, a heat pump, or a heat transformer. For this project, the authors propose the H_2O-LiBr vapor absorption cycle.

The present work discusses a new integration of forward osmosis with a thermal recovery (FO-TR) system and an absorption cycle for the co-production of desalted water and air conditioning. This innovative system has been granted a U.S. patent (No—US 11,407,659 B1) from the United States Patent and Trademark Office [17]. The proposed system involves an integrated system for desalination and cooling applications using FO-TR assisted by an H_2O-LiBr-VAC. The system will use LiBr-VAC to produce chilled water for air conditioning, while the waste heat from the LiBr-VAC will power the FO-TR desalination system. Fig. 2 shows a simplified block diagram for the proposed system. Heating steam, either from the solar field or waste heat from the power plant, is used to operate the generator of the absorption cycle. This process separates the water vapor from the diluted LiBr solution, thereby producing concentrated LiBr solution and water vapor streams. The concentrated LiBr solution will absorb the refrigerant in the absorber, and the water vapor will be condensed in the condenser, producing two waste heat streams. The thermal energy from absorption and condensation constitutes two streams of waste heat emanating from the absorption cycle. This waste heat is used for preheating the feed water and for the thermal recovery of the drawing solution of the FO-TR system.

Fig. 3 below shows a schematic diagram of the patented system. Additional details about the system and its mode of operation can be found [17].

2. Materials and methods

The results in the present work are derived from the mathematical modeling and simulation of the proposed system, preceding the construction of a pilot system for experimental validation of the results. In developing the mathematical models of the proposed system, the following assumptions were implemented [18]:

- Steady-state conditions in all components.
- Pressure drops in the system are deemed minimal, except in the S.EV, R.EV, and pumps.
- The R.EV and S.EV processes are irreversible and isenthalpic.

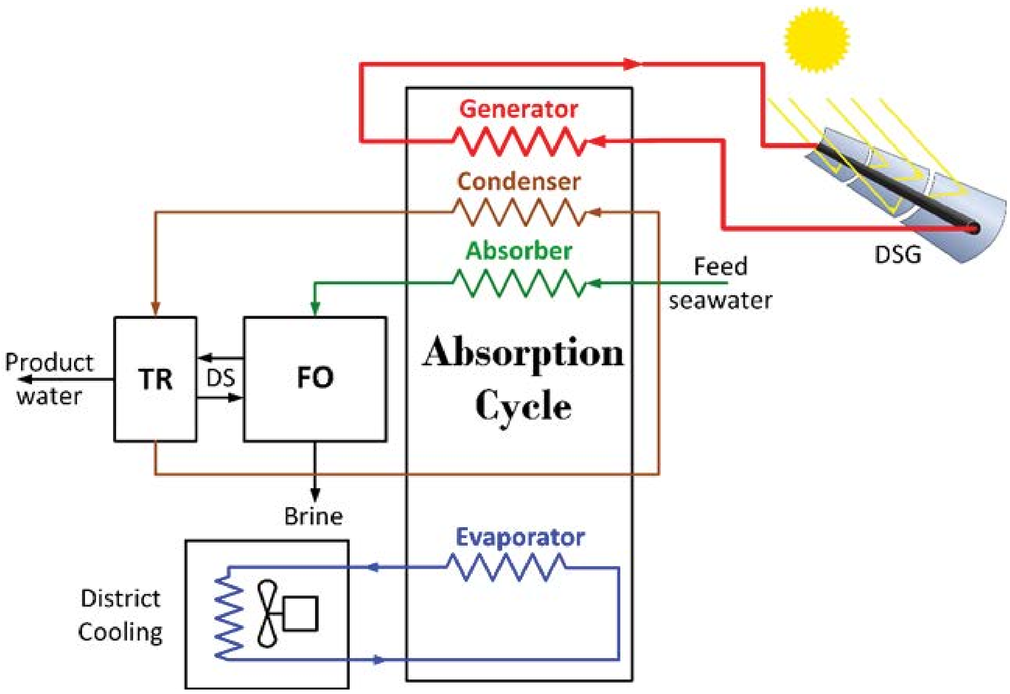

Fig. 2. Block diagram of the integrated desalination and cooling system.

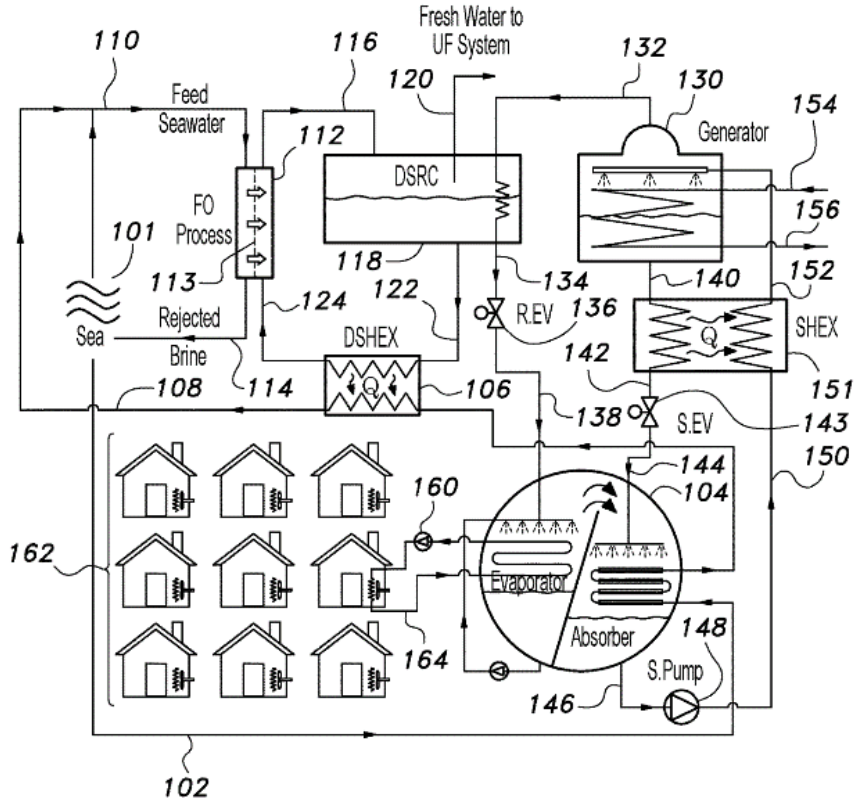

Fig. 3. Schematic diagram for the proposed system [17].

- Isentropic compression is considered in pumps.
- Only the generator, condenser, evaporator, and absorber are allowed to interact with the system's surroundings.
- Phase equilibrium has been reached for the solution exiting the generator and absorber.
- The temperature of the water vapor exiting the generator matches that of the solution.
- The refrigerant exiting the evaporator is saturated vapor, whereas the refrigerant leaving the condenser is saturated liquid.
- The strong solution is only heated, and there is no vapor production in the solution heat exchanger (SHEX).
- Any mass buildup in all machine components is disregarded.
- Changes in kinetic and potential energy are not taken into account.
- Radiative heat transmission is disregarded.
- Pressures in both the generator and condenser pressures are equal, as are the pressures in the evaporator and absorber.

The equations on detailed steady-state mass and energy balance equations of the absorption cycle can be found [5]. The osmotic pressure (π) of an ideal dilute solution is given by Van't Hoff's equation.

$$\pi = RT\Delta c \tag{1}$$

where π is the osmotic pressure of a solution (bar), Δc is the concentration difference of the non-permeable solute across the membrane (mol/L), R is the universal gas constant, and T is the absolute temperature of the solution.

However, the Van't Hoff equation applies only to ideal and dilute solutions where ions behave independently [19]. In concentrated solutions, the interactions between the solutes increase rendering the solution non-ideal. Eventually, the activity coefficient of each solute per ion and the osmotic pressure of the solution will be changed [20,21]. Hence, for real solutions, the osmotic pressure can be determined using a Virial equation as shown subsequently [22,23].

For real solutions, the osmotic pressure can be determined using a Virial equation as shown subsequently [22,23].

$$\frac{\pi}{c} = RT\left(\frac{1}{M_w} + Bc + Cc^2 + Dc^3 + \dots\right) \tag{2}$$

where c is the concentration measured in grams of solute per liter; M_w is the molecular weight of large molecules; B, C, and D are the osmotic viral coefficients, which are functions of the temperature and the chemical potentials of the species in the salt solution [22]. The viral coefficient can be determined empirically by fitting experimental osmotic pressure data. Typically, determining *B* and *C* is sufficient to reproduce the observed data [19].

The water flux (J_w) represents water transport through a semipermeable membrane and is theoretically determined by the following formula [24]:

$$J_w = A\left(\sigma\Delta\pi - \Delta P\right) \quad (3)$$

where *A* is the permeability coefficient of pure water of the membrane, Δπ is the osmotic pressure difference across the membrane, σ is the reflection coefficient, which is defined as the ratio between the negative solute water phenomenological coefficient divided by the pure water permeability [21,25,26]. Δ*P* is the applied hydraulic pressure, which is equivalent to zero in the case of the FO process. Thus, the water flux across an FO membrane is shown below [27]:

$$J_w = A\left(\pi_{DS} - \pi_{FS}\right) \quad (4)$$

Owing to the concentration gradient across the membrane, a small amount of solute is transported from the draw solution (DS) to the feed solution (FS), consequently reducing the applied osmotic pressure across the membrane [28]. Hence, the salt flux (J_s) is analytically determined subsequently [27].

$$J_s = B\left(C_{DS} - C_{FS}\right) \quad (5)$$

where *B* is the salt permeability coefficient, and C_{DS} and C_{FS} are the solute concentrations at the membrane-solution interface on the DS and FS sides, respectively.

The salt permeability coefficient can be described as follows [29]:

$$B = \frac{A\left(1-R\right)\left(\Delta P - \Delta\pi\right)}{SR} \quad (6)$$

SR is the salt rejection of the membrane and is analytically described below.

$$SR = \left[1 - \left(\frac{C_P}{C_{FS}}\right)\right] \times 100 \quad (7)$$

C_F and *Cp* are the salt concentrations of FS and product water, respectively. The equations comprising the proposed system's mathematical model were

Table 1
EES simulation results

Item	Value	Unit	Description
$AC_{Capacity}$	500	TR	The cooling capacity of the system
A_a	389.7	m²	Absorber heat transfer area
A_c	138.6	m²	Condenser heat transfer area
A_d	173.2	m²	Desorber heat transfer area
A_e	458.5	m²	Evaporator heat transfer area
A_{shx}	25.66	m²	Solution heat exchanger heat transfer area
A_{tot}	1186	m²	Total heat transfer area
COP	0.692	–	Coefficient of performance of the absorption system
η_{pump}	0.8	–	Pumps efficiency
P_{high}	12.0	kPa	Desorber pressure
P_{low}	0.697	kPa	Absorber pressure
$\dot{Q}_a$	2420.1	kW	Absorber heat transfer
$\dot{Q}_c$	1879.6	kW	Condenser heat transfer
$\dot{Q}_d$	2541.2	kW	Desorber heat transfer
$\dot{Q}_e$	1758.4	kW	Evaporator heat transfer
$\dot{Q}_{FW}$	3222	m³/d	Amount of feed water
$\dot{Q}_{PW}$	1289	m³/d	Amount of product water
Q_{TR}	35	kWh/m³	Specific energy of the thermal recovery system
Rec	0.4	–	FO system recovery
SEC	0.534	kWh/m³	FO system-specific energy consumption
T_H	383.2	K	High temperature of heat source
$\dot{W}_{Abs\ Pump}$	0.075	kW	Pumping power of the absorption system
$\dot{W}_{FO\ Pump}$	23.31	kW	Pumping power of the FO system

solved using the Engineering Equation Solver (EES) package [30].

3. Results and discussion

The equations of the mathematical modeling presented [5] and the fluxes equations mentioned in this paper were solved using EES software. The obtained results were promising. The invented system provides fresh water and a cooling effect in the form of chilled water. By utilizing hot water at 110°C and consuming 2550 kW of low-temperature thermal energy, the system can produce 1300 m^3/d of desalted water with a specific energy consumption of 0.54 kWh/m^3. It is also capable of providing 500 RT (1760 kW, 250 ton/h of chilled water at 5°C) of cooling effect, typically consuming 176 kW of electric power if a vapor compression chiller of COP of 10 is used. Other simulation results can be found in Table 1. The system is also capable of raising the temperature of the feed water by 14°C, which enhances the performance of the FO system. Recent studies by [31,32] have demonstrated that increasing the temperature of FS or DS in FO leads to increased water flux and reverse draw solute flux. Increasing the DS temperature exerts a stronger impact on FO performance compared to increasing the FS temperature.

4. Conclusions

To conclude, this research paper presents a groundbreaking, dual-purpose system that ingeniously combines forward osmosis with thermal recovery (FO-TR) and a vapor absorption cycle (VAC) for simultaneous desalination and cooling. The system is not only technically feasible but also highly efficient, as evidenced by comprehensive mathematical modeling and simulation results. The patented technology (US 11,407,659 B1) leverages low-grade heat sources, such as solar energy or waste heat from power plants, to operate a LiBr-VAC, which in turn produces chilled water for air conditioning. The waste heat generated from this cycle is then effectively utilized to power the FO-TR desalination system. Generally, the following points can be concluded:

- The system demonstrates high energy efficiency, with a specific energy consumption of remarkably low 0.54 kWh/m^3 for desalination.
- With a thermal energy input of 2550 kW, the system can produce 1300 m^3/d of desalted water and 500 RT of cooling effect.
- The system efficiently recovers waste heat, raising the feed water temperature by 14°C, significantly enhancing the performance of the FO system.

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Balaban Desalination Publications

The 15th Gulf Water Conference

(2024) 54–68
doi: 10.5004.dsal.2024.700092

WSTA 15th Gulf Water Conference
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28–30 April 2024, Doha, Qatar

Revolutionizing desalination: KISR's breakthrough projects addressing water crisis challenges

Mansour Ahmed*

Kuwait Institute for Scientific Research, Water Research Center, P.O. Box 24885, 13109, Safat, Kuwait, email: mahmed@kisr.edu.kw

ABSTRACT

Desalination, a vital solution to the rapidly increasing global water crisis, faces persistent challenges in efficiency, sustainability, and economic viability. This article presents a comprehensive overview of innovative research activities of the Water Desalination Technologies (WDT) program at the Water Research Center (WRC) of the Kuwait Institute for Scientific Research (KISR) aimed at revolutionizing desalination technologies to combat these challenges. The article explores a multidimensional approach, showcasing WRC's intensive efforts in exploring innovative processes and cutting-edge technologies. This paper highlights various innovative projects conducted at laboratory and pilot scales and covers diverse solution areas. From exploring forward osmosis processes to pioneering hybrid membrane systems and zero liquid discharge treatment for oil-produced water, the WRC's initiatives cover a broad spectrum of technological advancements. Notably, the research also explores mineral extraction technologies and cutting-edge developments in membranes, showcasing a holistic approach to addressing desalination challenges. The article emphasizes KISR's commitment to innovation by spotlighting the institute's intellectual property developments in the desalination and water treatment domains. These initiatives collectively underscore a dedicated effort to overcome hurdles in desalination, offering promising pathways toward heightened efficiency, sustainability, and the realization of a water-secure future. By presenting a detailed overview of WRC's pioneering research, this article contributes valuable insights into the evolution of desalination technologies, paving the way for impactful advancements in the field.

Keywords: Desalination, Cutting edge technologies, hybrid membrane systems, zero liquid discharge, mineral.

1. Introduction

The scarcity of water has become a critical issue not only in the Gulf Cooperation Council (GCC) region but globally. Approximately two-thirds of the world's population, around 4 billion people, face severe water scarcity for at least one month annually [1,2]. Factors like global warming, limited rainfall, rapid evaporation and pollution of water sources, substantial economic growth and resulting growing demand from various activities (municipalities, commercial activities, agriculture, and industries), high per capita water consumption, and a shortage of natural drinking water sources have intensified the challenge of water availability in the GCC [3–5]. Consequently, there is a growing reliance on desalination technology to secure

*Corresponding author.

drinking water. To address this, numerous large-scale desalination plants have been constructed across GCC countries. However, these plants are characterized by high energy consumption, low recovery rates, significant environmental impacts, the need for extensive technical expertise, and a capital-intensive nature [6–9]. Kuwait has established eleven desalination plants with a daily capacity of 682.8 Million Imperial Gallons per Day (MIGPD) as shown in Table 1 to meet the surging water demand. The daily water consumption has soared to an average of 451.35 MIGPD [10].

1.1. Desalination challenges and desalination brine challenges

While Reverse Osmosis (RO) and Multi-Stage Flash (MSF) technologies have been successfully employed in the GCC region for over five decades to desalinate seawater, demonstrating reliability in supplying a potable water source for the Gulf area, their sustained use is challenged by high investment and operational costs [11]. Additionally, these technologies demand substantial spatial requirements and are reliant on nonrenewable energy sources, rendering them time-consuming and energy-intensive methods for desalination. The viability of conventional technologies in Kuwait faces a significant limitation due to their reliance on fossil fuels, resulting in the substantial emission of greenhouse gases that detrimentally impact the environment. Kuwait currently contributes 6% of the global desalinated water production, ranking as the fourth-largest seawater desalination capacity [12]. Notably, co-generation plants, responsible for 90% of the nation's freshwater supply, operate on energy derived solely from the combustion of heavy crude oils. These plants have generated 42 million MWh of electricity and produced 443 million m^3 of desalinated water [13]. Moreover, the energy consumption by desalination plants amounts to 462 million GJ, representing 54% of the national fuel usage. The corresponding emission factors stand at 0.7 kg/kWh for electricity and 15.7 kg/m^3 for desalination, resulting in total CO_2 emissions of 18,840 tons/d for the production of 1.2 Mm^3 of water daily [13,14].

While desalination holds promise for addressing water scarcity, it brings a significant challenge—brine, a highly concentrated salty byproduct. The quantity of brine produced globally is approximately 142 Mm^3/d, marking a 50% increase from previous estimates. Notably, Saudi Arabia, UAE, Kuwait, and Qatar collectively contribute 55% of this global brine production (15). This brine, with its high salt content, can harm marine life when discharged into the Arabian Gulf or other water bodies, affecting ecosystems and posing risks to marine life [15–18]. Additionally, chemicals used in desalination processes, like anti-scalants and biocides; contribute to water pollution when found in the brine, impacting the environment negatively [15]. Thermal desalination processes also generate warmer brine, potentially harming temperature-sensitive marine organisms [19]. Inland desalination plants encounter greater obstacles in determining appropriate brine disposal solutions. Directly releasing brine into nearby water bodies might not be viable or environmentally responsible [20]. Moreover, the economic aspect adds complexity: managing and disposing of desalination brine comes with extra expenses for inland facilities, potentially impacting the overall affordability of desalinated water [21].

Therefore, it is crucial to address these challenges by exploring innovative non-conventional desalination and brine treatment technologies. These advancements prioritize energy efficiency, reliability, sustainability, and eco-friendliness, distinguishing

Table 1
Desalination plants in Kuwait and its capacity

Plant name	Technology and capacity (MIGPD)			
	Multi-Stage Flash (MSF) Technology	Reverse Osmosis (RO) Technology	Multiple Effect Distillation (MED) Technology	Total
Shuwaikh power station and water distillation	18	30		48
Shuaiba north power plant and water distillation	45	–		45
Shuaiba south power plant and water distillation	30	–		30
Doha east power plant and water distillation	42	–		42
Doha west power plant and water distillation	110.4	60		170.4
Az-Zour south power plant and water distillation	110.4	30		140.4
Sabiya power station and water distillation	100	–		100
Az-Zour north power plant	–	–	107	107
TOTAL	455.8	120	107	682.8

them from existing desalination systems. This shift emphasizes the development and promotion of these newer approaches.

2. Water research centre at Kuwait institute for scientific research

The Water Research Center (WRC) applies KISR's multidisciplinary approach to address some of Kuwait's most crucial challenges in water resource management and develop innovative desalination technologies. WRC is the focal point of KISR's research, policy, and technical service activities in support of Kuwait's water requirements. The center's strategy includes programs focused on making breakthroughs in desalination technologies to meet the need for potable water while mitigating the environmental footprint. The research team from the Water Desalination Technologies (WDT) Program of the WRC at Kuwait Institute for Scientific Research (KISR) has remarkably conducted laboratory and pilot-scale research studies on innovative non-conventional desalination and brine treatment technologies. The WDT's solution areas are Innovative membrane & thermal desalination technologies; Turbid seawater treatment & desalination processes; Salts and minerals extraction technologies; Minimal liquid discharge (MLD) technologies; Zero liquid discharge (ZLD) processes; Desalination technologies using renewable energy; innovative desalting processes using waste heat; and innovative desalination technologies for emergency.

2.1. Development of emerging forward osmosis technologies for desalination at KISR

Over the past decade, there has been significant interest in osmotically driven Forward Osmosis (FO) membrane processes, particularly in power generation and desalination [22,23]. Unlike RO systems that rely on hydraulic pressure generated by a high-pressure pump, the driving force in the FO process is the osmotic pressure gradient ($\Delta\Pi$) between the feed solution (FS) and the draw solution (DS). Fig. 1 provides a simplified schematic comparison of the fundamental principles behind FO and RO [24].

FO represents a technical term primarily utilized in the water purification sector. FO, similar to standard osmosis, consumes significantly less energy compared to RO. In FO desalination, the FS, usually any saline water source is designated as the feed water. This process involves the utilization of a DS possessing a higher concentration than the FS, often seawater. This concentration disparity prompts the natural movement of freshwater from the FS through a semi-permeable membrane due to the osmotic pressure gradient across it [40]. The DS typically comprises water-attracting (hydrophilic) fluids devoid of water content in their original form. Consequently, the FS exhibits high water concentration while the DS has low water content.

When the FS and DS are introduced into a chamber separated by the semi-permeable membrane, driven by osmosis, pure water is extracted from the FS and moves into the DS. This process leaves highly concentrated brine on the FS side and diluted DS on the opposite side of the membrane. The diluted DS is further divided into pure water and concentrated DS. The resulting pure water is collected as usable product water, while the concentrated DS is recirculated back into the membrane chamber to facilitate the extraction of more pure water across the membrane.

As illustrated in Fig. 2, the typical FO desalination technology comprises an FO stage and a subsequent regeneration stage [25]. In the FO stage, the DS extracts freshwater molecules from seawater through a semi-permeable membrane. The regeneration stage is a subsequent system designed to generate freshwater and recover the DS, which is then recycled to an FO stage.

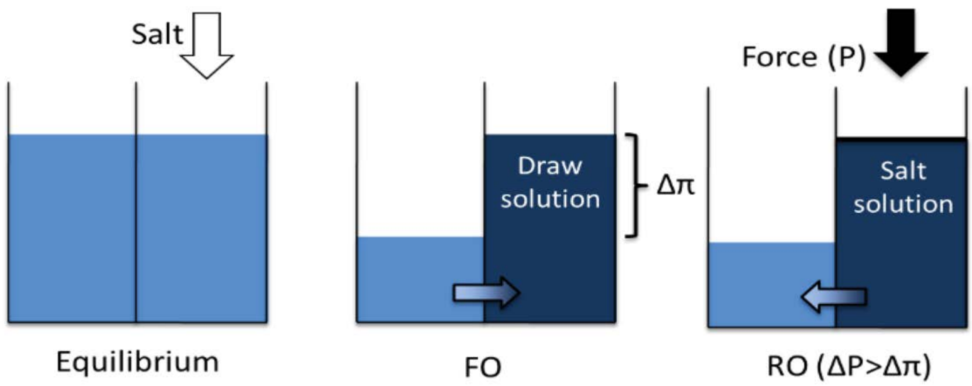

Fig. 1. Simplified schematic diagram on the principles of forward osmosis and reverse osmosis [24]. P: hydraulic pressure; FO: forward osmosis; RO: reverse osmosis.

Numerous studies have highlighted the advantages of FO over RO, including:

- Higher water recovery ratios range between 60% and 80% [26,27]
- 20% to 30% lower energy consumption compared to RO [28]
- Reduced brine volume [25]
- Lower fouling potential [29]
- Enhanced fouling removal and greater physical cleaning efficiency [30]
- Higher boron rejection [31]
- Environmental friendliness [32]

Consequently, leading research institutes and universities are actively engaged in comprehensive research and development on FO technology for diverse applications, such as desalination, wastewater treatment, power regeneration, enhanced oil recovery, produced brine treatment, fluid concentration, etc. [33–40].

2.1.1. Forward osmosis process: Bench-scale laboratory investigation - Phase 1

The project aimed to assess the effectiveness of FO desalination on a lab scale, focusing on examining commercially available spiral wound FO membranes and DS for R&D purposes. The findings of this study are published in Desalination and water treatment journal [41–43]. The laboratory test unit is shown in Fig. 3. Two types of FO membranes (Cellulose triacetate and thin-film composite) were tested with various feed solutions (Deionized water, synthetic NaCl solutions, Arabian Gulf seawater, and RO brine) and different draw solutions (NaCl, Ammonium bicarbonate, Calcium chloride). Results highlighted that the concentrations of feed and draw solutions significantly influenced

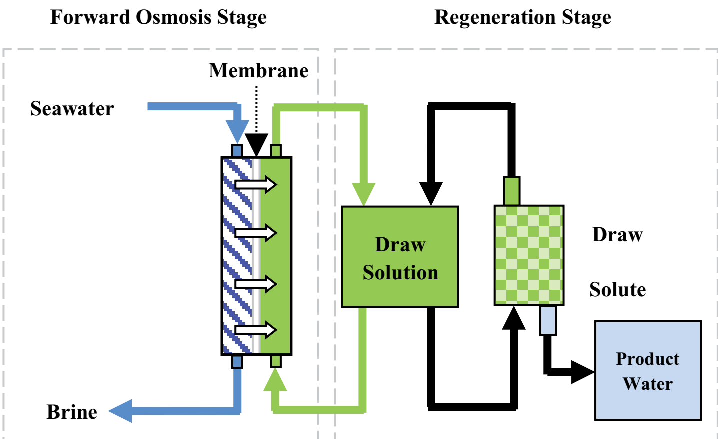

Fig. 2. Simplified schematic diagram of the principle of FO process for seawater desalination [25].

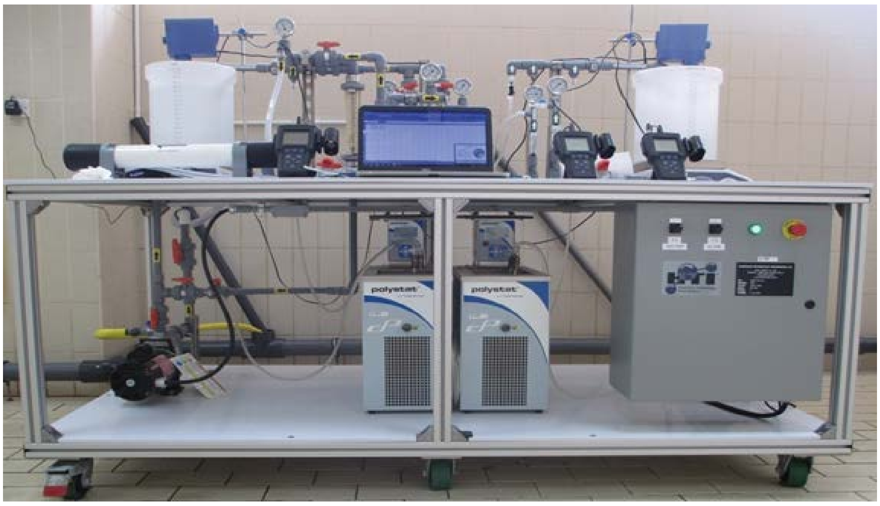

Fig. 3. Laboratory scale FO test unit.

separation performance, impacting water flux, recovery ratio, salt flux, and ionic rejection. Additionally, the study explored the influence of temperature on improving water flux and recovery while mitigating reverse salt flux. NaCl draw solution exhibited the highest water flux values across various feed solutions, while NH_4HCO_3, despite its lower osmotic pressure difference and higher molecular weight, showed the lowest water flux. Overall, the study demonstrated the potential of FO membranes in extracting freshwater from diverse sources and salinities. The findings offer valuable insights for designing pilot plant test units for further research and development in this field.

2.1.2. Assessment of viability and effectiveness of forward osmosis membranes and polymer draw solutions for seawater desalination: Pilot plant

The research project aimed to demonstrate the viability of FO technology using various hollow fiber FO (HF-FO) membranes and thermo-responsive draw solutions for seawater desalination in Kuwait's conditions at a pilot scale. The pilot plant was developed by Trevi Systems Inc (TSI), USA, and installed at the Desalination Research Plant (DRP) at KISR's site in Doha East Power Station in Kuwait. The pilot scale FO-thermal test unit is shown in Fig. 4.

The beach-well seawater available at DRP was used as FS. The FO–TS pilot plant with a capacity of 10 m^3/d is a hybrid system utilizing FO membrane technology and innovative DS regeneration technology. The novel DS regeneration stage of the pilot plant was used for recovering the thermo-responsive DS and supernatant (SNT) water. The commercial-scale HF-FO membranes used in the study were developed by TOYOBO Co, Japan, and had a bore diameter of 135 and 230 microns. Fig. 5 shows the commercial-scale HF-FO membranes used in the study. Polyalkylene glycol (PAG) based thermo-responsive polymer DS used in this study was developed and supplied by TSI. This pilot study effectively assessed large-scale FO modules feasibility for real seawater desalination and the process's energy efficiency for potential future expansions. The comparison of different FO membranes with varied bore diameters explored the impact of draw and feed solution concentrations across membrane areas.

A polyelectrolyte draw solution exhibited significant potential, generating high osmotic pressure (~4 times that of seawater), leading to an optimized

Fig. 5. Commercial scale FO module from Toyobo, Japan.

Fig. 4. Pilot scale FO-thermal test unit.

30% average water recovery in the desalination process using Arabian Gulf Seawater (AGS) [44–46]. The study utilized electrical energy for the FO process but recommended integrating solar energy for future high-energy efficiency. The energy consumption of the FO pilot plant, excluding conventional electrical heaters, averaged around 3.0 kW/m^3, with a significant portion used by the pilot plant's control systems. The study highlighted an optimal temperature of ~85°C for draw solution recovery, making it compatible for integration with solar energy [44–46]. Encouragingly, the study achieved reasonable water recovery with low energy requirements and low product water total dissolved solids (140 ppm) using a single hollow fiber FO membrane in a single-stage operation. To further reduce energy requirements, the study recommends piloting FO integrated with solar and waste heat energy from power and nuclear plants, emphasizing the potential for energy-efficient FO technology.

2.1.3. Assessment of viability and efficiency of two forward osmosis membrane technologies for seawater desalination–pilot plant scale

The project investigated two pilot plants, FO-thermal separation (FO-TS) and FO-Reverse osmosis (FO-RO), aimed at desalinating seawater, showcasing their significant potential. Notably, these pilot facilities differed primarily in how they regenerated their draw solutions, yet both effectively utilized high-performing HF membranes sourced from TOYOBO, Japan, spanning an impressive 320 m^2 surface area. In terms of water recovery, FO-TS achieved a respectable 40%, whereas FO-RO surpassed this, achieving up to 55%. This discrepancy in water recovery rates primarily stemmed from the distinct characteristics of their draw solutions. An interesting observation emerged was that by increasing the flow rate of the draw solution, there was a noticeable improvement in water flux across both systems, showcasing a potential avenue for enhancing water recovery. The draw solutions used in these processes varied; FO-TS utilized a thermo-responsive copolymer solution, while FO-RO relied on NaCl. Despite this difference, both draw solutions exhibited the ability to effectively extract water from saltwater due to their high osmotic pressure properties. FO-TS demonstrated a relatively lower thermal energy requirement less than 40 kWh/m^3, notably less than what is required by conventional thermal desalination methods [45,46]. Conversely, FO-RO consumed electrical energy in the range of 11–15 kW/m^3 due to its operation involving high-pressure pumps. Both FO systems showed promising results, each with its unique strengths and considerations. FO-RO, in particular, displayed slightly superior economic viability in the assessment conducted. The FO-RO product water total dissolved solids (TDS) were around 120 ppm, and the salt rejection percentage and water recovery percentages were 99.8% and 55%, respectively. The pilot scale FO-RO test unit is shown in Fig. 6.

2.1.4. Hybridization appraisal of forward osmosis and membrane distillation processes for seawater desalination

This project provided the information and knowledge for the pilot-scale implementation of the forward osmosis -air gap membrane distillation system

Fig. 6. Pilot scale FO-RO test unit.

(FO-AGMD) seawater desalination plant in Kuwait [47]. This project included extensive experimental investigations to assess the viability and efficiency of the integrated FO-MD system. NaCl and $MgCl_2$ solute as well as a mixture of NaCl and $MgCl_2$ were investigated as the DS in this project. The key elements used for evaluating the performance of the FO system are flux and reverse salt flux. As for the MD process, the influencing process parameters are low temperature stream, high temperature stream, and FS and permeate flow rate to determine the flux; whereas the key elements for evaluating the performance of the hybrid system of FO-MD are water recovery and salt rejection, permeate quality, and power consumption for heating and cooling by the MD system. The spiral-wound FO membrane used in the study witnessed the least fouling and scaling. After each test, the FO membrane was re-used by simple backwashing with the de-ionized water. The least pressure drop across the FO module for any tested concentrations of the FS and DS observed was attributed to the design of the module in its spiral-wound form. For deionized water (DI) water as FS, the FO-MD process produced water recovery in the range of 46%–51% and 30%–41% for the DS of 35,000 ppm and 150,000 ppm NaCl solutions respectively. The water recoveries experienced a decreasing trend for both DS concentrations of DS at 70,000 ppm and 150,000 ppm NaCl solutions at the fixed AGS as the FS. This could be the effect of the complex chemistry of the seawater and the increased salinity of the DS causing internal concentration polarization and fouling of the FO membrane. The variation in the FS concentration influenced the water recovery of the FO-MD process at a fixed concentration of DS at 70,000 ppm. The highest water recovery in the range of 50%–60% was observed for the DI water as the FS at the MD operating temperature of 85°C. For AGS as FS and 70,000 ppm solution of NaCl as the DS, the water recoveries at 75°C and 85°C were varied in the range of 25%–35% and 30%–38%, respectively. Temperature as a driving force of the MD process increased the overall water recovery of the FO-MD process at higher temperatures. For AGS as FS and 70,000 ppm solution of NaCl as the DS, the reverse salt flux values (RSF) decreased in the range of 85–100 g/m^2h and 28–83.9 g/m^2h at MD operating temperatures of 85°C and 75°C, respectively. The higher operating temperature of the MD system increased the RSF values in the FO section due to the higher dosing of DS at higher temperatures. The FO-MD pilot system used in the study does not require any high-pressure hydraulic pumps. The major energy requirement in the system is for heating (~85°C–90°C) and cooling (~5°C–10°C) of the feed and permeate streams respectively in the MD section. Therefore, the energy requirement by the MD section can be supplied by the easy integration of the FO-MD system utilizing industrial waste heat or natural solar or geothermal energy resources. Considering the competency of the FO-AGMD system with the conventional desalination system, a further scale-up of the system was recommended for the future by integrating the system with the waste heat generated from the power plants or with solar energy. Also, such a demonstration plant enables the evaluating of the techno-economic benefits of the FO-MD system after integrating with renewable energy sources. The pilot scale FO-AGMD test unit is shown in Fig. 7.

2.2. Development of salts and minerals extraction technologies

2.2.1. Zero liquid discharge treatment and desalination model for oilfield produced water (collaboration with Japan cooperation center petroleum)

Oilfield produced water is by far the largest volume by-product in oil and gas upstream operations, and it is considered a waste stream. Its amounts have increased over the years due to increasing oil and gas

Fig. 7. Pilot scale FO-AGMD test unit.

production as well as the maturity of producing wells. In Kuwait, oilfield-produced water is extremely saline (TDS ~ 150,000–250,000 ppm), acidic (pH < 6.7), and highly loaded with oil, H_2S, and scaling substances. This project comes as a collaborative effort between KISR and the Japan Cooperation Center, Petroleum (JCCP). The pilot setup is based on integrating microfiltration (MF) ceramic membrane and low-temperature flash evaporation (LTFE) to target the zero liquid discharge (ZLD) solution. Subsequently, produced salts from ZLD were used in a downstream chloralkali process in Japan to produce byproducts that are of commercial value. Fig. 8 shows the process diagram used in this study. Figs. 9 and 10 show the ceramic microfiltration unit, LTFE system, and centrifuge, respectively.

The study observed that the ceramic membrane MF combined with H_2S stripping can be used effectively as pretreatment for ZLD processes. The LTFE process is capable of desalting high salinity oilfield-produced waters (>250,000 ppm) and producing distillate <100 ppm. The turbidity, Total Organic Carbon (TOC), and Oil & grease of the oil-produced water were 20.8 NTU, >5 mg/L, and 17.8 mg/L, respectively. It is worth mentioning that the TDS and ammonia content of the feed were 262,336 ppm and 80 mg/L, respectively. The MF Ceramic Membrane Unit reduced the turbidity to 0.11 NTU, and oil & grease to 1.2 mg/L. The TOC of ceramic membrane treated feed was 1.92 mg/L. The TDS and ammonia content of the LTFE distillate was 28 ppm and 13.5 mg/L, respectively.

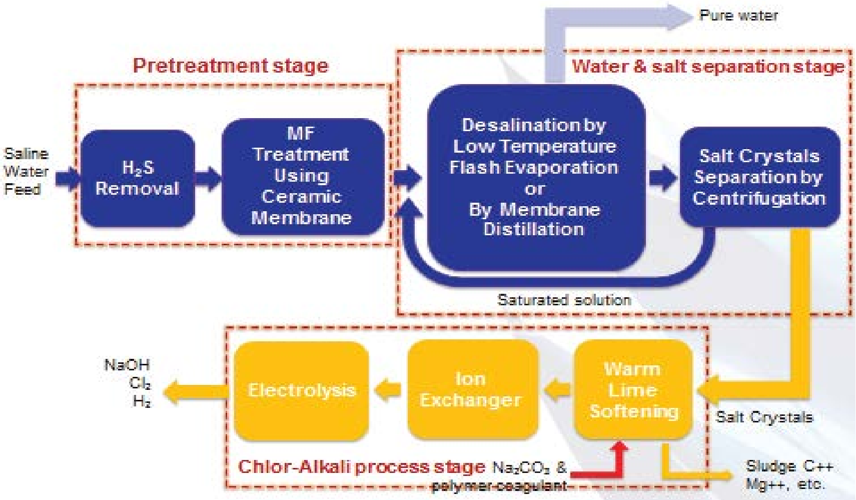

Fig. 8. Process diagram for the Zero Liquid Discharge Treatment of Oil Produced water.

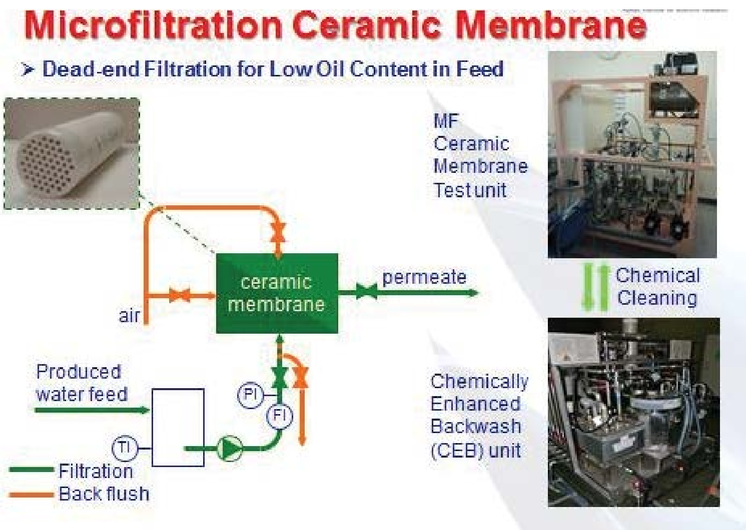

Fig. 9. Microfiltration ceramic membrane and process diagram.

2.2.2. Appraisal of extraction of valuable minerals from concentrated brine - Phase-1

The primary concern of this study was the appraisal of the extraction of valuable minerals from concentrated brine. The literature review and experimental data from this project show that it is more feasible to extract minerals from seawater reverse osmosis (SWRO) brine than from MSF brine, as the concentration of RO brine is higher (total dissolved solids, TDS ≈ 58,00–78,000 mg/L) than MSF brine (TDS ≈ 45,000–50,000 mg/L). Minerals extraction is carried out using the chemical precipitation method and the schematic diagram of the experimental setup is shown in Fig. 11. The laboratory-scale experiments were conducted with calcium hydroxide, ammonium hydroxide, and sodium hydroxide as bases at different temperatures from 50°C to 90°C and pH from pH 8.0 to 10.0. The results of experiments showed that there is a change in the total concentration of extracted mineral with an increase in temperature from 50°C to 90°C as well as with an increase in pH from 8.0 to 10.0. The major extracted mineral from Desalination Research Plant SWRO brine was magnesium at about 98%, and other minerals extracted are lithium, 78%; boron, 51%; sulphate, 18%; calcium, 15%; and strontium, 14%. The highest extracted minerals from the Shuwaikh SWRO brine are boron 83%, magnesium 78%, lithium 34%, strontium 21%, calcium 18% and sulfate 11% at 90°C at 10.0 pH. The calculated magnesium oxide production from Desalination Research Plant SWRO brine is about 228 ton/y and Shuwaikh SWRO brine is 97,909 ton/y. This investigation was the first study by KISR to appraise the recovery of valuable by-products from SWRO brine rejected from desalination plants in Kuwait [48].

2.2.3. Extraction of magnesium oxide from concentrated brine: pilot plant

In this project, the WRC of KISR has taken the initiative in conducting experimental studies to extract magnesium ions selectively from Shuwaikh SWRO and DRP SWRO brines. The experiments were conducted on a laboratory scale to extract magnesium for the brine rejected from the Shuwaikh SWRO plant, while experiments were conducted on a pilot scale to extract magnesium for the brine rejected from the SWRO plant in DRP. Fig. 12 shows the process diagram for the extraction of magnesium oxide from SWRO brine.

Laboratory experiments on Shuwaikh SWRO brine extracted 2,681 mg/L (99%) of crude magnesium salt at pH 11.0 and a temperature of 90°C. The market value of crude magnesium salt with a purity ratio of 81.15% obtained from Shuwaikh SWRO brine is $76,617,450/y, whereas the market value of magnesium salt with 95.33% purity is $153,234,900/y. The pilot scale experiments have shown that the crystallizer process for extracting magnesium oxide from DRP SWRO brine is capable of producing 1,610 mg/L

Fig. 10. Low-temperature flash evaporation unit with salt crystals and centrifuge to separate salt from slurry.

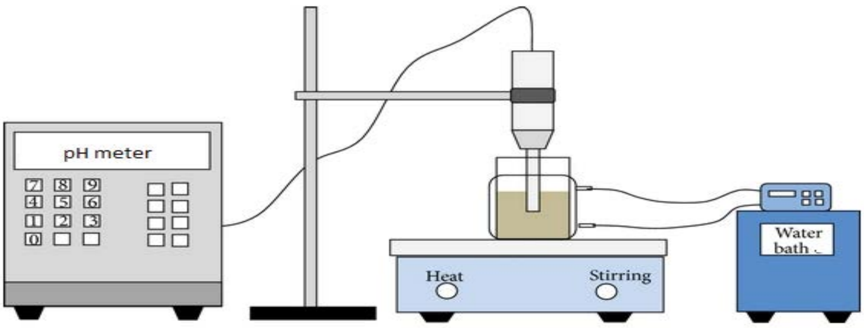

Fig. 11. Schematic view of the experimental setup for laboratory-scale mineral extraction.

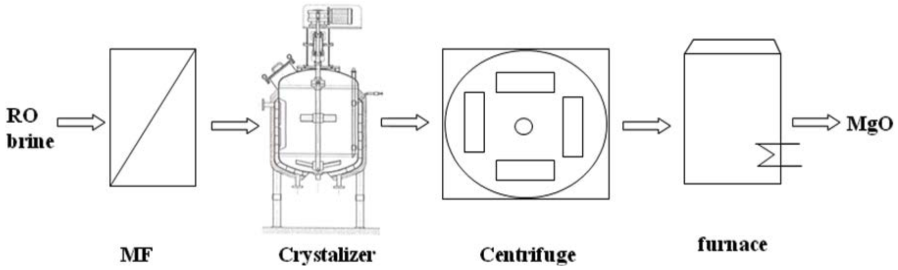

Fig. 12. Process diagram of the extraction of magnesium oxide from SWRO brine.

(96.3%) at pH 11.0 and a temperature of 50 C. The calculated market value of crude magnesium salt with a purity ratio of 87.8% obtained from DRP SWRO brine is $236,880/y, whereas the market value of magnesium salt with 95.1% is $473,900/y. Based on the conceptual design results, the magnesium extraction process on a semi-commercial plant with a capacity of 100 m^3/d, specifically designed for DRP SWRO, can produce approximately 161 kg/d of crude magnesium hydroxide salt under the defined optimal operating conditions. The cost/benefit analysis calculated for a period of 5 y shows no direct profits in the first 5 y because of higher capital investment. However, any step that reduces the capital investment and increases the magnesium concentration in brine can lead to financial gain. This can be achieved by nanofiltration pre-treatment of brine as well as by adopting patented innovation technology from the US patent US10, 940,439 B1 granted to KISR.

2.3. Development of cutting-edge membranes

2.3.1. Development of carbon nanotube membranes for dissolved gases removal as seawater pre-treatment

The main objective of this study was to develop high-performance degasification hydrophobic membranes using different nanoparticles and hydrophobic polymer matrix [49,50]. The membranes were fabricated by blending carbon nanotube (CNT) and graphene oxide (GO) nanoparticles with polyvinylchloride (PVC), polyvinylidene fluoride (PVDF), and polypropylene (PP). The degasification performance of CNT and GO nanoparticle-incorporated PVC and PVDF membranes showed an improvement in oxygen removal efficiency with increased nanoparticle concentration in the membrane matrix because of the increased porosity of the membranes. The newly fabricated membranes with 0.5 wt% CNT in the PVC and PVDF membranes showed higher dissolved oxygen removal efficiency than the selected commercial membranes. The degasification performance of the newly fabricated PVC hollow fiber membranes was similar to that of commercial hollow fiber polytetrafluoroethylene (PTFE) and polypropylene (PP) membranes, but they showed better antifouling character. Most of the CNT and GO nanoparticle incorporated fabricated PVC and PVDF membranes demonstrated better performance than the commercial PP, PVDF, and PTFE flat sheet and hollow fiber membranes.

2.3.2. Fabrication of fouling control forward osmosis membranes for Kuwait seawater desalination

In this project, different types of nanotubes were utilized to enhance the performance of thin-film nanocomposite (TFN) forward osmosis (FO) membranes [51–54]. Amine and sulfate-modified titania nanotubes showed improved flux and rejection rates, outperforming commercial membranes. Polyethylene imine in place of meta-phenylenediamine in the polyamide layer also enhanced membrane performance. Halloysite nanotubes were effective in dispersion within the polyamide layer, resulting in high-performing membranes. Hydrophilic modification of hydrophobic multiwalled carbon nanotubes (MWCNT) using -COOH groups improved their compatibility in TFN membranes, achieving better performance than existing commercial membranes. Mixed matrix membranes (MMM) utilizing various nanotubes and polymers like cellulose acetate (CA) showed superior performance compared to commercial membranes, with CA performing better than cellulose acetate butyrate (CAB). Polyvinylidene fluoride (PVDF) was deemed unsuitable due to its hydrophobic nature. A novel draw solution developed through the hydrolysis reaction of Poly (isobutylene-alt-maleic anhydride) polymer showed advantages over conventional NaCl draw solutions, minimizing reverse salt diffusion and enhancing efficiency. Additionally, a membrane distillation technique demonstrated an easy recovery method for this novel draw solution.

2.3.3. Assessment of newly fabricated thin-film composite nanofiltration membranes for seawater treatment

The study aimed to develop nano-based nanofiltration (NF) membranes tailored for seawater pre-treatment [55–57]. A novel membrane coating technique by the WRC project team facilitated the creation of thin film composite (TFC) NF membranes. These TFC membranes were produced through a molecular self-assembly method involving trimesoyl chloride (TMC) and triethyl amine (TEA) on a polyethersulfone ultrafiltration membrane substrate. The thin film nanocomposite (TFN) membranes emerged as promising options for enhancing pre-treatment efficiency in seawater desalination. Various nanoparticles known for their compatibility with the self-assembled NF active layer—such as carboxylated multiwalled carbon nanotube (CMWCNT), graphene oxide (GO), aminated multiwalled carbon nanotube (NH_2-MWCNT), ethylenediamine modified GO (EDA-GO), a novel phosphonic acid-modified titanium dioxide (POOH-TiO_2), and TiO_2 nanoparticles—were chosen as nanofillers in synthesizing trimesic acid (TMA)-based NF membranes. The incorporation of these nanoparticles led to alterations in membrane morphology and hydrophilicity, contributing positively to improved performance in seawater pre-treatment applications. Overall, these membranes, tailored with nanofillers, exhibited varying flux and exceptional selectivity for ion and boron separation, showcasing the potential for large-scale seawater pre-treatment applications with improved efficiency compared to existing commercial NF membranes.

3. Intellectual property developments by KISR

3.1. Patent No.: US 10, 124, 297 B1. Thin film nanocomposite nanofiltration membrane [58]

This invention involves a simple coating process to prepare the nanofiltration membrane for wastewater treatment applications. Most of the commercial membranes will be fabricated by interfacial polymerization technique between meta-Phenylene diamine (MPD) and trimesoyl chloride (TMC). But, MPD chemical has stability problem since it is sensitive to light and moisture and a undergoes degradation upon storage over a period of six months. The proposed invention includes a new technique called "self-assembly" and does not include handling any unstable MPD monomer. Instead, NF coating was achieved by reacting triethylamine with the TMC over a support. The innovative NF membrane has shown highest rejection towards the ionic composition during the pre-treatment of AGS. The NF membrane produced highest rejection for both divalent ions and monovalent ions compared to any commercially available NF membranes in the market. Generally, boron is the toxic element present in the seawater which varies in the range of 3.5 to 5.0 ppm. According to world health organization (WHO) a boron level above >0.5 ppm is not recommended for human health. The commercially available NF membranes are not suitable for boron rejection at seawater pH (7.5–8.5), since at seawater pH boron exist as neutral (charge less) boric acid. Generally, boron is the major problem in employing a single-phase NF-RO hybrid system to produce potable water. The novel membrane served as the best performance membrane in rejecting boron. In the current invention, a boron rejection of >50% was achieved during seawater pre-treatment, whereas the previously reported highest boron rejection value by any commercial NF membrane was 15%–20% at seawater pH.

3.2. Patent No.: US 10, 183, 882 B1. System and method for pretreating turbid seawater [59]

The system and method for treating turbid seawater utilize polyelectrolyte dosing, clarification through a clarifier system, and centrifugation in a decanter centrifuge followed by microfiltration to treat seawater before it feeds the seawater to a desalination plant. The system and method for pretreating turbid seawater may be applied to the feeds of desalination technologies, such as MSF, RO, etc. The system and method for treating turbid seawater allows for the operation of desalination plants with less capital investment, less chemical usage, and reduced energy requirements.

3.3. Patent No.: US 10, 280, 095 B1. Desalination system with mineral recovery [60]

The desalination system with mineral recovery is a system for desalinating water using spray drying, which allows for both the production of purified water and the recovery of mineral salts. The desalination system with mineral recovery is a two-stage system for zero-liquid discharge (ZLD) desalination of feed water. The feed water may be, for example, seawater, RO brine (i.e., the waste brine from an RO process), nano-filtration (NF) reject, MSF brine, or the like. The first stage receives the feed water and uses a spray drying process to produce concentrated brine and a first volume of purified water. The concentrated brine is fed to the second stage, which also uses a spray drying process to produce a second volume of purified water and a volume of recovered mineral salts.

3.4. Patent No.: US 10, 308, 524 B1. Pressure - reduced saline water treatment system [61]

The pressure-reduced saline water treatment system and innovation include the integration of FO and RO desalination systems to produce fresh water. The pressure-reduced saline water treatment system uses seawater with low osmotic pressure on the feed solution side and RO brine with higher hydraulic pressure on the draw solution side of the FO desalination system. This results in a concentration of the RO brine and dilution of the seawater within the FO system. The diluted seawater is then delivered from the feed side of the FO system to the feed side of the RO system. The RO system produces product water and RO brine. The drawing side of the FO system receives the RO brine and outputs highly concentrated brine. A single-phase RO-FO hybrid system reduced the operating pressure of RO to a new lowest value of 30 bar without compromising its freshwater recovery of 30%. A further reduction in pressure up to 10 bar was achieved by integrating the RO system with three-phase FO systems. This hybrid system can be operated with lower electrical energy or by integrating the system with renewable energy systems.

3.5. Patent No.: US 10,940,439 B1. High water recovery hybrid membrane system for desalination and brine concentration [62]

The high water recovery hybrid membrane system for desalination and brine concentration combines nanofiltration (NF), RO, and forward osmosis (FO) to produce pure water from seawater or other sources of saline solution or salt-contaminated water. The nanofiltration unit outputs a stream of reject brine and a permeate stream. The RO desalination unit receives the first portion of the NF permeate stream and outputs a reject stream and pure water product. The forward osmosis desalination unit receives the RO reject stream and outputs a concentrated saline solution. The other side of the forward osmosis desalination unit receives a second portion of the NF permeate stream and outputs a dilute saline stream, which mixes with the first portion of the NF permeate stream fed to the RO desalination unit. The initial feed stream may include seawater, brine, brackish water, produced water, wastewater, or any other type of saline stream(s).

3.6. Patent No.: US 11,035,581 B1. Integrated desalination and air conditioning system [63]

The integrated desalination and air conditioning system is an innovative desalination system that generates freshwater and cooling effects while utilizing low-grade thermal energy. The system incorporates a humidification-dehumidification (HDH) desalination system with a water-lithium bromide (H_2O-LiBr) vapor absorption cycle (AbC) system, as shown in the schematic drawing above. This combination allows the HDH system to utilize the rejected thermal energy from the AbC system, which reduces the energy consumption of the integrated system. The AbC system includes an AbC generator to separate water vapor from a LiBr solution and provides a heating source for an AbC condenser that heats the atmospheric air input of the HDH. There are also two AbC absorbers that absorb the refrigerant vapor from the evaporators and provide heating sources for the feed seawater. The heat input for the AbC generator is a direct heat source or a motive steam input. The energy source can be low-grade heat sources like waste heat or solar thermal energy.

3.7. Patent No.: US 11,254,691 B1. Method for making metal-organic frameworks and thin film nanocomposite membranes using the same [64]

Metal-organic frameworks (MOF) are a new class of materials for water desalination applications. However, the synthesis of MOF targeting desalination applications is challenging due to the less water and thermal stability and compatibility issues existing with the majority of MOF's available in the market. This KISR patent discloses a facile and efficient method for the synthesis of novel water and thermally stable MOF with specific characteristics for membrane fabrication to desalinate seawater. The invention includes a MOF synthesis protocol by reacting metal salt (applicable for a variety of salts) with cyclic propyl phosphonic anhydride (T3P®) reagent as a novel phosphonic acid organic linker in a water medium. As such, the process does not include any high-temperature heating and is more eco-friendly due to the use of water as the reaction medium and non-toxic T3P as the organic linker.

3.8. Patent No.: US 11,407,659 B1. Desalination and cooling system [65]

A desalination and cooling system includes a single-effect water-lithium bromide vapor absorption cycle (VAC) system and forward osmosis with a thermal-recovery (FO-TR) desalination system. The FO system employs a Thermo Responsive Draw Solution (TRDS). Fresh water flows from the FS to the TRDS without the application of pressure on the saline water. Afterward, only thermal energy is required to extract fresh water from the TRDS and recover or regenerate the draw solution. The VAC system serves as a cooling source for cooling or air conditioning applications, generating waste heat as a result. The waste heat generated by the VAC system provides the thermal energy needed to recover the draw solution (DS). The VAC system can be powered by low-grade heat sources like solar thermal energy.

4. Exploring future initiatives: potential projects under consideration

The integration of renewable energy into desalination processes holds immense promise across various scales, from large industrial operations to small-scale applications, including emergencies. WRC is planning to conduct studies on solar desalination, such as photovoltaic (PV) systems coupled with thermal or membrane-based desalination methods. These systems can work efficiently in remote areas or emergencies where access to conventional power sources might be limited. The integration of these renewable energy sources with desalination technologies not only addresses sustainability concerns by reducing reliance on fossil fuels but also ensures water security, particularly in regions prone to water scarcity or emergencies where conventional infrastructure might be disrupted. Another area of interest is the development of innovative desalination processes leveraging waste heat to address both water scarcity and energy efficiency. The thermal energy requirement in the FO systems can be further reduced by integrating FO with solar and waste heat energy from power and nuclear plants, highlighting the potential for energy-efficient FO technology. Similarly, studies at the laboratory and pilot scale will be conducted using waste heat to drive MD systems, multi-effect distillation (MED) systems, adsorption desalination, vapor compression distillation (VCD), etc. In addition, the potential collaborative initiatives on nuclear desalination signify a forward-looking approach. The surplus of waste heat from nuclear plants can be used to produce fresh water by integrating with MED and MSF desalination plants, whereas, electricity from nuclear plants can be used to operate RO systems. WRC's dedication to innovation paves the way for sustainable desalination, ensuring a water-secure future.

Acknowledgements

The author is thankful to the Kuwait Foundation for the Advancement of Sciences (KFAS), the Ministry of Electricity and Water and Renewable Energy (MEWRE), the management of the Kuwait Institute for Scientific Research (KISR) and Water Research Centre (WRC) for their continued support and encouragement towards the research activities.

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Balaban Desalination Publications

The 15th Gulf Water Conference

(2024) 69–76
doi: 10.5004.dsal.2024.700069

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Multi-objective optimization of innovative renewable energy-powered desalination and cooling system: a cutting-edge approach

Hassan Abdulrahim*, Mansour Ahmed, Yousef Al-Wazzan, Salah Al-Jazzaf

Water Research Center (WRC), Kuwait Institute for Scientific Research (KISR), P.O. Box 24885, 13109 Safat, Kuwait, email: habdulrahim@kisr.edu.kw

ABSTRACT

Addressing water scarcity and elevated energy demand becomes imperative in arid regions like Kuwait and its fellow GCC nations. This study introduces a sophisticated system that synergistically pairs the Forward Osmosis (FO) with the Thermal Recovery (TR) desalination process with a Water-Lithium Bromide (H_2O-LiBr) Vapor Absorption Cycle (VAC). This configuration propels the cooling cycle by leveraging low-grade thermal sources, including solar energy and excess heat from power generation infrastructure. Concurrently, the residual heat from the VAC facilitates the TR component of the FO process. This harmonized integration overcomes common challenges encountered in conventional desalination processes, including scaling, fouling, and precipitation, with optimal energy utilization. A thorough assessment of the system's technical feasibility, performance indicators, and operating conditions was numerically estimated. The extracted results underscore the notable potential of the system. Such a coordinated approach yields significant strides in energy conservation, emphasizing the practicality of multifunctional solutions when facing extreme environmental challenges and water deficits. Single objective optimization reveals the system's potential when optimized for a sole parameter, such as achieving maximum Q_{pw}, which resulted in 4,450 m³/d. Conversely, when optimized for Q_d, the energy demand drops significantly to 220 kW, suggesting a trade-off between water production and energy efficiency.

Keywords: Combined cooling and desalination; Forward osmosis with thermal recovery; Vapor absorption cycle; Multi-objective optimization; Genetic algorithm; Weighted sum; Aggregated objectives

1. Introduction

Water scarcity is a prominent issue in the Gulf Cooperation Council (GCC) countries due to their arid climate, marked by low and infrequent rainfall and high evaporation rates. These countries are considered in absolute water scarcity situations [1]. Climate change exacerbates the water scarcity issue in the GCC, with groundwater depletion through unsustainable consumption and rising global temperatures further dwindling the region's potable water supplies [2]. The escalating energy demand for desalination to meet water needs is notable, with about 4%–12% of the GCC countries' energy consumption being utilized for water desalination. In contrast, in 2019, desalination accounted for 8% of the final energy demand in

* Corresponding author.

Kuwait. [3,4]. Conventional desalination technologies that are used commercially primarily fall into two categories: (a) membrane, such as Reverse Osmosis (RO), and (b) thermal, including Multi-Effect Distillation (MED) and Multi-Stage Flash distillation (MSF) [5]. Emerging desalination technologies nearing commercialization include Forward Osmosis (FO), Membrane Distillation (MD), and Electrochemical Processes [6]. Conventional desalination technologies often require high energy supply and expert labor for operation and maintenance, making them less accessible and energy-intensive [7]. Some desalination plants utilize the heated cooling water from power plants as feedwater to the desalination units to reduce energy consumption. However, this still presents challenges in managing the high-TDS concentrate byproduct [8]. Amid these challenges, Kuwait's abundant solar energy presents a compelling sustainable water and energy management opportunity. The solar resource data [9], indicates that Kuwait receives a significant amount of direct normal irradiation (DNI) annually, which is crucial for power generation and other energy applications. DNI is a key parameter for assessing the performance of concentrating solar power (CSP) and concentrator solar photovoltaic (CPV) technologies and for estimating the global irradiation received by tilted or sun-tracking photovoltaic modules.

The GCC region also experiences a scorching climate, particularly during summer when daytime temperatures exceed 50°C in Kuwait. As a result, there is a high demand for air conditioning, which accounts for 60%–70% of annual peak electricity consumption [4,10]. A study discusses the cooling degree day values for the capitals of the GCC and mentions that the total electrical energy consumption of the GCC countries is expected to increase to 1094 TWh by 2025 [11]. A recent report published by Research and Markets predicted that the value of the Middle East and Africa (MEA) heating, ventilation, and air conditioning (HVAC) market would exceed $16.2 billion by 2020 [12]. It's highlighted also that the energy demand for air conditioning in the GCC is expected to nearly triple by 2030 [13]. An extensive review of electricity consumption indicators and energy efficiency in residential buildings in GCC countries revealed that the residential sector in the GCC countries accounts for approximately 43% of the total electricity consumption, with air conditioning systems being the major electricity consumer, accounting for 60%–80% of the total electricity consumption. [14]. This encompasses the prevailing challenges in the GCC region regarding water scarcity and elevated energy demand for HVAC in general and air conditioning in specific. For these reasons, an efficient and sustainable desalination and air conditioning system is highly needed, especially for GCC and arid countries. This paper presents and investigates an innovative integrated desalination and air conditioning system [15].

Vapor compression (VC) and vapor absorption cycles (VAC) are two thermodynamic cycles used for heating and cooling applications. VC cycles use mechanical energy to transfer heat from a low to a high temperature, while VAC uses thermal energy for the same purpose. An absorber and a generator in VAC replace the compressor in a VC cycle. Vapor absorption refrigeration systems are best for locations where heat energy is readily available at a low cost [16]. The VAC can address the energy crisis, increased fuel prices, and environmental problems associated with conventional compression refrigeration systems. The technology has attracted interest due to its advantages, such as utilizing low-grade heat sources and environmentally friendly working fluid pairs. However, it suffers from two significant obstacles: the large footprint of the unit and the low coefficient of performance (COP), preventing the absorption systems from being commercially successful [16]. VC refrigeration systems consume a significant amount of electricity, and the dramatic rise in energy consumption for such applications has exerted intense pressure on conventional energy sources. Furthermore, the increasing demand for energy has raised prices, emphasizing the need to increase the energy supply by either exploring new energy sources or saving the existing sources by reducing energy consumption [17]. Numerous research works have been done to develop strategies to improve the COP of absorption systems to make absorption refrigeration technology more competitive with conventional compression refrigeration systems; among effective and promising workarounds for increasing the COP of absorption refrigeration systems cycle design improvement, heat recovery method, development of new working pairs, adding sub-components, and improvement of operating conditions [18].

Wang et al. [19] present a high-efficiency multi-function system based on thermal desalination and absorption cycle for water, water-cooling, or water-heating production. The system comprises a single-effect water-lithium bromide absorption heat pump and a low-temperature multi-effect evaporation desalination unit. The study proposes and analyzes the system to take full advantage of the synergy that can be achieved by the combination and overcome the disadvantages of existing systems. Water-refrigeration cogeneration systems combining thermal desalination and absorption cycle have been identified as an effective and promising way of utilizing low-grade heat. This paper provides insights into the key features of this multi-function system, its advantages over other methods of water production, and its potential applications in different industries or settings [19]. Nikkhah and Beykal [20] presented a multipurpose seawater desalination process that integrates a Water-Lithium Bromide (H_2O-LiBr) absorption chiller, humidification-dehumidification (HDH), multi-effect evaporator, and mechanical vapor recompression (MVR) to improve the energy effectiveness of conventional desalination processes. The proposed approach uses the LiBr absorption chiller cycle in the multi-effect evaporators to preheat the seawater before steam generation while the MVR system activates the LiBr cycle. The authors conducted an extensive sensitivity analysis to characterize the effects of internal and external factors on the process performance. They also performed a techno-economic analysis of the proposed process to assess its viability. The results showed that this multipurpose desalination plant achieved a recovery ratio of 81%, a cooling capacity of 6 kW, and a levelized cost of produced water at \$8.4/m^3. This study provides valuable insights into designing efficient and cost-effective zero-liquid discharge desalination systems for various applications [20].

Integrating two distinct systems into a singular, innovative framework necessitates thoroughly exploring optimization techniques. Such a discipline is crucial for refining these systems, ensuring they reach peak performance while adhering to specific constraints. The following section delves into the principles of optimization and examines how they can be effectively applied to enhance the functionality of these multifaceted desalination technologies. Optimization is a mathematical discipline used in engineering, economics, operational research, and systems control [21]. It is used as a modeling and a solution tool to achieve several objectives. Optimization deals with decision problems that are formulated in a mathematical language. It is the art of maximizing or minimizing an objective function(s) while satisfying particular constraint(s). Optimization problems consist of three essential ingredients [22]: (a) Objective function, (b) Decision variables, and (c) Constraints.

Objective function: represents the quantity to be maximized or minimized, such as water cost and freshwater production rate in the case of the desalination plant. It is worth mentioning that almost all optimization problems have single-objective functions, with the following two exceptions: No objective function and multiple objective functions [23].

Decision Variables are parameters that control the objective function's value. In the case of desalination, variables might include operating temperature and pressure and various flow rates. Variables are the keys that the designer can adjust to achieve the desired performance. Variables can be classified as [24]: (i) design variables, (ii) dependent variables, (iii) state variables, (iv) operating variables, (v) environmental, and (vi) external variables.

Constraints are the set of boundaries that allow variables to take on specific values and exclude others. Flow rates or temperatures cannot be negative for desalination applications, so constraints are placed on all flow rates and temperature variables to be non-negative.

Multi-objective optimization (MOO) is a crucial area of research that deals with multi-criteria, multi-performance, or simultaneous optimization problems. This field is critical because most real-world problems are multi-disciplinary [25]. Unlike single-objective optimization problems, MOO problems lack a universally accepted definition of 'optimum'. In MOO, more than one objective function can be satisfied simultaneously [26,27]. For instance, designers must simultaneously consider essential characteristics such as product cost, performance, and environmental impact when designing a desalination plant. To achieve this, designers must make trade-offs between these characteristics. The main aim of conducting MOO is to make these trade-offs visible and quantifiable.

Pursuing innovative and sustainable solutions becomes crucial considering the pressing challenges of water scarcity and high energy demands for desalination and air conditioning in the GCC region, as outlined in the introduction. This study introduces a groundbreaking integrated system that adeptly combines Forward Osmosis (FO) with Thermal Recovery (TR) for desalination and pairs it with a Water-Lithium Bromide (H_2O-LiBr) Vapor Absorption Cycle (VAC) for cooling. This synergistic approach addresses the inherent inefficiencies of conventional desalination and cooling systems and leverages low-grade thermal energy sources, such as solar energy and waste heat from power plants, to optimize energy utilization. The following section delves into the specifics of this integrated FO-TR and H_2O-LiBr VAC system, elucidating its operational mechanics, energy efficiency, and potential for sustainable water and energy management in arid environments. This system's innovative design and operational flexibility, capable of functioning in desalination and cooling modes, both separately and concurrently, represent a significant advancement in addressing the intertwined challenges of water scarcity and energy consumption in regions like Kuwait and its neighboring GCC countries.

2. System description

FO as a membrane desalination process has recently drawn significant attention as a low-energy consumption technology [28]. The FO desalination system is a two-step process; the primary energy consumption step in the FO desalination system is the Draw Solution (DS) regeneration process. Among the different regeneration methods is heating the DS to liberate the fresh water and re-concentrating the DS in a process called thermal recovery (TR). In a thermal DS regeneration system, a particular thermo-responsive draw solution (TRDS) is used to absorb fresh water from the feed solution (FS) and seawater in the case of seawater desalination. Then, the thermal energy is used to separate the water from the diluted DS [29]. Using thermoresponsive materials as regenerable draw solutes has gained particular interest because of low-temperature regeneration [29]. A comprehensive analysis of their use for FO and the overall plant assessment is still very limited in the open literature. The proprietary thermoresponsive draw solute of Trevi Systems® has been used in a study by Ahmed et al. [28]. Fig. 1 shows a schematic diagram of the FO with a thermal recovery (FO-TR) system.

Fig. 2 shows the schematic diagram of the innovative combined desalination and air conditioning system. The diluted DS is heated in the Draw Solution Recovery Chamber (DSRC) and separated from the water for the DS recovery. The water is collected from the top of the DSRC due to the density difference. The DSRC uses the waste heat from the VAC, reducing water desalination costs significantly. Although the VAC can be run using solar energy or industrial waste heat, in this paper, the VAC will be modeled directly using motive steam.

It is important to emphasize that the proposed system is exceptionally well-suited for operation with solar energy, enhancing its sustainability and operational efficiency. Utilizing a Direct Steam Generator (DSG) system, coupled with advanced solar collection technologies such as Parabolic Trough Collectors (PTC) or Linear Fresnel Reflectors (LFR), provides an effective means of harnessing solar thermal energy. Moreover, integrating Photovoltaic (PV) panels complements this setup by providing electric power to the electric motors running the system's pumps, further diversifying the system's energy sources. By integrating these solar technologies, the proposed system aligns with renewable energy goals and represents a significant step forward in addressing water scarcity and energy demand challenges in arid regions. The dual use of solar thermal and photovoltaic technologies ensures the system can operate effectively under varying solar conditions, maximizing energy capture and utilization throughout the year.

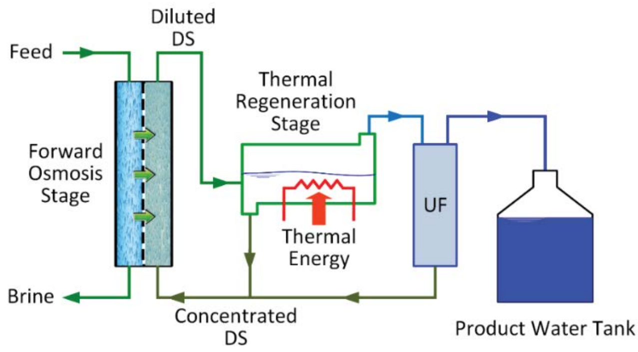

Fig. 1. The schematic diagram of the FO-TR process.

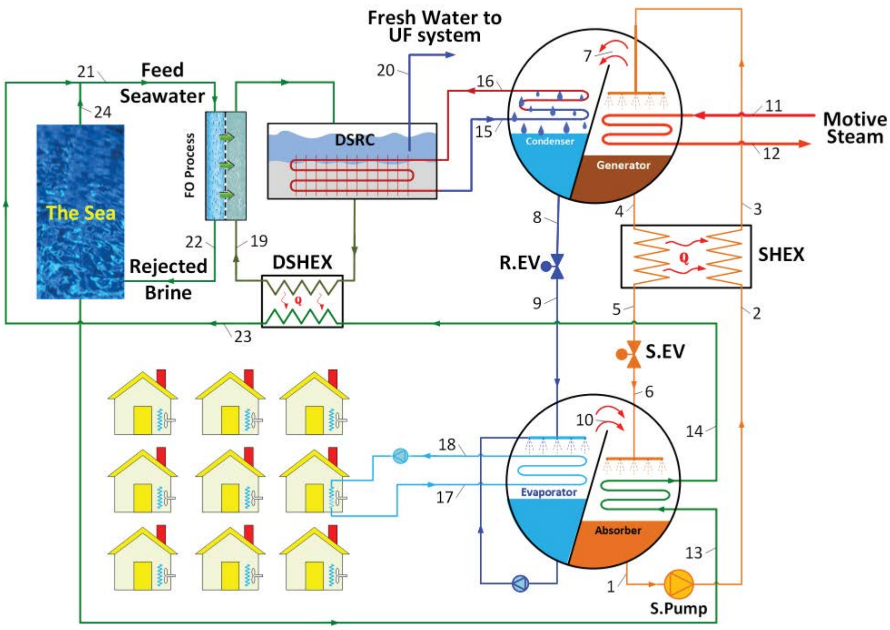

Fig. 2. Schematic diagram of the VAC-FO-TR innovative combined system.

3. Methodology

The results presented in this work are based on mathematical modeling and simulation. The following assumptions were made during model development [30]:

- All components are operating under steady-state conditions.
- Pressure drops are negligible throughout the system, except in the solution expansion valve (S.EV), refrigerant expansion valve (R.EV), and pumps.
- The R.EV and S.EV processes are irreversible and isenthalpic.
- The pumps perform isentropic compression.
- Only the generator, condenser, evaporator, and absorber can interact with the surroundings.
- The solution exiting the generator and absorber has reached phase equilibrium.
- The temperature of the water vapor exiting the generator matches that of the solution.
- The refrigerant leaving the evaporator is saturated vapor, whereas the refrigerant entering the condenser is saturated liquid.
- The strong solution is only heated, and there is no vapor production in the solution heat exchanger (SHEX).
- Any mass buildup in all machine components is disregarded.
- Changes in kinetic and potential energy are not taken into account.
- Radiative heat transmission is disregarded.
- The generator and condenser pressures are equal, as are the pressures in the evaporator and absorber.

The detailed steady-state mass and energy balance equations for the VAC are presented in Appendix-A and can be found in reference [31] by the authors. The equations that make up the model for the FO process are explained in Appendix-B and can be found in reference [32] by the authors. This research aims to perform a Multi-Objective Optimization (MOO) study for an innovative integrated desalination and air conditioning system using the Genetic Algorithm (GA) technique. The augmented objective function technique is used in this work as the multi-objective method. The integrated desalination and air conditioning system has been simulated rigorously using the above-mentioned mathematical models. Five objectives have been considered in this analysis: the VAC system capacity ($AC_{capacity}$), the coefficient of performance of the VAC system (COP), the distillate production (Q_{wp}), the energy consumption $\left(\dot{Q}_d\right)$, and the total heat transfer area (A_{tot}). The integrated desalination and air conditioning systems have been optimized for single, double, and triple simultaneous objectives. The general multi-objective problem is expressed as follows.

$$\begin{aligned} \min/\max F(X) &= \left(f_1(X), f_2(X), f_3(X), \ldots, f_k(X)\right) \\ \text{s.t.} \quad & X \in S \\ & X = \left(x_1, x_2, x_3, \ldots, x_n\right) \end{aligned} \tag{1}$$

where $F(X)$ is the general multi-objective function, $f(X)$ is the individual objectives, and x represents the decision variables.

3.1. Weighted-Sum Method

The most widely used method in MOO is the weighted-sum technique [24,27,33]. This method adds all normalized objectives together using different weighting coefficients. Thus, the MOO problem is transformed into a single-objective optimization problem of the form presented in eq. (8) through (13) below.

$$\begin{aligned} &\text{AOF} = \min \sum_{i=1}^{k} \omega_i f_i \\ &\text{s.t.} \quad \omega \in R; \quad \omega_i \geq 0; \quad \sum_{i=1}^{k} \omega_i = 1.0 \end{aligned} \tag{2}$$

where AOF is the normalized Aggregated Objective Function and the weighting coefficients represent the relative importance of each objective, multiple optimizations run can be conducted at different weight vectors (ω_i) to locate various points on the Pareto front. However, this method has a few minor drawbacks; depending on the scaling of other objectives, it can be hard to select the weights to ensure that points are spread evenly over the Pareto front.

Nine decision variables are used, five are flow rates and four are the heat exchangers UA factor, and five objectives are chosen in the optimization study as shown in Table 1.

For the single objectives, the following objective functions are implemented:

$$\text{Obj}_1 = \text{AC}_{\text{Capacity}} \tag{3}$$

$$\text{Obj}_2 = \text{COP} \tag{4}$$

$$\text{Obj}_3 = Q_{\text{pw}} \tag{5}$$

$$\text{Obj}_4 = \dot{Q}_d \tag{6}$$

$$\text{Obj}_5 = A_{\text{tot}} \tag{7}$$

For double objectives, the following objective functions are implemented:

Table 1
The objectives and decision variables used in the optimization study

The Objectives	The Decision Variables
The cooling capacity $AC_{Capacity}$	The flow rate of the diluted solution from the absorber, $\dot{m}_1$
The VAC's COP	The flow rate of motive steam to the generator, $\dot{m}_{11}$
The product water Q_{pw}	The flow rate of cooling water to the absorber, $\dot{m}_{13}$
The generator energy consumption $\dot{Q}_d$	The flow rate of heating water to DSRC, $\dot{m}_{15}$
	The flow rate of the chilled water to the evaporator, $\dot{m}_{17}$
The total heat transfer area A_{tot}	The UA of the absorber, condenser, generator, and evaporator, UA_a, UA_c, UA_d, and UA_e respectively

For maximum $AC_{capacity}$ and minimum heat transfer area

$$OF_1 = w1_1\left(\frac{Obj_1}{Obj_{1,max}}\right) - w2_1\left(\frac{Obj_5}{Obj_{5,min}}\right) \quad (8)$$

For maximum $AC_{capacity}$ and maximum COP

$$OF_2 = w1_2\left(\frac{Obj_1}{Obj_{1,max}}\right) + w2_2\left(\frac{Obj_2}{Obj_{2,max}}\right) \quad (9)$$

For maximum $AC_{capacity}$ and maximum product water

$$OF_3 = w1_3\left(\frac{Obj_1}{Obj_{1,max}}\right) + w2_3\left(\frac{Obj_3}{Obj_{3,max}}\right) \quad (10)$$

For maximum $AC_{capacity}$ and minimum energy consumption

$$OF_4 = w1_4\left(\frac{Obj_1}{Obj_{1,max}}\right) - w2_4\left(\frac{Obj_4}{Obj_{4,min}}\right) \quad (11)$$

For triple objectives, the following functions are implemented:

For maximum $AC_{capacity}$, maximum product water, and minimum energy consumption

$$OF_5 = w1_5\left(\frac{Obj_1}{Obj_{1,max}}\right) + w2_5\left(\frac{Obj_3}{Obj_{3,max}}\right) - w3_5\left(\frac{Obj_4}{Obj_{4,min}}\right) \quad (12)$$

For maximum $AC_{capacity}$, maximum product water, and minimum heat transfer area

$$OF_6 = w1_6\left(\frac{Obj_1}{Obj_{1,max}}\right) + w2_6\left(\frac{Obj_3}{Obj_{3,max}}\right) - w3_6\left(\frac{Obj_5}{Obj_{5,min}}\right) \quad (13)$$

In eqs. (8) to (13), the max/min of the objectives is obtained by applying single objective optimization according to the eqs. (3) to (7), as shown in Table 2 below.

Table 2
Optimum values of the single objectives

Parameter	Objective	value	unit
$AC_{capacity}$	$Obj_{1,max}$	1,688	ton
COP	$Obj_{2,max}$	0.740	–
Q_{pw}	$Obj_{3,max}$	4,450	m^3/d
$\dot{Q}_d$	$Obj_{4,min}$	220	kW
A_{tot}	$Obj_{5,min}$	1,161	m^2

4. Results and discussions

The optimization of the innovative renewable energy-powered desalination and cooling system focuses on achieving the best performance in terms of air conditioning capacity, efficiency, water production, energy consumption, and system size. In Table 2, the optimal values for each objective, setting a benchmark for the system's capabilities are presented. These values serve as a reference for the trade-offs discussed in Table 3, where multi-objective optimization scenarios are evaluated, and balanced solutions are sought that consider the interplay between different system performance metrics.

The results presented in Table 3 depict a multi-objective optimization strategy, aiming to balance various performance metrics of the system. The objectives considered include air conditioning (AC) capacity, coefficient of performance (COP), product water flow rate (Q_{pw}), energy demand $\left(\dot{Q}_d\right)$, and total heat transfer area (A_{tot}). The table segregates the outcomes into three categories: single objectives, double objectives, and triple objectives, highlighting the system's performance under different optimization criteria. Single objective optimization reveals the system's potential when optimized for a sole parameter, such as achieving maximum Q_{pw}, which resulted in 4,450 m^3/d. Conversely, when optimized for $\left(\dot{Q}_d\right)$, the energy demand drops significantly to 220 kW, suggesting a trade-off between water production and energy efficiency.

Table 3
Multi-Objectives optimization results

Objectives		Single Objective					Double Objectives				Triple Obj.	
		Obj_1	Obj_2	Obj_3	Obj_4	Obj_5	OF_1	OF_2	OF_3	OF_4	OF_5	OF_6
$AC_{Capacity}$	ton	1,688	1,688	411	786	370	204	573	1,688	620	1,212	1,315
COP	–	0.71	0.74	0.641	0.64	0.603	0.689	0.71	0.71	0.611	0.676	0.662
Q_{pw}	m^3/d	4,340	4,340	4,450	2,040	965	524	1463	4,340	662	3,129	2,292
Q_d	kW	2,417	1,621	1,868	220	266	989	10,889	1,105	1,542	2,458	1,765
A_{tot}	m^2	3,418	3,418	2,328	2,521	1,161	1,297	1,641	3,418	1,574	1,715	2,575

The double objective optimizations balance two competing metrics at a time, using weighted objective functions (OFs). For instance, OF_1 emphasizes maximum AC capacity and minimum heat transfer area, with associated weights (w_1 and w_2) reflecting the relative importance of each objective. This dual approach allows for tailored optimization that can prioritize crucial aspects of the system's performance based on specific operational or economic considerations. The triple objective scenarios, OF_5 and OF_6, introduce a more complex optimization landscape by simultaneously considering three different objectives. These scenarios demonstrate the feasibility of achieving a high-performing desalination and cooling system that not only maximizes water production and AC capacity but also minimizes energy consumption or heat transfer area. Such an approach highlights the sophisticated balance between efficiency, productivity, and sustainability in renewable energy-powered systems.

In summary, the optimization results emphasize the system's versatility and the effectiveness of the multi-objective optimization approach. The study provides valuable insights into how different performance objectives can be prioritized and balanced, which is crucial for the design and operation of energy-efficient and sustainable desalination and cooling systems powered by renewable energy. This approach is particularly relevant as the demand for such integrated systems increases in response to global water scarcity and the imperative for reduced energy consumption.

5. Conclusions

This study has successfully demonstrated the potential of an innovative renewable energy-powered desalination and cooling system, emphasizing its suitability for arid regions like Kuwait. By integrating Forward Osmosis (FO) with Thermal Recovery (TR) desalination processes alongside a Water-Lithium Bromide Vapor Absorption Cycle (VAC), the system addresses the dual challenges of water scarcity and high energy demand. The harmonized combination effectively utilizes low-grade thermal sources, significantly reducing the operational challenges such as scaling, fouling, and precipitation commonly associated with conventional desalination methods.

The multi-objective optimization approach, leveraging advanced techniques like Genetic Algorithms, facilitated the achievement of a balanced and efficient design, optimizing both energy consumption and system performance. The results from the numerical estimations underscore the remarkable efficiency and feasibility of this system, projecting it as a viable solution for sustainable water and energy resources management in regions facing severe environmental and water challenges. Single objective optimization reveals the system's potential when optimized for a sole parameter, such as achieving maximum Q_{pw}, which resulted in 4,450 m^3/d. Conversely, when optimized for Q_d, the energy demand drops significantly to 220 kW, suggesting a trade-off between water production and energy efficiency.

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Balaban Desalination Publications

مؤتمر الخليج الخامس عشر للمياه
The 15th Gulf Water Conference

(2025) 77
doi: 10.5004.dsal.2025.700103

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Airborne VHF sounding radar for desert subsurface exploration of shallow aquifers: DESERT-SEA

Essam Heggy[a,b]

[a]*University of Southern California, CA, USA,* [b]*NASA Jet Propulsion Laboratory, CA, USA*
email: essam.heggy@jpl.nasa.gov

ABSTRACT

Shallow fossil aquifers are the largest freshwater bodies in the North African Sahara and the Arabian Peninsula. Their groundwater dynamics and response to climatic variability and anthropogenic discharge remain largely unquantified due to the absence of large-scale monitoring methods. Currently, the assessment of groundwater dynamics in these aquifer systems is made primarily from sporadic well logs that barely cover a few percent of the geographical extent of these water bodies. To address this deficiency, we develop the use of an Ultra-Wide Band (UWB) Very High Frequency (VHF) interferometric airborne sounding radar, under a Space Act Agreement between NASA and the Qatar Foundation, to characterize the depth and geometry of the shallowest water table in large hyper-arid hydrological basins in North Africa and the Arabian Peninsula. We describe herein the science objectives, measurement requirements, instrument design, expected performance, flight implementation scenarios, primary targets for investigation, and the first technology demonstration of the concept. Our performance analyses suggest that an airborne, nadir-looking sounding radar system operating at 70-MHz center frequency with a linearly polarized folded-dipole antenna array—enabling a bandwidth of 50 MHz—and a surface SNR of 85 dB flying at an altitude of 500-2000 m, can map the uppermost water table depths of aquifer systems spanning tens of kilometers at a vertical resolution of 3 m in desiccated terrains to an average penetration depth of 50 m, with a spatial resolution of 200 m. For the first time, this airborne concept will allow time-coherent high-resolution mapping of the uppermost water tables of major aquifer systems in hyper-arid areas, providing unique insights into their dynamics and responses to increasing climatic and anthropogenic stressors, which remain largely uncharacterized. The above significantly surpasses the existing capabilities for mapping shallow aquifers in these harsh and remote environments, which today rely on data collected on different time scales from sparse well logs that do not cover their geographic extents.

Keywords: Airborne sounding radar; VHF radar; Synthetic aperture radar; Desert hydrology; Subsurface imaging; Groundwater and aquifers

ISBN 0-86689-078-5

Balaban Desalination Publications

مؤتمر الخليج الخامس عشر للمياه
The 15th Gulf Water Conference

(2025) 78–80
doi: 10.5004.dsal.2025.700104

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

New developments in mathematical modeling of groundwater systems

Abdelkader Larabi

Senior Professor and Director of the Regional Water Centre of Maghreb, Mohammed V University, Rabat, Morocco
emails: larabi_abdelkader@yahoo.fr, larabi@emi.ac.ma

EXTENDED ABSTRACT

The numerical modeling of groundwater flow in unconfined aquifers is much more involved than in confined aquifers. This is because the governing equation (i.e., Richard's equation) is highly nonlinear and is subject to nonlinear boundary conditions as well. This nonlinearity is related to the dependence of the relative permeability and the water retention in the unsaturated zone on the pressure head. Moreover, fully saturated models are typically associated with boundary conditions such as constant head, pumping/injection flow rates, and leakage flux through a semi-confining bed. These are essentially linear and do not pose additional challenges to standard numerical solution techniques. This is not the case for unconfined flow models where some boundary conditions are nonlinear and therefore are unknowns a priori; thus, they are an integral part of the numerical solution. A typical example is the free and moving water table boundary. Another complication in modeling unconfined groundwater flow is to locate the position of seepage faces when the water table reaches the land surface. The seepage boundary faces are not known prior to the numerical solution and are, therefore, not fixed as typically done with other boundary conditions. Additionally, wells pumping groundwater from unconfined aquifers might become dry as the water table drops below the well screens, and natural or artificial drains may stop draining groundwater as the levels drop below predefined elevations. These are typical examples that necessitate additional bookkeeping procedures during the nonlinear iterative solution process when solving for an unconfined groundwater flow model. Furthermore, natural groundwater flow occurs mostly in highly heterogeneous and anisotropic materials, thus increasing the nonlinearity of the resulting discrete algebraic systems of the equations. Hence, robust and advanced numerical methods are needed in this context.

Modeling unconfined groundwater flow subject to free and moving boundaries is performed using two broad classes of methods. The first category assumes a fixed mesh. Within this class, an algorithm should determine the spatial and temporal distribution of three types of cells: wet, dry, and partially wet cells (i.e., crossed by the water table). The second category considers a moving mesh that adapts to the dynamics of the water table boundary. Hence, unlike for a fixed mesh method, the dry zone (i.e., approximate unsaturated zone) is not part of the computational domain. The main advantage of an adaptive mesh technique is to solve a saturated groundwater flow equation, hence a linear system of algebraic equations, during each iteration of the mesh adaption process. Meanwhile, more elaborate algorithms are needed for mesh adaption and the interpolation of hydraulic properties between moving cells.

The fixed mesh approach is probably the most widespread owing to the availability of many computer

ISBN 0-86689-078-5

implementations such as MODFLOW developed by the USGS at the United States of America. Legacy versions of MODFLOW were criticized for an unphysical representation of unconfined groundwater flow dynamics, leading to a numerical instability for highly nonlinear problems. This was due, in part, to the heuristics upon which the decision to rewet a previously dry cell are based. Second, Picard iteration for some highly nonlinear problems may converge at a very slow rate or not at all. The latest releases include, however, a new Newton–Raphson-based formulation that substantially improves the computational stability. Another known difficulty within the fixed mesh approach derives from the way to artificially hide the flow patterns in the dry cells. Because this is not possible as the mesh is fixed, different approaches have been developed to tackle this problem. Desai (1988) developed a two-dimensional finite element model that linearizes the relative permeability function and recast it as a function of hydraulic head. The same approach was used by scientists in the framework of three-dimensional finite element models. Other authors used a sharp representation of this function; that is, the hydraulic conductivity in all dry cells is multiplied by a small residual factor (i.e., ~10−2–10−3). New developments presented the numerical solution of 3D unconfined seepage problems with the smoothed finite element method borrowed from solid mechanics (Kazemzadeh-Parsi, 2013). A limitation of the fixed mesh approach is that the exact position and shape of the water table could only be determined by post-processing computed groundwater heads. Hence, it is expected that a moving mesh technique will always lead to a more accurate position and a smooth shape of the phreatic surface when compared with a fixed mesh approach using the same resolution.

The second class of methods solve a series of linear equations on a deforming mesh. The mesh is adapted iteratively to fit the water table position. Here, again, many sub-approaches have been developed that could be categorized as rigorous or simplified. As described in standard textbooks of Bear (1972), the phreatic surface does not only fulfill the zero-pressure condition, but it is a kinematic boundary condition too. In other words, it is an interface through which the effects of unconfined storage, net recharge, and nonlinear effects related to the changing shape of the surface geometry are balanced. To the best of our knowledge, the only published numerical model taking into account both conditions was presented by Knupp (1996); such kinematic boundary condition, even under steady-state conditions, cannot be neglected.

Solving unconfined groundwater flow with a moving mesh technique using a finite difference method has some limitations. These problems do not exist when using a conforming (i.e., nodal-based) finite element technique such as the Galerkin weighted residual approach. However, while the groundwater head and the water table shape obtained by the conforming FEM using a moving mesh method might be accurate, it is well known that this is not the case for the specific discharge field. Moreover, the conforming FEM is not exactly mass conservative, which is problematic for nodes sharing elements with a high contrast of hydraulic conductivities. Post-processing techniques were introduced to derive continuous nodal-specific discharge fields, but it was reported that this procedure has a high computational cost. Mixed finite element methods were introduced to simultaneously approximate a scalar variable and its first-order derivative fields. Promising results highlighting a higher accuracy of this approximation technique when compared with alternative techniques were obtained for flow problems. The mixed finite element method leads, however, to an indefinite system of algebraic equations which is difficult to solve with direct or iterative methods. A hybridization technique avoids this problem by reformulating the mixed problem with primary unknowns on the faces of the mesh and using local algebraic relationships to recover the cell-centered heads and the normal specific discharge components. This gives rise to a method formally known as the mixed hybrid finite element method (MHFEM). Previous works established the outstanding behavior of this method to tackle groundwater flow problems in highly heterogeneous and anisotropic formations. While the MHFEM approximation was used for many classes of groundwater flow problems such as unsaturated flow and two-phase flow, to the best of the authors' knowledge, this is the first time that it has been used in combination with a deforming mesh approach to solve an unconfined flow in phreatic aquifers.

The objective of this paper is to introduce a new state-of-the-art three-dimensional MHFEM numerical model for confined–unconfined groundwater flow in complex aquifer systems characterized by irregular geometries, heterogeneous and anisotropic materials, and nonlinear boundary conditions of a practical relevance. These include, in particular, the nonlinear kinematic and seepage face boundary conditions generally ignored or weakly dealt with in previous studies. The work also deals with the model formulation and numerical discretization on layered unstructured grids.

In summary, determining the water table shape and position in unconfined aquifers is fundamental to many groundwater flow assessment studies. The commonly used industry standard fixed mesh models, contrary to popular belief, do not provide an accurate description of the phreatic surface. When using such models, the water table position is post-processed from the simulated groundwater heads, leading to an approximation error. This error becomes larger for coarse vertical grids.

This paper introduces a novel moving mesh technique to simulate the groundwater table in three-dimensional unconfined aquifers under steady-state or transient conditions. We adopt the face-based mixed-hybrid finite element discretization approach in space, leading to a more accurate approximation of the specific discharge field. The model uses an adaptive unstructured but layered mesh which is iteratively adjusted until its top fits the phreatic surface. The developed algorithm accounts for a linearized form of the kinematic boundary condition prescribed on the moving boundary and also supports usual boundary conditions as well. The model was compared to the existing analytical, fixed mesh, and previously published solutions. The obtained results show that the developed model is superior in terms of its numerical stability, convergence behavior, and accuracy. Furthermore, the simulated phreatic surface is free from a cellwise interpolation error and independent of the vertical grid size as used in fixed mesh methods. We also found that the ro-bustness of the moving mesh method cannot be surpassed by a fixed mesh alternative. The model's efficiency is supported by an almost quadratic rate of convergence of the outer iteration loop. Several theoretical and realistic examples are provided to demonstrate the model's accuracy, efficiency, and capability to successfully simulate unconfined groundwater flow with this novel moving mesh technique.

Keywords: Numerical modelling; Unconfined flow; Kinematic boundary condition; Water table position; Moving mesh; 3D mixed hybrid finite elements

Balaban Desalination Publications

The 15th Gulf Water Conference

(2025) 81–83
doi: 10.5004.dsal.2025.700105

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Artificial intelligence application in hydrogeology and groundwater management

Khalid ElHaj[1,2], Dalal Alshamsi[1,2]

[1]*Department of Geosciences, United Arab Emirates University, Al Ain, P.O. Box 15551, UAE*
[2]*National Water and Energy Center, United Arab Emirates University, Al Ain, P.O. Box 15551, UAE*
emails: 200734761@uaeu.ac.ae (K. ElHaj); dalal.shamsi@uaeu.ac.ae (D. Alshamsi)

EXTENDED ABSTRACT

Groundwater management involves overseeing groundwater resources to ensure their ideal utilization and long-term sustainability. More than two billions of the world population depend on groundwater resources as their main water source (Famiglietti, 2014), as result, managing such an important resources would be of paramount importance to governments. This would be even more important for countries like UAE where groundwater provides about 51% of the total water budget (Al Rashed et al., 2023; Ministry of Environment & Water, 2014). Managing groundwater resources involves many aspects, including observing its usage and predicting its future utilization, evaluating the scenarios affecting its utilization and any kind of adverse effects it can have on public health. In addition to aquifer delineation, pollution indicators, and any kind of relation the different aquifers may maintain with each other.

Our work involved exploring many of the key aspects of groundwater management. We utilized state-of-the-art Artificial Neural Networks to predict the fluctuations in Al Ain city groundwater levels. The algorithm utilized state-of-the-art Artificial Neural Networks that used the location, time and meteorologic conditions to predict the groundwater level in any location within Al Ain city. It achieved an accuracy of 0.952 in Coefficient of Determination (R^2). The trained model was used in conjunction with a geomodelling framework that utilized GIS to create variability maps to visually highlight the changes with time in a spatial form (ElHaj et al., 2023b)

We also investigated the critical issue of rising groundwater salinity using machine learning techniques. In a recent study submitted to COP28, we developed predictive models trained on historical total dissolved solids (TDS) data from multiple wells across Al Ain. The models were then used to forecast potential future changes in groundwater salinity under business-as-usual conditions. Additionally, we leveraged the trained models to simulate salinity responses under various climate scenarios, including substantial increases or decreases in precipitation and temperature. This provided actionable insights into how groundwater quality could evolve under different climate futures, enabling proactive management strategies to mitigate salinization risks. Overall, our integrated modeling approach generated data-driven projections to support evidence-based policies aimed at sustaining fresh groundwater resources in the face of environmental change.

We developed an integrated machine learning workflow to elucidate relationships between aquifers using their unique hydrogeochemical fingerprints. The approach involved first leveraging supervised learning

*Corresponding authors

ISBN 0-86689-078-5

techniques to train models on the available hydrochemical data. These models were then used to impute any missing values in the dataset — a crucial step enabling robust subsequent analysis. We next utilized unsupervised clustering algorithms to objectively group wells based solely on similarities in their hydrochemical makeup. This delineated distinct groundwater bodies in a completely data-driven manner. The clustered wells were then visualized spatially using our custom GeoZ library for visualizing clustering outputs, revealing meaningful spatial patterns aligning with the hydrostratigraphy (ElHaj et al., 2023a). By integrating supervised learning for imputation with unsupervised clustering for classification, the workflow provided an automated means of elucidating connections between aquifers based on their hydrogeochemical signatures. The approach extracted new hydrogeological insights, including groundwater mixing, flow paths, recharge sources, and more. Overall, it demonstrated the power of artificial intelligence techniques to uncover meaningful patterns in complex and imperfect hydrochemical data.

Accurately delineating aquifer boundaries provides numerous critical benefits that support sustainable groundwater management and utilization. Well-mapped aquifers empower decision-makers to effectively monitor, regulate, and protect groundwater resources. Aquifer delineation further aids pollution prevention efforts, disaster preparedness planning, informed land use development, efficient infrastructure sitting, and environmental conservation. Additionally, clearly defined aquifer boundaries enable cooperative legal and transboundary management of aquifers spanning multiple jurisdictions. Aquifer mapping also facilitates economic development planning that accounts for available groundwater resources. It can even assist geothermal energy exploration by elucidating subsurface hydrogeological structures. Overall, precise aquifer delineation is an essential foundation that facilitates informed, integrated groundwater management from local to regional scales.

To address the need for accurate yet efficient aquifer delineation, we developed a novel data-driven methodology leveraging hierarchical clustering analysis of groundwater hydrographs. The approach depends solely on leveraging existing hydrograph data from monitoring wells to delineate aquifer boundaries, without requiring expensive and time-consuming geophysical surveys. A key novelty lies in the custom distance metric we formulated to specifically address unique aspects of hydrogeological time-series data. This custom function compares the hydrographs from different wells based on similarities in groundwater level fluctuations over time. Wells with similar hydrographs are grouped into clusters using agglomerative hierarchical clustering. We selected this algorithm for two main reasons; first, agglomerative hierarchical clustering had the most flexibility in tuning among all the clustering methods tested during the project first phase, this allowed us to customize it to work more efficiently with hydrogeological datasets. The second reason we chose agglomerative hierarchical clustering was due to its hierarchical nature when choosing the number of clusters. We utilized this characteristic to address the issue of aquifer heterogeneity.

The algorithm is embedded within an overarching optimization framework enabling systematic tuning of parameters for optimal performance. This allowed further flexibility in tuning the preprocessing aspect of the data pipeline in addition to manipulating the clustering algorithm parameters. Creating the method in this way allowed us to test numerus scenarios, different methods, and use different metrics to assess the model performance. Not to mention that this approach also made the model future proof, as introducing any new methods within the framework would be done with minimal effort and without any major change to the main codebase. The output of the clustering algorithm would be general clusters containing the most similar wells. We developed GeoZ to map these clusters into geographic maps and used these maps to delineate the aquifer boundaries based on the available data.

The last step of the project was to enclose the developed framework within an objective function and run it in an optimization algorithm to find the best parameters to achieve the highest accuracy in addition to find the limits of the requirement to operate the model on any area of interest. The optimization algorithm achieved 90% accuracy in aquifer delineation using a monthly average of synthetic observation data that spanned a minimum of 400 months (33 years and 4 months). Using the same observation period limit on real groundwater observation data obtained from Texas state aquifers resulted in 73% accuracy. Longer hydrograph records improve accuracy but reduce the number of usable wells. Striking an appropriate balance is key to maximizing delineation while utilizing the most data.

The method can be optimized in many ways, including new imputation methods, outlier detection, similarity calculations among others, and the framework approach would make implementing them much easier. Also, the method was tested on monthly average regional scale datasets. With the advancement of groundwater observations methods and the new continuous telemetric observation equipment introduced in the Gulf Cooperation Council (GCC) Countries, this approach might provide new insights with more granular data with local and regional scale aquifers in the middle east. The efficiency of the method has not yet been tested on local aquifers with more granular data such as local dataset with daily or hourly readings, so it could be a very good research opportunity to explore the feasibility of the method in this aspect.

Overall, the methodology provides an inexpensive and efficient means of extracting value from existing hydrograph data to map aquifer boundaries. Precisely delineated aquifers empower communities and governments to enact informed, sustainable groundwater management practices. The work highlights the power of machine learning to advance large-scale hydrogeological characterization from imperfect data sources.

Keywords: Groundwater management; Machine learning; Aquifer delineation; Groundwater salinity; Artificial neural networks; Hydrogeochemistry; Hydrochemical fingerprints; Hierarchical clustering; Geomodelling

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Balaban Desalination Publications

مؤتمر الخليج الخامس عشر للمياه
The 15th Gulf Water Conference

(2025) 84
doi: 10.5004.dsal.2025.700106

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Mainstreaming the outcome of the UN summit on groundwater in the Arab strategy for water security

Bisher Imam

Reginal Hydrologist for the Arab States, UNESCO
email: b.imam@unesco.org

ABSTRACT

The United Nations Summit on Groundwater was held at UNESCO headquarters in Paris, France, from 6 to 8 December 2022. This summit was the conclusion of a year in which the focus was on groundwater (the hidden resource). In parallel, with the summit, the United Nations Commission on Water also held an expanded meeting that resulted in the issuance of a joint letter and call to action from the United Nations Commission on Water Resources/ Groundwater: The Hidden Resource for Sustainable Development. The message called on the countries of the world to enhance financing, data collection and exchange, human and institutional capacities, deployment of innovative technologies, and groundwater governance. Following the summit, and at the request of the Arab Ministerial Water Council, UNESCO Cairo Office, jointly with other regional agencies and academics, organized a series of regional consultations on groundwater management in the Arab Region with the objective of mainstreaming the Summit's outcome in the implementation plan of the updated Arab Strategy for Water Security. This presentation will provide and discuss the outcome of the UN Summit on Groundwater, as well as the outcome and recommendation of the Cairo Regional Ground Water Experts Meeting (October, 2023) on the mainstreaming of the summit's outcome in the Arab Strategy for Water Security along the following key priorities: Data and information; Capacity developmen; Innovation; Finance; Governance; Groundwater in Africa; and Strengthening the Science-Policy Interface.

Keywords: Groundwater; Financing; Data collection; Innovative technologies; Governance; Arab Strategy for water security; Capacity envelopment; Innovation

ISBN 0-86689-078-5

Balaban Desalination Publications

مؤتمر الخليج الخامس عشر للمياه
The 15th Gulf Water Conference

(2025) 85–96
doi: 10.5004.dsal.2025.700015

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Assessment of groundwater quality and its implications for drinking purposes in Najran, Southern Saudi Arabia

Abdulnoor A.J. Ghanim*, Abdulmohsen Ali Al-Swar, Saleh Mohammed Naser, Jarallah Mohammed Al-Yami, Hamad Thari alsaqoor, Salem Naser Al-Haider

Department of Civil Engineering, College of Engineering, Najran University, Najran 61441, Saudi Arabia, aaghanim@nu.edu.sa

ABSTRACT

In arid and semi-arid regions of Saudi Arabia, where water scarcity is an issue, monitoring groundwater quality is crucial. The main goal of this study is to assess the quality of groundwater and investigate the characteristics of water wells in Najran City, Saudi Arabia. A total of 10 groundwater wells in the study area were analyzed for physical, chemical, and microbial properties. The physical tests were conducted on-site for each well, while the chemical and microbial tests were carried out in the central laboratory for water and sanitation in Najran province. The results showed that the physical and microbial properties of all 10 wells were within the recommended limits. However, the chemical analysis results varied among the wells, with some showing high levels of TDS, nitrate, chloride and total hardness, making the water unsuitable for drinking. This study highlights the importance of safeguarding drinking water in Najran City through regular monitoring and treatment of groundwater wells. Furthermore, controlling potential pollution sources originating from agricultural activities, septic systems, and other anthropogenic practices is crucial.

Keywords: Groundwater wells; Groundwater quality; Drinking water standard; Heavy metal; Najran

1. Introduction

Groundwater is the most important source of water for domestic and agricultural use in Saudi Arabia, where surface water resources are scarce. However, groundwater quality may vary depending on the region's geology, climate, and human activities. Therefore, periodic monitoring and assessment of groundwater quality are essential for ensuring its suitability for different purposes and for protecting it from contamination and depletion.

Najran is a region in southern Saudi Arabia that relies heavily on groundwater for its water supply. The main source of groundwater in Najran is the Wadi Najran aquifer, which is recharged by rainfall and runoff from the nearby mountains. However, the groundwater quality in Najran may be affected by various factors, such as salinization, agricultural activities, urbanization, and industrial development.

Drinking water quality and safety continue to be a major public health concern. Also, drinking water

*Corresponding author

ISBN 0-86689-078-5

contamination has been implicated on a number of occasions for the spread of infectious diseases that have resulted in significant illnesses and deaths throughout the world. Each year, an estimated 1.9 million people die as a result of contaminated drinking water, the majority of whom are children under the age of five. According to the World Health Organization (WHO), improving water, sanitation, and hygiene may prevent almost 9.1% of global illnesses and 6.3% of all fatalities [1]. About 783 million people still lacked access to better water sources at the end of 2010, and over 2.5 billion people lacked access to decent sanitation. A recent report from UNICEF and WHO states that unless progress is quadrupled, billions of people worldwide will not have access to household drinking water, sanitation, or hygiene services by 2030 [2].

Groundwater is a vital resource for both urban and rural areas, as it is widely regarded as the sole supply capable of fulfilling household and agricultural demands in towns and villages [3].

For safe and dependable drinking water, groundwater is still and always will be the primary source in desert countries like Saudi Arabia where surface water is limited, rainfall is erratic, and evaporation rates are high [4]. Groundwater quality assessment has been the subject of research in many different fields by researchers all over the world [5–11].

Numerous studies have evaluated Saudi Arabia's drinking water quality. A study conducted in Riyadh, Saudi Arabia utilized inductively coupled plasma (ICP) spectrometry to analyze trace elements in drinking water. Samples were collected from 101 households and 21 retail bottled water brands. The analysis revealed that levels of cadmium (Cd), iron (Fe), mercury (Hg), nickel (Ni), and zinc (Zn) in household water exceeded the safety thresholds established by the European Economic Community (EEC) guidelines of 1980 [12]. This concerning finding highlights the need for further investigation and improved water treatment strategies to ensure safe and compliant drinking water supplies for Saudi households. The study proposed that the reason some of the metals were in the tap water may be attributed to their dissolution in the water from the residential plumbing system (from fittings, pipes, solder, or service connections) or to their existence in natural water.

Another study analyzed 21 bottled water brands (14 domestic,7 imported) and found trace metal levels in all samples fell below permitted standards. This suggests these bottled waters posed no immediate health concerns regarding trace metal contamination [13]. Continuing with the positive trends observed in certain water sources, mineral water stands out for its low levels of potentially harmful metals. A study analyzing these supplies found concentrations of cadmium, copper, lead, and zinc consistently below the World Health Organization's (WHO) permitted limits [14]. This finding highlights the potential of mineral water as a safe and reliable source of hydration, particularly within the context of broader water quality concerns in the region. Furthering the picture of water quality in the Riyadh region, a study focused on groundwater revealed a different story. ICP spectrophotometry analysis detected levels of aluminum, barium, iron, mercury, manganese, and selenium exceeding drinking water standards in some samples. This finding reinforces concerns about the suitability of certain water sources in the area and highlights the importance of assessing different water types to guarantee public health [15]. While mineral water boasted generally low metal levels, concerns arose for other water sources. A study examining 12 bottled water brands (9 domestic, 3 imported) found they met physicochemical quality standards for pH, TDS, and minerals. However, trace metal analysis revealed inconsistencies: labeled values and analyzed values differed for some parameters, and even bottles within the same brand showed variation [16]. Contributing to the growing body of evidence on water quality challenges in Saudi Arabia, a study conducted near Mecca explored well water quality with a focus on food safety. Investigating potential contamination sources and limitations in traditional monitoring methods, the study revealed valuable insights. It found adherence to standards regarding specific water quality parameters but raised concerns about potential food safety impacts on cultivated vegetables due to compromised water sources. Given the region's reliance on scarce freshwater and non-renewable groundwater, the study emphasizes the critical need for improved monitoring strategies to ensure both safe consumption and sustainable agricultural practices [17]. With a few exceptions, the groundwater in Najran Town, Kingdom of Saudi Arabia, is typically suitable for human use, according to a research that examines the quality of the groundwater in the area. The World Health Organization's requirements are compared to the levels of electrical conductivity (EC) and total dissolved solids (TDS) in the groundwater samples. The results of the study have consequences for the local government and people living in Najran town and the surrounding villages [18]. The watery scenery of Najran paints a different picture. Roof tanks are plagued with total coliforms and E. coli, casting a shadow of contamination over well and tanker sources, which appear promising. This confirms earlier worries regarding unsafe storage methods. Roof tanks are still widely used even though 80% of homeowners are aware of the risks associated with water, indicating a knowledge-action gap. This is consistent with differences seen in other areas, necessitating focused education and actions to close the gap and advance safe water management techniques [19]. Adding to the complexities of Najran's water quality, a new study delves into trace elements. While ICP-MS analysis revealed generally safe levels of 16 elements (Ag, Al, etc.) in bottled water and treatment plant samples, concerns emerge for boron and uranium. Three bottled water brands significantly exceeded the national limit for boron, and some samples surpassed the uranium threshold set by Saudi standards [20]. TDS, hardness, and chloride levels in the Wadi Najran basin have been found to be increased in recent studies, above WHO drinking water limits. The study found that although groundwater is not suitable for direct drinking, it can be used for irrigation. [21]. This finding emphasizes how crucial it is to comprehend the unique appropriateness of water in order to safeguard human health and practice responsible resource management in dry areas like Najran . Some of these studies provide valuable insights into the groundwater quality in Najran region and its suitability for different purposes. However, most of these studies focused on specific locations or parameters and did not provide a comprehensive overview of the groundwater quality variations along Wadi Najran. Moreover, some of these studies used outdated or limited data and did not consider the recent changes in land use and water demand in the region. Therefore, there is a need for a more comprehensive and updated study on the groundwater quality along Wadi Najran and its implications for drinking and irrigation purposes. This study aims to fill this gap by investigating the groundwater quality variations along Wadi Najran using a large number of samples and a wide range of parameters. The study also aims to identify the sources and mechanisms of groundwater contamination along Wadi Najran using multivariate statistical analysis and geochemical modeling.

2. Study area

The study area is located in Wadi Najran southern Saudi Arabia. Its geographical coordinates are 17˚30′20′′ North, 44˚11′3′′ East, as shown in Fig. 1. The semi-mountainous region of Najran is situated approximately 980 kilometers from Riyadh, the capital, in the southwest corner of Saudi Arabia. Compared to most of the surrounding desert, Najran has a colder climate due to its average elevation of 1,250 m above sea level. Yemen lies to the south, the rough Assir Mountains to the west, and the vast Rub′ al-Khali desert to the east all encircle the area. Fertile agricultural lands are supported by the Wadi Najran, a vital water source that flows through the region from west to east. Along the wadi lies the majority of Najran's towns and villages. The groundwater of Najran is kept below the wadi in a shallow alluvial aquifer. Rainfall causes seasonal variations in this unconfined aquifer's water table. Historically, irrigation, cooking, and drinking have all been done with water pumped

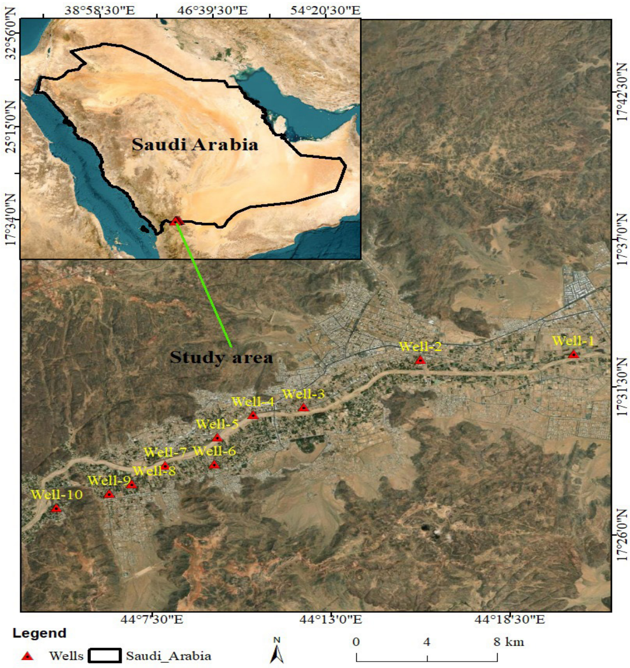

Fig. 1. Location of the study area.

from aquifer wells. In Najran, there is 100 to 200 millimeters of rainfall on average per year. For centuries, Najran has been a significant crossroads due to its unique location and climate. The area's numerous archaeological sites bear witness to its rich history as a major hub of the incense trade. Today, Najran is a well-liked travel destination because of its breathtaking landscape, hospitable locals, and mouthwatering cuisine.

Najran, historically characterized by bountiful groundwater resources, presently faces a critical water scarcity challenge. Decades of rapid population growth and urban expansion have significantly depleted the region's aquifers, rendering vast agricultural fields barren and domestic water supplies vulnerable. This unsustainable consumption transcends demographic pressures, with unrestrained agricultural demands further exacerbating the issue by overexploiting groundwater reserves. The consequence is stark: water quality has deteriorated to unprecedented levels, plagued by a concerning rise in salinity.

Recognizing the urgency of this situation and its crucial implications for human health, this study focuses on evaluating the suitability of well water within the Wadi Najran basin for human consumption. Through meticulous analysis of key water quality parameters and their spatial distribution, this investigation aims to provide critical insights into the potability of this resource. By rigorously characterizing the water quality at various well locations, the study seeks to inform evidence-based water management strategies. This study investigates the water quality of ten operational wells situated along the Wadi Najran basin, extending from west to east (Fig. 1). These wells, established long ago, continue to serve as crucial water sources for the region. Analyzing their water quality is essential for ensuring the health and well-being of the local population who rely on them.

3. Hydrogeological features of wadi Najran basin

The wadi Najran basin acting as a closed shallow basin, its water potential hinges on the remarkable properties of its underlying sediments. The basin's floor is carpeted with alluvial deposits, a treasure trove of sand, gravel, and silt laid down by ancient rivers. These loose sediments boast an exceptionally high transmissivity, meaning water flows through them with remarkable ease, this characteristic plays a crucial role in replenishing the basin's groundwater reserves. Studies have shown that Wadi Najran is a champion of rainwater absorption. A whopping 95% of the total runoff over a 50-km stretch infiltrates the ground, replenishing the precious groundwater. This efficient infiltration translates to an impressive annual recharge of approximately 100 million m^3 (Mm^3) for the wadi system. Estimates suggest that in the early 1980s, Wadi Najran's basin held a staggering 33,350 Mm^3 of stored water.

4. Materials and methods

This study employed a rigorous approach to analyze the water quality of ten wells across the Wadi Najran basin. Groundwater samples were collected from each well using 1-L polyethylene plastic bottles to ensure minimal contamination. Only functioning boreholes were selected to accurately represent the current state of water quality. The number of collected samples were (n = 20) which refers to that (n = 2) samples from each groundwater well. Those 20 samples were divided to half, the first half (n = 10) were used to conduct the physical tests at the site of studied area, where the other ones (n = 10) were taken to the lab for the chemical and microbial test.

The collected samples underwent comprehensive analysis within 12 h at the Najran Water and Sanitation Lab, covering physical, chemical, and microbial parameters. The analysis focused on a range of physical,chemical and microbial parameters which are as follow:

Physical parameters:

pH: Measured using a HANA pH meter (model Hi 8424) to assess acidity/alkalinity.

Turbidity: Measured with a Lovibond turbidity meter to determine the presence of suspended particles.

Temperature: Measured with thermometer instrument.

Electrical conductivity (EC) and total dissolved solids (TDS): determined using a conductivity-TDS-salinity meter (model 850,038) to gauge the overall level of dissolved ionic species.

Chemical parameters:

Cations: Ammonia (NH_3), calcium (Ca) hardness, magnesium (Mg) hardness, and total alkalinity were analyzed using ion chromatography separation technique. Iron (Fe) cation was analyzed using DR5000 spectrophotometer instrument.

Anions: Nitrite (NO_2), nitrate (NO_3), chloride (Cl), sulphate (SO_4) and fluoride (F) were quantified via ion chromatography separation technique.

Microbial parameters:

Membrane filtration technique method was employed for the detection of microbial count, total coliforms and fecal coliforms

By employing standardized instruments and established analytical techniques, this comprehensive approach ensures reliable and accurate data on the physical,chemical and microbial characteristics of the well water in Wadi Najran. This information serves as the foundation for evaluating the water's suitability for various purposes, including drinking, and informing responsible water management strategies for the region

5. Results and discussion

Table 1 presents the average values of all the well water samples collected from the study area for the following parameters: pH, electrical conductivity, total dissolved solids, total hardness, total alkalinity, Fe,Cl, NO_3, SO_4, Mg, Ca, Na, K, Cl, NO_3, SO_4, total microbial count, total coliforms, and fecal coliforms. The World Health Organization (WHO) and Saudi Arabian Standard Organization (SASO) standard values for each of these elements are listed at the final two raws of the same table. It has been demonstrated that all measurements from three groundwater wells fall within the permissible limits. The remaining seven groundwater wells, on the other hand, displayed some variation in terms of high total dissolved solids, electrical conductivity, nitrate, chloride, sulfate, and total hardness.

The quality of the water that people consume has a big impact on their health. The water becomes unsafe to drink and may have negative health effects if the amount of dissolved organic and inorganic elements in it beyond a particular threshold. Based on the effects of a given dissolved matter when consumed in excess or in smaller amounts, the World Health Organization and Saudi Arabian Standard Organization have established a desirable limit and a maximum allowable limit for it in water (WHO 2011, SASO,1994) (Table 1).

Table 1
Physical, chemical and microbial analysis of major elements in samples of groundwater wells collected from Wadi Najran basin

Well No.	TDS (mg/L)	EC (µs/cm)	Turbidity (NTU)	pH	Total alkalinity as $CaCO_3$ (mg/L)	Iron Fe (mg/L)	Chloride Cl (mg/L)	Nitrate NO_3 (mg/L)	Sulfate SO_4 (mg/L)	Mag-nesium hardness (mg/L)	Calcium hardness (mg/L)	Total hardness as $CaCO_3$ (mg/L)	Total bacterial count (CFU/ 100 ml)	Total coliforms (CFU/ 100 ml)	Fecal coliforms (CFU/ 100 ml)
Well-1	1100	750	0.53	8.2	181	0.03	134.3	55.6	192.1	140	539.3	679.3	0	0	0
Well-2	2260	1530	0.39	7.9	197	0.01	421.9	126.9	485.8	291.7	975	1266.7	0	0	0
Well-3	580	390	0.37	8.4	119	0.03	37.6	21.9	81.3	69.6	232.8	302.3	0	0	0
Well-4	710	480	0.41	8.2	151	0.02	83.4	30.1	0	87.5	280.5	368	0	0	0
Well-5	280	190	0.56	8.3	112	0.04	10.5	9.3	29.9	20.8	123.8	144.6	0	0	0
Well-6	360	240	0.48	8.4	123	0.02	13.5	16.8	35.1	34.2	140.8	174.9	0	0	0
Well-7	320	210	0.27	8.3	119	0.05	12	10.4	31.9	27.1	130	157.1	0	0	0
Well-8	1000	680	0.31	8	172	0.01	108.5	50.1	148.3	150.4	446.8	597.2	0	0	0
Well-9	1350	910	0.44	8	189	0.03	170.7	24.8	244.4	200.8	580	780.8	0	0	0
Well-10	1120	760	0.33	7.4	180	0.01	121.3	9.4	185.7	215.4	384.3	599.7	0	0	0
WHO (2011)	Up to 1000	300–750	>5	6.5–8.5	200	>0.3	250	>50	250	150	200	>500	None	None	None
SASO (1994)	100–700		>5	6.5–8.5		>0.3	250	45	250	30	75	300	None	None	None

World Health Organization (WHO) [22]
Saudi Arabian Standard Organization (SASO) [25]

The highest amount of chloride that can be present in drinking water is 1000 mg/L, while 250 mg/L is the desired limit based on WHO and SASO standard specifications. In current study, the Cl content varies between 12 and 421.9 mg/L (Table 1, Fig. 3). With the exception of the water sample taken from the Al-Shurfa location in the northeast of the study area, all of the collected water samples have levels of chloride that are within the allowable limit. This may be due to pollution from fertilizers and septic systems because the well is situated in an agricultural area close to a residential area.

Natural and human activities (geogenic and anthropogenic factors) play a crucial role in shaping the levels of dissolved components in water. Assessing water quality involves comparing these dissolved constituents to established standards, which vary depending on the intended use. Whether for agriculture, industry, or household needs, different water quality parameters are prioritized.

5.1. Evaluation of water quality

The quality of the water that people consume has a big impact on their health. The water becomes unsafe to drink and may have negative health effects if the amount of dissolved organic and inorganic elements in it is beyond a particular threshold.

5.1.1. TDS

Total dissolved solids (TDS) represent the collective mass of inorganic chemical constituents, primarily mineral ions, dissolved in water. This metric is typically expressed in milligrams per liter (mg/L) and represents the sum of major ion concentrations (e.g., calcium, magnesium, potassium, sodium, bicarbonates, chlorides, and sulfates).

Increased TDS concentrations may dramatically affect the physical and sensory characteristics of water. High TDS concentrations are often associated with salty or bitter taste, increased hardness, and potential scaling issues. While the World Health Organization (WHO) has not established a specific health-based guideline for TDS, they acknowledge a noticeable change in palatability exceeding 1000 mg/L. Conversely, extremely low TDS levels can result in a bland taste perception. Water lacking dissolved minerals exhibits an insipid taste [8]. Geological characteristics impacts TDS levels due to varying mineral solubilities in water [22].

Table 1 indicates that higher total dissolved solids (TDS) levels in the study area limit groundwater suitability for drinking purposes. The TDS values of the groundwater samples that were collected ranged from 280 to 2260 mg/L with an average value of 1270 mg/L. Fig. 2 demonstrates that, in accordance with WHO and SASO standard specifications, the recorded values in the samples from around five wells exceed the allowed limits for drinking water. The deep, broad salt layers to the east of the study area are the cause of this high salinity. These salt deposits are found throughout the region at different depths and greatly contribute to the elevated TDS levels in the wells under investigation. They are distinguished by their homogeneity and uniform density with depth [23] .

5.1.2. Electrical conductivity (EC)

A common criterion for dividing between drinking and irrigation waters is EC. The current study's EC values range from 210 to 1530 μs/cm (Table 1). According to WHO standards from 2011, the highest allowable amount of EC is 750 μs/cm. In this study, thirty percent of the samples have higher values. With an EC value of 1530 μs/cm, the water sample taken from the AL-Shurfa location has the highest value. Human health may suffer from higher EC values [24]. High EC values are a result of various geochemical processes, including sulfate reduction, oxidation, silicate weathering, ion exchange, reverse exchange, evaporation, and rock water interac-

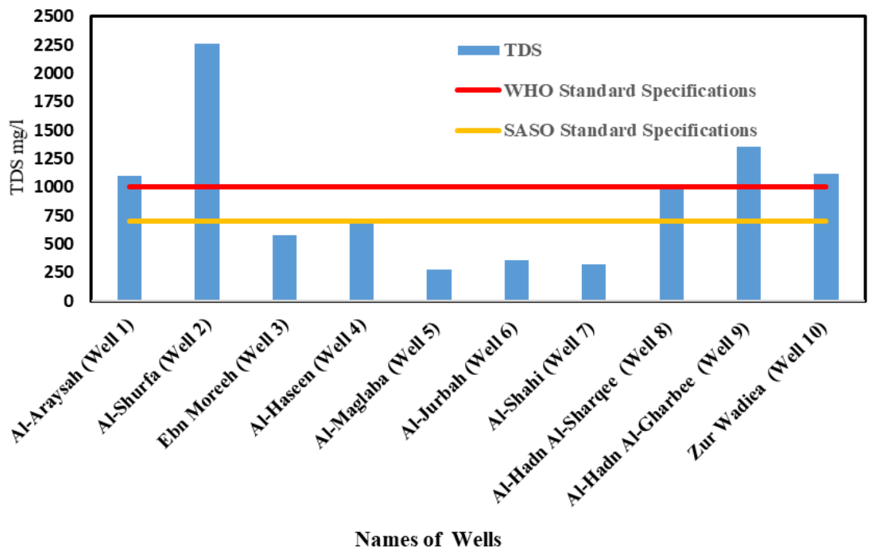

Fig. 2. Total dissolved solids (TDS) in water samples.

tion. High evaporation rates and an arid climate could be the cause of the elevated EC values in this study.

5.1.3. Turbidity

The cloudiness of water caused by suspended particles (such as silts and clay), chemical precipitates (such as iron and manganese), organic particles (such as plant debris), and microorganisms is known as turbidity, and it is measured in nephelometric turbidity units (NTU). Water that is turbid is less aesthetically acceptable to drink. Turbidity can take on a variety of forms and colors, such as muddiness from sediments and soils, reddish-brown iron particles, black manganese particles, and milky-white clay-based particles. Turbidity in clear water is less than 1 NTU, and above 4 NTU, the water turns murky. The research area's turbidity values range from 0.27 to 0.56 NTU. According to this study, all of the wells' groundwater turbidities are within the WHO and SASO-established acceptable ranges.

5.1.4. Predominant level of ions in the study area

The major ion distribution in groundwater provides information on the areas of recharge and discharge, the hydrochemical facies, the primary hydrochemical processes, and the relative groundwater flow rates. The level of important ions and hydrochemical facies were assessed in the current investigation.

5.1.5. Total alkalinity

The alkalinity of surface and groundwater is influenced by their carbonate, bicarbonate, and hydroxide contents. Increased alkalinity increases water's ability to neutralize acids and vice versa. The examined samples have an alkalinity ranging from 112 to 197 mg/L. Every groundwater sample is within the 200 mg/L maximum allowed (WHO 2011). The primary sources of bicarbonate ions in groundwater include silicate and carbonate weathering, as well as recent rainfall recharge.

5.1.6. Iron (Fe)

The concentration of iron in anaerobic groundwater, which is present as iron ions (Fe^{2+} and Fe^{3+}), varies between 0.5 and 10 mg/L and can even exceed 50 mg/L (National Research Council 1979) [26]. The amount of naturally dissolved iron in water rarely rises above 0.3 mg/L, but if iron salts are added to water treatment facilities as coagulating agents, that amount may rise dramatically. Additional sources of increased iron concentration in water include the use of steel, galvanized iron, and cast iron pipes for water distribution. The range of iron concentration in the studied area is 0.01–0.05 mg/L as shown in Table 1.

5.1.7. Chloride (Cl)

The taste threshold of the chloride ion in water is determined by the associated cation. Calcium and sodium chloride in water have a range of taste thresholds between 200 and 300 mg/L. Consumers grow accustomed to levels of chloride exceeding 250 mg/L. There could be an unpleasant taste in groundwater if the amount of Cl in it is more than 200 mg/L. However, there could be negative health consequences on humans if the concentration is more than 250 mg/L. There could be a geological and human component contributing to the high Cl levels in groundwater. High levels of Cl in water can be caused by salty water incursion, reverse ion exchange, or halite breakdown. The usage of inorganic fertilizers, septic tanks, landfill leachates, and industrial waste disposal sites are examples of anthropogenic sources. Another significant source of increased Cl content in water is irrigation return flows. Uncontaminated waters typically have a chloride concentration of less than 1 mg/L and seldom more than 10 mg/L.

5.1.8. Nitrate (NO_3)

Uncontaminated surface water typically has a low nitrate concentration (0–18 mg/L). but irrigation return flows and agricultural runoff can significantly raise the nitrate concentration in groundwater and surface water, respectively. Unintentional releases of industrial waste and sewage effluent can potentially contaminate water with nitrates. Seldom do nitrate levels in uncontaminated water rise over 10 mg/L. The range of nitrate concentrations in the study area is 9.3– 126.9 mg/L (Table 1, Fig. 4). In 30% of the water samples that were obtained, the levels were higher than the allowable limits. Northeast of the research region, at the Al-Shurfa location, were the highest values. Excessive nitrate levels in water can be caused by sewage, landfills, runoff from fertilized soil, and septic tanks.

5.1.9. Sulphate (SO_4)

WHO (2011) and SASO (1994) states that the highest allowable limit of sulfate in groundwater is 250 mg/L. In the current study, the sulfate concentration varies between 0 and 485.8 mg/L (Table 1, Fig. 5). Only one sample taken from the Al-Shurfa location had a Sulphate level higher than permitted. The presence of minerals containing sulfide, the dissolution of gypsum, the use of fertilizers containing sulfate, and industrial wastes are the causes of sulfate in groundwater.

5.1.10. Calcium and magnesium

The maximum amount of calcium that can be present in groundwater, according to WHO (2011) and SASO (1994) is 200 and 75 mg/L as shown in Table 1.

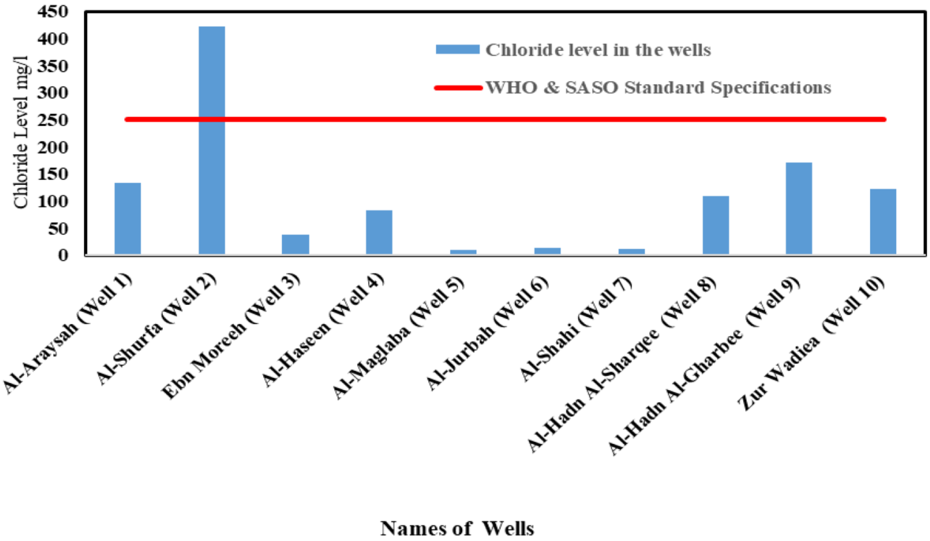

Fig. 3. Chloride concentration in water samples.

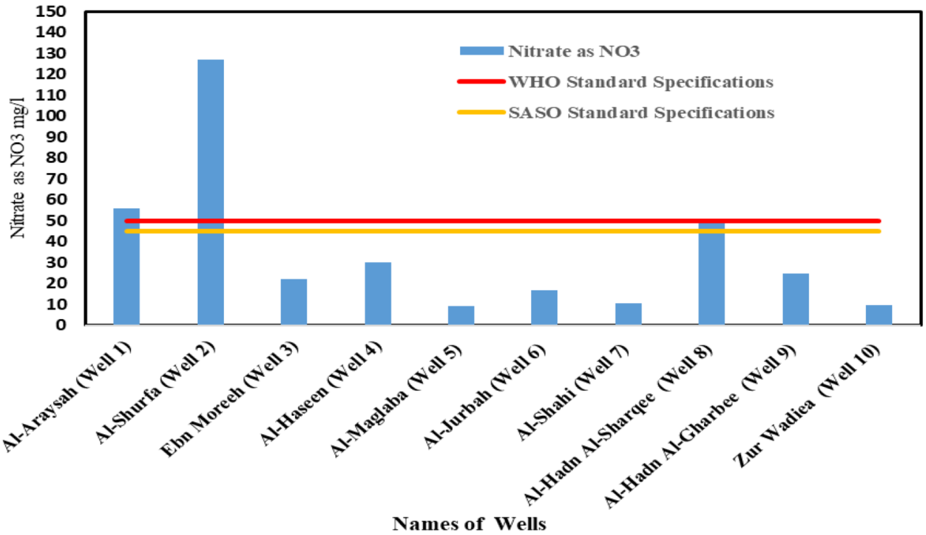

Fig. 4. Nitare concentration in water samples.

The range of the Ca concentration in the groundwater sample was between 123.8 and 580 mg/L. Important sources of calcium include limestone and the carbonate cement found in sandstone. 70% of the wells had Ca concentrations above WHO (2011) criteria, while 100% of the wells had Ca concentrations above SASO (1994) norms. In groundwater, Mg concentrations are often lower than Ca concentrations; this is also the case in the current study. Table 1 shows that the Mg concentrations vary between 20.8 and 291.7 mg/L, with certain samples surpassing the maximum allowable limits for drinking water quality. The primary source of magnesium is found in ferromagnesian minerals found in igneous rocks. According to WHO (2011) and SASO (1994), the highest amount of magnesium that can be found in groundwater are 150 and 30 mg/L respectively. Groundwater with high magnesium concentrations has an unpleasant taste.

5.1.11. Total hardness

The percolating rainfall becomes acidic due to the presence of CO_2 in the atmosphere and the roots of plants. The ability of the percolating acidic water to dissolve insoluble carbonates and other anions, such as sulfates, chlorides, and silicates, increases groundwa-

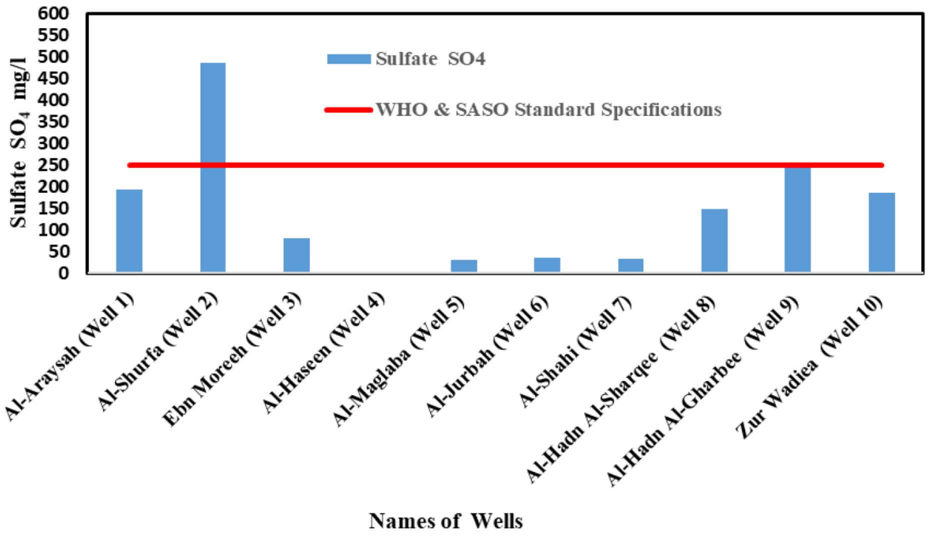

Fig. 5. Sulphate concentration in water samples.

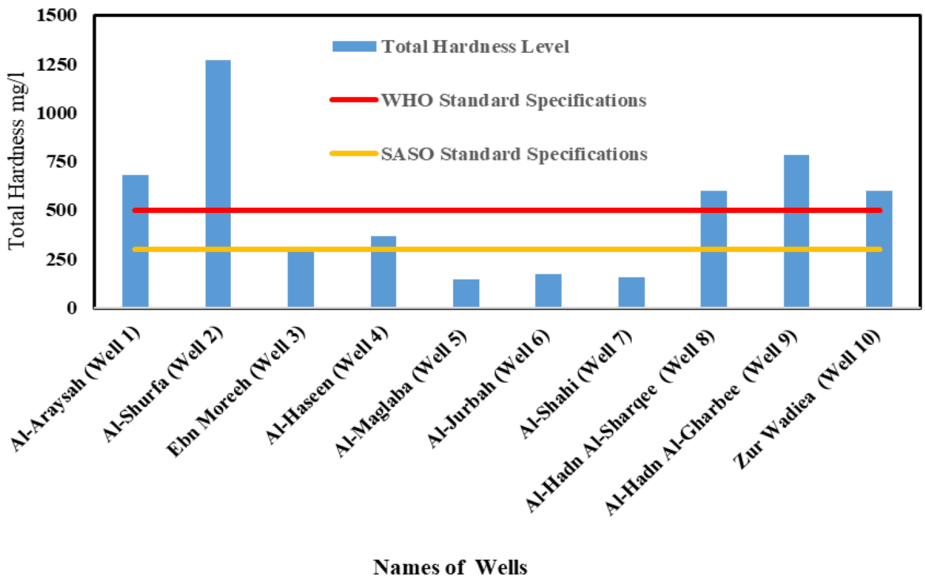

Fig. 6. Total hardness in water samples.

ter's hardness and renders it unfit for use in homes and businesses [27,28]. The presence of calcium and magnesium bicarbonate salts is responsible for the carbonate hardness. The non-carbonate hardness is caused by calcium and magnesium salts other than carbonate and bicarbonate. Salts like $CaSO_4$ and $CaCl_2$ are examples of non-carbonate salts. However, both carbonate and non-carbonate components contribute to the overall hardness of groundwater. Generally speaking, anions associated with calcium account for the majority of groundwater hardness rather than those associated with magnesium, sodium, and potassium. Carbonate hardness is caused by the dissolution of carbonate minerals such as dolomite and calcite. Hardness is defined as the equivalent concentration of issolved calcite ($CaCO_3$) and is a measure of the presence of calcium and magnesium in water.

The water samples used in this study range in total hardness from 144.6 to 1266.7 mg/L (Table 1, Fig. 6). According to Sawyer's classification [29], approximately 60% of the wells under investigation can be classified as extremely hard since the total hardness levels in the groundwater samples that were obtained surpass 300 mg/L.

5.2. Statistical analysis

To gain insights into water quality variations across the Wadi Najran basin, a two-pronged statistical analysis was employed. Firstly, descriptive statistics were calculated to summarize the key characteristics of the measured water quality parameters (Table 2). This initial exploration identified patterns in the data, such as standard deviation and skewness. Subsequently, Pearson's correlation coefficients were utilized to assess the strength and direction of relationships between various water quality parameters (Table 3). This analysis aimed to identify potential co-occurring factors influencing water quality across the sampling locations.

Table 2 presents the descriptive statistics for various water quality parameters analyzed in the water samples collected from 10 operational wells within the Wadi Najran basin. Notably, the table reveals a pattern of relatively high standard deviations (SD) for the concentrations of chloride, nitrate, and sulphate compared to their respective mean values. This indicates considerable variability in the data for these specific ions. Additionally, the table shows positive skewness values for these three parameters, suggesting that the data distribution is skewed to the right. In simpler terms, there's a tendency for more data points to cluster towards the lower end (low concentrations) of the range, with a longer tail extending towards higher concentrations (outliers) for chloride, nitrate, and sulphate.

While the reasons for this variability require further investigation, it's worth noting that one well, specifically the Al-Shurfa well, exhibits significantly higher concentrations of these ions compared to the others. This finding suggests a potential localized source of contamination for these specific parameters. Given the well's location in an agricultural area close to a residential area, possible sources of pollution could include fertilizers used in farming practices or improper wastewater disposal from septic systems.

Following the analysis of descriptive statistics (Table 2), a Pearson's correlation analysis was conducted (Table 3) to explore the relationships between various water quality parameters across the sampling locations. This analysis considered a 5% significance level. The interpretation of correlation values follows a standard range: (1–0.9) very high, (0.89–0.7) high, (0.69–0.5) moderate, (0.49–0.26) weak, and (0.0–0.25) very weak.

Interestingly, Table 3 reveals a pattern of moderate negative correlations between turbidity, pH, and Fe. This suggests that higher turbidity (cloudiness) and iron concentrations tend to coincide with lower pH levels (more acidic water) across the sampling locations. This relationship might be attributed to factors influencing both turbidity and acidity, such as natural organic matter or acidic rain.

On the other hand, a contrasting pattern emerges with strong positive correlations between chloride (Cl), nitrate (NO_3), sulfate (SO_4), magnesium (Mg), and calcium (Ca). These parameters exhibit high to very high positive correlations with most other water quality measurements. This indicates that these elements tend to co-occur in the water samples, potentially due to a common geological source or shared contamination sources. Additionally, a similar trend is observed with total dissolved solids (TDS) exhibiting high to very high positive correlations with most other parameters. This suggests that locations with higher TDS levels also tend to have higher concentrations of other dissolved ions.

These findings provide valuable insights into the potential underlying factors influencing water quality variations within the Wadi Najran basin. The negative correlations between turbidity, pH, and iron warrant further investigation to pinpoint the specific drivers

Table 2
Descriptive statistics of water quality parameters of water samples of the study area

Parameters	Concentration in the water samples of the study area					
	Range	Minimum	Maximum	Mean	SD	Skewness
TDS	1980	280.0	2260.0	908.0	605.6	1.20
Total alkalinity as $CaCO_3$	85	112.0	197.0	154.3	33.3	–0.12
Iron (Fe)	0.04	0.0	0.1	0.0	0.0	0.50
Chloride (Cl)	411.4	10.5	421.9	111.4	123.1	1.99
Nitrate (NO_3)	117.6	9.3	126.9	36.1	38.1	2.01
Sulfate (SO_4)	485.8	0.0	485.8	143.5	146.5	1.50
Magnesium (Mg)	270.9	20.8	291.7	123.8	91.7	0.55
Calcium (Ca)	851.2	123.8	975.0	383.3	266.8	1.22
Total hardness as $CaCO_3$	1122.1	144.6	1266.7	507.1	353.4	1.03

* All values are in mg/L.

Table 3
Pearson correlation matrix for the water quality parameters

	TDS	EC	Turbidity	pH	Total alkalinity	Fe	Cl	NO_3	SO_4	Mg	Ca
TDS											
EC	1.00*										
Turbidity	–0.10	–0.10									
pH	–0.59*	–0.59*	0.35*								
Total alkalinity	0.89*	0.89*	–0.09	–0.71*							
Fe	–0.59*	–0.59*	0.17	0.61*	–0.62*						
Cl	0.98*	0.98*	–0.07	–0.50*	0.80*	–0.54*					
NO_3	0.84*	0.85*	–0.01	–0.19	0.62*	–0.50*	0.90*				
SO_4	0.97*	0.97*	–0.07	–0.54*	0.81*	–0.48*	0.96*	0.87*			
Mg	0.96*	0.96	–0.19	–0.77*	0.93*	–0.66*	0.90*	0.69*	0.92*		
Ca	0.99*	0.99	–0.04	–0.49*	0.88*	–0.53*	0.97*	0.89*	0.96*	0.92*	
Total hardness	1.00*	1.00	–0.08	–0.57*	0.91*	–0.57*	0.97*	0.85*	0.96*	0.96*	1.00*

Note: * Sig. corr. ($p < 0.05$)

behind these relationships. Conversely, the strong positive correlations between other parameters suggest potential common sources, geological or anthropogenic, that merit exploration.

6. Conclusions

The groundwater supplies in the Najran district are the main source of residential and agricultural water for the local people. The present investigation examined the chemical composition and the physical and microbial characteristics of groundwater samples extracted from 10 wells. The study revealed a concerning deviation from established safety standards. Except for three wells that admirably fulfilled the strict requirements set forth by SASO (1994) and WHO (2011), the other wells showed a number of alarming patterns. Three of the wells were found to have excessive quantities of nitrate, which could pose a risk to human health. The problem was made worse when one well (located on Al-Shurfa) had levels of TDS,EC,sulfat,Nitarate chloride and hardness that were higher than allowed, indicating that groundwater in Al-Shurfa well had been excessively contaminated by human activity. Increases in electrical conductivity in three wells and total dissolved solid in six wells were also cited as causes for worry. A surplus of dissolved ions or elevated salinity may be indicated by these trends. This terrifying image is completed by seven wells that are harder than the total hardness threshold making groundwater falls into the hard to extremely hard category and is typically not appropriate for drinking, but it can be used for agricultural and irrigation .

In the eastern and southeast regions of Saudi Arabia, thicker and more massive salt layers are found at varying depths; these events and rock-water interaction are the principal causes of the elevated concentrations of certain anions in groundwater. Overuse of the aquifer could cause the quality of the groundwater in the area to deteriorate, hence periodic monitoring is crucial.

While this study raises public awareness about the local problems with water quality in the wadi Najran basin, more research is necessary to fully evaluate and resolve the issues. It is advised that more in-depth and frequent research be done to determine the precise contamination sources and determine the precise actions or elements influencing the pollution levels in the impacted wells. Its is also necessary to create long-term monitoring systems to monitor changes in the quality of the water and evaluate the success of any treatments that are put into place. Implementing pollution mitigation methods, improving sanitation, and looking into alternate water sources are all critical steps towards protecting the health of Wadi Najran people. We can ensure that the community has access to clean, plentiful water in the future by making thoughtful decisions.

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مؤتمر الخليج الخامس عشر للمياه
The 15th Gulf Water Conference

(2025) 97–106
doi: 10.5004.dsal.2025.700026

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28–30 April 2024, Doha, Qatar

Flood hazard maps generation caused by hypothetical failure of the Tabqa Dam by use of HEC-RAS 2D model

Sadeq Oleiwi Sulaiman

Dams & Water Resources Engineering Department, University of Anbar, Iraq
email: sadeq.sulaiman@uoanbar.edu.iq

ABSTRACT

One of the most devastating natural calamities is flooding. Time of occurrence, mode of spread, and magnitude are all crucial pieces of information to have. Catchments and regions are frequently reported to have been flooded, with tragic results including loss of life, destruction of property, suspension of traffic, loss of power, and suspension of community activities. The height of infrastructure like bridges and levees is based in part on the predicted flood water level; thus, its calculation is essential. The failure of dams occurs from several factors, including what is natural, such as heavy rains in excess of the capacity of the dam reservoir, violent earthquakes that strike the dam area, or a result of human action, such as explosions resulting from wars and defective maintenance of the dam's facilities. This leads to flooding on neighboring properties when water flows out of its channel. Decision-makers can use flood analysis to better foresee and prepare for floods. In this case study, a numerical model was constructed for the Euphrates River to predict how flood waves would flow via the river's channel and floodplains. It is based on a slightly altered version of the full Saint-Venant equations of unsteady flow. The hydrodynamic model was used to look into what would happen if Tabqa Dam failed and how it would affect the Euphrates River's peak flow, peak water level, lag time of peak flow, and lag time of peak water level along the river reach under study. This was done for different values of the Manning roughness coefficient of the floodplain. The study area spanned 575 km from Tabqa Dam to Haditha Dam along the Euphrates River. The HEC-RAS 6.4.1 model in two dimension was applied to the study area to simulate and produce maps showing the latitudinal spread of water, inundation areas, and wave arrival time over most of the major cities along the Euphrates River in the study area. The ability of Haditha Dam to drain the flood wave reaching the dam lake was also simulated.

Keywords: Flood wave; HEC-RAS 2D; Tabqa dam; Haditha dam

1. Introduction

Extreme natural phenomena have been considered among the most dangerous disasters for humans since ancient times. Earthquakes, volcanoes, lightning strikes, hurricanes, droughts, and floods are a danger threatening human societies and require taking all necessary measures to ward them off [1,2]. Floods are considered highly destructive natural disasters because they occur relatively quickly and over a large area [3]. The reason

ISBN 0-86689-078-5

for increasing the scale of human and material losses from floods is that most major cities, residential complexes, and various projects are built on the banks of rivers and waterways [4]. In recent years, the risk of floods has increased significantly as a result of climate change and also as a result of the expansion of the construction of large dams that hold huge quantities of water [5], [6]. The cause of floods is no longer limited to natural phenomena, but rather maintenance errors, inaccurate designs, acts of sabotage, and military operations may become one of the causes of dam collapse and floods. Tracking the flood wave and knowing the time of the wave's arrival, the width of the inundation area, and the height of the flood wave along the course of the rivers downstream of the dams is very important for decision-makers [7]. Having knowledge and accurate forecasting of this issue greatly helps in being prepared and taking the necessary precautions to work quickly to save lives and property when an emergency flood occurs [8]. It has become very necessary to create early warning maps for all areas along the course of the river downstream of the large dams, showing the time of arrival, depth of the flood wave, and width of the inundation area. The process of following the flood wave and knowing its characteristics along the course of the river is complex. This results from the fact that the flow of water in the river is unsteady during a flood, as well as due to the many changes in the roughness coefficient of the main river channel and the floodplain, and also due to the frequent presence of meanders on the way of natural rivers. During floods, due to the high level of the flood wave, some of the flow will take a shorter path due to the presence of meanders in the river's path and along the floodplains, which makes the water move differently within the river channel and across the floodplains, and this increases the complexity of representing the flow.

The HEC RAS 2D model uses the Navier–Stokes equations that describe the movement of fluids in two dimensions (2D). The movement of floods in rivers is modeled by combining mass and momentum conservation equations as shown in Eqs. (1)–(3) [9]. The equations are made simpler by assuming that water has a uniform density, incompressible flow, and hydrostatic pressure.

$$\frac{\partial H}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}+q=0 \qquad (1)$$

$$\frac{\partial u}{\partial t}+\frac{u\partial u}{\partial x}+\frac{v\partial u}{\partial y}=-g\frac{\partial H}{\partial x}+vt\left(\frac{\partial u^2}{\partial x^2}+\frac{\partial u^2}{\partial y^2}\right)-C_f u+fv \qquad (2)$$

$$\frac{\partial v}{\partial t}+\frac{u\partial v}{\partial x}+\frac{v\partial v}{\partial y}=-g\frac{\partial H}{\partial x}+vt\left(\frac{\partial v^2}{\partial x^2}+\frac{\partial v^2}{\partial y^2}\right)-Cfv+fu \qquad (3)$$

where H — elevation of the water surface (L), h — water depth (L), u and v — components of velocity in two dimensions (LT^{-1}), q — source/sink flux (L^2T^{-1}), g — gravity (LT^{-2}), vt — horizontal eddy viscosity coefficient, C_f — bottom friction coefficient, and f — Coriolis parameter (T^{-1}).

It was also assumed that the flow is shallow (SW), meaning that gravity and bed friction are the dominant parameters in the momentum equation, so the momentum equation represents the diffusion wave. When combining the conservation of mass and momentum equations, we produce an equation model known as the wave approximation equations for shallow water (DSW). [9]. Many researchers have conducted studies to simulate flood wave propagation for a large number of dams around the world by using the HEC RAS model. Mhmood et al. and Al-Kazwini et al. [10,11] were used the HEC RAS model to simulate the effect of the flood wave resulting from the hypothetical collapse of the Haditha Dam and estimate the effect of the flood wave on the cities located on the banks of the river. Karim et al. [12] also conducted a study to determine the impact of multiple dam collapses. They were used the HEC RAS 2D model to track the flood wave resulting from the Mosul Dam and determine the extent of the ability of the Makhoul Dam, which is located along the Tigris River behind the Mosul Dam, to absorb and calm the flood wave and release it safely. Many researchers [12–18], have used the Hec Ras 2D model for inundation mapping and to estimate the behavior of flood waves along the river course through the flow simulation process. For most researchers, the results obtained from applying the model were consistent with historical flood data in the study area.

The study's goal is to use a two-dimensional hydrodynamic model (HEC RAS 2D) to follow the flood wave that would happen if the Syrian Tabqa Dam collapsed. The model will be used to find out how fast the wave would arrive, how high it would be, and how wide the area it would cover along the Euphrates River from the Tabqa Dam in Syria to the Haditha Dam in western Iraq.

2. Materials and methods

2.1. Study area

The study area is located in eastern Syria and western Iraq along the Euphrates River in the area between the Tabqa Dam in Syria and the Haditha Dam in Iraq. The distance between the two dams along the Euphrates River is about 575 km, including 370 km in Syria and 205 km inside Iraqi territory [19]. Tabqa Dam, or what is sometimes called the Euphrates Dam, is located in Raqqa Governorate on the Euphrates River in Syria. It is an earthen-type dam that was operated in 1973. The length of the dam is 4500 m, its height is 60 m, its crest elevation is 307 m a.s.l., the width of the base of the dam is 512 m at ground level, and the width of the top of the dam is 19 m at the top. The reservoir formed upstream of the dam is Al-Asad Reservoir. Its length is 80 km, its average width is 8 km, and its surface area is 525 km^2. The maximum storage capacity of the lake is 11.7 billion m^3. Haditha Dam, or what is sometimes called Al-Qadisiya Dam, is located in Anbar Governorate near the city of Haditha in western Iraq. It is an earthen dam that was operated in 1985. Its length is 8700 m, its height is 57 m, its crest elevation is 154 m a.s.l., and the crest width is 20 m. The reservoir formed upstream of the dam is Haditha Reservoir, with a max length at elevation 147 m a.s.l. of 155 km, an average width of about 5.5 km, and a surface area of about 418.4 km^2 at a maximum storage capacity of 8.28 billion m^3 [20] (Fig. 1). These two dams are used to generate electricity, prevent floods, and store water for use in times of scarcity. The study area spanned 575 km from Tabqa Dam to Haditha Dam along the Euphrates River. Large earthen dams, including the Tabqa and Haditha dams, may be exposed to failure or collapse due to natural factors such as earthquakes or heavy rains at the catchments upstream of the dam area or due to military or sabotage actions near the dam area [21]. These two possibilities have been exposed to the areas of the two dams during the recent period.

2.2. Hydrodynamic model generation

To simulate the dam failure and flood routing, hydraulic, geometric, topographical, and land use land cover data must be prepared for the dam under study and also for the study area. Digital elevation models (DEM) of the study area were prepared with a resolution of 12.5 m from NASA Earth science data (https://www.earthdata.nasa.gov/) to meet the topographic and geomorphological characteristics of the river and floodplain. The digital elevation model of the study area was entered into the Hec Ras 6.4.1 model by using the RAS Mapper tool, and the boundaries of the study area were represented between the Haditha and Tabqa dams, as shown in Fig. 2. An image of the land use land cover of the study area was prepared and included in the model through the Ras Mapper tool to determine some of the hydraulic characteristics of the study area. It was used to determine the values of the Manning roughness coefficient of the study area (Fig. 3).

The values of the Manning coefficient were estimated to be 0.028 for the main river channel, and for the areas surrounding the river, the Manning coefficient values were distributed between 0.05 and 0.1 according to the type of land use land cover, such as barren lands, agricultural lands, or residential areas. To calculate the value of the flood hydrograph resulting from the collapse of the dam, the height, length, type of the dam, and size and length of the reservoir upstream of the dam must be known to estimate the shape of the hydrograph. A lot of equations were developed based on the analysis of the failure of real dams. From these equations the Froehlich (2008) equation [22] was used here to find the shape parameters of the collapse opening according to the following equations:

$$B_{\text{avg}} = 0.27\ K_o V_w^{0.32} H_b^{0.04} \tag{4}$$

$$t_f = 0.0176 \left(\frac{V_w}{g \cdot H_b^2} \right)^{0.49} \tag{5}$$

where B_{avg} — average width of the breach (m), K_o — factor equal 1 in the case of overtopping model, V_w — vol-

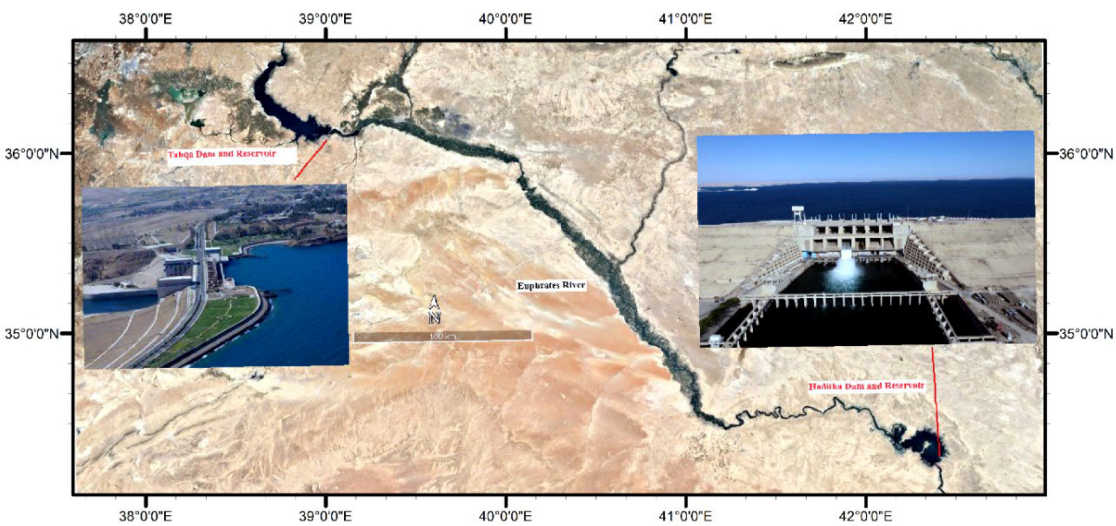

Fig. 1. Location of the study area.

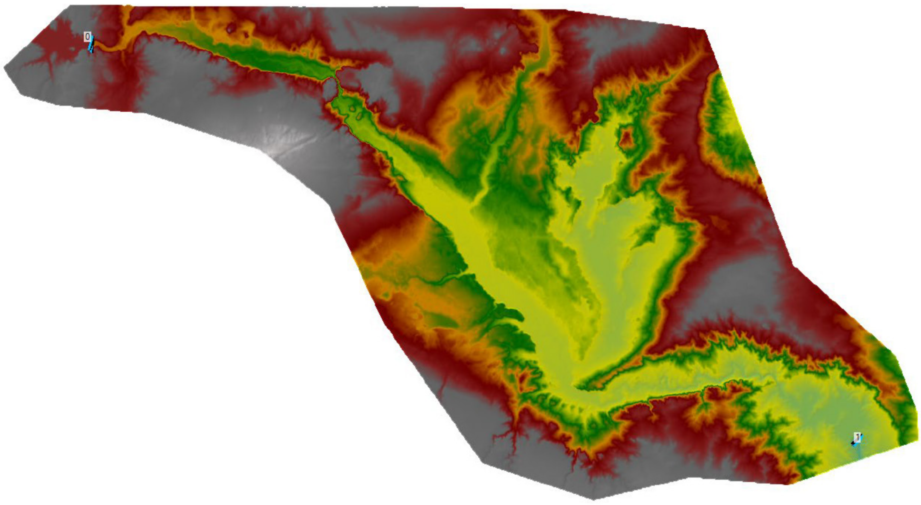

Fig. 2. The digital elevation model of the study area.

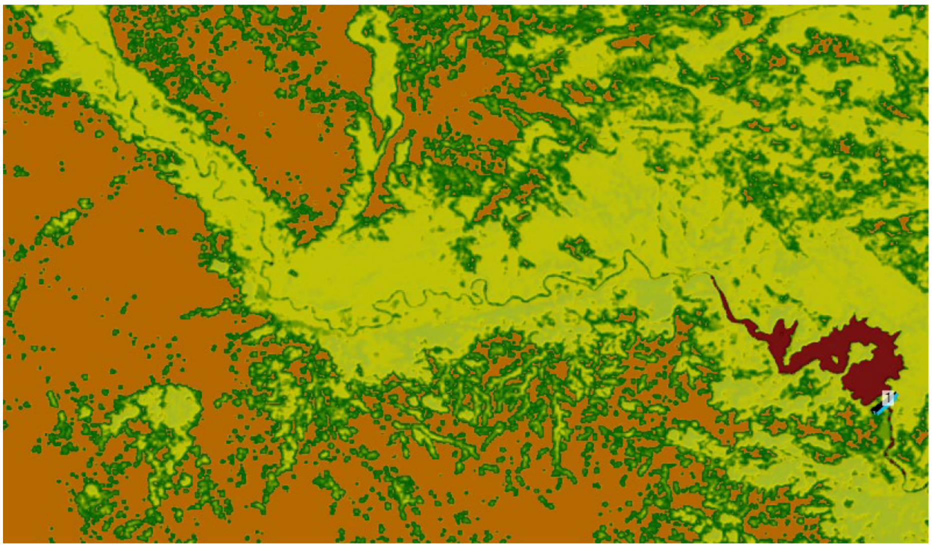

Fig. 3. The land use land cover of the study area.

ume of reservoir (m^3), H_b — vertical distance between crest of the dam and the breach invert (m), t_f — time (h), and g — gravity (m/s^2).

The flood hydrograph of Tabqa dam was calculated based on the collapse breach parameters extracted from the Froehlich equation (2008) using the Hec-Ras model (Fig. 4).

The overtopping failure hydrograph of Tabqa dam was used as an upstream boundary condition for the study area. The rating curve of Haditha dam was used as a downstream boundary condition of the study area, as shown in Fig. 5 [23].

3. Results and discussion

The upstream and downstream boundary conditions of the study area, as well as digital elevation models from Ras Mapper, were used to run the Hec Ras 2D model with an unsteady flow case. We also got hydraulic parameters like the Manning coefficient of roughness from the land use and land cover images. Flood wave tracking data were obtained along the study area. Table 1 shows the flood wave characteristics along the study area that were obtained by the Hec Ras 2D model simulation, such as arrival time, flow velocity, flow depth, elevation, and width of the inundation area of the flood wave for all important areas along the study area.

Three significant cities along the path of flood waves had their flood hazard charts created due to the hypothetical failure of the Tabqa Dam. The Euphrates River water depth, water surface elevation, and flow velocity at AR Raqqa, Deir Ezzor, and Qaim cities were explained from the beginning of the dam failure to the end of the simulation in Figs. 6, 7 and 8.

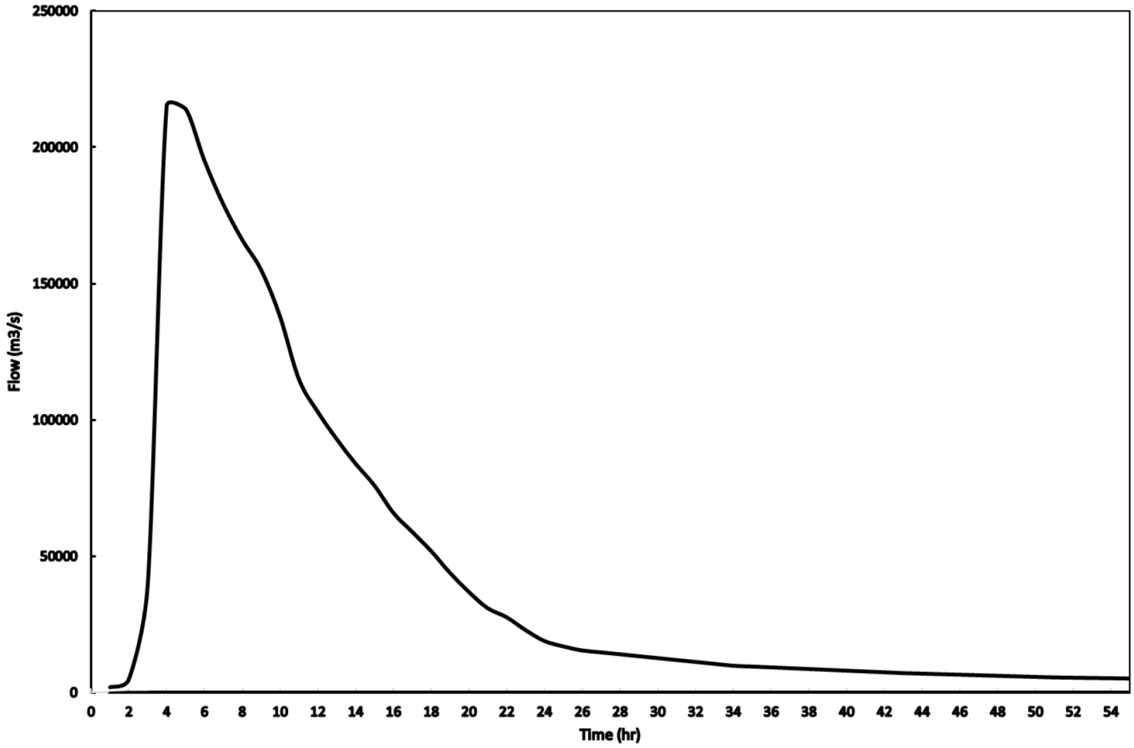

Fig. 4. The flood hydrograph of Tabqa dam due to overtopping failure.

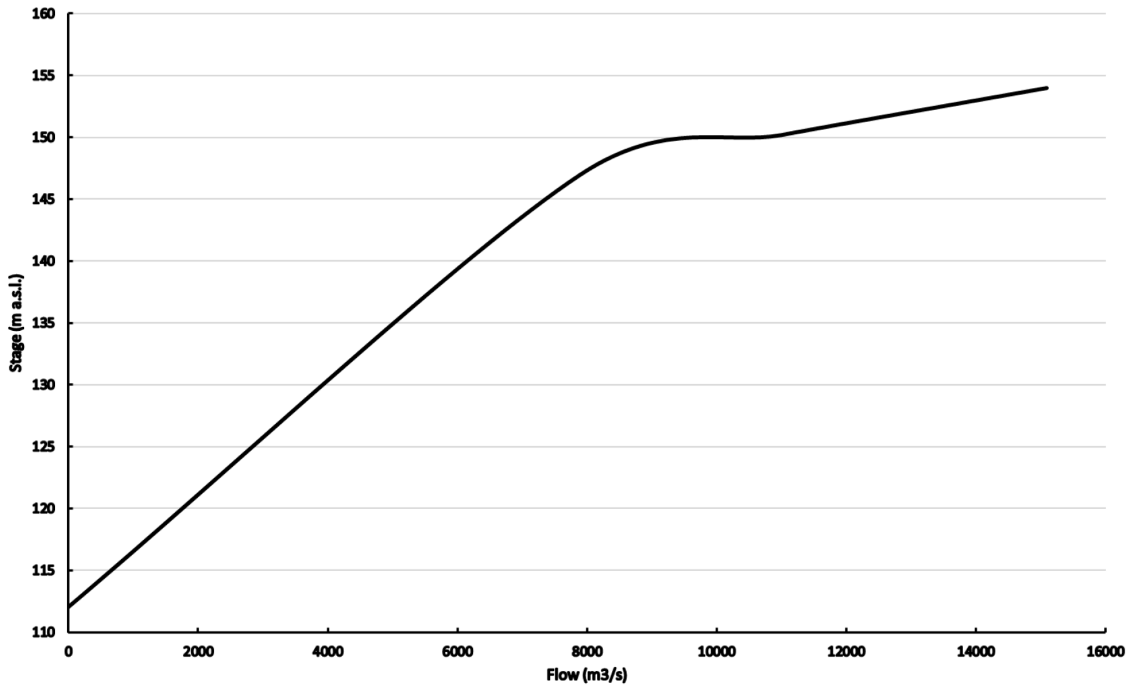

Fig. 5. The stage-flow hydrograph of Haditha Dam.

Table 1
Flood wave characteristics along the study area

City	Distance from Tabqa dam (km)	Time of flood wave arrive after dam breach beginning (h)	Max water surface elevation (m a.s.l.)	Max depth (m)	Max velocity (m/s)	Max width of inundation (km)
Downstream Tabqa dam	1	4:20	284.5	28.4	10.7	3.71
Ar Raqqa	43	6:10	253.2	17.1	3.3	15.8
Deir Ezzor	199	31:50	208.7	8.9	2.3	11.1
Mayadeen	260	48:10	195.1	10.1	2.1	11.4
Sayyal	347	72:50	179.7	10.7	1.2	13.5
Qaim	375	81:20	178.2	11.9	1.7	4.9
Rawa	510	109:40	156.2	18.2	1.9	1.1
Upstream Haditha dam	574	138:1	154 then Haditha dam will collapse at time 151:30	54	0.42	9.5

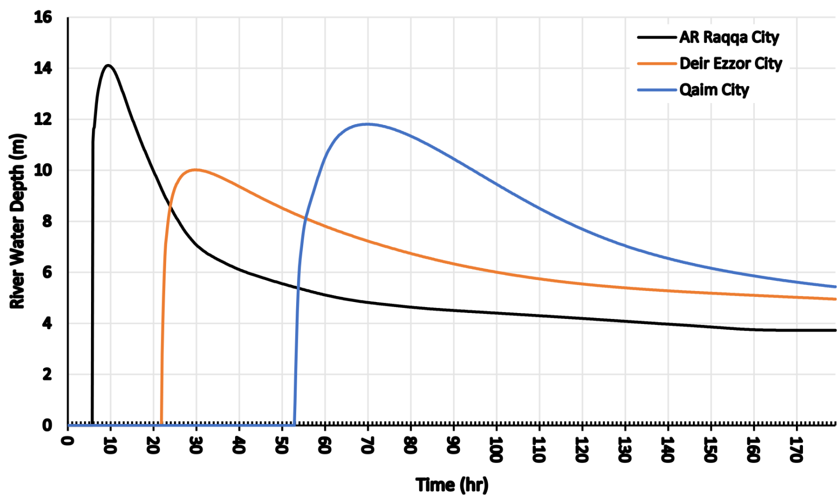

Fig. 6. The Euphrates River water depth at Ar Raqqa, Deir Ezzor, and Qaim cities.

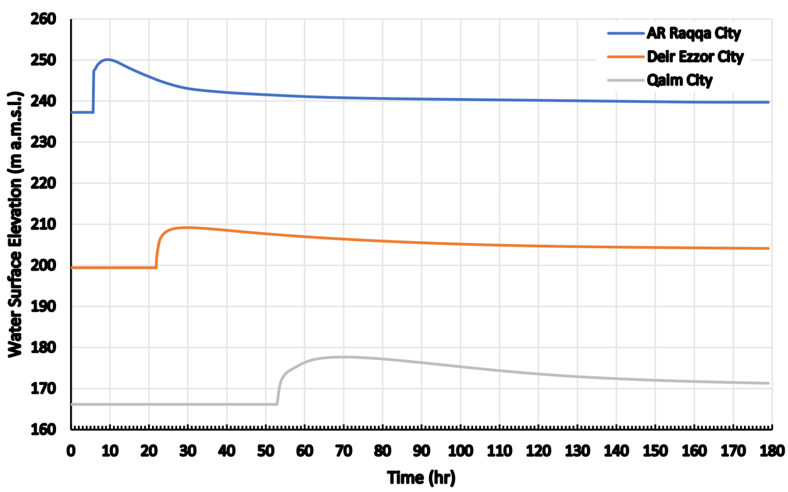

Fig. 7. The Euphrates River water surface elevation at Ar Raqqa, Deir Ezzor, and Qaim cities.

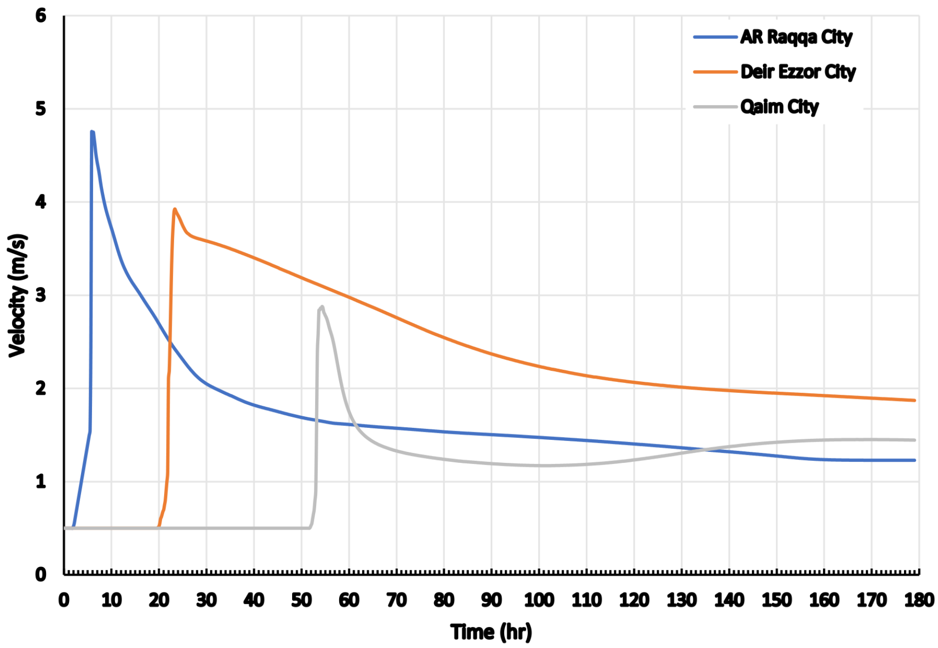

Fig. 8. The Euphrates River flow velocity at Ar Raqqa, Deir Ezzor, and Qaim cities.

Maps were prepared to represent the maximum flood depth, the maximum flow velocity, and the maximum water surface elevation along the study area that extends for 575 km, as shown in Figs. 9–11.

It is clear from the simulation results of tracking the flood wave resulting from the collapse of the Tabqa Dam that the depth of the flood wave begins at a height of 28.4 m and gradually decreases as it moves down the study area due to the dissipation of energy and the decrease in speed as it advances towards the back of the study area. The flow speed also begins with the highest value near Tabqa dam at a rate of 10.7 m/s and then

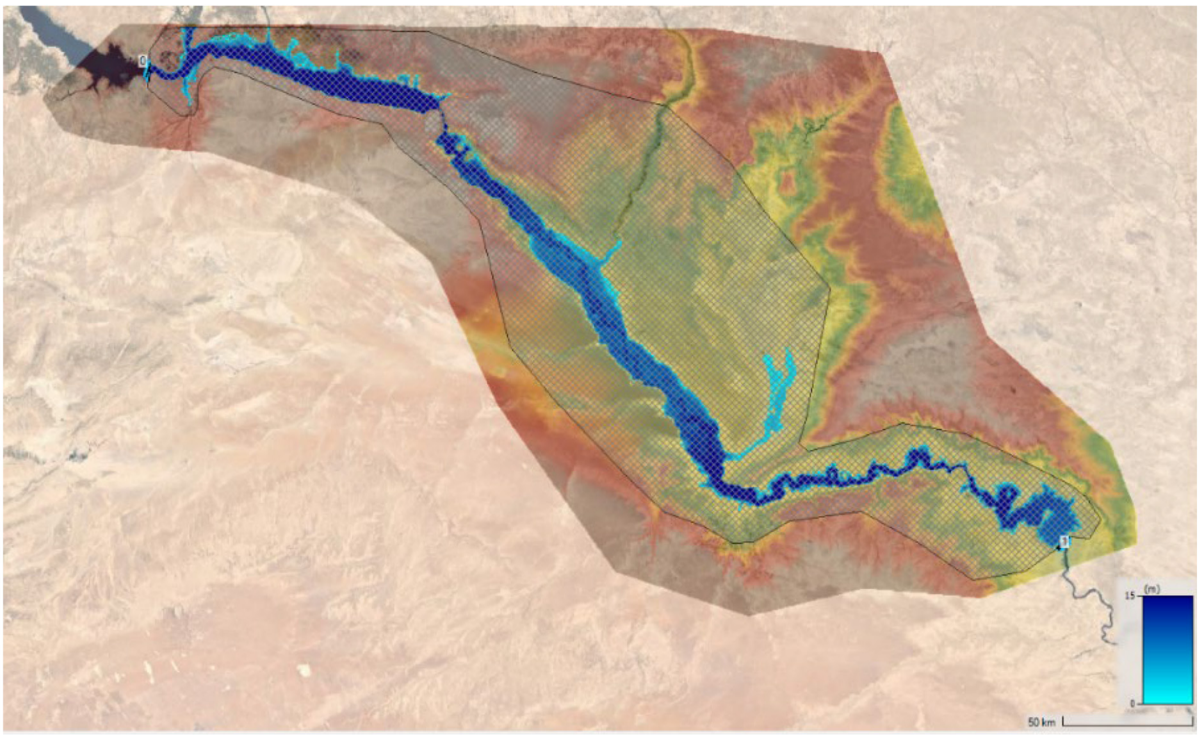

Fig. 9. The maximum flood depth along the study area.

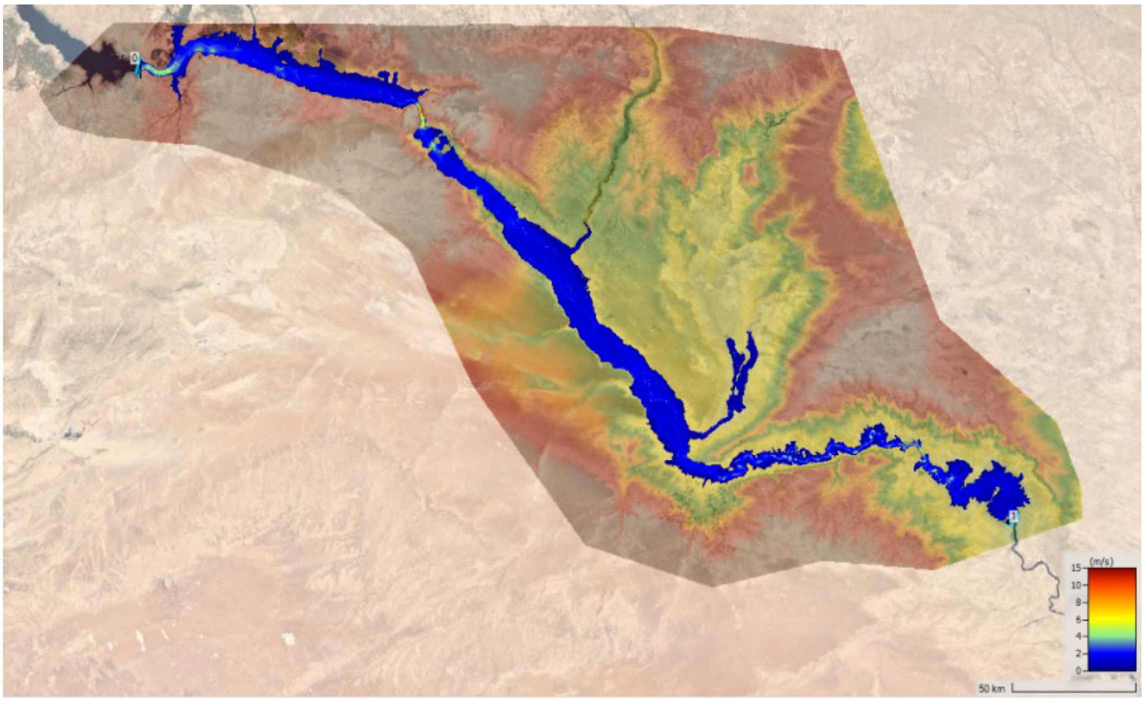

Fig. 10. The maximum flow velocity along the study area.

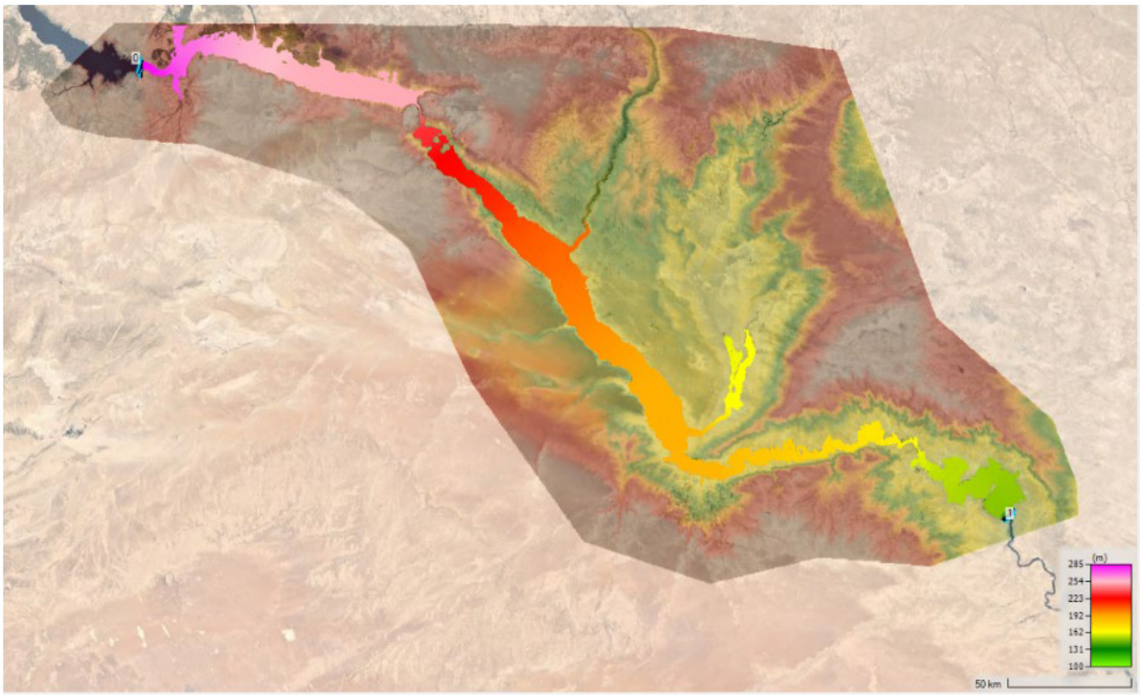

Fig. 11. The maximum water surface elevation along the study area.

decreases gradually, with a sudden increase sometimes at narrowing areas in the river and when the shoulders are high enough to not allow the transverse spread of the flood wave. It is also clear from observing the results that there are areas where the width of the inundation area is limited due to the presence of high terrain on the shoulders of the river, and there are areas that are inundated over long distances, such as the mouths of valleys, especially in the Baghuz depression, where the flood extended over a distance of more than 48 km. By following the flood wave as it enters Haditha reservoir and observing the behavior of the dam with the flood wave. It becomes clear that the wave reaches the dam after 130 h, and the water level in the lake begins to rise rapidly despite the dam's discharge outlets and waterways operating at full speed. The amount of discharge coming into the dam becomes the highest of the dam's discharge capacity, which is estimated at 11×10^3 m^3/s, after which the dam will collapses by overtopping after 151.5 h. from the beginning of Tabqa Dam breach.

Conclusions

A two-dimensional hydrodynamic model called HEC-RAS 2D was used to simulate the flood wave that would happen if the Tabqa Dam in Syria failed. The model then tracked the flood wave through the Euphrates River in the study area and found out how much damage it did to the Haditha Dam in Iraq and how well it could handle it.

1. The results of the study showed that there are risks related to the submergence of a large number of cities, villages, and important facilities on both sides of the Euphrates River in both Syria and Iraq along the study area.
2. Maps were prepared of the areas vulnerable to inundation, the time of arrival of the flood wave, and its depth to adopt precautionary measures in construction, evacuation work, and civil defense methods, and to create early warning methods, depending on the expected danger category of the site.
3. The results showed that Haditha reservoir absorbed a large portion of the flood wave, with the dam operating at full capacity to drain the next flood wave, but due to the large size of the wave, the lake level exceeded the top of the dam, leading to the failure of the dam at 151.5 hours after the collapse of the Tabqa Dam.

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(2025) 107–118
doi: 10.5004.dsal.2025.700029

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28–30 April 2024, Doha, Qatar

Groundwater aquifers susceptibility index of waterborne diseases outbreaks (ASIWD) in Nile Delta, Egypt

Osama M. Sallam[a], Karim Soliman[b]*

[a]Research Institute for Groundwater, National Water Research Centre, Cairo, Egypt, email: sallamosama@hotmail.com
[b]Water Resources Research Institute, National Water Research Centre, Cairo, Egypt, email: karim_soliman@nwrc.gov.eg

ABSTRACT

The Corona pandemic and its significant economic and social effects, as well as the large spread of parasites, motivated us to conduct this research to develop a map of the sensitivity of groundwater pollution to waterborne pathogens. This study aims to create an index for evaluating groundwater aquifers' susceptibility to waterborne diseases outbreaks risks. During this study, groundwater Aquifer Susceptibility Index to Waterborne Disease outbreaks (ASIWD) was developed by appending a new attribute designated as waterborne diseases parameters such as urbanization, population density, water drains density, and existing sewage treatment systems. The study area covers eight governorates in Egypt, Menoufia, Beheira, Kafr El-Sheikh, Sharqia, Daqahlia, Qalyubia, Gharbia, and Damietta. By analyzing the ability of the aquifer to transmit infection for waterborne diseases, the main conclusions are: (i) In Qalyubia governorate, the percentage of the area is exposed to very high risks reaches more than 90% of the total area, while in Menoufia, Gharbia, Dakahlia, and Sharqia, it reaches 51%, 48%, 18%, and 17% respectively. (ii) the area is exposed to very high risks reaching 32%, 24%, 32%, and 32% of the total area in the governorates of Menoufia, Beheira, Gharbia, and Dakahlia, respectively. (iii) the area is exposed to medium risks representing 32%, 24%, 32%, and 32% of the area of Damietta, Sharkia, and Beheira governorates, respectively, and (iv) the area is exposed to Low to very low risks, reaches 98%, 55%, and 44% of the total area of Kafr El-Sheikh, Dakahlia and Beheira governorates respectively. ASIWD approved the importance of including anthropogenic parameters in susceptibility computations and its reliability as an effective tool for investigating groundwater aquifer susceptibility to waterborne disease outbreaks in Egypt's Nile Delta study area. Groundwater in the study is in hydraulic connection with surface water from Nile River branches, irrigation canals, and drainage networks; therefore, maintaining groundwater quality requires an integrated approach for both ground and surface water.so, it is recommended to improve the irrigation system and prevent the continuous drainage of sewage and wastewater to the canals and the drainage system. Sewage treatment services must be developed and concentrated in very high-risk governorates such as Qalyubia, Menoufia, and Gharbia. Also, highly recommended to make public awareness about the threats of pollution on groundwater resources, especially in susceptible areas.

Keywords: Nile delta; Groundwater; Aquifers; Susceptibility index; Waterborne diseases

*Corresponding author

ISBN 0-86689-078-5

1. Introduction

The primary source of microbiological contamination in groundwater is mainly sewage water from humans or animals. Sewage includes a large variety of pathogens that may be present in pathogenic bacteria, viruses, and protozoa, this contaminant can represent a potentially severe threat to public health if they are present in the used water supply. Microbiological pollutants may enter the groundwater aquifers by septic tanks, leaking sewage, digging sinks, or landfills. The groundwater movement and pollution degree will be subject to loads of waste liquid and groundwater exposure to surface-derived pollution. (Briffett, 1996).

Egyptian Ministry of Health and Population surveillance diseases data system provides data about notifiable communicable to identify trends in the incidence of the diseases by governorate, season, age, and sex. From 2006 to 2013, composite risk-index scores ranked the 27 Egyptian governorates into three groups: high, medium, and low risk. The 15 diseases with the highest incidence were food and waterborne diseases (5 diseases), vaccine-preventable diseases (7 diseases), and others, e.g., hepatitis C infection (Abdel-Razik et al., 2017).

Abdel-Razik et al. (2017) has assigned a composite index score for the risk status of infectious diseases. The lowest risk governorates had a 28–42% (5 governorates), and the medium-risk governorates had composite risk index scores between 42% and 56% (11 governorates). The high-risk governorates had 57% and 71% (11 governorates). Fig. 1 shows the Egyptian governorates ranked according to the magnitude of the incidence of the 15 diseases for 2006–2013 and their composite risk index scores.

Barbosa et al. (2022) comment that 'Poor sanitation conditions, water scarcity, hyper-dense dwellings, crowded household, lack of health care access, among other factors, make urban slums and other vulnerable communities major COVID-9 hotspots and relevant areas for application of wastewater surveillance.' He used their wastewater surveillance program to assess trends in SARS-CoV-2-RNA in four vulnerable urban communities (informal settlements and low-income neighborhoods) in metropolitan Sao Paulo. They were able to positively correlate new cases of COVID-19 with N1 viral loads from the two largest communities. In Hungary, Róka et al. (2022) demonstrated wastewater surveillance as an efficient tool in tracing emerging SARS-CoV-2 variants of concern, with sewage data closely correlated with the clinical emergence of some cases. In Austria, Daleiden et al. (2022) report wastewater monitoring program initiated by health authorities in Tyrol province and show how wastewater Surveillance provided value as an early warning system; provided independent confirmation of temporal trends in COVID-19 prevalence; enabled the assessment of the effectiveness of measures.

Previous studies on the movement of microbiological pollutants in the groundwater aquifer environment were more commonly associated with groundwater contamination incidents and, to a lesser degree, with investigative surveys. Both studies concentrated on bacteriological and viral contamination to a lesser degree. Nyanganji et al. (2011) evaluated Groundwater quality and related waterborne diseases in Dass town, Bauchi state, Nigeria. They found E-coli, Calcium carbonate, and Manganese concentrations exceeded the safe standards by274%, 1035%, and 600%, respectively. E-coli CFU decreased with well depth and distance from pit latrines. They stated that the cases of waterborne diseases in the town are due to the excessive concentrations of these parameters.

Hossain et al. (2020) assessed the groundwater quality and health risk of Setabganj sugar mills limited, Dinajpur, Bangladesh. They investigated the contamination level in the groundwater surrounding the study area, particularly the associated health risk of the dwellers residing there. They confirmed more groundwater

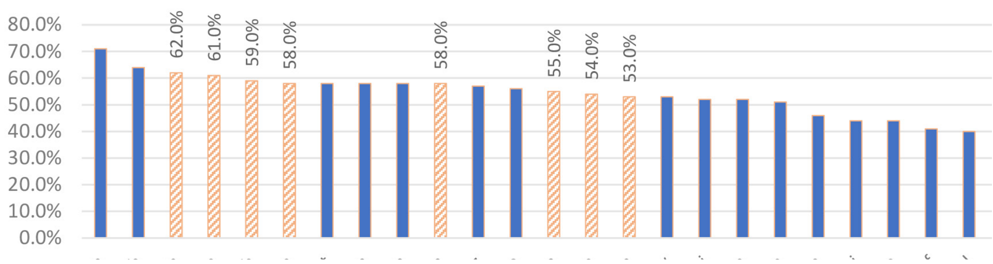


Fig. 1. The Egyptian governorates ranked according to the magnitude of the incidence of the 15 diseases for 2006–2013 and their composite risk index scores. The orange color mentions to Nile Delta Governorates (Data sources: Madiha, et al., 2017).

contamination in the vicinity of the sugar mill. They stated that Health risk assessment ensures that infants and children are significantly susceptible to the contaminated groundwater all over the study area. At the same time, the adults are at high risk only in the sugar mill region. Rezig et al. (2021) evaluated the origin and consequences of groundwater pollution risks in the part of Bouira, the North center of Algeria, where the region of Bouira has seen waterborne diseases occurrence caused by groundwater pollution. They considered the area a high risk because it has recorded many Toxic-food collectives, Viral Hepatitis A, typhoid fever, and Choléra cases in 2018. they found a solid relationship between diseases and the irrigated areas. Hamadieha et al. (2021) systematically reviewed the relative concentrations of noroviruses and fecal indicator bacteria in wastewater for quantitative microbial risk assessment. Hegazy et al. (2018) studied the impacts of human and agricultural activities on the groundwater quality in the Mostored area, Abu Zabel, East Nile Delta, Egypt. They stated that the groundwater quantity and quality in the study area are highly affected by agricultural, industrial, and urbanization activities. Also, they reported high concentrations of the total coliform count vary from 2 to 43 CFU/100 ml, indicating a potential mixing between the domestic sewage and returned irrigation water to the groundwater system.

1.2. Objective and methodology

The main aim of this study is to develop an index for evaluating groundwater aquifers' susceptibility waterborne diseases outbreaks risks in Nile Delta, Egypt. The main goals to be achieved during this study are:

- Develop groundwater Aquifer Susceptibility Index to Waterborne Disease outbreaks (ASIWD)
- Developing ASIWD by appending a new attribute designated as waterborne diseases parameters such as urbanization, population density, water drains density, and existing sewage treatment systems.
- The developed index ASWID is applied in the Nile Delta governorates in Egypt, which are classified as the most dramatic waterborne diseases outbreaks. (Abdel-Razik et al., 2017)
- Validate ASIWD parameters that affect waterborne diseases.
- Classification of the aquifer in the study area according to its sensitivity to the transmission of waterborne diseases.

2. Materials and methods

2.1. Study area

The study area covers the governorates of Menoufia, Gharbia, Beheira, Kafr El-Sheikh, Sharqia, Daqahlia, Qalyubia, and Damietta. The Mediterranean Sea bounds it in the north, Port Said and Ismailiya governorates in the east, and Alexandria, Giza, and Cairo governorates in the west and south. Fig. 2 shows the study area location map.

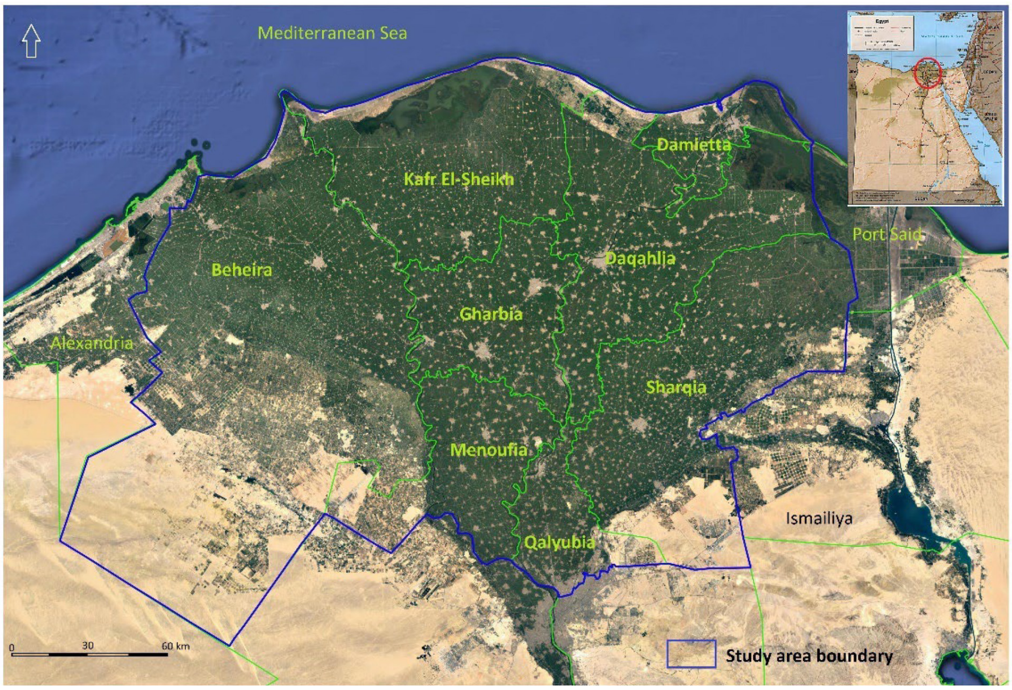


Fig. 2. Study area location map.

2.2. Groundwater aquifer characteristics

The principal aquifer in the study is the quaternary Nile Delta aquifer which is considered a semi-confined aquifer with a thickness that varies from 1000 m in the northern parts to reach less than 200 m in the southern regions, and the depth of the groundwater ranges from 1–2 m in the north, 5 m in the south while reaching more than 50 m in the southwestern and southeastern parts of the study area. (Dahab, 1993). The groundwater levels range from 0 m in the north to 5 m above mean sea level in the south while reaching more than 40 m above mean sea level in the southwestern and southeastern parts of the study area.

The primary aquifer is formed by Quaternary deposits, which transformed into a large reservoir due to the hydraulic connections among these deposits supplied directly by the Nile water through the canals and drains networks and extensive irrigation, especially in the southern part of the study area. (Abdel Maged, 1994). The Quaternary aquifer in the study area is covered by a clay layer, which varies from 5–20 m in the south and the middle part and reaches more than 50 m in the north. The clay layer disappears in the southeastern and southwestern parts of the study area. (Diab et al., 1997). Groundwater aquifer in the study area is characterized by spatially varying hydraulic conductivity for different locations and layers which ranges from 28.7 m/d in the northern parts to more than 82 m/d in the southern regions (Wolf, 1987; Arlt, 1995), while Sherif et al. (2012) used a vertical hydraulic conductivity about 0.67 m/d in the study area.

Average rainfall in the study area is minimal and ranges from 25 mm/y in the south and the middle part of the study area to 200 mm/y in the north (RIGW, 1992). Another significant influence on the recharge of the primary aquifer comes from the water levels in the irrigation canals and drains. The percolation rate ranges between 0.25 and 0.8 mm/d in the central and southern part of the study area, depending on the type of soil and irrigation and drainage practices. In the west of the study area, dominant percolation rates range from 1.0 to 1.5 mm/d for furrow irrigation. (Warner, 1991). In the eastern parts of the study area, the percolation rates ranged between 0.2 mm/d and 5 mm/d in the large reclamation projects due to the subsurface drainage that prevailed (Leaven, 1991).

2.3 Groundwater vulnerability indexes

Currently, groundwater vulnerability assessment has become a valuable tool to mitigate groundwater pollution, where groundwater vulnerability maps provide essential data to protect groundwater resources, manage available water resources, and protect the general health of groundwater users. Several researchers have recognized two different types of factors that affect the susceptibility of groundwater to pollution, the internal hydrogeological factors of the aquifer and the external factors, by adding features that determine the potential human impact. The most widely used method for groundwater vulnerability assessment is the DRASTIC index, which facilitates computation with minimal data requirements (Aller, 1985). The most commonly used groundwater vulnerability assessment method, DRASTIC, is a parametric system method developed by Aller et al. (1987). It was applied in many countries such as Sweden (Rosen, 1994), the United States (Rupert, 2001), South Africa (Lynch et al.,1997), and South Korea (Kim and Hamm, 1999). In recent years, various vulnerability assessment methods for groundwater have been developed with different approaches. Various classic vulnerability methods are available such as GOD and AVI; empirical vulnerability methods, such as DRASTIC, SINTACS, and SI, are based on overlay and indexing techniques, depending on the type of aquifer, the type

Table 1
Groundwater vulnerability index main methods (Stigter et al., 2006)

Index	Parameters	References
DRASTIC	Depth to water (*D*), Net recharge (*R*), Aquifer media (*A*), Soil media (*S*), Topography (*T*), Impact of the vadose zone (*I*), and Hydraulic conductivity (*C*)	Aller et al., 1987
SINTACS	Was created for vulnerability assessments and mapping in medium and large-scale maps, and the multiplier weights of regular string were used	Civita, 1994
AVI	This index measures groundwater vulnerability based on two physical parameters: the thickness (*d*) of each sedimentary layer above the saturated aquifer surface and the second is the estimated hydraulic conductivity (*K*) of each of these sedimentary layers.	Van Stempvoort et al., 1993
GOD	Classical system for quick assessment of the aquifer vulnerability to pollution. Three main parameters are groundwater occurrence, lithology of the overlying layers, and depth to groundwater.	Foster, 1987
SI	Depth to water (*D*), Net recharge (*R*), Aquifer media (*A*), Topography (*T*) and Land use (*LU*)	Ribeiro, 2000

of contaminations, and data availability. (Rizka, 2018). Table 1 shows the groundwater vulnerability index main methods.

DRASTIC has good accuracy and is more effectively used in detailed environmental studies. The Susceptibility Index (SI) is an adaptation of the DRASTIC method and was developed to evaluate aquifer vulnerability to diffuse agricultural pollution; and it is recommended for the future because the risk is effectively represented. SINTACS method generates very high vulnerability zones in the areas concerned with surface waters and aquifer interactions. GOD method was relatively close to DRASTIC and can be used in areas with limited information. A comparison of the vulnerability methods can be used to estimate their efficiency for the vulnerability of any study area. (Rizka, 2018).

2.4. Aquifers susceptibility index of waterborne diseases (asiwd)

Developing ASIWD is based on two concepts: (i) the hydrogeological setting, which is defined as a composite description of all the major geologic, hydrologic factors that affect and control the groundwater movement into, throughout, and out of the area, and (ii) the anthropogenic influence parameters which concerned with actions that help or limit the transmission of waterborne diseases. So, in the ASWID model, the parameters have been categorized into two groups as follows:

- The first group concerns the parameters that significantly affect the pollutant's arrival and movements to the groundwater, which are depth of groundwater (D), rate of recharge (R), type of aquifer medium (A), and aquifer hydraulic conductivity (C).
- The second group of parameters that effects infection transmission such as water drains density (DD), population density (PD), urbanization factor (UF), and sewage treatment systems (STS) which is represented by the extent of coverage of the area with sanitation services.

2.4.1. ASIWD parameters weights

Each ASIWD parameter is evaluated concerning the others to determine the relative importance of each and is then assigned a relative weight, ranging from 1 to 5. The most significant parameters are given a weight of 5, while the least effective receive a weight of 1. Table 2 shows the developed ASWID relative weights parameters and comparison with the standard methods DRASTIC, DRASTIC pesticide, and SI. The developed ASIWD index for any area is computed using the following equation:

$$\mathrm{ASIWD}_{index} = D_W + R_W + A_W + C_W + DD_W + UF_W + \mathrm{STS}_W + PD_W \quad (1)$$

The ASIWD index analyzes factors affecting groundwater contamination. It combines hydrogeological parameters like aquifer depth and permeability with anthropogenic parameters like population density and wastewater treatment quality. Each parameter is assigned a weight based on expert opinion and statistical analysis to reflect its influence on contamination risk.

2.4.2. ASIWD parameters ranging and rating

Table 3 shows the ratings of ASIWD index parameters, the purpose of the ASWID index implies multiplying each factor's weight by its category rating, where rating (*r*) reflects the significance of classes and weight (*w*) designates the importance of the parameter, as follows:

$$\mathrm{ASIWD}_{index} = (D_r \times D_w) + (R_r \times R_w) + (A_r \times A_r) + (C_r \times C_w) + (STS_r \times STS_w) + (DD_r \times DD_w) + (PD_r \times PD_w) + (UF_r \times UF_w) \quad (2)$$

The final ASIWD index produces a relative measure of the aquifer's susceptibility to waterborne diseases. Higher ASIWD index values indicate areas more susceptible to waterborne diseases than low susceptible index areas.

Table 2
Definition and weights of the developed ASIWD modified after Stigter et al. (2006)

Letter	Meaning	DRASTIC weight	DRASTIC pesticide weight	SI weight	ASIWD weight
D	Depth to water	5	5	0.186	5
R	Net recharge	4	4	0.212	4
A	Aquifer media	3	3	0.259	3
C	Hydraulic conductivity	3	2	—	3
STS	Sewage treatment systems	—	—		5
DD	Drains density	—	—	—	4
PD	Population density				3
UF	Urbanization factor				2

Table 3
Ratings of ASIWD index parameters

Hydrogeological parameters				Anthropogenic influence parameters			
Parameter	Weight	Range	Rating	Parameter	Weight	Range	ASIWD rating
Depth to groundwater (D) (m) (Aller et al. 1987)	5	0.0–1.53	10	Sewage treatment systems (STS) (Yes/No) (created and validated by the author)	5	Fully wastewater treatment	0
		>1.53-4.58	9			No wastewater treatment	10
		>4.58–9.15	7				
		>9.15–15.25	5				
		>15.25–22.8	3				
		>22.8–30.5	2				
		>30.5	1				
Recharge rate (R) (mm) (Aller et al. 1987)	4	<50	1	Drains density (DD) (km/km^2) (created and validated by the author)	4	Low density	6
		50–100	3			Medium density	7
		>100–150	6			Very high density	9
		>150–300	8				
		>300	9				
Aquifer media (A) (m)	3	>30	0	Population density (PD) (capita/km^2) (created and validated by the author)	3	<500	1
		>10–30	2			500–1000	2
		>5–10	4			>1000–2000	3
		>0–5	6			>2000–3000	4
		0	10			>3000–4000	5
						>4000–5000	6
						>5000–10000	8
						>10000	10
Hydraulic conductivity (C) (m/d)	3	28.7–41	4	Urbanization (UF) % (created and validated by the author)	2	>80–100%	2
		>41–82	6			>60–80%	4
		>82	8			>40–60%	6
						>20–40%	8
						0–20%	10

2.4.3. ASIWD sensitivity analysis

The final index of ASIWD is based on four hydrogeological parameters (D, R, A, and C) and four anthropogenic parameters (STS, DD, PD, and UF), which map the intrinsic aquifers susceptibility index of waterborne diseases outbreaks in the study area. There are two methods to analyze the ASWID sensitivity as follows:

a) *Map removal sensitivity analysis* test identifies groundwater susceptibility by removing one of the hydrological parameters from the susceptibility map. The map removal sensitivity analysis is computed from Eq. (3) (Lodwick et al., 1990).

$$S = \left| \left(V / N \right) - \left(v / n \right) \right| x \left(100 / V \right) \tag{3}$$

where *S* is the sensitivity measure expressed in terms of variation index; *V* and *v* are the unperturbed and the perturbed susceptibility indices, respectively; and *N* and *n* are the numbers of data layers used for *V* and *v* computing.

b) *Single parameter sensitivity analysis* was proposed by Napolitano and Fabbri (1996) to evaluate the impact of each parameter on the susceptibility index. Napolitano and Fabbri (1996) derived Eq. (4) to determine the effective weight of each parameter.

$$W = 100\left(P_r P_w \right) / V \tag{4}$$

where W is the effective weight of each hydrological parameter, P_r and P_w are each parameter's rating value and weight, and *V* is the overall vulnerability index.

3. Results and discussion

3.1. ASIWD parameters of the study area

In the present study, the developed ASIWD method is used for evaluating groundwater Susceptibility to pollution. The acronym ASIWD corresponds to two main groups of parameters, the initials of the eight parameters that drive aquifers' susceptibility to waterborne diseases

3.1.1. Hydrogeological parameters layers

Hydrogeological parameters consist of four layers as follows:

– *Depth to groundwater (D)* is considered one of the most critical factors affecting pollutant access from the ground surface to the groundwater table because there is a greater chance for the attenuation process of the pollutant to occur with the increase in the depth of the groundwater due to longer travel times (Aller et al., 1987) (Fig. 3a).

– *Net recharge rate (R)* represents the water that penetrates from the ground surface through the unsaturated zone and reaches the groundwater table. Available recharge water can transport waterborne disease vertically to the water table and horizontally through the aquifer (Aller et al., 1987). Groundwater recharge rates in any region depend on numerous factors, including precipitation, rock permeability, water table depth, type of soil and moisture conditions, slope, wind speed, and temperature. (Fig. 3b).

– *Aquifer media (A)*: the thickness and lithological differences of the clay layer significantly affect the degree of hydraulic connection between the groundwater and surface water (Abdel Maged,1994.) Pollutant attenuation results from physicochemical retention or interaction of pollutants and includes the processes of decomposition, absorption, filtration, and sedimentation. (Fig. 3c).

– *Hydraulic conductivity (C)* represents the capacity of the aquifer materials to transmit the water and control the groundwater flow and the contaminant transport in the aquifer (Aller et al., 1987). Areas with higher hydraulic conductivities are more vulnerable to groundwater pollution and are assigned higher ratings, while areas with lower hydraulic conductivity are assigned lower ratings. (Fig. 3d).

Using GIS, ASIWD hydrogeological parameters Layers have been ranged and categorized in the study area as shown in Fig. 3 and Table 4

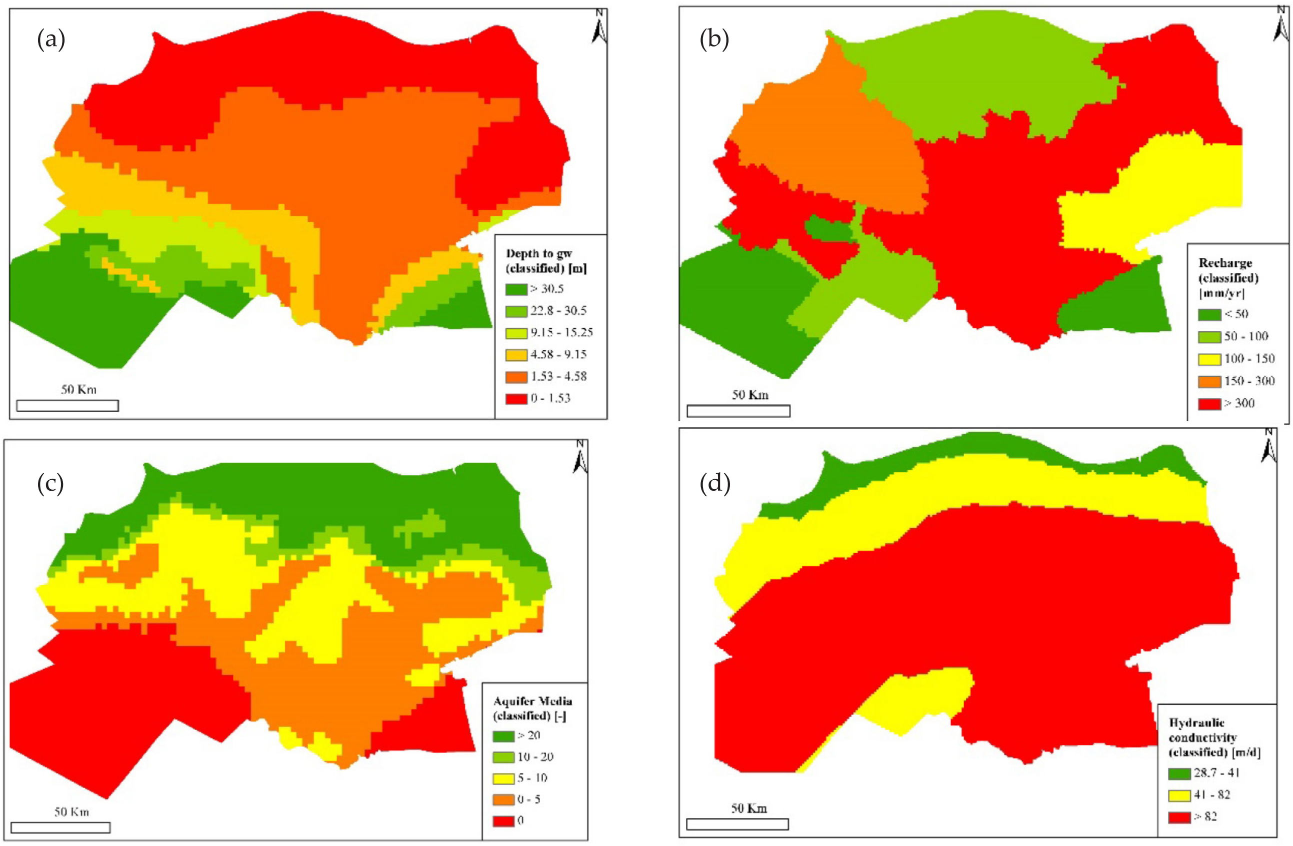


Fig. 3. ASIWD hydrogeological parameters layers. (a) Depth to groundwater (m). Data source Mursy (2009), Dahab (1993), and Armanuos et al. (2016); (b) Net recharge rate (mm). Data source: Farid (1985), RIGW (1992a), Masterson et al. (2007), and Armanuos et al. (2016); (c) Aquifer media (m). Data source: Elewa and Nahry (2009), CONOCO, Co. (1987) Diab et al. (1997), Dahab (1993), and Armanuos et al. (2016); (d) Hydraulic conductivity m/d. Data source: Wolf (1987), Arlt (1995), Sherif et al. (2012), Mursy (2009), and Armanuos et al. (2016).

Table 4
Range's percentages for the ADIWS hydrogeological parameters in the study area

Depth to groundwater		Net recharge rate		Aquifer media		Hydraulic conductivity	
(m)	Area (%)	(mm)	Area (%)	(m)	Area (%)		Area (%)
>30.5	12.7	<50	13.90	0	21.55	28.7–41	6.6
22.8–30.5	5	50–100	23.24	0–5	6.02	4–82	23.0
15.25–22.8	5.5	100–150	9.68	5–10	22.01	>82	70.4
4.58–9.15	10.7	150–300	13.80	10–20	26.15		
1.53–4.58	37.0	>300	39.36	>20	24.26		
0–1.53	29.0						

3.1.2 Anthropogenic parameters layers

Anthropogenic parameters consist of four layers as follows:

– *Sewage treatment systems (STS)*: in developing countries, most cities discharge 80–90% of their untreated sewage directly into rivers, and streams, then reach groundwater, which is used for drinking, bathing, and washing. This lack of sewage treatment has allowed dangerous microorganisms to spread, posing one of the greatest threats to human health (Tibbetts, 2000). The sewage treatment systems are a decisive factor in groundwater pollution with waterborne diseases (Fig. 4a).
– *Drains density (DD)*: there is a direct relationship between the arrival of pollution from agricultural drains and sewage drains to the underground reservoir; therefore, this criterion was developed to calculate the density of drains at the level of each center of the study area governorates. The drains

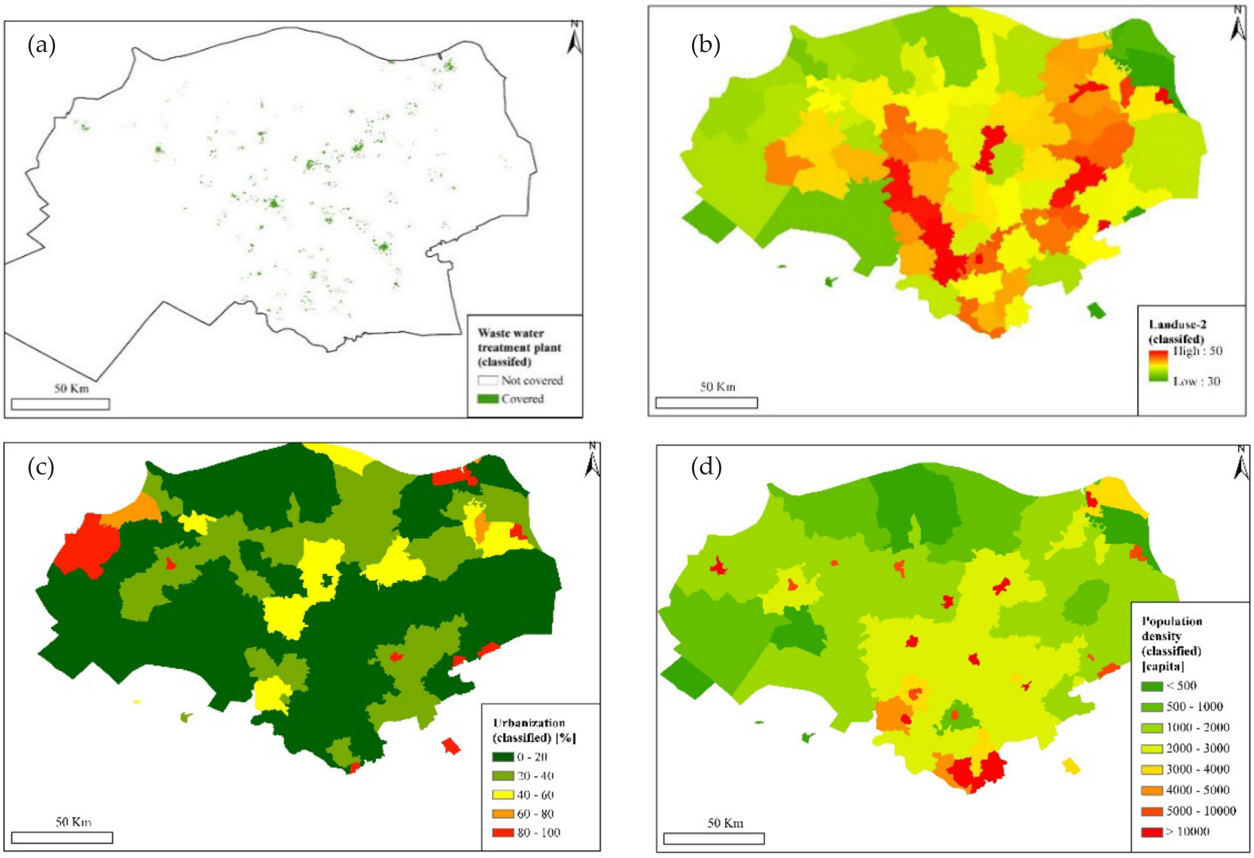


Fig. 4. ASIWD anthropogenic parameters layers. Data source Capmas2021 (a) Sewage treatment system; (b) Drains density; (c) Urbanization factor; (d) Population density.

Table 5
Range's percentages for the ADIWS anthropogenic parameters in the study area

Sewage treatment systems		Drains density		Urbanization factor		Population density	
Covered area	(%)	(km/km^2)	(%)	(%)	(%)	(capita/km^2)	(%)
Not covered	98	Low	34.4	80–100	3.60	<500	9.33
Covered	2	Medium	65.32	60–80	1.28	500–1000	18.70
		High dense	0.3	40–60	8.42	1000–2000	40.11
				20–40	24.87	2000–3000	25.16
				0–20	61.82	>3000	6.65

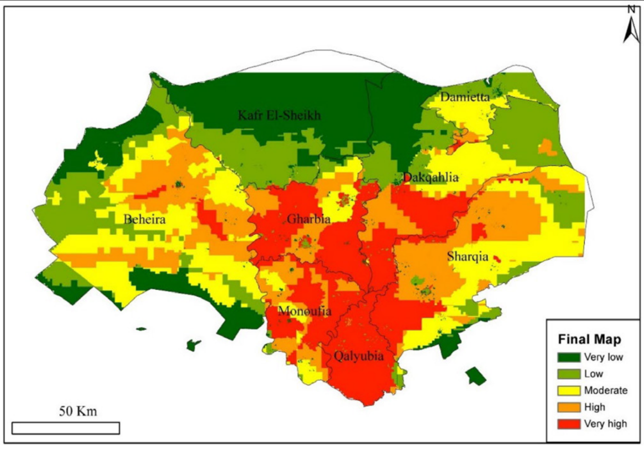
density is equal to the result of dividing the lengths of the drains in linear kilometers inside the center by the area of the center in km^2 (Fig. 4b).

- *Population density (PD)* is a crucial factor in groundwater pollution with waterborne diseases where dangerous practices are increasing, such as the disposal of waste into water bodies or septic tanks. population density is calculated by dividing the population by the total area at the level of governorates centers in the study area, which is an essential indicator of the transmission of waterborne diseases through groundwater (Fig. 4c).
- *Urbanization factor (UF)* is a crucial factor in groundwater pollution with waterborne diseases; the higher the urbanization, the lower the water pollution with waterborne diseases where dangerous practices decrease, such as the disposal of waste into water bodies or the use of septic tanks. The percentage of urbanization factor is calculated by dividing the population into urban areas by the total population at the level of governorates centers in the study area. (Fig. 4d).

Using GIS, ASIWD anthropogenic parameters Layers have been ranged and categorized in the study area as shown in Fig. 4 and Table 5.

3.2. ASIWD index of the study area

Fig. 5 presents maps of the groundwater aquifer's susceptibility index of waterborne diseases outbreaks (ASIWD), where groundwater aquifer in the study area has been classified into five categories according to its susceptibility to waterborne diseases. The study area, in general, is divided into five sectors in terms of the sensitivity of the aquifer and the possibility of transmitting waterborne diseases. The southern region ranges from high to very high due to the shallowness of the mud layer and the proximity of groundwater to the surface of the earth, in addition to the increase in population densities and the spread of the network of drains, while the eastern and western regions range from low to medium. Fig. 5 shows that the very low areas represent 19.8% of the total study area, while the low areas are 19.9%. The medium areas represent 21.7%, the high susceptible areas represent 19.5%, and the very high areas represent 19.1% of the study area. It is also noted that the areas served by sewage treatment systems have very low sensitivity.



ASIWD index	Area (%)	ASIWD index	Area (%)
Very low	19.80	High	19.5
Low	19.9	Very high	19.1
Moderate	21.7		

Fig. 5. Groundwater aquifer's susceptibility index of waterborne diseases outbreaks (ASIWD) in the study area.

3.3. ASIWD sensitivity analysis

Using map removal sensitivity analysis, the clay layer is observed to be the most significant input of the ASIWD 20%, followed by depth to water level 12% for hydrogeological parameters. The sewage treatment system layer is observed to be the most influential input 16% for anthropogenic parameters layers, followed by drains density at 11%. Using the map removal method in the ASIWD model, the highest sensitivity index is observed upon removal of the impact of the clay layer, followed by the Sewage treatment system layer, depth to water level, and drain density

Hegazy D al et. (2018) stated that the groundwater quantity and quality in the Qalyubia area are highly affected by urbanization activities. Also, they reported high concentrations of the total coliform count vary from 2 to 43 CFU/100 ml, indicating a potential mixing between the domestic sewage and returned irrigation water to the groundwater system; this proves the study analysis and results.

4. Conclusion and recommendation

The study area covers eight governorates, Menoufia, Beheira, Kafr El-Sheikh, Sharqia, Daqahlia, Qalyubia, Gharbia, and Damietta. By analyzing the ability of the aquifer to transmit infection for waterborne diseases, the main conclusions are: (i) in Qalyubia governorate, the percentage of the area is exposed to very high risks reaches more than 90% of the total area, while in Menoufia, Gharbia, Dakahlia, and Sharqia, it reaches 51%, 48%, 18%, and 17% respectively, (ii) the areas is exposed to very high risks reaches 32%, 24%, 32%, and 32% of the total area in of the governorates of Menoufia, Beheira, Gharbia, and Dakahlia, respectively. (iii) the area is exposed to medium risks representing 32%, 24%, 32%, and 32% of the area of Damietta, Sharkia, and Beheira governorates, respectively, and (iv) the area is exposed to Low to very low risks, reaches 98%, 55%, and 44% of the total area of Kafr El-Sheikh, Dakahlia and Beheira governorates respectively. Fig. 6 shows ASIWD index classification of each governorate and its percentage.

The current study assessed groundwater susceptibility to waterborne disease outbreaks in the Nile Delta based on hydrogeological and anthropogenic parameters. ASIWD approved the importance of including anthropogenic parameters in susceptibility computations and its reliability as an effective tool for investigating the groundwater aquifer susceptibility to waterborne diseases outbreaks in the study area in Nile Delta, Egypt.

Groundwater in the study area is in hydraulic connection with surface water from Nile River branches, irrigation canals, and drainage networks; therefore, maintaining groundwater quality requires an integrated approach for both ground and surface water. So, it is recommended to improve the irrigation system and prevent the continuous drainage of sewage and wastewater to the canals and the drainage system.

The sewage treatment services must be developed and concentrated in high-risk governorates such as Qalyubia, Menoufia, and Gharbia. Also, highly recommended to make public awareness about the threats of pollution on groundwater resources, especially in vulnerable areas. Considering the demonstrable public health significance of the concurrent impacts of groundwater susceptibility, strategies to increase awareness about potential sources of contamination and motivate precautionary behavior are necessary. Mainstreaming climate adaptation concerns into planning policies will also be required to reduce human exposure to waterborne sources of enteric infection.

The ASIWD framework can be applied in other regions, but adjustments are needed. Local hydrogeology and dominant human activities will influence which parameters are most important and how they are weighted. Data availability is also crucial. Researchers may need to find alternative data sources if local data is limited. By considering these factors, the ASIWD index can be a valuable tool for managing groundwater worldwide.

The ASIWD index is a valuable tool for assessing groundwater vulnerability to contamination in the GCC region. For instance, in the Al Ain groundwater basin (UAE), the ASIWD index can consider factors like aquifer depth, agricultural practices, and wastewater treatment to identify areas at risk. This information can then be used to guide interventions like sustainable irrigation or improved sanitation.

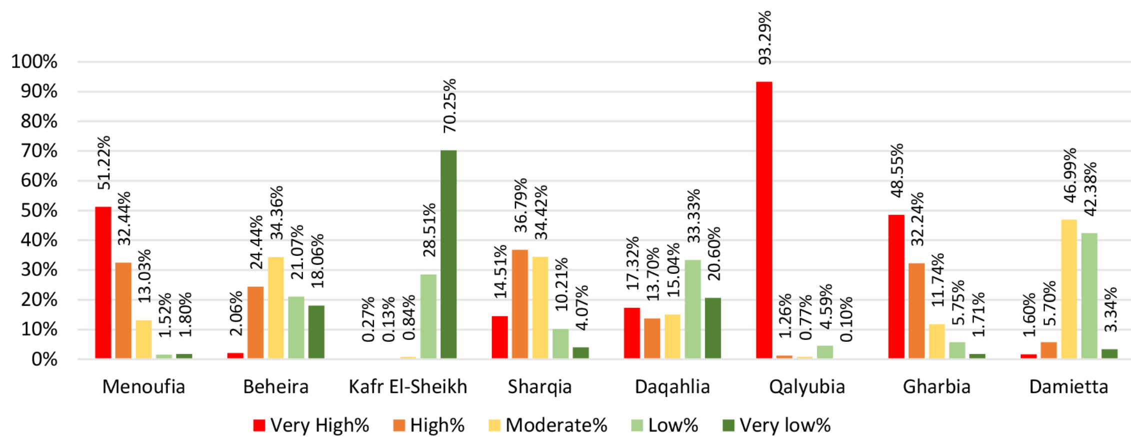


Fig. 6. ASIWD index classification of each governorate and its percentage.

Data limitations such as: data availability, quality, and resolution can affect accuracy. To improve future assessments, researchers can collaborate with stakeholders to collect more data, standardize data collection methods, and integrate high-resolution geospatial data. Long-term monitoring programs would also be beneficial. By addressing these limitations, the ASIWD index can become even more reliable for informing water management decisions and protecting public health.

Poverty, land use, and education all influence water quality. The ASIWD index could be improved by including data on these factors. This would allow policymakers to target high-risk areas with better sanitation, sustainable agriculture practices, and educational campaigns.

Based on this study results, policymakers should target high-risk areas with stricter regulations and better irrigation practices. Public awareness campaigns are also important. Collaboration across sectors and stakeholder engagement are crucial for success.

The current ASIWD index focuses on traditional waterborne pathogens. Future research could expand the scope to include emerging contaminants such as pharmaceutical residues and microplastics. Investigating how these contaminants impact the spread of waterborne diseases and incorporating them into the index would provide a more comprehensive picture.

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(2025) 119–132
doi: 10.5004.dsal.2025.700040

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28–30 April 2024, Doha, Qatar

Assessing the hydrological and hydraulic behaviour of an arid catchment which determines flood impacts in the Dhofar governorate, Oman

Manal A. Al Balushi[1]*, Joseph Holden[1], Mark A. Trigg[2]

[1]*School of Geography, University of Leeds, Leeds, LS2 9JT, UK, *email: gymaha@leeds.ac.uk*
[2]*School of Civil Engineering, University of Leeds, Leeds, UK*

ABSTRACT

Oman has experienced several major recent flood events, most of them considered as deadly flash floods. The Dhofar governorate has been at the brunt of such floods, most recently in 2018 and 2020. This study seeks to identify appropriate flood risk mitigation measures by understanding the hydrological processes operating in the Darbat catchment in the region. We utilize hydrological and hydraulic models to simulate previous floods events in 2002, 2018 and 2020. The predictions from the coupled hydrological and hydraulic models provide good results as validated by multiple evidence sources including remote sensing, local community surveys and data from regional agencies. Scenario modelling can now be used to indicate key areas of the landscape that could be modified to reduce flood risk downstream under different intensities of rainfall – these scenarios could include grazing management, large flood dams, and the potential use of more cost-effective small temporary wadi dams.

Keywords: Flood modelling; Ephemeral streams; Arid; Dhofar; Flash floods

1. Introduction

In most arid and semi-arid environments with ephemeral catchments, the largest floods occur when there is heavy rainfall over a few days. River discharge levels rise rapidly, and floodplain inundation can occur extremely quickly via flash flooding. Thus, severe floods in arid zones have often caused fatalities and significant financial losses (Elfeki et al., 2017; Sakai and Yao, 2023; Subyani, 2011) While flood studies have predominantly concentrated on temperate and humid climate zones, arid and semi-arid regions have received comparatively less attention. In these water-scarce environments, hydrological research has traditionally centred around water resources management (Sumi et al., 2022). Nevertheless, the scarcity of water and the infrequency of rainfall, recent floods in dry and semi-arid regions have shown that flooding can be catastrophic. The management of flood risk presents particular difficulties for these areas, which call both thorough comprehension and practical answers (Nabinejad and Schüttrumpf, 2023).

In most countries with drylands environment, there is insufficient data on rainfall and discharge in the majority of catchments. Furthermore, it can be difficult to rely on some of the available data for research because they are often of low quality (Ikirri et al., 2022). As a result, that is creates significant challenges for use of hydrological and hydraulic modelling in flood research which is a crucial approach to propose effective methods

*Corresponding author

ISBN 0-86689-078-5

to mitigate flood risk (Pilgrim et al., 1988; Rogger et al., 2012; Tegos et al., 2023). There are general similarities between drylands and humid regions in terms of hydrology response to rainfall. For example, various sub-catchments will react differently to rainfall due to their distinct catchment characteristics, affecting both the volume and rate of runoff (Pattison et al., 2014). Still, other factors should be taken into account when modelling the flood in arid regions like the soil type, shortage of vegetation cover, and the absence of the baseflow (Al-Qurashi et al., 2008; Camarasa-Belmonte, 2016; McIntyre et al., 2007). Studying the behaviour of ephemeral catchments is required to expand the knowledge on the main triggers of dangerous floods in arid and semi-arid regions. Such improved understanding will help when seeking practical flood mitigation or adaptation techniques (Nouh, 2006). Effective flood modelling could enhance the decisions and strategies used to reduce the destructive effects of floods in key populated catchments or where there is important infrastructure to be protected (El-Hames and Richards, 1994).

In Oman, floods are the most common natural hazard, though little research has been done on flood hydrology and hydraulic modelling (Al-Manji et al., 2021; Saber et al., 2022) notably in the Dhofar governorate. Based on observed patterns since 1950 for an increase of 0.5°C or higher, the Intergovernmental Panel on Climate Change (IPCC) indicated in its sixth assessment report that there was a medium confidence on the increase in precipitation linked with tropical storms (Seneviratne et al., 2021). Since Oman is subject to tropical cyclones this puts the region at higher risk of future floods (Galvin, 2008).

The main aim of this study is to identify the core data elements which can be used via modelling to enable estimation of the flood extent, depth and velocity in an arid catchment in Dhofar governorate. To achieve this aim, a coupled hydrology-hydraulic modelling approach is utilized for three extreme events (2002, 2018 and 2020) in Darbat catchment in the south of the Dhofar governorate (Fig. 3). A range of different sources of data and tools were employed for validation under the circumstances of unreliable gauged discharge data. The outputs of this study can be tested in different catchments with similar environments. Furthermore, in future work, different scenarios can be applied to the base model to test the impacts of flood management, climate change and overgrazing.

2. Methods

The main approaches used are to set up a hydrology model and couple it to a hydraulic model, and then to validate outcomes using a range of data sources from previous flood events. The hydrology model is used to generate the hydrographs needed as the inputs for the hydraulic modelling since the available discharge data for the study area is unreliable. The purpose of the hydraulic model is to estimate the flood inundation, depth, and water velocity across the flooded areas of the catchment. A public online survey, satellite data analysis, and analysis of social media content were employed to validate the flood modelling results. Fig. 1 represents the overall data and tools used in this study.

2.1. Building the hydrology model

Rainfall stations are generally distributed unevenly in the Darbat catchment, they are located on the edges of the catchment. These rainfall stations are spaced between each other at about 7–11.8 km (Fig. 2). Besides, neither the north nor the south of the catchment has a rainfall station. It is essential to have multiple rainfall stations that are equally spaced throughout the catchment area to precisely determine the range of rainfall values and how they impact the runoff volume in various catchment areas during an event (Hohmann et al., 2020).

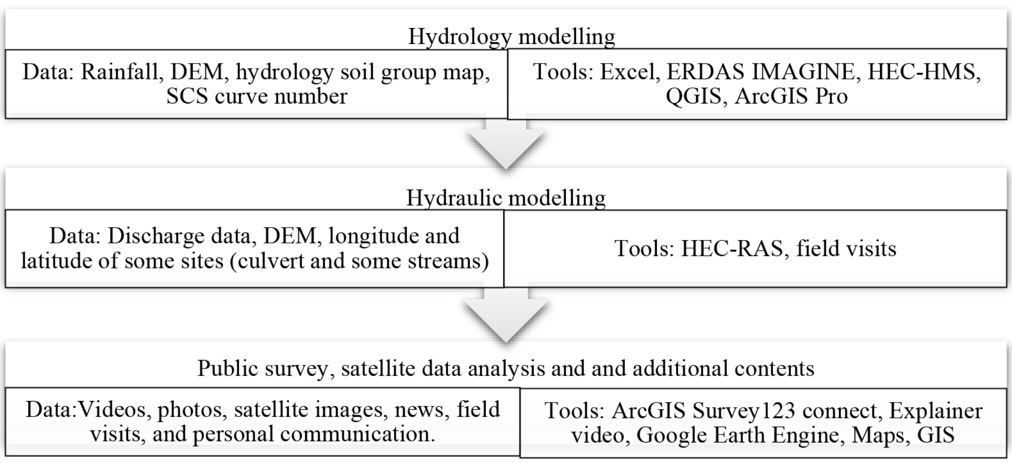


Fig. 1. Methodology used in the study.

Therefore, since there is a limitation in rainfall data observed in 5-min interval only limited available rainfall data were used. The rainfall data for storm events in 2002 and 2020 were collected from Ministry of Agriculture, Fisheries and Water Recourses (MAFWR, 2002, 2020). In case of the 2018 event (Cyclone Mekunu), the ground rainfall stations in Darbat stopped recording for 4 d causing missing rainfall values. We therefore used rainfall radar data for event 2018 (DGMET, 2018). The raw rainfall data recorded by radar was converted to a Dual Polarised Surface Rainfall Intensity product (DP-SRI) with the assistance of two meteorological experts at the Directorate General of Meteorology/Civil Aviation Authority in Oman (Table 1) (DGMET, 2022b). For greater accuracy, we validated the rainfall from radar data with neighbouring stations in nearby catchments and with the Global Satellite Mapping of Precipitation (JAXA, 2018).

Row tiles of a digital elevation model (DEM) were obtained from the National Survey Authority (Ministry of Defence, 2012). The DEM was produced in 2012 with a resolution of 5 m. The mosaic tool in ERDAS IMAGINE (Hexagon, 2020) was used to combine the tiles. A numerical, physically-based, semi-distributed model type for a catchment-scale was utilised in this study using the (Hydrologic Engineering Center of the U.S. Army Corps of Engineers, 2023) Hydrology Modelling System (HEC-HMS) software provided by Hydrologic Engineering Center of the U.S. Army Corps of Engineers (2023). The catchment, sub-catchments, and tributaries were delineated using the DEM via the GIS hydrology tools in HEC-HMS. The tributaries were named in this study according to the Atlas of Wadis of Oman (El-Baz, 2002) and how they are known by local people. Four main tributaries can be distinguished in the Darbat catchment: Hizam, Jilawb, Thahak and Nujub. Two smaller tributaries were called herein small east and small west tributaries (Fig. 3).

The hydrological modelling was applied on the whole catchment of Darbat which is 439.5 km^2. The Gage Weight method was used for rainfall events in 2018 and 2020 in HEC-HMS program. Since the 2002 event had reliable rainfall data in 5-min intervals from one station only, the rainfall was assessed with the Specified Hyetograph method for this event. The Thiessen Polygon tool in ArcGIS Pro 3.0 (Esri, 2022) was used to calculate the weights of the rainfall in each sub-catchment. A number of parameters were determined for the hydrological model to simulate the main arid zone processes. The soil conservation service-curve number method (SCS-CN)

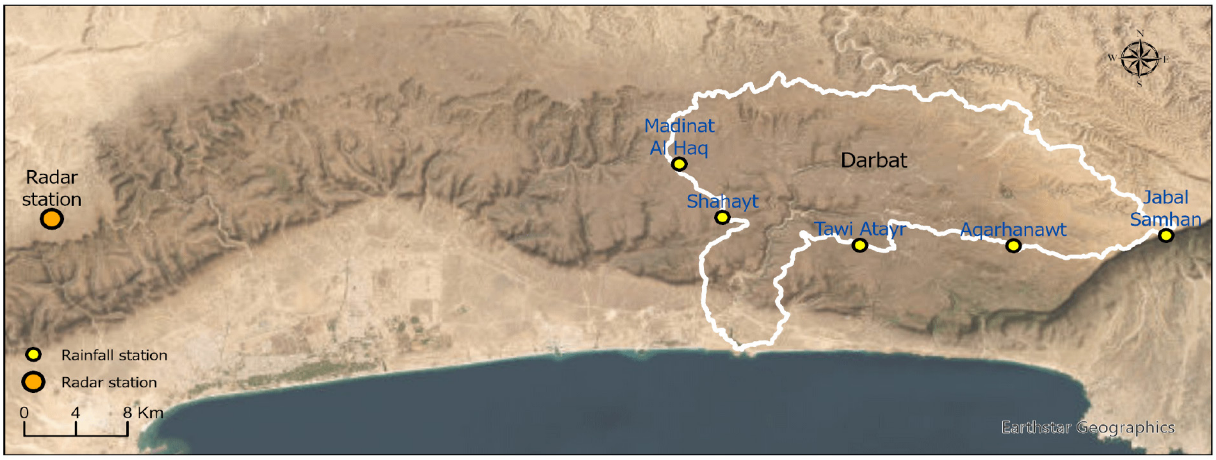


Fig. 2. Ground rainfall stations in Darbat catchment and radar station in South Dhofar (DGMET, 2022a; Esri, 2022; MAFWR, 2020).

Table 1
The total rainfall for each event in the Darbat catchment and the sources of rainfall data

Name or site of station	Total rainfall in 2002 in 2 d (mm) during tropical storm	Total rainfall 2018 in 6 d (mm) during Cyclone Mekunu	Total rainfall 2020 in 4 d (mm) during deep depression
	Source		
	Rainfall ground station	Weather radar data	Rainfall ground stations
Tawi Atayr	157	303.1	484.8
Aqarhanawt	—	500.4	788.2
Jabal Samhan	—	493.7	—

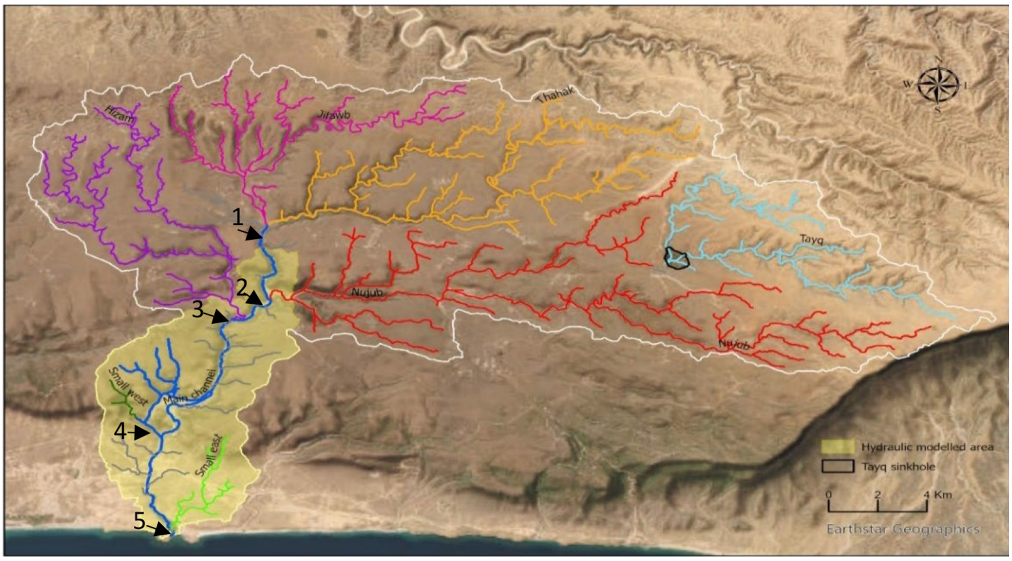


Fig. 3. Tributaries and the main channel in Darbat catchment (Esri, 2022).

was utilized to calculate the excess rainfall over infiltration. To transform excess rainfall (direct runoff) into a runoff hydrograph, the SCS unit hydrograph method was used. The Muskingum method was used to calculate the inflow water from upper tributaries and the outflow loss water into the subsequent downstream tributary. Each method was selected to fit the study area condition and based on best evidence available for arid and semiarid regions (Bucała-Hrabia et al., 2020; Elfeki et al., 2014; Niyazi et al., 2020; Shaheed and Mohammad, 2010).

The SCS CN values for the study area were obtained from considering the curve number table suitable for arid catchments (Hydrologic Engineering Center, 2022) and from the Hydrologic Soil Group raster data (Ross et al., 2018). To determine the lag time values required in the SCS Unit Hydrograph method to assess the transformation of excess rainfall we multiplied the time of concentration (T_c) by 0.6 (Natural Resources Conservation Service, 2010). We used the Kirpich method to calculate the T_c since it is suitable for wadi conditions (Al-Weshah, 2002; Ministry of Transport and Communications, 2017). As the three flood events occurred in May, the pre monsoon period, the baseflow was not included in the hydrology model as the overall condition of the catchment was dry.

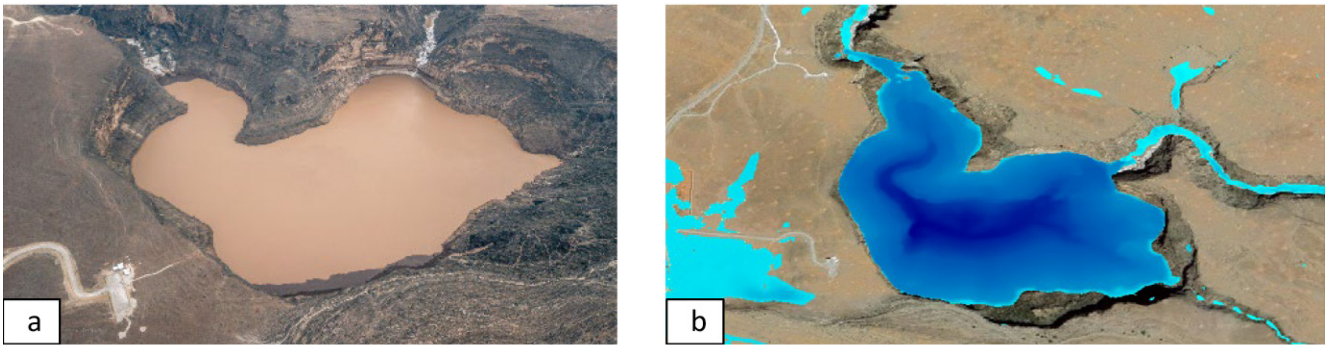
2.2 Building the hydraulic model

A two-dimensional unsteady flow model was employed for Darbat catchment using HEC-RAS (Hydrologic Engineering Center of the U. S. Army Corps of Engineers, 2022). The hydraulic model was applied on the downstream area and part of the middle area of the Darbat catchment, covering a total of around 68.8 km^2 (Fig. 3). The DEM, flow hydrographs, geometries, and map layers are the main input components to the hydraulic model. The flow hydrographs that were produced from the hydrological model in this study were input as entries in the unsteady flow data. To account for internal hydrology in the flooding zones, rainfall data were incorporated over the model area.

Under the breaklines layer (in the geometries section), the reach centrelines and two culverts were added to recognise the modified elevations and structures in the 2D mesh (Hydrologic Engineering Center, 2023). The locations of the main tributaries and the culverts were confirmed through field visits in September 2021 and August 2022 and then the terrain was modified in the DEM accordingly.

The cell size was set to 90 m resolution for the domain area and 20 m resolution for the breaklines. HEC-RAS operates a sub grid ability which retains the hydraulic details from the 5 m DEM as long as the breaklines are included where needed to capture topographical features required in the model. The time step for computation for the hydraulic model was an adaptive time step (generally tens of seconds), however, the interval was set to 5 min for the output mapping.

One hydrologically challenging feature of the catchment is Tayq sinkhole. It is a vast sinkhole located in the northeast of the Darbat catchment (0.70 km^2). Through observing the area from Google Earth, a field visit and previous studies (Müller et al., 2023; Zerboni et al., 2020) we determined that during intensive rainfall events (Fig. 4a), surface water flowed through reaches into the sinkhole. As inflow was greater than outflow rates, water levels rose and water accumulated for a few days in the sinkhole while water continued to be released via an the underground passage at the bottom of Tayq sinkhole.



Fig, 4, Tayq sinkhole from (a) aerial photo (Al Shahri, 2020a) and (b) the maximum extent-depth from hydraulic model for event 2020.

One of the steps to delineate the basin and its elements in HEC-HMS with GIS hydrology tools is to fill the pits in the DEM. Consequently, the sinkhole was experimentally filled (ignored) and the reaches before the sinkhole assumed to be connected to the reaches downstream after the sinkhole (Fig. 5.). This means an additional water volume will be added to the flood water downstream adding some element of uncertainty. The maximum previously assessed water volume which can be held in Tayq sinkhole is 85 million m^3 (Siegl, 2022). However, we ran a hydraulic model for the area around Tayq sinkhole to estimate the total water volume that was captured using the water surface elevation and storage area layers (Fig. 4b). The result was about 33 million m^3 of water held for the 2020 event.

In the 2018 event, it took about two days for the water to reach the highest level in Tayq sinkhole. Then the water level decreased until most of it had drained underground in the fifth day of the storm (30th May) (Al Mashani, 2023). Since there is a shortage of studies in the hydrological system around Tayq and its connection to the stream systems in Dhofar, it is not certain where exactly most of this water flows or its residence time (Zerboni et al., 2020). In this study, we assumed that the water was captured by the sinkhole for a few days and released later on downstream in the same surface water catchment. Hence some of the flow was delayed in the model to realistically represent the idea that some of the water held by Tayq sinkhole would not directly contribute to the flood peak downstream due to temporary storage. Therefore, we adjusted the elements inside the sinkhole to restrict the upstream reaches from connecting to the next sub-catchment, so they terminated inside Tayq sinkhole (Fig. 5b). This, modification was designed to represent the sinkhole effect on the flood hydrology of the catchment.

2.3. Validation methods

Recorded data from water level and discharge gauging stations should assist in the validation of flood modelling work (Beven, 2012). However, a key challenge in flood modelling studies in arid and semi-arid regions is obtaining reliable discharge data. There are only a few gauging stations in Dhofar as a whole. Some of them stopped recording for several years and others have several hours or days of missing data for the previous flood events. Even where data were available from river gauging loggers, we evaluated these and deemed them as entirely unreliable, presumably due to incomplete

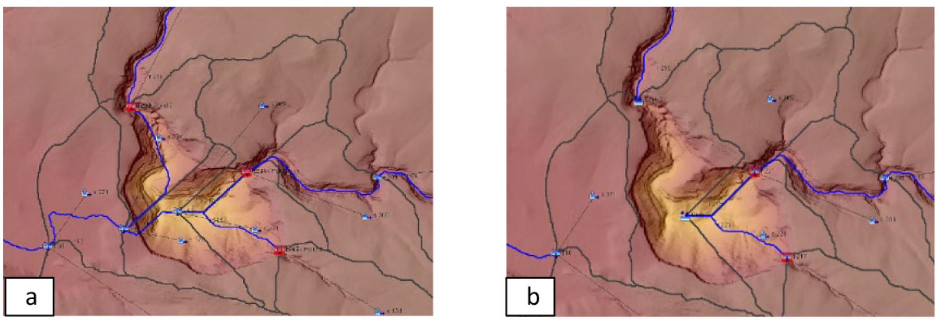


Fig. 5. (a) The reaches connected before and after Tayq sinkhole, ignoring the effect of the sinkhole in the hydrology model, (b) modified reaches to terminate inside the sinkhole.

high flow calibrations or problems with the sensors. Thus, we use alternative methods to validate the model wherever possible.

Satellite images from Sentinel-1 and Sentinel-2 were analysed through Google Earth Engine to detect the inundation extent of flooding for events in 2018 and 2020. Sentinel-1 and Sentinel-2 have accessible data and water area is one of the main features they can present (ESA, 2023b, c). Sentinel-1 has a single C-band Synthetic Aperture Radar (SAR) instrument. SAR has the capability to penetrate clouds, unlike the optical sensor in Sentinel-2. In this study we selected satellite data with Interferometric Wide Swath (IW) mode in Sentinel-1. The band VH (transmits vertical waves and receives horizontal waves) was selected from the VV+VH dual polarisation mode. The IW is the less conflicting mode over land, and it preserves the revisit function (De Zan and Monti Guarnieri, 2006; ESA, 2023a). A script was used to analyse Sentinel-1 satellite images for the 2018 flood event. The same scripts implemented previously to detect flooded area in different catchments provided acceptable results, (Gandhi, 2020) so these were simply modified to meet the requirements of the study area (GEE, 2023).

The optical sensor in Sentinel-2 produces high-resolution (10 m in most bands) multispectral satellite images, and each image contains 13 spectral bands (GISGeography, 2022). To detect the flooded area from Sentinel-2 satellite images for the 2020 event, a combination of bands 8 (Visible and Near Infrared), 4 (Red) and 3 (Green) were used to present false colour infrared composite images. The false colour infrared composite reflects the water clearly with black or dark blue colours (Li et al., 2021; Riebeek, 2014), which makes flood waters easier to depict compared to within true colour composites which can appear brown and hard to distinguish from bare ground (Riebeek, 2014).

Several aerial photos and videos of flooded areas taken by local photographers using unmanned arial vhichels were examined (Al Mashani, 2020; Al Shahri, 2020b). Additionally, we created an online survey using the ArcGIS Survey 123 Connect application (Esri, 2021a). It was targeted at people who experienced the most recent flood events in Darbat in 2018 and 2020. One of the important questions in the survey was to identify the precise areas that represent a flooded area encountered by the participants by drawing a polygon on the map. Other questions were used to get respondents to estimate the water level and velocity (Esri, 2021b).

3. Data analysis and results

3.1. Modelling results

Thahak meets the Jilawb tributary and joins the mainstream at site 1. The Thahak tributary contributed 64.3%, 70.0% and 69.0% of total water volume in the 2002, 2018 and 2020 events respectively. Accordingly, Thahak tributary produced higher peak discharge reaching 254 m^3/s (2002), 397 m^3/s (2018) and 507 m^3/s (2020) (Figs. 6a–c). The contributions estimated from the Nujub tributary to the main channel at site 2 were 45% (2002) and 50% (2018 and 2020) which is higher than the contribution from Hizam to the main channel at site 3 (16.8% in 2002, 13.5% in 2018, and 13.8% in 2020 (Table 2). The Nujub tributary produced greater peak discharge compared to the Hizam tributary in the three events (Figs. 7 a-c). In addition, the discharge peaked 30–45 min earlier (in the three events) in the main channel at site 2 after the Nujub tributary joined the main channel. However, peak discharge in main channel at site 3 was delayed 3 h (2020), 15 min (2018), and 1.6 h (2020) after the Hizam tributary joined it.

The small west tributary contributed between 5–6.4% of total water volume in the three events to the main channel at site 4, while the small east tributary contributed with only 2.7–2.8% of the total volume water to the main channel at site 5. In addition, the small east tributary resulted in higher peak discharge in the three events compared to the small west tributary (Table 2). The peak discharge increased gradually from site 3 to site 4 in the main channel. However, it grew from 1517 m^3/s (2018) to 1979 m^3/s (2020) at site 4, and from 1493 m^3/s (2018) to 1834 m^3/s (2020) in site 5.

In terms of the area-weighted contribution of each tributary in units of mm of discharge, the Jilawb tributary contributed a lower total discharge compared to other tributaries in the three events (Table 3). While the Nujub tributaries contributed with highest mm of discharge in event 2018 (280 mm) and event 2020 (619 mm).

To illustrate maximum water depth and velocity we represent the estimated values taken from the event 2020. The water depth varied in the catchment (0.1–36 m) (Fig. 10a). The depth ranged between 1 to 3 m after Thahak and Jilawb tributaries joined the main channel and increased to 3–9 m after each of Nujub and Hizam joining the main channel. The depth reduced to 0.1–2 just before the waterfall areas, and increased directly just after the waterfall areas to 3–9 m. In the south down the catchment and before the catchment mouth, the maximum depth reached to 3–6 m and 6–7.5 m near to Darbat bridge.

The overall water velocity ranged between 0.1 to 37 m/s (Fig. 10b). The highest velocities (15–37 m/s) were in found in a few sites north of site 1 in the main channel. The water velocities were between 1.5 and 6 m/s after the Nujub tributary joined the main channel. The velocity increased up to 6–9 m/s after the Hizam tributary joined the main channel. Then it reduced gradually until the waterfalls area in the centre of the modelled area. The velocity declined gradually after that from 3–6 m/s until

Table 2
Model results for peak discharge and total water volume in the tributaries and five sites in the main channel for events in 2002, 2018, and 2020 in Darbat catchment

Tributary name/site in map	Event 2002			Event 2018			Event 2020		
	Peak (m^3/s)	Time of peak	Total volume (Mm^3)	Peak (m^3/s)	Time of peak	Total volume (Mm^3)	Peak (m^3/s)	Time of peak	Total volume (Mm^3)
Jilawb	205.4	10 May 2002, 13:50	5.7	226	25 May 2018, 23:20	12.3	241	31 May 2020, 03:50	20.4
Thahak	254	10 May 2002, 17:05	10.4	397.3	26 May 2018, 00:00	28.7	507	31 May 2020, 05:00	46.1
Main channel 1 (Jilawb and Thahak met)	420	10 May 2002, 15:35	16.1	619	25 May 2018, 23:05	40.9	735	31 May 2020, 04:20	66.6
Nujub	372.6	10 May 2002, 18:20	15.4	591	25 May 2018, 22:55	46.7	966	31 May 2020, 04:10	76.0
Main channel 2 (Nujub joined)	807	10 May 2002, 17:35	33.8	1227	26 May 2018, 00:20	92.7	1672	31 May 2020, 04:40	151.3
Hizam	197	10 May 2002, 14:25	7.0	235	25 May 2018, 23:40	14.9	256	31 May 2020, 03:20	24.9
Main channel 3 (Hizam joined)	989	10 May 2002, 17:40	41.6	1480	25 May 2018, 23:55	109.6	1913	31 May 2020, 04:35	179.4
Small tributary in the west	33	10 May 2002, 10:45	0.48	32	26 May 2018, 09:30	1.0	49	31 May 2020, 00:50	1.7
Main channel 4 (small tributary in the west joined)	198	10 May 2002, 17:50	7.5	271	25 May 2018, 23:45	20.3	444	31 May 2020, 04:15	32.6
Small tributary in the east	55	10 May 2002, 11:20	1.2	70	26 May 2018, 09:45	3.3	92	31 May 2020, 01:05	5.6
Main channel 5 (small tributary in the east joined)	1060	10 May 2002, 18:40	47.5	1493	26 May 2018: 00:25	121.2	1834	31 May 2020, 05:10	199.8

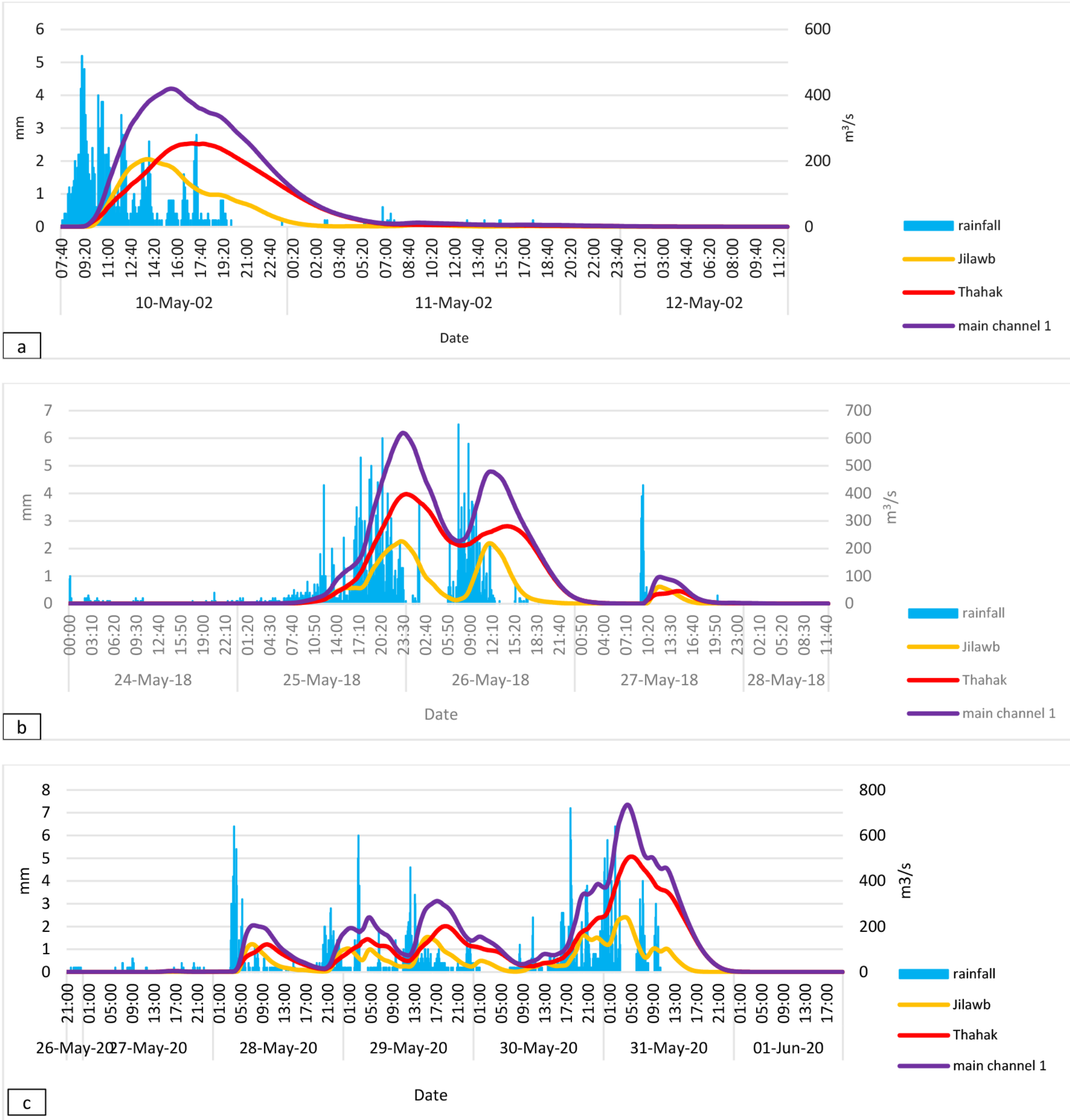


Fig. 6. Hydrographs of the Jilawb and Thahak tributaries and main channel at site 1 in events (a) 2002, (b) 2018, and (c) 2020.

Table 3
The contribution of each tributary in mm of total discharge

The main sub-catchments in Darbat catchment		Discharge from tributaries in units of mm		
Name	Area (km^2)	2002	2018	2020
Jilawb	50	115	244	408
Thahak	84.2	123	341	548
Nujub	123	125	380	619
Hizam	55	127	272	453
Small west tributary	3.9	124	260	435
Small east tributary	10.8	119	313	524

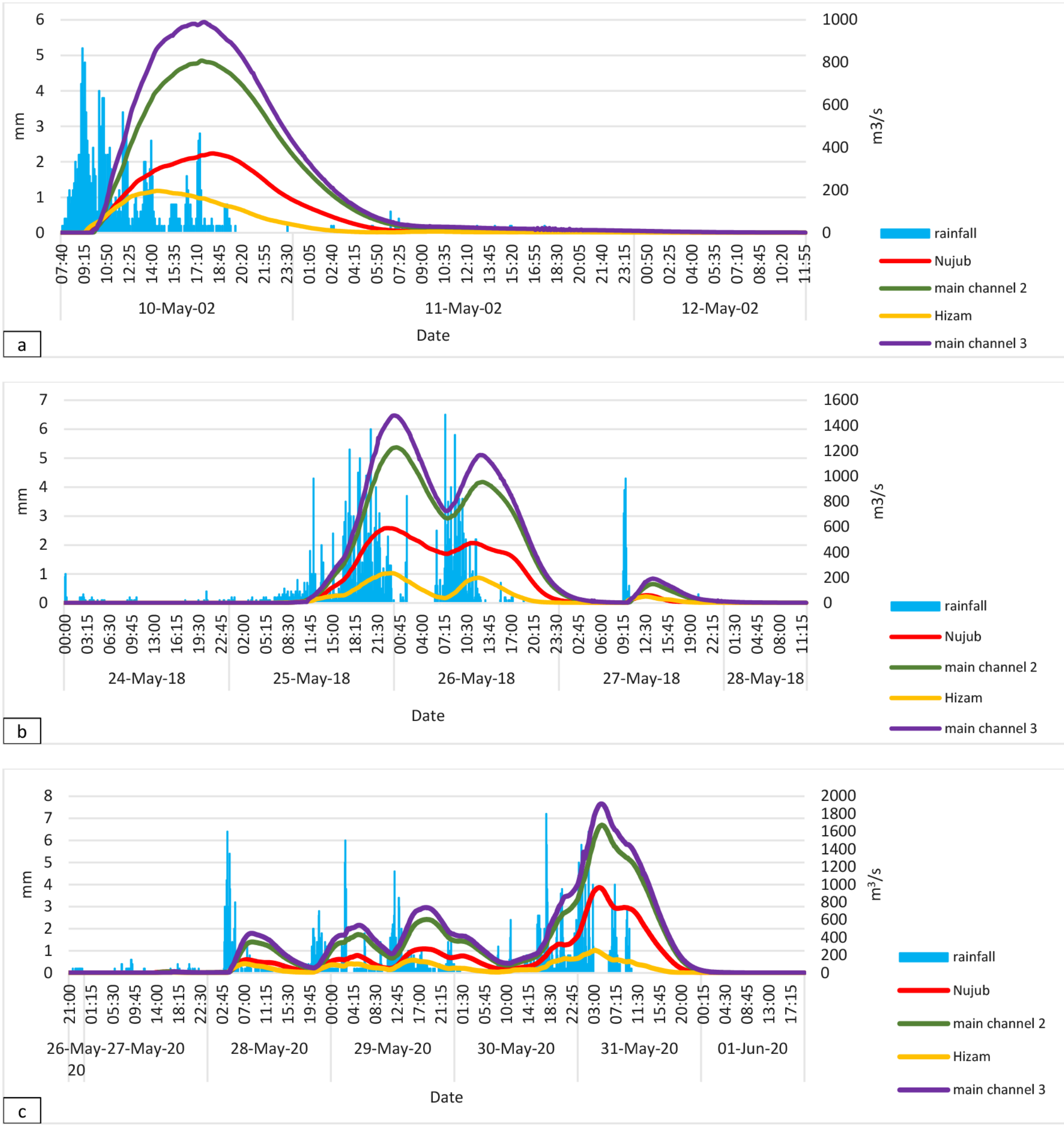


Fig. 7. Hydrographs of the Nujub and Hizam tributaries and main channel at sites 2 and 3 in events (a) 2002, (b) 2018, and (c) 2020.

0.75–-3 while the water was passing to the south of the catchment.

3.2. Validation results

Several sites were examined for modelling validation purposes. However, in this paper we only refer to example sites to illustrate the findings. The overall results from Sentinel-1 (event 2018) and Sentinel-2 (event 2020) imagery compared to model results were reasonable, however maximum inundation extent did not perfectly match (Fig. 8) because several areas were already dried when the Sentinel-1 and Sentinel-2 covered the study area.

Fig. 8a represents the result from detecting the changes before and after flooding (on 31 May 2018 at 14:30) from Sentinel-1. The yellow areas reflect the initial flooded areas, while the blue areas represent the flooded areas after adding an additional two filters in the script in Google Earth Engine. The first masks all areas with 5% degree or greater. The second filter was applied to remove the noise triggered by isolated pixels (Gandhi, 2020; GEE, 2023). Generally, Sentinel-2 better represents the flooded area compared to Sentinel-1. This could be due to a noise issue which appears with the SAR sensor in Sentinel-1 (Wakabayashi and Arai, 1996). In addition, the retrieval date for satellites in the study area was toward the end of the flooded period. For example, event

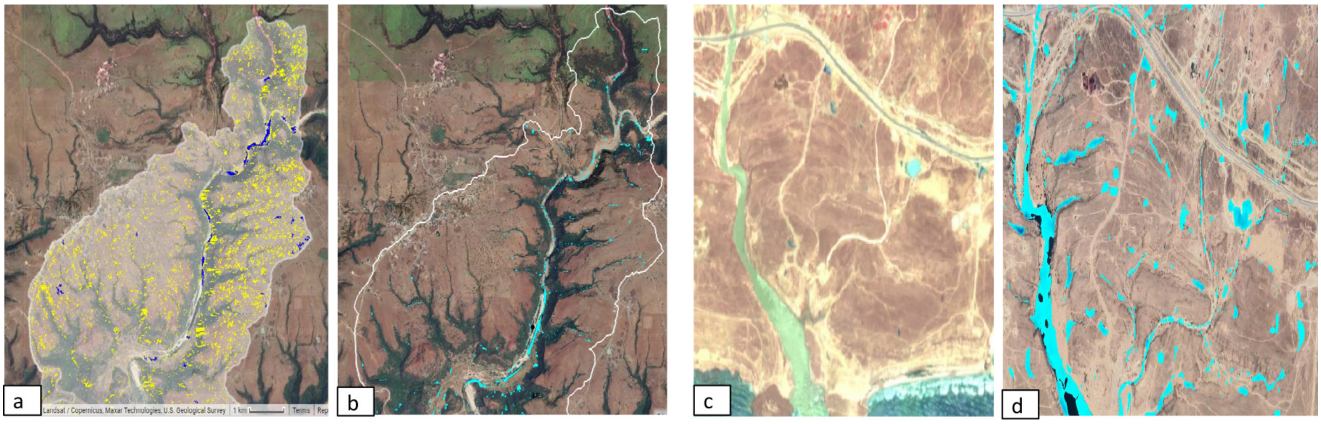


Fig. 8. Flood extent (a) estimated from Sentinel-1 on 31 May 2018, less noise layer represents the blue colour areas, (b) flood extent from the hydraulic model result for middle of Darbat catchment on 31 May 2018 at 2:30. Flooded area reflected from (c) Sentinel-2, the visited day of the satellite was on 2nd June 2020 at 06:46, (d) the flooded depth-extent simulated in HEC-RAS on 2nd June 2020 at 06:45 southeast Darbat catchment.

2020 was between 27 May and 31 2020, and the Sentinel-2 visited the area on 2nd June 2020 (S2 visits an area every 5 d) (ESA, 2023c).

Almost all of the aerial videos and photos taken for the flooded sites indicated a close comparison to the flood extent that resulted from the flood model of the study area. For example, photos from Figs. 9a,b, and e represent the flood extent and flood trace just before the end of the event in 2020.

In terms of the online survey, three out of 14 responses for Darbat catchment estimated the depth as half of or an entire car depth (Fig. 10a). The respondents to these answers described that the flood effects they experienced were a flooded road or both a flooded road and a car was dragged by the flow water, or a car was fully covered. In one site in the survey the estimated water depth that of an entire house. Two other expressions were added by the respondents to express the depth level to which the Tayq sinkhole was filled and the flood water near to a bridge height downstream. All answers for estimating the velocity of the flood water in Darbat were fast (Fig. 10b). This reflects the flood model results which showed velocity between 1 and 6 m/s in the most areas and up to 9 m/s in few areas that indicated by the respondents in the survey.

4. Discussion

The overall outputs from the hydrology and hydraulic models showed sensible simulations for events in 2002, 2018, and 2020 in the Darbat catchment. Generally, we can notice more detailed variation in discharge

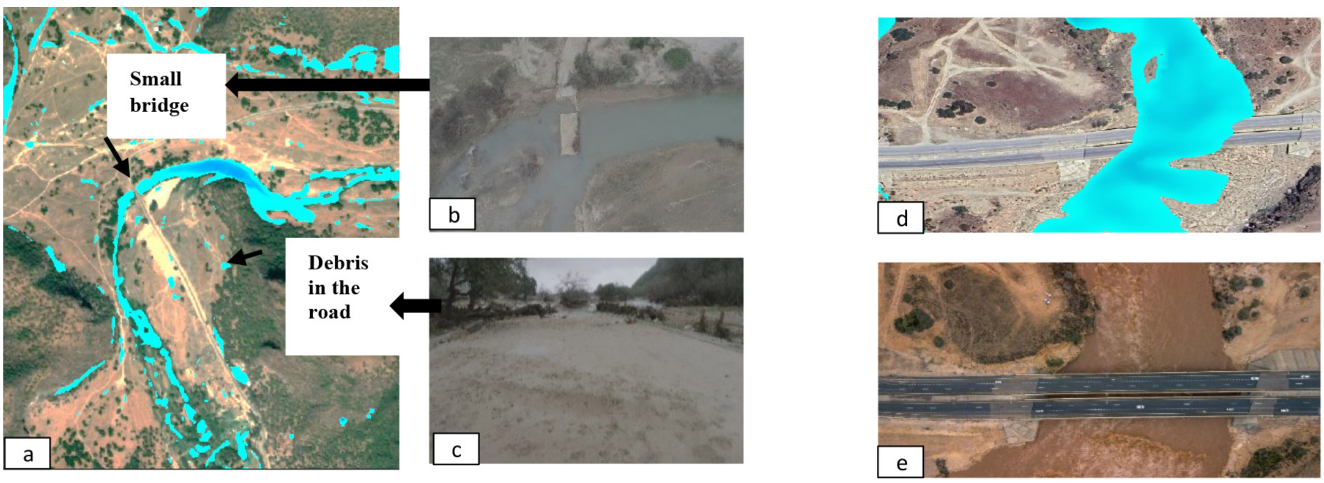


Fig. 9. (a) Flood extent resulting from the model post the intensive period for event 2020, (b) a small broken bridge, (c) debris in the road for event 2020 (Al Mashani, 2020). The area around Darbat bridge south Darbat catchment (d) flooded depth-extent resulting from the hydraulic model on 1st June 2020, (e) photo taken on 1st June 2020 (Al Shahri, 2020b).

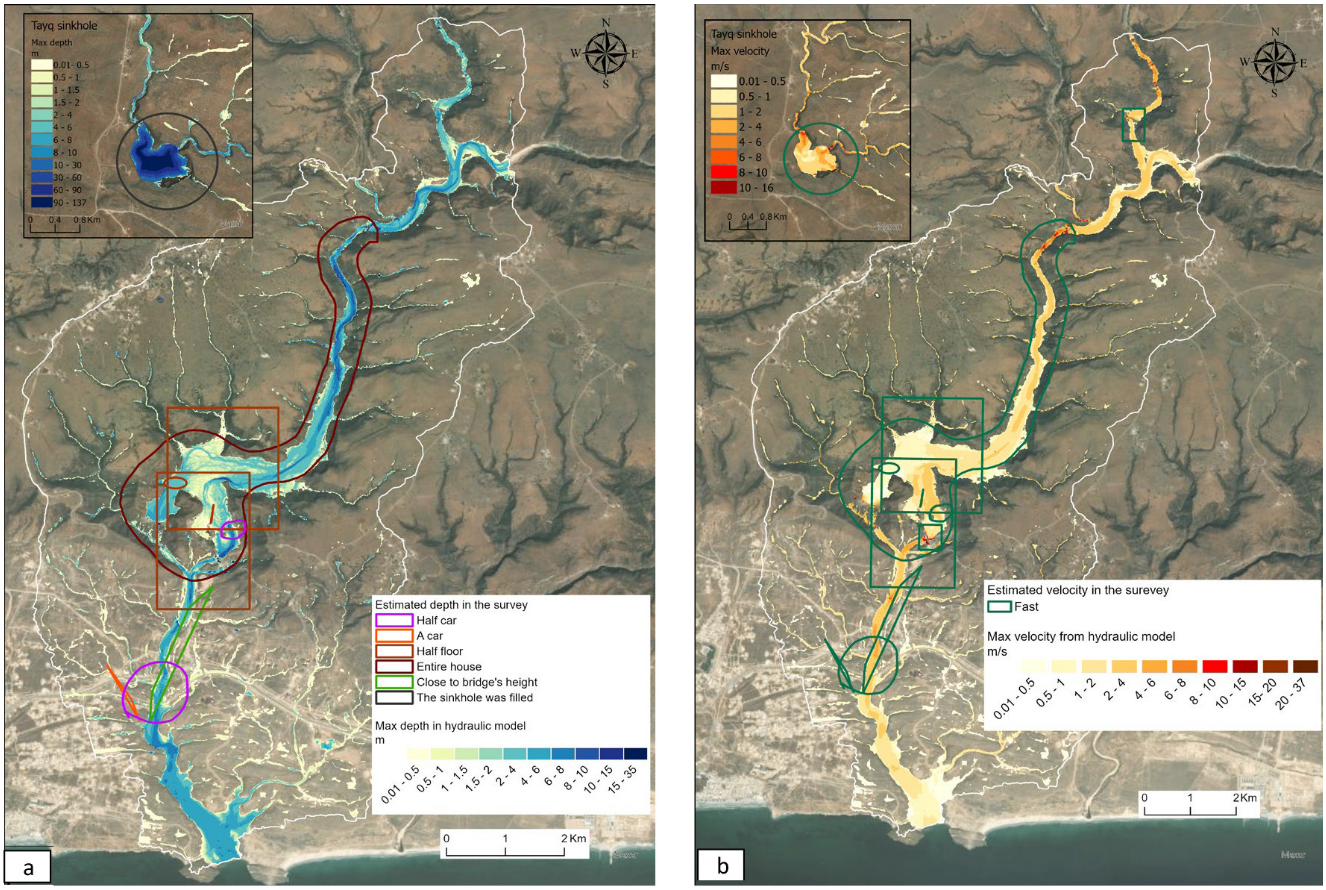


Fig. 10. The maximum of (a) water depth and (b) velocity for event 2020 estimated from the model and the estimated (a) depth and (b) velocity in the survey for the study catchment.

outputs especially for event 2018 and 2020 compared to event 2002, this could be due using one rainfall gauge station in event 2002. However, there are slight differences in the percentage of total water volume contributed to each tributary within the three events (Section 3.1). Different sources for validating model outputs in several spots inside the Darbat catchment reduced some of the uncertainty, especially on flood extent. Therefore, these outputs are credible and might support future insights into flood management in the area. The initial note from this study is the huge impact of the rainfall pattern on the flood generation. For example, in the event 2018 the flood hydrograph represented two high peaks (Fig. 6b and Fig. 7b) caused by the precipitation condition during Cyclone Mekunu. The estimation of the total water volume produced in the 2020 event is 200 Mm^3 (Fig. 11). This is greater than the water volume produced in the 2002 event (48 Mm^3) and the 2018 event (121 Mm^3) (Table 2). In addition, the flood event in 2020 resulted in more flood inundation (8.7 km^2) compared to 2018 (8.3 km^2), and 2002 (7.8 km^2).

In this study, the peak discharge times for Jilawb tributary were closer to that of the main channel at site 1 compared to the Thahak tributary which was more delayed (from 40 min to 1 h 30 min) before it joined the main channel at site 1 (Table 2). Consequently, slowing down the flow of water from Thahak tributary might be more preferable in terms of flood mitigation planning than managing the flow of water from Jilawb. Indeed, an unfavourable outcome may occur if management interventions slowed the Jilawb peak slightly as it could coincide more with the peak time of the main channel at site 1 and increase the flood magnitude downstream.

The peak discharge at site 2 occurred 1 h 25 min (event 2018) and 30 min (event 2020) after that of the nearby Nujub tributary, although it peaked 40 min earlier than Nujub in the 2002 event. Delays in peak discharge (15 min–3 h) were found at site 3 in the main channel compared to the peak time in Hizam tributary which joined the main channel just upstream. If possible, some focus on delaying flood waters in the Nujub tributary could therefore be beneficial to reduce downstream flooding, particularly since Nujub contributes around 38% of the total runoff generated in (2020 event) (Fig. 11).

The main channel at site 4 showed delay (7 h in 2002, and 3 and 25 min in 2020) after the small west tributary

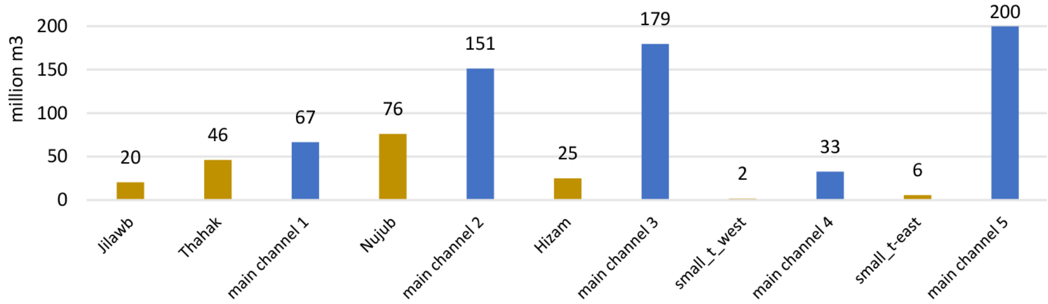


Fig. 11. Total volume of flood water in different tributaries and main channel in Darbat catchment for event 2020.

joined it. However, the main channel at site 4 peaked earlier than the small west tributary with 9 h and 45 min difference in event 2018. This tributary contributed between 0.48–1.7 Mm^3 of the total water volume produced from flood event in the three events (Table 2). The small east tributary peaked much earlier than site 5 when it joined the main channel. The peak discharge was delayed at site 5 (7 h in 2002, 14 h in 2018, and 4 h and 25 min in 2020) compared to the small east tributary. In addition, this tributary contributed between 1.2–5.6 Mm^3 of the total water volume in the three events. Therefore, the small west tributary has a lower role on the flood peak in Darbat catchment compared to the small east tributary.

5. Conclusion

The outputs from this study provide a new understanding of general behaviour of the flood hazard in Darbat catchment for three major flood events in 2002, 2018, and 2020. The study used hydrological and hydraulic modelling approaches for a data poor arid region, supplemented with a range of novel validation data. For Darbat, the new spatio-temporal understanding can aid further investigation into spatial approaches to reduce flood risk through understanding impacts on flood peak synchronicity from tributaries and the relative total flow contributions at different timepoints during storms. Hence the modelling framework developed in this study can now be used to test future management and rainfall scenarios that could impact flood discharge and flood extent and can also be applied to other catchments and other arid and semi-arid regions.

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(2024) 133–140
doi: 10.5004.dsal.2024.700050

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28–30 April 2024, Doha, Qatar

Development of flood risk mapping and mitigation strategies for Al-Qassim region

Atef Q. Kawara, Ibrahim H. Elsebaie*

Civil Engineering Department, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia, email: 439106883@student.ksu.edu.sa (A.Q. Kawara), elsebaie@ksu.edu.sa (I.H. Elsebaie)

ABSTRACT

In this study, a research project aiming at producing a comprehensive map of flood risk in the Al-Qassim region is described. Flooding has become a pressing issue in this region, and this initiative aims to apply fundamental scientific principles to advance our understanding of flood risks, resulting in the development of innovative mitigation strategies. Flood risk mapping is vital in watershed management and planning, especially in reducing flood damage. In this study, a flood risk map will be developed for AL-Qassim by combining geographic information system techniques with a multi-criteria decision-making method known as the Analytical Hierarchy Process (AHP). Several factors will be investigated in the study, including elevation, slope, topographic wetness index, drainage density, rainfall, soil and land use, and land cover. The watershed will be divided into five regions: very high, high, moderate, low, and very low flooding danger areas. The obtained results will provide helpful knowledge for the policy and decision-makers to make the right decisions regarding the effectiveness of the protective structures of the study area against the risk of flash flooding in the future.

Keywords: Flood risk; Al-Qassim; Hydrological modeling; AHP; GIS

1. Introduction

Floods have a more detrimental impact on both urban and non-urban areas compared to other types of natural disasters (Khosravi et al., 2016). Annually, flood occurrences impact a substantial number of people (Sahana & Sajjad, 2019; Chan et al., 2022). According to Wahlstrom and Guha-Sapir (2015), floods accounted for 43% of all recorded natural disasters between 1995 and 2015. These floods affected a total of 2.3 billion individuals globally, resulting in losses amounting to USD 662 billion and causing the death of 157,000 people.

Floods may be caused by various sources, including climate change and human activity (Kourgialas & Karatzas, 2011). The primary drivers of differences in seasonal precipitation, which might result in flooding catastrophes, are climate change and environmental fluctuations (Seenirajan et al., 2017; Shreevastav et al., 2021). By 2050, almost 2 billion people will face the risk of flooding due to climate change, rising sea levels, the fast expansion of populations in flood-prone regions, and deforestation (Abubakar & Dano, 2020). Furthermore, climate change has a substantial impact on the hydrological cycle and water resource systems. Consequently, there has been considerable scholarly attention towards examining the water cycle and its temporal and spatial changes in response to environmental shifts (Tanteliniaina et al., 2021). The process

*Corresponding author.

of global warming, which involves the increase in temperature of the atmosphere, oceans, and land, has been seen since the onset of industrialization (Masson-Delmotte et al., 2021).

Flash floods often transpire in hilly watersheds and result from substantial and concentrated precipitation occurrences. Flash floods are generally acknowledged as a primary cause of the most dangerous and costly natural disasters worldwide (Trigo et al., 2016; Saharia et al., 2017). Between 1975 and 2002, a comprehensive analysis revealed that each flash flood incident resulted in the loss of 181 lives. According to Jonkman (2005), the average mortality rate, which measures the number of persons who die in relation to the number of people affected by the event, is 3.62%.

Saudi Arabia is susceptible to flash floods, which may cause various damages. Precipitation patterns in arid to semi-arid regions, like Saudi Arabia, exhibit temporal and spatial variability. Summers in these areas may range from hot to extremely hot, while winters tend to be moderate to warm (Peel et al., 2007). As a result, there are occasional flash floods that result in limited harm to roads, people, buildings, and dams (Youssef et al., 2021). Saudi Arabia has annual instances of flooding in different regions (Hijji et al., 2013; Youssef et al., 2015). Flash floods are the most common natural disasters in Saudi Arabia. They are mostly triggered by geographical and topographical factors, as well as other natural and human causes (Youssef et al., 2015).

Flood risk mapping can reliably anticipate the locations of flood disasters, therefore aiding in mitigating their impacts (De Risi et al., 2020). The detailed mapping and identification of several parameters greatly impact the location of the flood. Consequently, the integration of numerous datasets enables the use of geographic information system (GIS) methodologies for conducting spatial analysis (Mishra & Sinha, 2020).

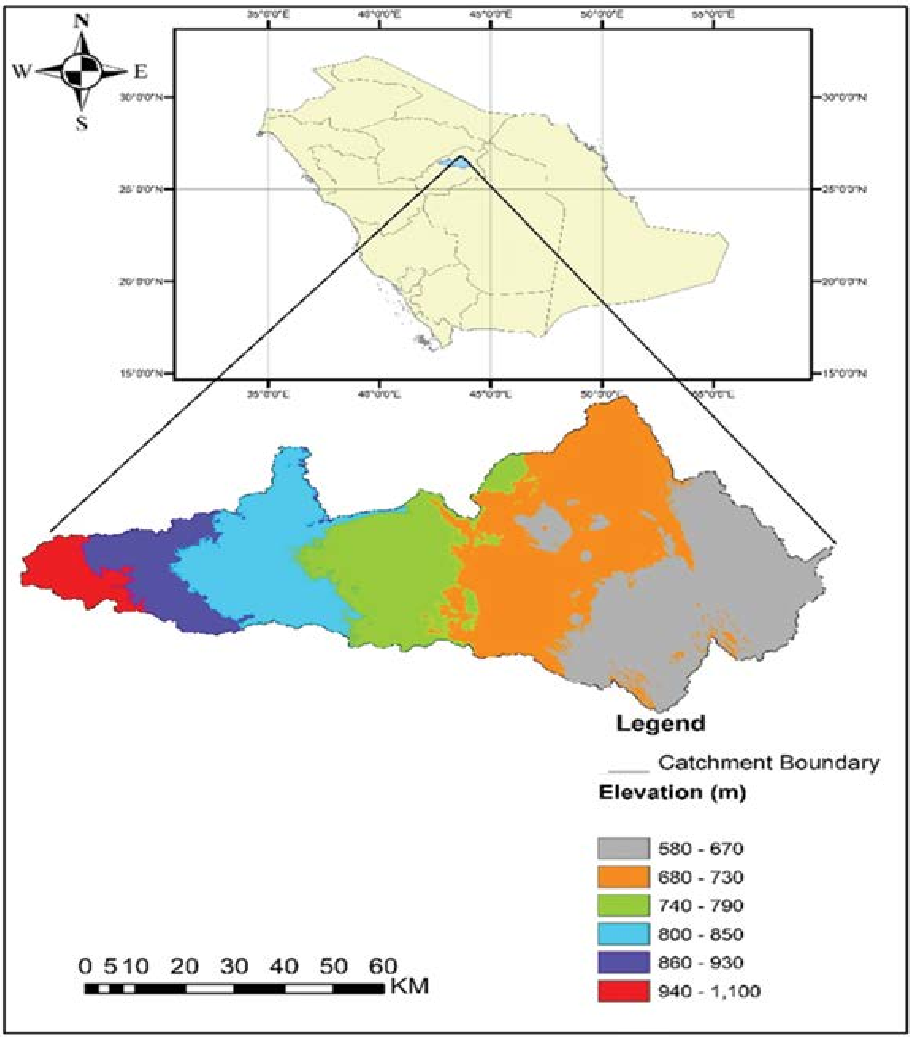

Fig. 1. Coordinates and digital elevation model of Burydah.

The Analytical Hierarchy Process (AHP) is a technique used to assess various options, as described by Vahidnia et al. (2009) and Rajasekhar et al. (2019). The Analytic Hierarchy Process (AHP) is a robust decision-making methodology that may be used in the creation of flood risk maps to evaluate and compare the effectiveness of different criteria (Gigović et al., 2017; Wang et al., 2019). The use of elevation, climate, land use data, soil data, and the GIS environment might augment the effectiveness of flood analysis (Tripathi et al., 2020).

The primary aim of the research was to assess the risks of flooding in the AL-Qassim region using a GIS, which is an approach that incorporates many criteria. The results of this research may assist local policymakers and regulatory bodies in developing a comprehensive analysis of the potential risks posed by floods. This analysis will enable them to identify and prioritize the most essential measures for mitigating these risks. Additionally, it will provide insights into how adjacent communities might enhance their resilience to future flooding events.

2. Study area

Buraydah is the regional capital of the Al-Qassim Region and it is situated on the northern side of Wadi Al Rumah, the longest valley in Saudi Arabia. Al Rumah Wadi begins in Al-Medina and extends around 600 km to the Sands of Althwairat. The city center of Buraidah is located at coordinates 26°21′ 33.23′′ N and 43°58′ 54.52′′ E. The city of Buraydah has a desert environment, which is distinguished by cold winters with uncommon but intense rainfall and very hot summers with low humidity. In the summer, the temperature varies from 32 °C to 36 °C at night and from 43°C to 48°C during the day. Fig. 2 shows the Coordinates and digital elevation model of Buraydah.

3. Database

The data processing technique is a crucial stage in the creation of a flood risk map. The data for the research area was obtained from several sources, as seen in Fig. 2. A Digital Elevation Model (DEM) with a resolution of 12 m has been downloaded. The analysis of the DEM model using ArcGIS software yielded many layers, including drainage density, slope, and elevation. The Ministry of Agriculture, Water, and Environment database provided daily precipitation statistics. The mean annual rainfall data of the study region was interpolated using the Inverse Distance Weighting (IDW) approach. The soil type data was obtained from a digital soil map of the globe, which may be viewed at the following URL: https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/metadata/446ed430-8383-11db-b9b2-000d939bc5d8. The Earth Explorer satellite images were obtained from the website of the US Geological Survey (https://earthexplorer.usgs.gov/) and analyzed for Land Use and Land Cover (LULC) data. The LULC map was built in ArcGIS 10.8 using satellite imagery, image recognition algorithms, and a maximum likelihood algorithm. The geographical layers were converted into a raster format by resampling, which enabled the formation of a consolidated database.

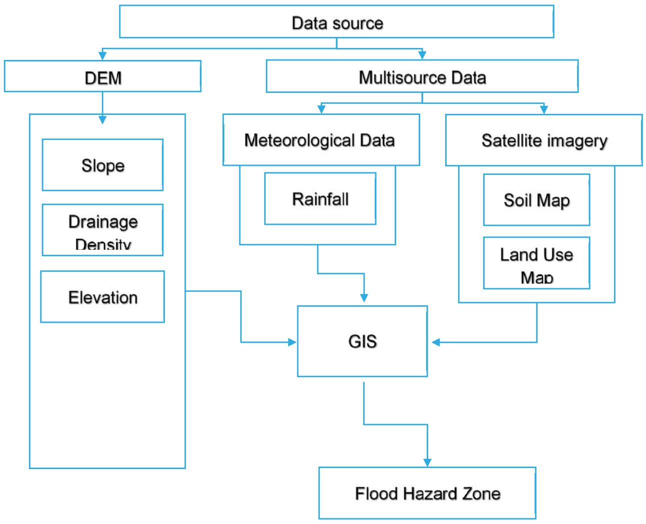

Fig. 2. Flow chart illustrating the approach used in the current research.

4. Methodology

The research methodology used for this study is shown in Fig. 2. The significance of these six components in defining flood danger zones was established. The flood danger zone map was generated using the AHP weightage combination technique after a comprehensive analysis that took into account several factors. Subsequently.

5. Results and discussion

The present study aimed to apply the GIS and AHP techniques to address the issue of flood risk criteria in an ungauged watershed during severe conditions. These techniques have been previously utilized in various watersheds, as documented in earlier research (Souissi et al., 2020; Ramkar & Yadav, 2021; Alarifi et al., 2022; Tariq et al., 2022). Elevation, slope, drainage density, rainfall, soil, and land use/land cover are the primary determinants of flood risk.

The results of this study are consistent with the findings reported by Gigović et al. (2017). Specifically, the study's findings demonstrated that elevation plays a crucial role in controlling the movements of the overflow route and the height of the water level. In addition, Rimba et al. (2017) demonstrated that slope has a crucial role in controlling the speed and duration of water flow since flatter surfaces are more susceptible to flooding compared to steeper places. Compared to studies conducted on comparable watersheds in the region and nearby areas. The research done by Alarifi et al. (2022) took place in the southwest area of Saudi Arabia. They determined that height has the most significance among the 10 chosen parameters. The main factor that initiated flash floods was the elevation, which was subsequently influenced by the slope and rainfall.

Flood risk maps provide significant advantages to policymakers, competent authorities, and local residents (Ogato et al., 2020; Dano, 2022). These sources (Dano, 2020; Ogato et al., 2020; Souissi et al., 2020) may help identify suitable methods for reducing flood risks in watersheds. Flood risk mapping facilitates the identification of vulnerable areas. Moreover, by using a systematic methodology like the Analytic Hierarchy Process (AHP), there would be uniformity in determining the specific strategies and locations for mitigating urban growth in high-risk regions. The existence of several facilities and the expansion of urban centers inside the floodplain region may amplify the severity of flooding. The findings indicated that urbanization

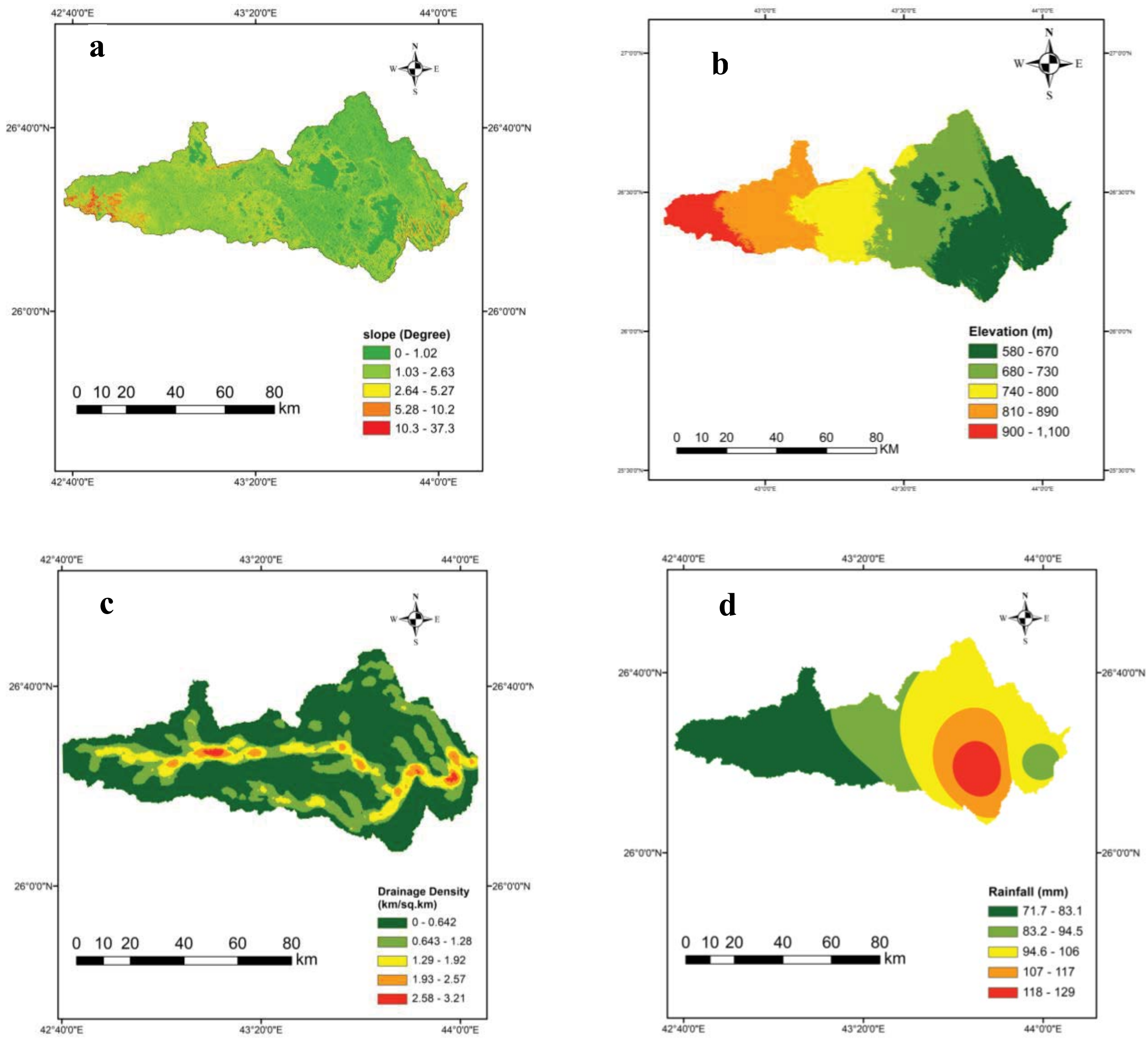

Fig. 3. Flood hazard factors: (a) slope, (b) elevation, (c) drainage density, (d) rainfall.

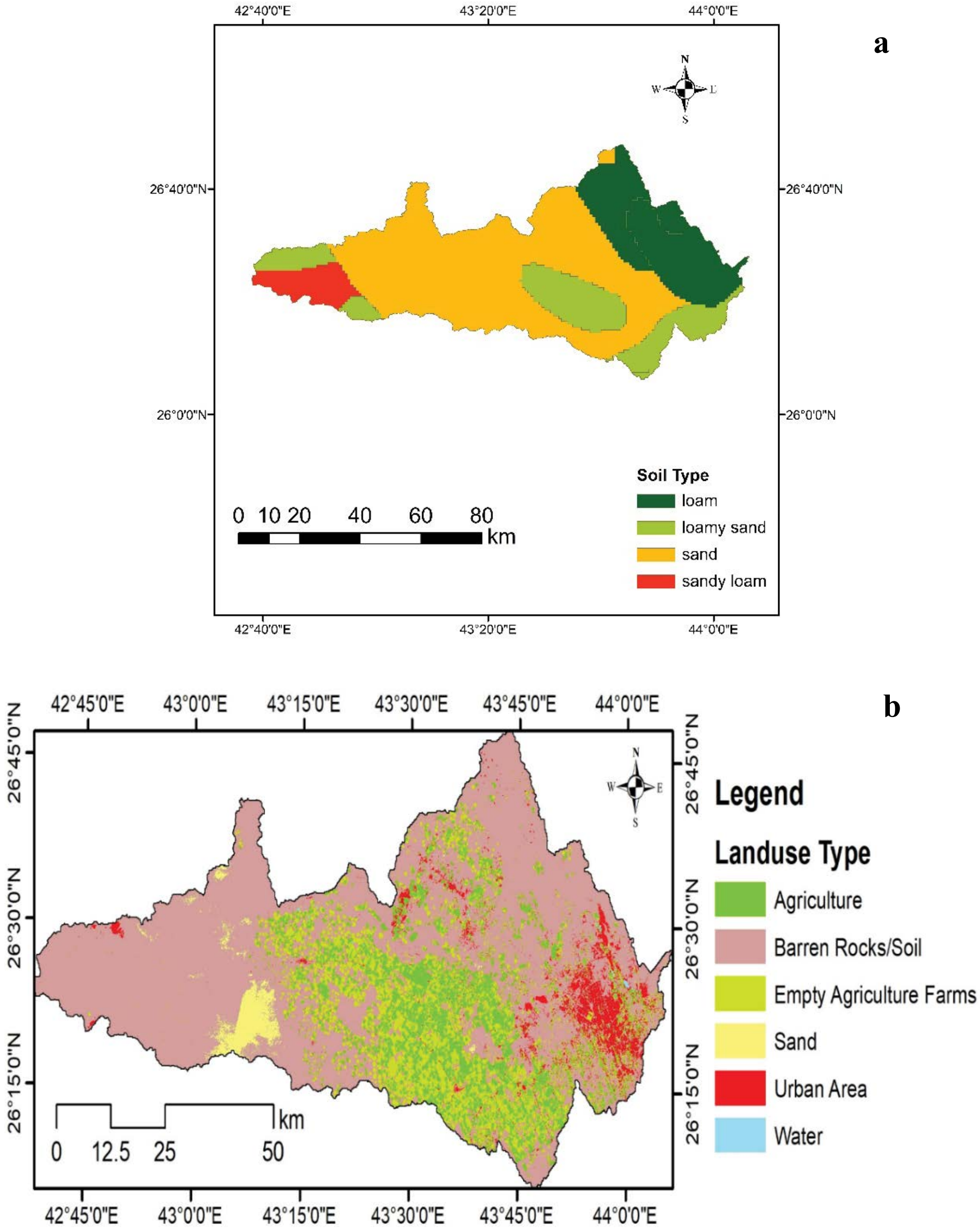

Fig. 4. (a) soil type map, (b) land use map.

has an impact on hydrological processes, leading to a reduction in the amount of water that seeps into the groundwater and an increase in the amount of water that flows off the surface.

The results of this research might assist land-use developers and government agencies in implementing efficient flood control measures to mitigate the risks associated with flash flooding. The flood risk map may inform decisions on the location of settlement zones, dams, and other flood control measures. The suggested model may assist authorities in determining optimal places for constructing structures and restricting the establishment of new buildings in areas susceptible to flooding.

In this work, HEC-RAS was used to perform two-dimensional hydraulic modeling to assess the success

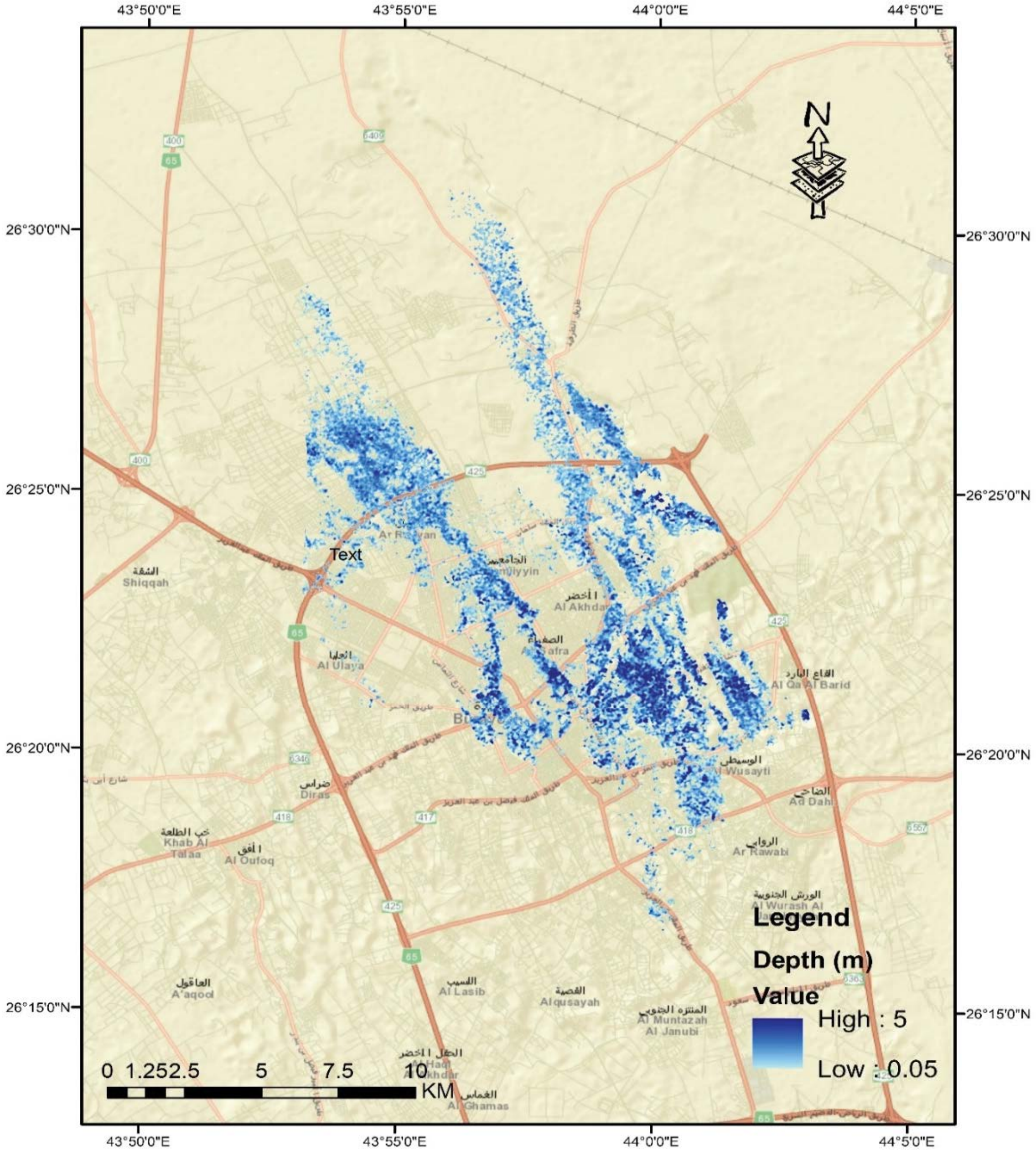

Fig. 5. Water runoff depth from a 2D HEC-RAS model with a 100 y return period.

and forecast proportion of the flood danger map. We validated the model by comparing the water runoff depth map from the HEC-RAS model to the acquired flood probability maps.

The extent of the flood zone for a return period of 100 y is shown, and the depth of water discharge is plotted to describe the level of risk. As shown in Fig. 5, which shows the expected depth of water runoff due to a rainstorm for a return period of 100 y, this can help protect areas within the watershed. As shown, the depth of surface runoff ranges between 0.05 and up to 5 m in very few places especially in pond zones.

6. Conclusions and recommendations

The research area identifies slope, rainfall, drainage density, land use/land cover (LU/LC), soil composition, and elevation as the primary parameters associated with designating flood zones. Regions characterized by loose wadi deposits exhibit elevated rates of infiltration and possess significant groundwater potential, whereas places dominated by huge hard-rock formations experience substantial surface runoff. Areas with extracted drainage and high drainage density exhibit elevated surface runoff and less infiltration.

AHP, paired with GIS, can successfully address complicated difficulties inside broad regions. When integrated with the GIS framework, AHP may be used as an alternative method for generating flood inundation in watersheds. In this work, the AHP approach was used to generate flood hazard maps. These maps serve as vital instruments for community leaders to clearly communicate the dangers of flooding and formulate emergency preparedness measures for different target populations, especially those living in high-risk areas. Subsequent research will examine and ascertain the most significant elements, and the examination will be broadened to include a comprehensive exploration of computer technologies, such as artificial neural networks (ANNs) and machine learning methods, for the anticipation of flood risks in the watershed.

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Balaban Desalination Publications

The 15th Gulf Water Conference

(2024) 141–145
doi: 10.5004.dsal.2024.700031

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Atmospheric water generation in Qatar: a sustainable approach for extracting water from air powered by solar energy

Aiyad Gannan

Department. of Mechanical Engineering University of Doha for Science and Technology, Doha, Qatar, email: aiyad.gannan@udst.edu.qa

ABSTRACT

In alignment with Qatar National Vision 2030's commitment to sustainable energy and a clean environment, this study is being carried out to review and investigate several sustainable water harvesting techniques from atmospheric humidity, fog, and dew. This investigation will show how well different fog/dew collectors function in collecting water. Furthermore, a feasibility study will be carried out to obtain the technical details of the fog collector and efficiency enhancements. Of course, the prevalence of fog globally restricts fog harvesting technologies. Dew water harvesters, on the other hand, are universally accessible but call for a cooled condensing surface. The dew water collection systems will also be investigated in this study. The main goal of all these strategies is the creation of an atmospheric water collector that can produce water regardless of the humidity level, location, cost, or materials available. This project aims to adapt the Atmospheric Water Harvesting (AWH) system design and material to ensure excellent performance and reliability of AWH in harsh conditions such as in Qatar. It will be particularly focused on the development of a passive system. High-efficiency solar cell technologies are proposed here as selected candidates for desert AWH development. Furthermore, a comprehensive Technoeconomic Environmental Risk Analysis (TERA) study will be conducted to investigate the cost-effectiveness of the proposed solar-powered AWG, compared to the desalination power plant and assess the environmental footprint of the solar-powered AWG system, considering water usage, carbon-based emissions, and other relevant factors.

Keywords: Atmospheric water harvesting; Material; Passive system; Solar energy; Sustainability

1. Introduction

This study was carried out to investigate and evaluate various sustainable water collection techniques from air fog and dew [1]. This review study will show how well different fog/dew collectors throughout the world work at collecting water. Furthermore, a feasibility study should be investigated in more technical details of the fog collector and efficiency enhancements. Innovations in modern fog harvesting are frequently based on biotechnology.

Of course, the prevalence of fog globally restricts fog harvesting technologies. Dew water harvesters, on the other hand, are universally accessible but call for a cooled condensing surface. The dew water collection systems will also be investigated in this study.

* Corresponding author.

The main goal of all these strategies is the development of an atmospheric water collector that can create water regardless of the humidity level, location, cost, or materials available.

This project aims to adapt the Atmospheric Water Harvesting (AWH) system design and material to ensure excellent performance and reliability of AWH in harsh conditions such as Qatar [2]. This research will be particularly focused on the development of passive systems [3]. High-efficiency solar cell technologies are proposed here as selected candidates for desert AWH development [4].

The obtained knowledge will be the basis for the development of a new candidate system for desert AWH with enhanced reliability and later transferred to local and international standards and certification of desert systems [5]

For the outdoor AWH performance assessment and reliability, AWH will be installed in real operating conditions at the UDST.

2. Objectives

- Design a reliable AWH with high water production suited for high RH and temperature
- Benchmark high standards for testing desert AWH systems
- The proposed research project is expected to improve the fabrication of AWH and develop a low-cost, high-production concept that suits GCC conditions.
- The project opens new opportunities for further development of the technology and materials for desert-specific AWH in this constellation also after finishing the project (networking).
- Reduce the carbon footprint with every sip (Fig. 1)
- Water is uncompromising on quality, safety, accessibility, and sustainability.
- Reinventing drinking water with technology that keeps both people and the planet healthy and thriving.

Sustainable Development Goals More water, less plastic:

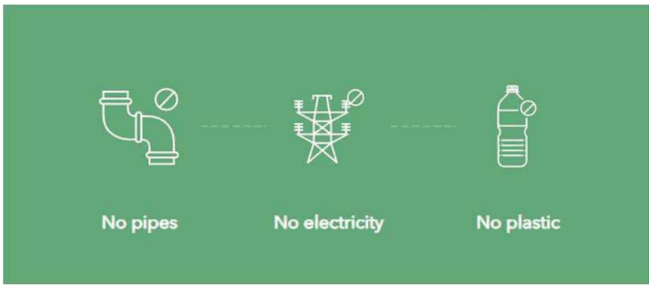


Fig. 1. Environmental impact.

- Mission: Provide access to quality drinking water, at low cost, in a sustainable way, and situations without access to water or energy supply
- Vision: Develop knowledge of heat transfer, control, and water treatment technologies; to implement reliable solutions for the distributed generation of drinking water
- Values: Technology, Innovation, Sustainability.

3. Methodology

This technology works in as little as 10% RH and requires ZERO electricity as the panels are completely self-powered. With 80% RH in Qatar, the overall efficiency of this system and the output are expected to be higher.

The output from the panels is purified, mineralized drinking water that requires no additional filtration or processing. This can be achieved by using a passive condensation technology [6,7].

The overall idea is that a combination of solar electric power harvested through a PV panel can be used as well as solar thermal power to heat the air as it passes through the system and then enters a cooler area and condenses [8].

Once the water is condensed it is collected in a reservoir that circulates the water through an ozonation machine to ensure sterility. Minerals are added to give the health and taste benefits [9].

This Hydropanel shown in Fig. 3 is powered by an integral combination of solar photovoltaics and high-efficiency solar thermal. Moreover, in some of the world's driest deserts, electrical and thermal energy is employed to produce water in an efficient modified psychrometric cycle.

Fig. 2. AWH sustainable development.

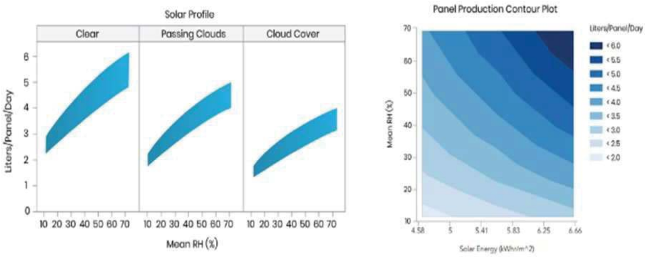
Fig.3. AWH powered with solar.

How does it work?

- It draws in ambient air through fans and gathers water vapor from it onto a hygroscopic substance using solar PV.
- With heat from the sun, it converts water vapor collected into liquid water, made pure
- The water vapor is extracted and passively condenses into liquid
- The pure water is mineralized with magnesium and calcium to achieve an ideal taste profile
- Hydro panels are plumbed to a Home Reservoir or Access Station where the water can be accessed
- Hydro panels are monitored in real-time for production and water quality
- It is fully self-sustained and off-grid.

As can be seen in Fig. 5, the process can be summarized as follows:

- The desiccant bed will absorb moisture from humid air during the first stage of the water absorption process, which occurs at night
- The second stage is water desorption during the day by heating the bed with solar radiation, which will regenerate the desiccant by driving out water vapor.
- The evaporated water will then be condensed into water droplets in the third and final stage, and collected in a tank.



AQ1 Fig. 4. Humidity effect on AWH.

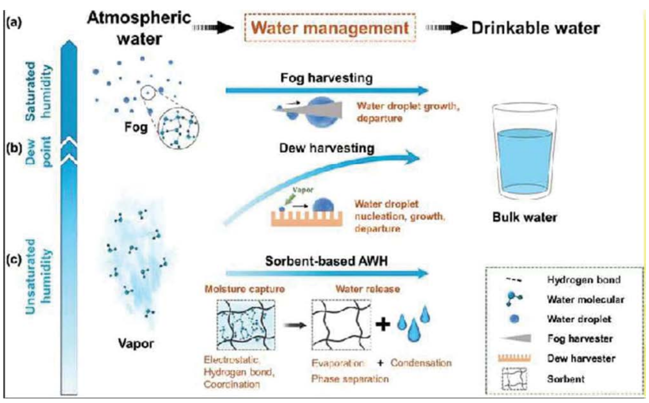


Fig. 5. AWH process.

Hydropanel is a solar-powered technology that needs only sunlight and air to make drinking water. It can be installed on the roof or the ground and extracts water vapor from the air to make, mineralize, and deliver drinking water to a tap or dispenser. Uniquely independent of infrastructure, this technology will be capable of making high-quality, delicious drinking water without plugging into an additional electric or water supply. Its purpose is to make water from the air.

4. The technology landscape

The field of atmospheric water harvesting can be broken down into two primary methods: condensation and absorption. Condensation works by using a machine that acts like a dehumidifier, pulling in air, filtering it, and cooling it until the water condenses. Although this method can produce a large amount of water, it can be energy-intensive and may require high temperatures and humidity levels to function effectively. In comparison, the absorption process involves passing air over a material that captures the water, which is then heated to extract the moisture. This method is typically more energy-efficient but currently has a limited daily output.

Recent advancements in the sector are improving the efficiency of both methods. A notable example is Drupps, a company specializing in atmospheric water generation that uses a patented heat exchanger made from food-grade polymer. This system has the advantage of producing water with no metal contamination, and can reportedly generate water even in low temperature and humidity conditions, although the yield may be reduced. Some companies now offer a range of machines that can produce up to 10,000 L of water per day, which works with the condensation-based method.

4.1. The headline opportunities

AWHs can already produce water more cheaply than the bottled water industry and without the vast plastic waste. Exploiting mobile water and industrial opportunities can depend upon improved energy efficiency (see Fig. 7).

Fig. 6. Atmospheric water generation.

4.2. The heat and humidity distributions

AWHs, especially those that use the condensation process, often need a relative humidity of at least 60% to function properly. As the map below shows, ideal conditions for AWHs do not always correlate with the most water-stressed areas, such as central Africa, central Asia, and the southwest United States (see Fig. 8).

4.3. Terminology

Absorption: A method of atmospheric water harvesting where air is passed over a highly absorbent material that traps moisture, which is then heated to extract the water.

Atmospheric water generator: A machine that collects moisture from the air and converts it into potable water using either the condensation or absorption process.

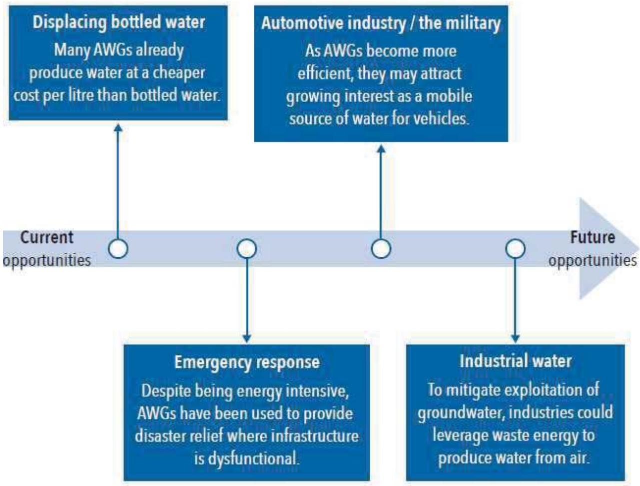


Fig. 7. The important future of AWH.

Condensation: The most commonly used method of atmospheric water generation. It works by drawing air into the machine, and filtering and cooling it until the water condenses.

Desiccant: A substance used to absorb moisture and act as a drying agent, and is the opposite of a humectant.

Metal-organic frameworks: Highly porous compounds created by linking inorganic and organic components with strong bonds. They are used in the absorption process of atmospheric water generation.

5. Conclusion

This project aims to adapt the Atmospheric Water Harvesting (AWH) system design and material to ensure excellent performance and reliability of AWH in harsh conditions such as in Qatar. It will be particularly focused on the development of a passive system. High-efficiency solar cell technologies are proposed here as selected candidates for desert AWH development. The obtained knowledge will be the basis for the development of a new candidate system for desert AWH with enhanced reliability and later be transferred to local and international standards and certification of desert systems.

This research will contribute to the understanding of atmospheric water harvesting and its potential as a sustainable water source in desert environments. The study will provide valuable information on the feasibility of atmospheric water harvesting in desert environments. It will be also demonstrated to identify the factors that influence the ability to collect water from the air and determine the most promising locations for further study. Furthermore, an intensive study will be conducted to evaluate the performance of different technologies and identify which ones have the greatest

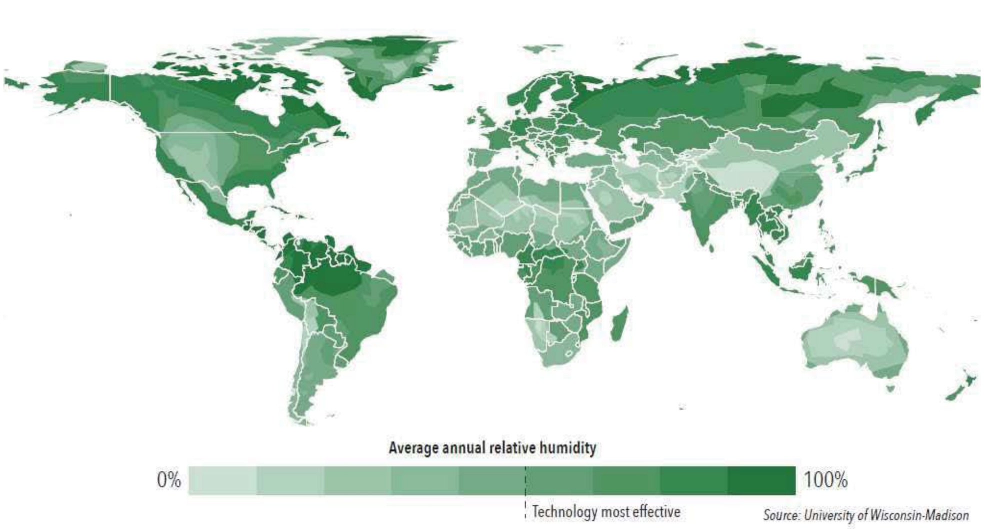


Fig. 8. Map of humidity distributions in the world.

potential for providing a sustainable source of water in desert environments.

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Balaban Desalination Publications

The 15th Gulf Water Conference

(2024) 146–152
doi: 10.5004.dsal.2024.700086

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Assessment of groundwater suitability for drinking and irrigation purposes using physicochemical parameters at Al-Jouf Area, Saudi Arabia

Raid Alrowais[1,*], Mahmoud M. Abdel Daiem[2]

[1]*Department of Civil Engineering, College of Engineering, Jouf University, Sakakah 72388, Saudi Arabia,*
[2]*Environmental Engineering Department, Faculty of Engineering, Zagazig University, Zagazig 44519, Egypt, Tel.: +966 502229973, email: rnalrowais@ju.edu.sa*

ABSTRACT

Al-Jouf region is one of the most agricultural areas in Saudi Arabia. Due to the increase in drinking and irrigation water requirements in this region, there is an urgent interest in studying groundwater quality. Thus, the main aim of this study is to analyze the physicochemical parameters of groundwater in the Al-Jouf region for irrigation and drinking purposes. Thus, this study investigated some parameters including total dissolved solids (TDS), pH, electric conductivity (EC), hardness, and various anions and cations were compared with national and international standards. The groundwater quality index (WQI) was estimated to evaluate the suitability of groundwater for drinking purposes. The electric conductivity (EC), sodium percentage (Na^+ %), magnesium hazard (MH), sodium adsorption ratio (SAR), potential salinity (PS), and Kelley's ratio (KR) were assessed to evaluate the suitability of groundwater for irrigation. The results of the water quality analysis showed the suitability of groundwater in most parts of the studied area for drinking and irrigation use except that of the Al Qaryat region. Moreover, the groundwater was dominated by alkali metals and controlled by rock–water interaction domain, and the ionic abundance ranking was $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ for cations, and $Cl^- > SO_4^{2-} > NO_3^-$ for anions.

Keywords: Groundwater; Drinking water; Irrigation

1. Introduction

Escalating water demand in Saudi Arabia, fueled by population growth and agricultural expansion, has led to increased reliance on seawater desalination and groundwater extraction, catering to various purposes including drinking, industry, and irrigation. Unfortunately, human activities have markedly degraded groundwater quality, introducing contaminants like sulfate, magnesium, CO_2, sodium, and chlorine, posing significant health and environmental risks [1–15].

Strict adherence to irrigation and drinking water quality standards established by national and international benchmarks such as Saudi Standards, Metrology and Quality Organization (SASO), Bureau of Indian Standards (BIS), and World Health Organization (WHO) has become pivotal [16–18]. The Water Quality Index (WQI) serves as a fundamental tool in evaluating water quality against these established criteria [19]. Additionally, assessing groundwater quality for irrigation requires the utilization of diverse indicators like electric conductivity (EC), sodium percentage (Na^+ %), magnesium hazard (MH), potential salinity

* Corresponding author.

(PS), sodium adsorption ratio (SAR), and Kelley's ratio (KR) [20–22].

Multiple studies across different regions in Saudi Arabia have scrutinized groundwater quality for agricultural and drinking purposes, emphasizing natural factors impact on groundwater contaminants [1–5,22,23]. In the Albaha region, most wells, exceeding two-thirds, were deemed unsuitable for both drinking and irrigation [4]. Similarly, in the Khulais region of Makkah Province, most groundwater sources were considered unsuitable for irrigation [1]. However, in Jazan, the groundwater adheres to acceptable standards for drinking and household use [23]. Conversely, in Salilah village, Madinah Munawara, the groundwater was deemed suitable for irrigation but unsafe for drinking [22].

Al-Jouf region, crucial for agriculture in Saudi Arabia, is experiencing heightened demands for drinking water and rapid agricultural expansion, necessitating an urgent and comprehensive inquiry into its groundwater quality, which has seen limited prior research. This investigation involves assessing key physical and chemical groundwater parameters, including the WQI, against established national and global standards. Statistical methodologies will explore correlations between these parameters. Al-Jouf's geological diversity encompasses diverse lithological units like the Sirhan formation with various materials such as calcareous sandstone, limestone, and shale. The Upper Tertiary and Quaternary strata at Harrat al Harrah comprise flood basalts overlying the Sirhan Formation. However, defining boundaries within Quaternary deposits, including calcareous duricrusts, gravel, eolian sand, alluvium, and sabkha deposits, is challenging due to their fused nature. The region features unconsolidated gravel, eolian sand, and alluvium. The extensive calcareous duricrust appears as weathered formations resembling large limestone structures. Eolian deposits exhibit diverse dune formations, moving in response to prevailing wind patterns. Basins contain significant alluvial deposits of silt, sand, and gravel with varying compositions. Elongated sabkhas, formed from interbedded materials, align along the northeast axis of the Wadi as Sirhan [3].

2. Material and methods

The research methodology (Fig. 1) commences by collecting water samples from groundwater wells, which are then meticulously analyzed in the laboratory. This analysis entails evaluating ions and cations, measuring pH levels, and determining salt concentrations within the samples. Subsequently, these findings were compared against both local and global standards to verify the compliance of the water samples with established regulatory thresholds.

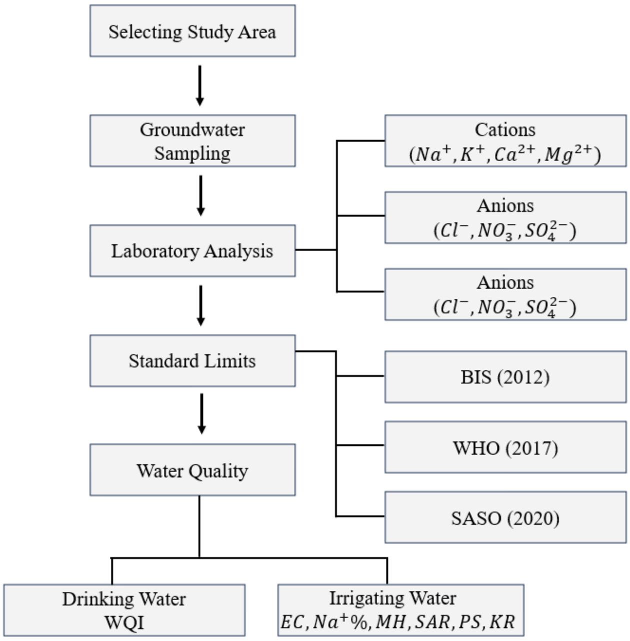


Fig. 1. Research methodology of the current study.

2.1. Water sampling and analysis

The research focused on the irrigated zones of Al-Jouf in KSA, where a total of forty-seven groundwater samples were gathered from farms of varying sizes (5–100 hectares), as illustrated in Figs. 2a and 2b. Well, depths ranged from 100 to 300 m. To ensure sample representation, the collection process lasted 2–3 hours per farm. Each well provided a 300 mL sample stored in sealed sterile plastic containers and refrigerated until laboratory analysis. The samples underwent analysis using ICP-OES (Agilent Technologies, Santa Clara, United States) for cation concentrations (Ca^{2+}, Na^+, K^+, and Mg^{2+}), while anion levels (Cl^-, SO_4^{2-}, and NO_3^-) were determined via ion chromatography (Dionex, ICS 1600, Thermo Scientific, Santa Clara, United States). Furthermore, pH, EC, total dissolved solids (TDS), and hardness were assessed using the Orion 5-star plus instrument (Thermo Scientific, Santa Clara, United States), with three measurements taken per sample to compute average values.

2.2. Water quality index

2.2.1. Drinking purpose

The evaluation of groundwater suitability for drinking purposes relied on the computation of a Groundwater Quality Index (WQI) using the prescribed drinking water standards established by BIS and WHO. Ten key physicochemical parameters were considered in the computation of the WQI, as outlined in Table 1. The methodology employed in determining

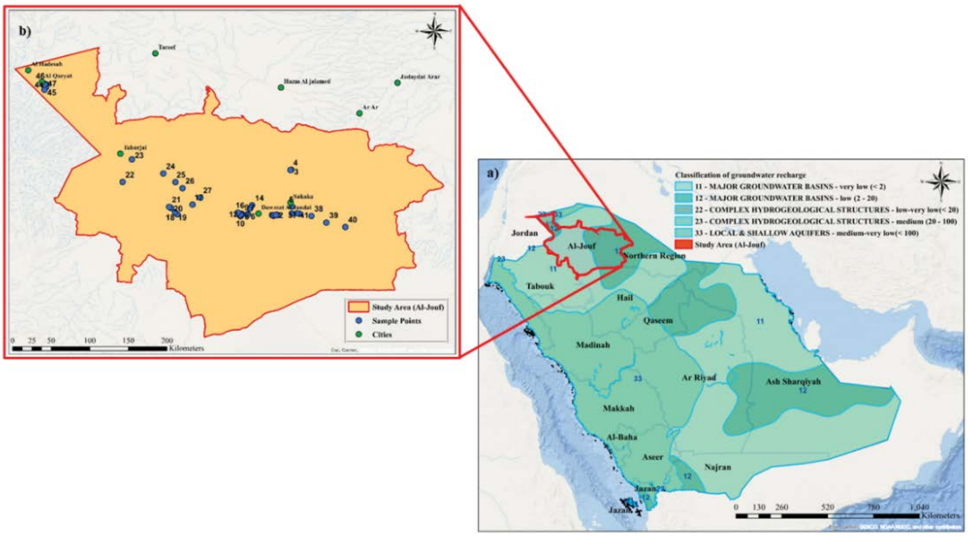


Fig. 2. Map of (a) groundwater resources in KSA and (b) water sample locations at Al-Jouf region [23,24].

Table 1
Weight and relative weight of the used parameters and desirable values for BIS and WHO

Parameters	Weightage (w_i) [10]	Relative Weigh (W_i)	Desirable Values	
			BIS [16]	WHO [17]
pH	3	0.09	8.50	8.50
TDS (ppm)	4	0.09	500	500
Hardness (ppm)	3	0.09	200	100
Ca^{2+} (ppm)	3	0.09	75	75
Na^{+} (ppm)	2	0.06	200	200
K^{+} (ppm)	2	0.13	12	12
Mg^{2+} (ppm)	3	0.06	30	50
Cl^{-} (ppm)	4	0.13	250	200
SO_4^{2-} (ppm)	3	0.09	200	200
NO_3^{-} (ppm)	5	0.16	45	50
	$\sum w_i = 32$	$\sum W_i = 1$		

the WQI aligns with procedures detailed in prior research [20].

2.2.2. Irrigation purpose

To ascertain the appropriateness of groundwater for irrigation applications, crucial groundwater quality parameters including EC, Na^{+} %, SAR, MH, KR, and PS were computed employing methodologies outlined in prior studies [20,25–28] through the following equations:

$$Na^{+}\% = \frac{Na^{+} + K^{+}}{Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}} \times 100 \quad (1)$$

$$MH = \frac{Mg^{2+}}{\left(Ca^{2+} + Mg^{2+}\right)} \times 100 \quad (2)$$

$$SAR = \frac{Na^{+}}{\sqrt{\left(Ca^{2+} + Mg^{2+}\right)/2}} \quad (3)$$

$$PS = Cl^{-} + \frac{1}{2} SO_4^{2-} \quad (4)$$

$$KR = \frac{Na^{+}}{\left(Ca^{2+} + Mg^{2+}\right)} \quad (5)$$

2.3. Multivariate statistical techniques

Statistical analysis was conducted using MS Excel and Statistical Package for Social Sciences (SPSS 22.0). Essential statistical parameters including Minimum (Min), Maximum (Max), Mean, and Standard Deviation (SD) were computed for each parameter. The term "hydrogeochemical facies" denotes the chemical characteristics of water solutions within systems. Diverse methods, including statistical and graphical analyses, are available to interpret groundwater hydrogeochemistry. However, Gibbs and Piper's diagrams are widely employed for developing hydrogeochemical facies [20]. Hence, these diagrams were utilized to assess similarities and disparities in water composition, aiding in the classification of distinct chemical types.

3. Results and discussion

3.1. Groundwater parameter analysis

Groundwater's potability for drinking was evaluated against BIS, WHO, and SASO standards [16–18]

(Table 2). Ca^{2+} levels averaged 103.93 ppm, within the acceptable limit of 200 ppm except in the Al Qaryat region. Na^{+} concentrations averaged 275.74 ppm; most samples met the recommended threshold (<200 ppm), except for high values in Al Qaryat. K^{+} averaged 23.88 ppm, with over 50% exceeding the 12 ppm limit. Mg^{2+} averaged 59.94 ppm, except for elevated levels in Al Qaryat (>150 ppm limit). SO_4^{2-} and NO_3^{-} levels were below limits, but elevated NO_3^{-} poses health risks. Cl^{-} levels were below permissible limits, affecting taste but not health. Groundwater hardness was suitable, apart from elevated levels in Al Qaryat. pH and EC aligned with standards, but high TDS levels in Al Qaryat suggested increased salinity.

3.2. Hydrogeochemical facies

In this study, the Piper diagram illustrates the categorization of samples into sodium and potassium types, as presented in Fig. 3a. Furthermore, the Gibbs plot serves to elucidate hydrochemical processes such as precipitation, rock-water interaction, and evaporation in groundwater chemistry [32]. The plotted ratio of major anions computed using Eqn. (6) against TDS values indicates the mechanism that governs groundwater composition, as depicted in Fig. 3b.

$$\text{Major anions} = \frac{Na^{+} + K^{+}}{\left(Ca^{2+} + Na^{+} + K^{+}\right)} \quad (6)$$

The outcomes indicate that most samples fall within the water-rock interaction category, with a few showing characteristics of the evaporation category. This signifies that the quality of groundwater was notably impacted by the chemical weathering of subsurface rock minerals due to water movement beneath the surface. Samples found in the evaporation category could be linked to semi-arid climate conditions and various surface sources of pollution like heavy fertilizer usage, irrigation runoff, industrial effluents, and domestic discharges. This aligns with earlier research findings [20,31,32].

3.3. Assessment of groundwater quality for drinking

The calculated Water Quality Index (WQI) values varied between 14.80 to 897.61 (average: 112.78) for BIS standards and between 5.64 to 1050.84 (average: 129.07) as per WHO standards. WQI classifications include five types: excellent (>50), good (50 to 100), poor (100 to 200), very poor (200 to 300), and unsuitable for drinking (<300) [29]. Fig. 4 displays representing WQI based on WHO and BIS standards. According to WHO criteria, fifteen samples (31.91% of the total) fall into the excellent category, while twenty-one samples (44.68%) represent good water quality for drinking, depicted in Fig. 4a. Under BIS criteria, twenty-one samples (44.68%) were considered excellent, and sixteen samples (34.04%) were classified as good for drinking water, as illustrated in Fig. 4b. However, the water from the Al Qaryat region exhibited WQI values exceeding 300, indicating its unsuitability for drinking purposes.

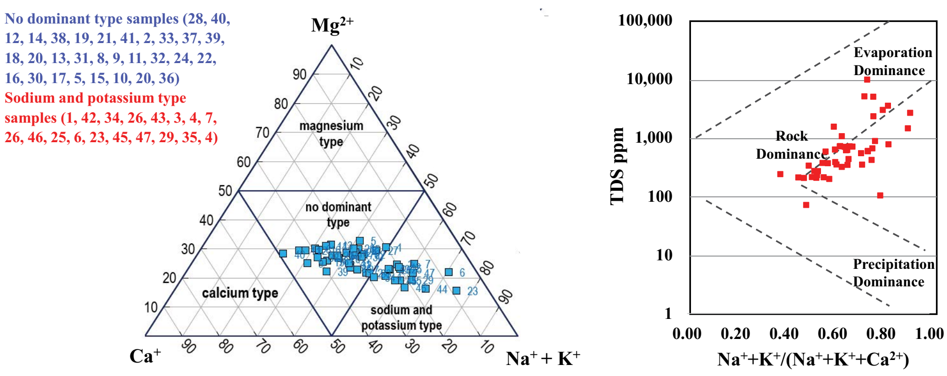
3.4. Assessment of groundwater quality for irrigation

Groundwater suitability for irrigation can be assessed through parameters like EC, Na^{+} %, MH, SAR, PS, and KR, delineated in Table 3 to classify their viability for irrigation. Electrical Conductivity (EC) indicates dissolved salt concentrations, signaling potential

Table 2
Descriptive statistical for physicochemical parameters and standard limits for drinking use

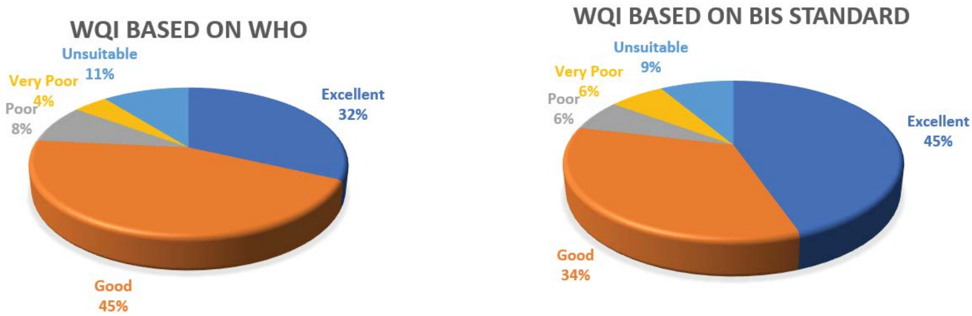
Sample	Unit	Min	Max	Mean	SD	BIS [16]		WHO [17]		SASO [18]	
						D	P	D	P	D	P
pH	–	6.92	8.46	7.74	±0.34	6.5	8.5	6.5	8.5	6.5	8.5
EC	(µS/cm)	142.00	19,470.00	2194.47	±3483.80	–	–	–	–	–	–
TDS	(ppm)	71.00	9730.00	1090.40	±1723.08	500	2000	500	1500	1000	–
Hardness	(ppm)	26.82	4594.32	506.36	±803.91	200	600	100	500	–	–
Ca^{2+}	(ppm)	5.30	1010.40	103.93	±172.86	75	200	75	200	200	–
Na^{+}	(ppm)	5.30	2815.10	275.74	±519.32	–	200	–	200	200	–
K^{+}	(ppm)	1.60	138.30	23.88	±29.14	–	12	–	12	–	–
Mg^{2+}	(ppm)	3.10	503.00	59.94	±91.71	30	100	50	150	150	–
Cl^{-}	(ppm)	0.17	61.65	4.77	±10.06	250	1000	200	600	250	–
SO_4^{2-}	(ppm)	0.30	19.96	3.06	±4.55	200	400	200	400	250	–
NO_3^{-}	(ppm)	0.12	0.91	0.30	±0.21	45	–	50	–	50	–

Note(s): D: Desirable limits. P: Permissible limits.



(a) (b)

Fig. 3. Hydrogeochemical facies for the classification of groundwater (a) Piper diagram and (b) Gibbs plot.



(a) **(b)**

Fig. 4. WQI according to (a) WHO and (b) BIS standards.

Table 3
The classification of groundwater for irrigation purposes based on these parameters (EC, Na^+ %, MH, SAR, PS, and KR)

Parameter	Range	Classification	Number of Samples	Percentage of Sample (%)
EC μS/cm	<700	Excellent	17	36.17
	700–3000	Good	22	46.81
	>3000	Fair	8	17.02
Na^+ %	<20	Excellent	0	0.00
	20–40	Good	3	6.38
	40–60	Permissible	27	57.45
	60–80	Doubtful	15	31.91
	>80	Unsuitable	2	4.26
MH	<50	Excellent	45	95.74
	>50	Unsuitable	2	4.26
SAR	<10	Excellent	17	36.17
	10–18	Good	1	23.40
	18–26	Doubtful	9	19.15
	>26	Unsuitable	10	21.28
PS	<3	Excellent to good	30	36.17
	3–5	Good to injurious	7	23.40
	>5	Injurious to Unsuitable	10	21.28
KR	<1	Excellent	23	48.94
	>1	Unsuitable	24	51.06

salinity risks to crops [20,34]. Around 83% of samples demonstrate excellent to good levels, suggesting favorable conditions for crop growth. Elevated sodium percentages can harm soil structure, with 64% of samples meeting BIS standards by exhibiting Na^+ % values below 60%.

Magnesium Hazard (MH), driven by Ca^{2+} and Mg^{2+}, influences soil pH and crop productivity [35]. Approximately 95.74% of samples show MH values below 50, indicating suitability for irrigation. Sodium Absorption Ratio (SAR) results reveal 36.17% as excellent, 23.40% as good, and 21.28% as posing high sodium hazards, rendering them unsuitable for irrigation, particularly in the Al Qaryat region. Permeability Index (PS) designates 63.83% as excellent to good for irrigation, but 21.28% are unsuitable, primarily from Al Qaryat. Kelly's Ratio (KR) emphasizes 48.94% of samples as suitable for irrigation with values below 1.

4. Conclusions

The comprehensive analysis of physical, and chemical parameters, and the Water Quality Index (WQI) suggests that most groundwater samples in the study area are suitable for both drinking and irrigation, excluding those from the Al Qaryat region. According to WHO standards, 31.91% of samples were excellent, and 44.68% were classified as good for drinking. In line with BIS criteria, 44.68% demonstrated excellence, and 34.04% were categorized as good for drinking. Notably, unsuitable samples for drinking were observed in the Al Qaryat region. The prevalence of ions was ordered as $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ for cations and $Cl^- > SO_4^{2-} > NO_3^-$ for anions. Both Piper and Gibbs diagrams underscored the dominance of alkali metals (K^+ and Na^+) and highlighted the influence of the rock–water interaction process. For irrigation, most samples, except those from Al Qaryat, showed excellent to good EC levels. Na^+% and MH parameters indicated the suitability of 64.00% and 95.74% of samples for irrigation, respectively. SAR results showed that 36.17% were excellent, and 23.40% were good for irrigation. PS and KR outcomes demonstrated the suitability of 63.83% and 48.94% of samples for irrigation, respectively.

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The 15th Gulf Water Conference

(2025) 153–162
doi: 10.5004.dsal.2025.700033

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28–30 April 2024, Doha, Qatar

Evaluating the hydraulic feasibility of brackish groundwater supply for small-scale reverse osmosis plants in community centers in Kuwait

Amjad Aliewi*, Harish Bhandary

Water Resources Development and Management Program, Kuwait Institute for Scientific Research, Water Research Center, P.O. Box 24885, Safat 13109, Kuwait
**email: aaliewi@kisr.edu.kw*

ABSTRACT

The efficient operation of small reverse osmosis units in community centers in Kuwait necessitates a minimal supply of brackish groundwater with suitable water quality standards. Specific requirements were established for a public center in Al-Salmeyeh, Kuwait, demanding a brackish groundwater supply of 250 m^3/h with suitable quality parameters (TDS less than 15,000 mg/l and free from contamination). This volume should be extracted without inducing significant drawdowns. The methodology employed combined pumping tests and numerical modeling to evaluate the impact of pumping activities on water levels. Analysis of pumping tests revealed an average transmissivity of 292 m^2/d and a specific yield of 12%, indicating promising replenishment potential. However, due to formation damage around the wellbores, the total pumping rate achievable from the six wells (without well development) amounted to 215 m^3/h, falling short of the required 250 m^3/h. Nonetheless, the maximum drawdown observed after 5 d of continuous pumping stood at 8.04 m, well within the acceptable effective drawdown limit of 14 m, suggesting favorable hydraulic conditions in the project area. Numerical models were constructed using MODFLOW software to simulate long-term drawdown under simultaneous operation of all wells. It was determined that by operating the pumping rate per well at 50 m^3/h, the necessary water production of 250 m^3/h could be achieved without inducing undesirable drawdowns, with no anticipated significant deterioration in groundwater quality. Salinity analysis indicated levels ranging between 8,000 and 10,000 mg/l, with water classified as Na-SO_4-Cl type.

Keywords: MODFLOW; Small scale RO units; Pumping tests; Community centers; Kuwait

1. Introduction

The evaluation of hydraulic feasibility for utilizing brackish groundwater in small-scale reverse osmosis (RO) plants for community centers in Kuwait requires a comprehensive understanding of various factors including groundwater availability, quality, and treatment processes. Kuwait in particular and the GCC countries in general are characterized by limited freshwater resources (Al-Rashed et al., 2023), making brackish groundwater a significant alternative for water supply. Studies such as Tariq et al. (2022) provided insights into the distribution, quality, and potential utilization of brackish groundwater in Kuwait. Understanding the geological formations and hydrogeological condi-

*Corresponding author

ISBN 0-86689-078-5

tions (Al-Senafy, 2001; Al-Ruwaih, 2018) is crucial for assessing the feasibility of groundwater extraction for RO plants. The contamination level in brackish groundwater resources determines the suitability (Lalumbe et al., 2022) of using these resources for water supply to RO units. Several studies have evaluated the feasibility of small-scale RO plants for community water supply (Grag and Joshi, 2014). Assessing the efficiency of small to medium-scale RO desalination units to produce potable water for local purposes such as drinking and gardening (Schallenberg et al., 2014). The use of reverse osmosis (RO) membranes is becoming more suitable technology for desalination of groundwater due to their strong separation capabilities (Pangarkar et al. 2011). However, the RO process in order to be efficiently operated should have a continuous supply of groundwater with no contamination problems. Similarly, studies in neighboring Gulf countries, such as those conducted by Kariman et al. (2023) provided insights into the challenges and opportunities of implementing RO technology in community water projects. The utilization of RO technology for desalination of brackish groundwater has been extensively studied. Research by Elimelech and Phillip (2011) offers a comprehensive overview of RO processes, membrane materials, and system design considerations. Additionally, advancements in membrane technology, energy efficiency, and pretreatment methods are discussed by Shannon et al. (2008), highlighting the continuous improvements in RO systems. The sustainability of brackish groundwater extraction and RO desalination involves environmental considerations and energy requirements. Research by Jones et al. (2019) examines the energy and water integration in desalination processes, emphasizing the importance of energy-efficient technologies and renewable energy integration. Furthermore, studies by Elsaid et al. (2020) discuss the environmental impacts and mitigation measures associated with brackish groundwater abstraction and desalination activities. The successful implementation of RO plants in community centers necessitates supportive policy frameworks and effective governance structures. Research by Mohamed et al. (2020) explore the policy implications and regulatory frameworks for water desalination projects in the Gulf Cooperation Council (GCC) countries, providing insights into policy interventions and institutional arrangements for sustainable water management. Because of limited and mostly brackish groundwater resources and low rainfall rates, the prosperous future of Kuwait without desalination is being jeopardized (Al-Qallaf et al., 2020; Al-Rashed and Aliewi, 2018). The issue with brackish groundwater resources in Kuwait lies in the deterioration of their water quality due to unregulated water supply schemes for desalination and irrigation purposes (Greenlee et al., 2009; Sadeqi et al., 2024; Aliewi et al., 2020a, 2021; Aliewi, 1993, 2024a, 2024b).

The Abdulla Al-Salem Cultural Center (ASCC) in Kuwait is planning to extract 250 m^3/h of brackish groundwater from several existing groundwater wells, tapping into the uppermost layer of the Kuwait Group, for use in supplying small-scale reverse osmosis (RO) desalination plants. (Fig. 1.). The constraints for this water supply plan are as follows:

- The extraction rate from each well should not exceed 50 m^3/h, considering that the total depth of each well is 30 m.
- The total quantity of groundwater extracted from all existing wells and used as feed water for the RO units should not exceed 250 m^3/h.
- The salinity of the water must not deteriorate beyond a total dissolved solids (TDS) level of 10,000 mg/l. This ensures that the water quality remains brackish for operational purposes, preventing the salinity of the pumped water from increasing to a saline level over the duration of pumping.

The objectives of this paper are (a) to evaluate the potential of groundwater supply and its quality from the existing wells, one of which serves as a standby, drilled within the upper 30 m of the Kuwait Group Aquifer, to consistently yield 250 m^3/h. (b) Additionally, the paper aims to investigate the permissible limits of water quality for the water utilized from the existing wells within the study area, intended for feeding its RO unit. This paper focuses on the hydraulic feasibility of utilizing brackish groundwater for small-scale reverse osmosis (RO) plants in community centers in Kuwait which was not conducted before. The paper addresses the persistent need to explore alternative water sources to alleviate water scarcity challenges, particularly in arid regions like Kuwait. By evaluating the hydraulic feasibility, the paper contributes to the ongoing discourse on water resource management, offering practical implications for the deployment of RO technology in community settings. Furthermore, the paper's focus on small-scale RO plants underscores the importance of decentralized water treatment solutions, particularly in community centers where access to clean water is essential for public health and well-being. By assessing the viability of brackish groundwater supply, the research opens avenues for sustainable water management practices that can enhance resilience to water scarcity while minimizing environmental impact.

2. Methodology

This research employed a methodology encompassing pumping tests, analytical mathematical methods,

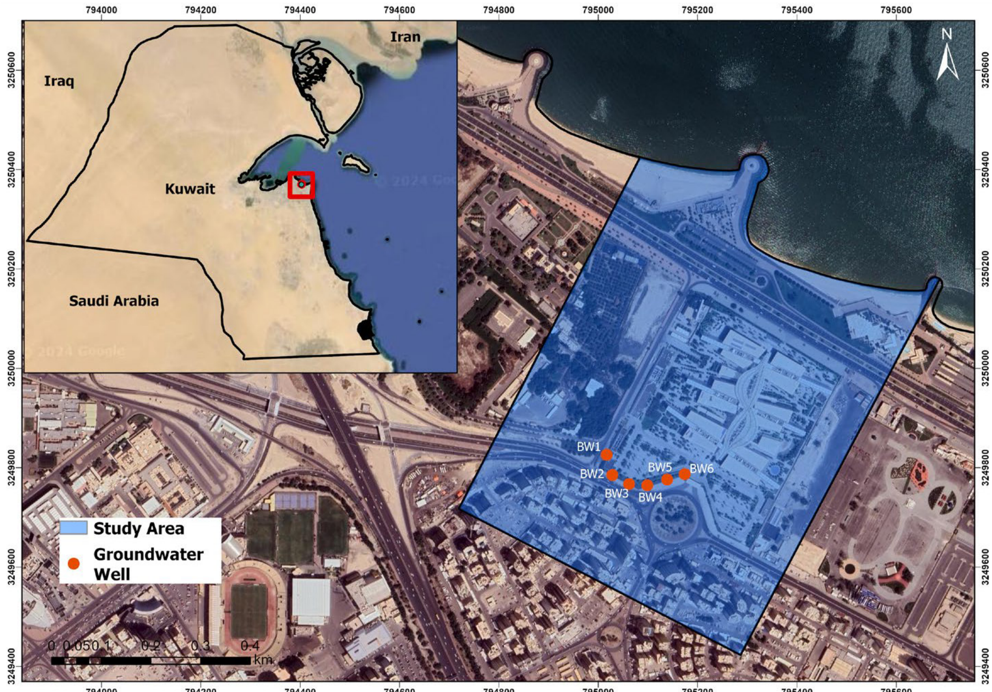

Fig. 1. Existing well locations for RO water supply: study area map.

and numerical modeling to analyze pumping data and groundwater hydraulics in the study area, similar to the approach utilized by Aliewi et al. (2013, 2020b), which has been demonstrated to be effective for assessing groundwater hydraulics in dewatering studies in Kuwait. Achieving the objectives of this study necessitated conducting a water quality sampling campaign supported by chemical analysis to ensure that the existing wells consistently supply brackish water of acceptable quality to the RO units under the yield of 250 m^3/h. Pumping tests were analyzed using AQTSOLV software, while numerical modeling was conducted using Visual MODFLOW (VMF) to assess the impact of pumping on aquifer water level decline in the study area, ensuring that the target aquifer remains above pump settings and is not overexploited. Basic groundwater data concerning existing wells near the project area, such as depth to the water table and hydraulic properties of the upper layer of the Kuwait Group aquifer, were also collected.

3. Results and discussion

3.1. Analytical hydraulic assessment of groundwater supply

The aquifer investigated in the study area is the Kuwait Group Aquifer, comprising sand, gravel, sandstone, clay, and silts, which blanket the entire surface of Kuwait and extend downward to the top of the underlying Dammam Formation. Table 1 illustrates the geologic classification and lithology of aquifers in the study area. The phreatic water table of the Kuwait Group delineates the upper boundary of the flow system. The sediments of the Kuwait Group, the primary focus of this study, have been classified into three classes based on lithology:

- Unconsolidated or very loosely cemented gravel and sand;
- Loosely cemented sand, silt and clay mixtures; and
- Silt and clay, as well as moderately cemented silt and clay mixtures.

The Kuwait Group aquifer in the study area can be categorized into three clastic subunits: (1) Upper aquifer (principal aquifer), (2) Middle aquitard, and (3) Lower aquifer.

The existing wells, totaling about 6 in the study area, only penetrate the upper 30 m of the upper aquifer. Drilling deeper could pose a problem due to hydrogen sulfide (H_2S) gas. The distance between any two wells in the study area is approximately 40 m. When all the existing wells operate simultaneously, they would create an exaggerated drawdown that could impact the production of the required 250 m^3/h for the on-site operation of the RO Unit that goes in line with the assessment of aquifer recharge (Al-Qallaf et al, 2020; Messerchmid and Aliewi, 2022). Several pumping tests were conducted, initially allowing a few wells to operate while monitoring water level changes over time in all wells. This approach aided in determining the hydraulic properties of the utilized aquifer in the study area. Subsequently, all wells were simultaneously put into operation, and the

Table 1
Geologic classification and lithology of aquifers in the study area (Al-Senafy, 2001)

Age	Group	Formation	Aquifer	Lithology
Recent	Kuwait Group	Recent	—	Surface deposits; beach sand, sand, gravel, silt, etc.
Pleistocene		Dibdibba	AQ-1	Coarse sand and gravel, calcretized at lower parts
Miocene		Fars	—	Evaporites, fine sand and clay with fossiliferous limestone
		Ghar	AQ-2	Sand and gravel occasionally calcretized with clay intercalations thicker towards the bottom
Eocene	Hasa Group	Dammam	AQ-3	Upper: chalky dolomicrite chertified at top
				Middle: laminated limestone and dolomicrite with lignetic seams
				Lower: nummulitic limestone with shale at the bottom
Paleocene		Rus	—	Anhydrite with dolomitic limestone
		Umm Radhuma	—	Limestone, dolomite, anhydrite

drop in water levels inside each well over a 24-h period was monitored. The combined effects of pumping all the wells simultaneously on the water level drop were evaluated in the field. Clearly, the number of wells and the geometry of the well field play crucial roles in determining drawdowns. Generally, wells in a well field designed for water supply should be spaced as far apart as possible to minimize interference. However, economic factors such as the cost of land or pipelines may lead to a layout with some level of interference. Operating all wells simultaneously increases the drawdown of the water level due to their close proximity to each other (within the radius of influence of each well). The interface effect estimates the cumulative drawdown effects on wells in the same vicinity. The total drilling depth of each well was 30 m. The critical question was whether 30 m would be adequate to maintain the pumping water level above the pump setting (Fig. 2) particularly when all wells were operated simultaneously. In Fig. 2a, the actual field conditions and well settings ended in locating the pump of the well in the mud section which is a reason of low efficiency of the well. The problem was solved by moving the pump to be located above the mud section as seen in Fig 2b.

Placing the well pump in the bottom section, where mud settles, has posed additional challenges. This includes a reduction in the efficiency of the pumping wells, leading to increased drawdowns within the wells themselves. The pumping investigations showed that water level dropped to 20.68 m bgl and 21.41 m bgl for wells Nos. 1 and 4 respectively. This showed how inefficient well Nos. 1 and 4 were because the mud reached the level of the pump. The problem in the operation of the wells was solved initially by raising the pump set-

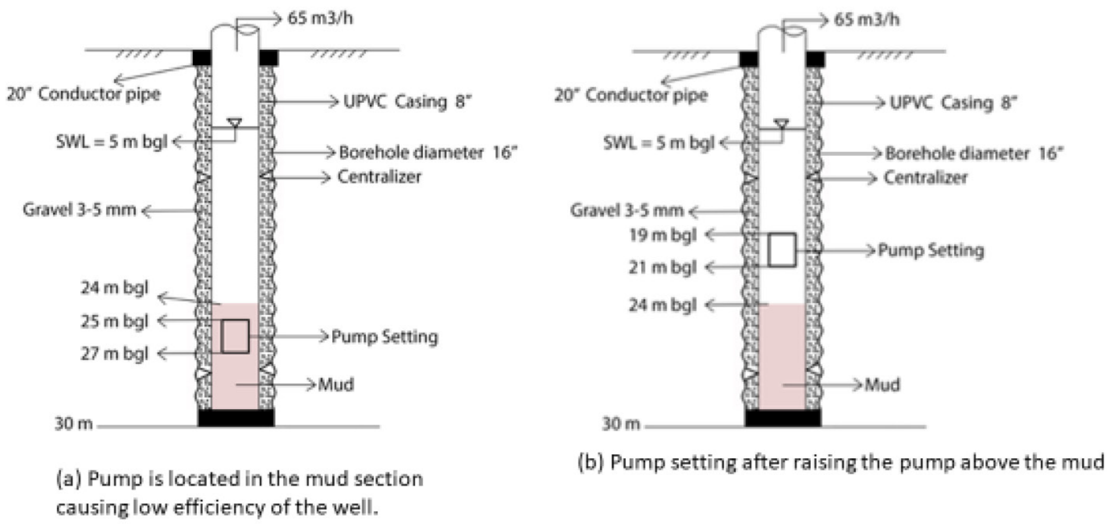

Fig. 2. Pump setting for one typical well in the study area.

ting to 21 to 19 m bgl. Then several pumping tests were conducted in the field. Analytical methods such as Tartakovsky-Neuman (2007) (through the software package AQTESOLV) for unconfined aquifers with some effect of confining clay were used to correlate drawdown, *s* (m) with transmissivity (hydraulic permeability × thickness) ($T = Kb$) (m^2/d), pumping time, *t* (d), storage coefficient, *S* (1) or *Sy* and the distance between the pumping wells and the observation wells distance, *r* (m). From all the aforementioned tests, it was possible to take the average of the results, because, the results come in the same level of significance as follows:

- $T = 292$ m^2/d yielding an average hydraulic conductivity of 9.73 m/d
- $Sy = 0.12$
- $S = 1.7 \times 10^{-3}$

3.2. Numerical modelling of hydraulic assessment of groundwater supply

The Visual MODFLOW software package was utilized to construct a local model of the study area. The grid of the numerical model (Fig. 3) of the study area is 1000 m by 1000 m (1 km^2), represented by 30 rows and 30 columns. The grid cells do not have equal areas, as the model was constructed to be finer near the locations of the pumping wells in the study area to deal with pumping stress with minimal approximation errors. The geometry of the local model for this case study problem covered only the upper part of Kuwait Group Aquifer as one layer. The bottom of this layer was assumed to be the aquitard within Kuwait Group Aquifer and therefore, the bottom of the upper layer of Kuwait Group Aquifer was treated as an impermeable base. Initial water levels were taken from available maps at Kuwait Institute for Scientific Research. Initial hydraulic properties (hydraulic conductivities, specific yield and specific storage) were used as obtained from the pumping tests at the wells in the study area. These values were calibrated later and before running the calibrated numerical model to predict the distribution of water level drawdowns. The southern boundary was simulated as a specified flux/head. The available water level contour maps in the modeled area were utilized to approximate the value of the head boundary to allow certain amount of flux moving from the south to the modelled area. The northern boundary was assigned as a fixed head equals to seal level as it contacts with the sea. The eastern and the western boundaries were assumed as no-flow boundaries, because they are located parallel to the direction of groundwater flow. The recharge from rainfall was approximated at 15 mm/y based on 12% of recharge from effective rainfall (rainfall minus evaporation-runoff). Evaporation was assumed to have a constant value per year to arrive at an effective recharge from rainfall according to Al-Qallaf et al. (2020)

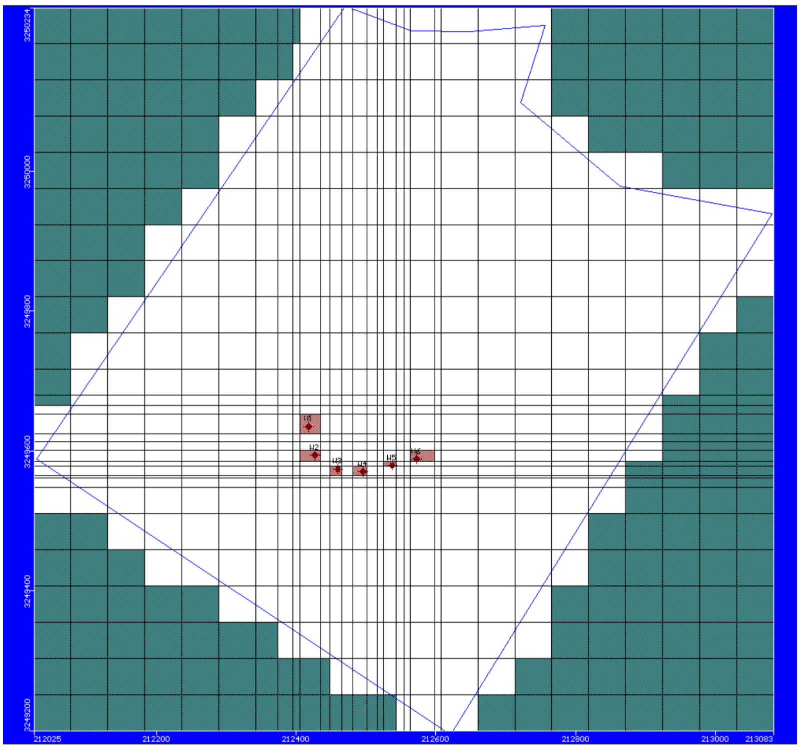

Fig. 3. Grid of the local model showing location of water supply wells.

and Messerchmid and Aliewi (2022). The modeled area included 6 pumping wells for water supply to the RO in Abdulla Al-Salem Cultural Center. The total pumping rate expected from these wells was 250 m^3/h (50 m^3/h from each well, because the sixth well was a standby well. This model aimed to simulate drawdown while operating the existing wells simultaneously, with the objective of determining whether the water level would drop below the pump level, set at 19 m below ground surface (Fig 2b). In this analysis, field data indicated that the maximum drawdown after pumping all five wells simultaneously should not exceed 14 m.

Subsequently, steady-state calibration was performed for the local model (Fig. 4a), revealing a favorable correspondence between the modeled (interpreted) heads and observed heads. Notably, all heads were found to fall within and at the boundaries of the 95% confidence interval, with a correlation coefficient of 0.98 between the modeled and observed heads. The standard error of estimation was a mere 0.13 m.

The spatial distribution of the calibrated hydraulic conductivity (m/d) of the steady state model was in the range of 10–15 m/d for horizontal values with anisotropy ratio of 10 (Fig 4b).

The transient calibration (Fig4c) aimed at approximating the value of specific yield (storage coefficient for the unconfined aquifer) in the study area. Storage values at the existing wells were adjusted to make a good match between the numerical model and the analytical model analysis of AQTESOLV for drawdown values. It was found that calibrated storativity (*Sy*) in the study area was around 12% (Fig 4c).

When a total pumping rate was set to 375 m^3/h (75 m^3/h for each well except well No. 6 (left as a standby) for a simulation period of 365 d, the pumps' curve indicated that the optimal pumping rate for each pump was 65 m^3/h. This scnario produced excessive drawdowns greater than 14 m at well No. 3. The overall picture of the drawdown for all the wells in the study area is shown in Fig. 5.

When the total pumping rate from the 5 wells was set at 250 m^3/h (each well at 50 m^3/h and well number 6 were left as a standby without pumping), the simulated drawdown results are shown in Fig. 6. The results show that maximum drawdown of 10 m was achieved in pumping well No. 3.

4. Conclusions

The following conclusions can be made from conducting the current study:

- The salinity of groundwater analysis of the collected

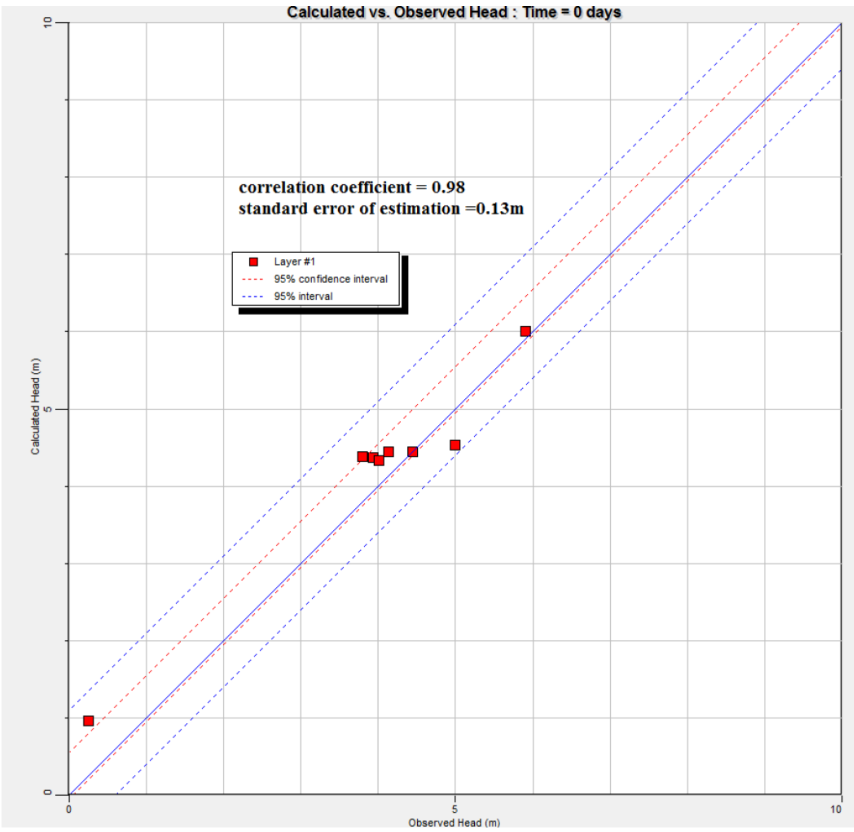

Fig. 4a. Steady state calibration results.

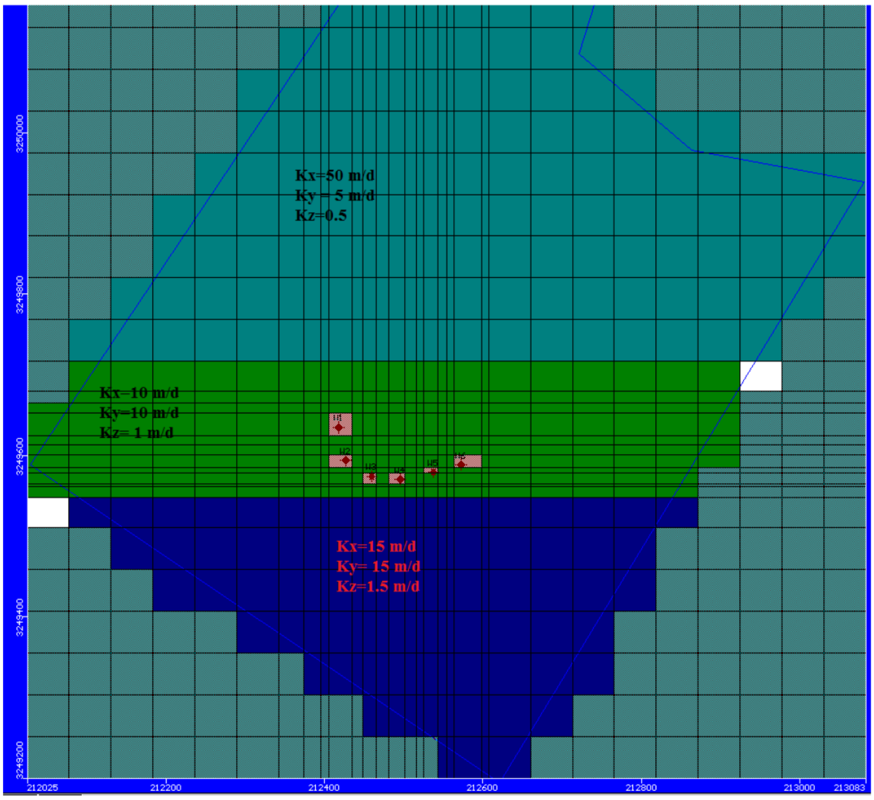

Fig. 4b. Spatial distribution of calibrated hydraulic conductivity in the study area.

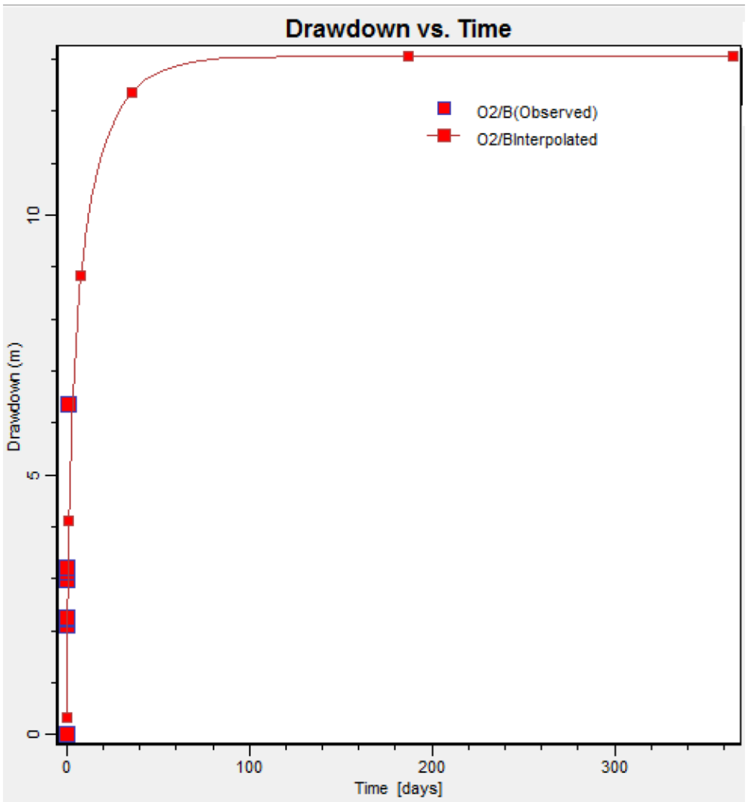

Fig. 4c. Transient calibration.

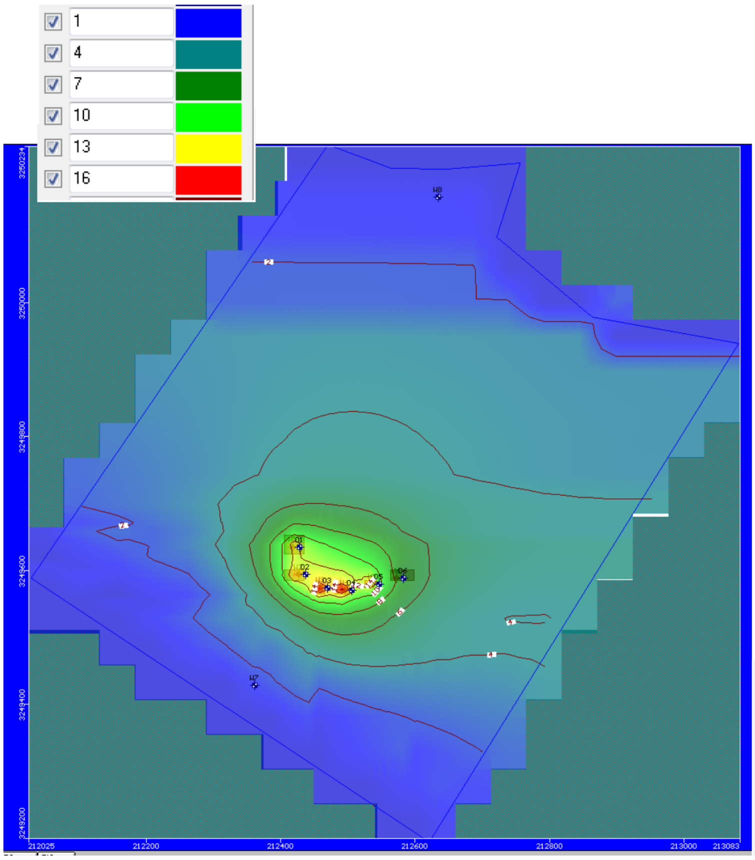

Fig. 5. Overall picture of the drawdown after 365 d when 5 wells were in operation simultaneously with a total pumping rate of 375 m^3/h.

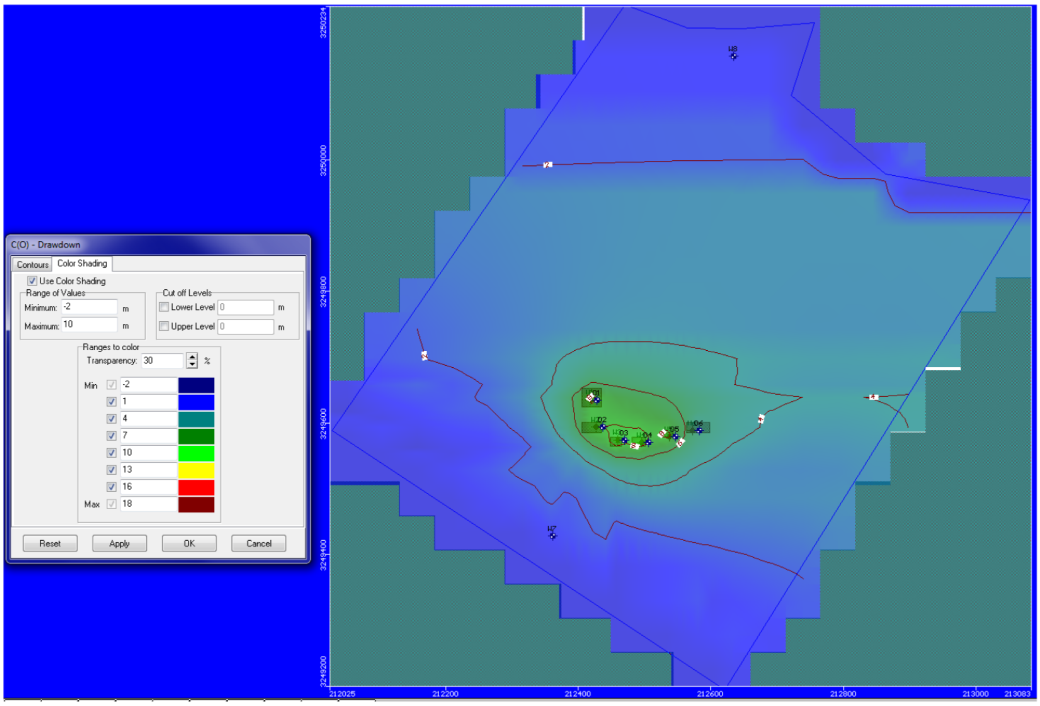

Fig. 6. Overall picture of the drawdown after 365 d when 5 wells were in operation simultaneously with a total pumping rate of 250 m^3/h with a maximum drawdown of 10 m.

samples (with some exceptions) in the study area indicate brackish water quality. The groundwater in the study area was of sodium chloride and sodium sulphate type and no contamination of groundwater was detected. There was no significant change observed in the groundwater quality during the pumping.

- The total pumping rates from the 6 wells without any airlifting development was 215 m^3/h which was less than the required total pumping rate at 250 m^3/h. The current setup allowed 86% of the total needed pumping rate to be achieved. The operational efficiency of 3 pumping wells was less than 50% which was low.
- Visual MODFLOW numerical models were developed to simulate drawdown over a longer period of time (months) under operating all the wells simultaneously to find out if the water level will drop below pump levels. Both steady state and transient state models were constructed and calibrated against water levels obtained from pumping tests data. The conclusions that were observed were the following:
  - There was a good match between early drawdown data observed in the field and modeled drawdown.
  - Steady state conditions of drawdown were achieved almost after 3 mo of continous pumping.
  - The maximam drawdown exceeded the allowable drawdown of 14 m when the pumping rate of each well was 75 m^3/h, but, when a pumping rate was 50 m^3/h from each well the allowable drawdown of 14 m was achieved. This means that the needed 250 m^3/h pumping rate could be achievable in this setup without creating undesirable drawdowns.

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مؤتمر الخليج الخامس عشر للمياه
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(2025) 163–170
doi: 10.5004.dsal.2025.700012

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28–30 April 2024, Doha, Qatar

Utilizing machine learning for short-term water demand forecast

Waleed Eldamaty*, Mohammed Abdallah, Khalid Al Zaabi

Emirates Water and Electricity Company, United Arab Emirates University, P.O. Box 22219, Abu Dhabi, UAE
email: waleed.eldamaty@ewec.ae (W. Eldamaty), mohammed.abdulla@ewec.ae (M. Abdallah), khalid.alzaabi@ewec.ae (K. Al Zaabi)

ABSTRACT

As technology continues to evolve, it has a profound impact on various aspects of our lives, including our water consumption. This becomes crucial as the GCC region is experiencing rapid social and economic transformation, leading to an increase in water demands and creating a gap between water supply and demand. This gap can be addressed by utilizing the new water demand forecast technologies that continue to evolve. With the advent of innovative technologies and methodologies, such as machine learning and artificial intelligence, there is a potential for significant improvement in the water management section. Having an accurate short-term water demand forecast is essential for preparing optimal and secure operational plans for water management. It allows for the precise determination of the required water reserve and the development of efficient plans for pumping stations and water production plants. There are multiple approaches to forecasting water demand depending on various factors such as network complexity, operational limitations, available data, forecast horizon, and the desired level of accuracy. This paper aims to bridge the gap between water supply and demand by introducing a reliable short-term water demand forecast method using machine learning (ML). The results obtained from a water utility in the United Arab Emirates (UAE) demonstrate the effectiveness of the proposed ML forecasting method, with a significant reduction in the mean absolute percentage error (MAPE) from 5.42% to 2.76% compared to the conventional forecasting method. Similarly, the root mean square error (RMSE) decreased from 11.14 million imperial gallons per day (MIGD) to 5.97 MIGD, and the total difference per year between actual and forecasted demand decreased from 2683 million imperial gallons (MIG) to 900 MIG. These findings highlight the importance of accurate demand forecasting in improving the efficiency and performance of water management systems.

Keywords: Demand forecast; Machine learning; Water demand; Technology; Sustainability; Water management

*Corresponding author

ISBN 0-86689-078-5

1. Introduction

Accurate water demand forecasting is integral to effective water management systems as it facilitates the optimization of water supply and demand. Consequently, over the past years, multiple methodologies for water demand forecasting have been extensively studied.

A framework of methodologies was formulated to create optimal operational plans for short-term water grid planning (Ashbolt et al., 2014). The study emphasized that various objectives could influence the decision on which demand forecast technique to utilize for operational planning. These objectives encompass water security, operational cost, energy consumption, environmental impact, water quality, storage tank levels, and more. The availability of data and the complexity of the network significantly affect the selection of the most suitable demand forecast method. The investigation in Cyprus focused on the short-term forecast for peak demand. Multiple linear regression (MLR) and three types of multilayer perceptron artificial neural networks (ANN) were utilized for this purpose. These included resilient back-propagation ANN models, Levenberg-Marquardt ANN models, and conjugate gradient Powell-Beale ANN models. Among these methods, the Levenberg-Marquardt ANN approach yielded the most accurate forecast (Adamowski & Karapataki, 2010). The investigation was extended, and the effectiveness of combining ANN and discrete wavelet transforms (WA) was compared to (MLR), multiple nonlinear regression (MNLR), and autoregressive integrated moving average (ARIMA) in Canada. The findings indicated that the (WA-ANN) models yielded a more precise demand forecast (Adamowski et al., 2012). The Holt-Winter's and Auto-Regressive Integrated Moving Average (ARIMA) models were utilized to predict water consumption expenditure in Malaysia. According to the findings, the ARIMA (2,1,4) model demonstrated superior accuracy with lower values of mean absolute percentage error (MAPE) and mean absolute deviation (MAD) compared to Holt-Winter's model (Razali et al., 2018). In Spain, an investigation was carried out on double seasonal univariate time series models like generalized autoregressive conditional heteroskedasticity (GARSH), ARIMA, and Holt-Winters. The outcomes demonstrated that combined forecasts yield higher accuracy rates for short-term demand predictions. Conversely, the utilization of GARCH models and Holt-Winters exponential smoothing can improve forecast accuracy for particular days of the week (Caiado, 2010). The researchers have created a predictive model that can estimate the water demand for the upcoming 48 hours in six distinct regions of the Netherlands (Bakker et al., 2013). The model relies on a single input, which consists of measured water demands and static calendar data. The findings indicate that the mean absolute percentage error (MAPE) for the 24-h forecasts ranged from 1.44% to 5.12%, while for the 15-min interval forecasts, it varied between 3.35% and 10.44%.

Vijai and Bagavathi Sivakumar (2018) presented a study that compared the performance of various techniques for forecasting water demand. The techniques analyzed included Gaussian process regression (GPR), least square support vector machine (LSSVM), random forest (RF), and multiple regression. The study found that the ANN models performed well in all short-term predictions. The long short-term memory (LSTM) model is employed to predict the future water requirements in the UAE, taking into account various factors such as population growth, gross domestic product (GDP), consumer price index (CPI), and the average temperature (Ahmed et al., 2020). To investigate the future water consumption in Spain, two hybrid models have been utilized (Pandey et al., 2021). The first model combines difference pattern sequence forecasting (DPSF) with ensemble empirical mode decomposition (EEMD), while the second model combines EEMD with DPSF and ARIMA. The EEMD-DPSF method demonstrated superior prediction accuracy compared to other state-of-the-art techniques. The study conducted in Korea (Koo et al., 2021) focused on analyzing short-term water demand forecasts for smart water grids (SWG). To evaluate the model's performance, various indices such as the pearson correlation coefficient, normalized root mean square error, root mean square error, and Nash-Sutcliffe efficiency were utilized. The findings indicated that the ARIMA, RBF-ANN, QMMP+, and LSTM models have limitations when it comes to managing a water supply system solely based on usage time and water consumption data. Therefore, it is crucial to incorporate additional factors into the model to achieve optimal results.

In their study, De Souza Groppo et al., (2019) conducted a comprehensive examination of artificial intelligence-based water demand forecasting techniques. The research explored various approaches, including soft computing and models built on standard statistical techniques like linear regression and time-series analysis. The findings of the study indicate that a universal optimal global model applicable to all cases and regions does not exist. Instead, each region presents its own unique challenges and factors that influence water demand. The challenge of manual feature extraction in deep learning was tackled by Chen et al. (2022) through the development of S-H-ESD (Seasonal Hybrid Extreme Student Deviate), a data preprocessing technique, and Conv1D-GRU (one-dimensional convolution-gated recurrent unit), a forecasting model. The evaluation of these methods yielded a MAPE value of 1.677%. In their research, Salloom et al. (2021) focused on mitigating the high forecasting errors observed at extreme points when employing deep learning techniques. To tackle this issue, they incorporated virtual data into the existing dataset in order to alleviate nonlinearity. Additionally, they developed a gated recurrent unit (GRU) model and utilized an unsupervised classification method (k-means) to generate new features, thereby improving the accuracy of the forecasts. The results demonstrated that expanding the dataset resulted in a 30% decrease in error, albeit with an increase in training time. In India, a study conducted by (Kavya et al., 2023) examined the differences between deep learning and machine learning approaches. The findings indicated that the LSTM model outperformed other models in both univariate and multivariate scenarios. The mean absolute error for the univariate model was 0.11 m^3/h, while for the multivariate model, it was 2.96 m^3/h.

Different techniques and models have been explored in the literature review to predict water demand. However, it is evident that there is no singular optimal technique suitable for every region or water network. Furthermore, certain methods mentioned in the literature may not be practical in our specific case due to their inability to provide real-time short-term demand forecasts, given their complexity and lengthy model training time. Additionally, most of the short-term demand forecast methods discussed in the literature were tested in regions with water supply and demand patterns that differed from those observed in GCC countries. Therefore, the objective of this paper is to bridge the gap between water supply and demand by utilizing new technologies and software to introduce a novel and reliable short-term water demand forecast method based on machine learning.

2. Method

Over the past few years, various techniques have been employed to predict water demand. These include time series analysis, exponential smoothing, autoregressive integrated moving averages (ARIMA), regression analysis, artificial neural networks, and hybrid methods. However, it is widely acknowledged that there is no universally optimal method for forecasting water demand. Instead, the approach taken depends on factors such as network complexity, operational limitations, available data, forecast horizon, and the level of model complexity. Nevertheless, machine learning models, particularly supervised machine learning, have demonstrated a distinct advantage over other methods due to their ability to handle complex systems. In this paper, our focus will be on regression modeling within the realm of supervised machine learning, as it enables the prediction of an output based on one or more inputs.

2.1. Regression modelling

The regression model's main goal is to find the relationship between a dependent variable (y) and one or more independent variables (x).

$$y = \alpha + \beta x + \varepsilon \quad (1)$$

The y-intercept (constant) is the mean value of the independent variable when all the dependent variables in the model are equal to zero (the value of y when $x = 0$). β is the average change in the independent variable for one unit increase in the dependent variable. The error ε is the difference between a predicted value and the observed actual value.

2.2. Model factors

There are multiple factors that influence the water demand forecast. These factors can be divided into two main categories: the first category pertains to the short-term forecast and is influenced by climatic conditions such as temperature, relative humidity, precipitation, and more. The second category, on the other hand, affects the long-term forecast and is influenced by socio-economic factors such as population growth, GDP, tariff rate, etc. In this discussion, we will primarily focus on the first category, specifically the temperature. Our model also takes into account additional factors, such as the previous day's demand and the type of day (weekday or weekend), to accurately capture the daily network behavior profile.

2.3. Machine learning software

Microsoft Power BI software © is used to create the regression model using its automated machine learning (AutoML) feature. The feature enables you to train, validate, and invoke machine learning (ML) models directly in Power BI. AutoML in Power BI integrates automated ML from Azure Machine Learning to create the ML models. The service automatically extracts the most relevant features, selects an appropriate algorithm, and tunes and validates the ML model.

2.4. Machine learning model flow chart

As can be seen in Fig. 1, the software takes in a dataset consisting of four variables: the historical water demand of a water utility in the UAE for 2017, the day name, the previous day demand, and the daily hourly temperature for 2017 obtained from the National Center of Meteorology (NCM) in the UAE. Prior to being inputted into the software, the data undergoes cleaning and processing to address any anomalies, errors, or abnormalities. Subsequently, the machine learning model divides the provided input data into training (80%) and testing

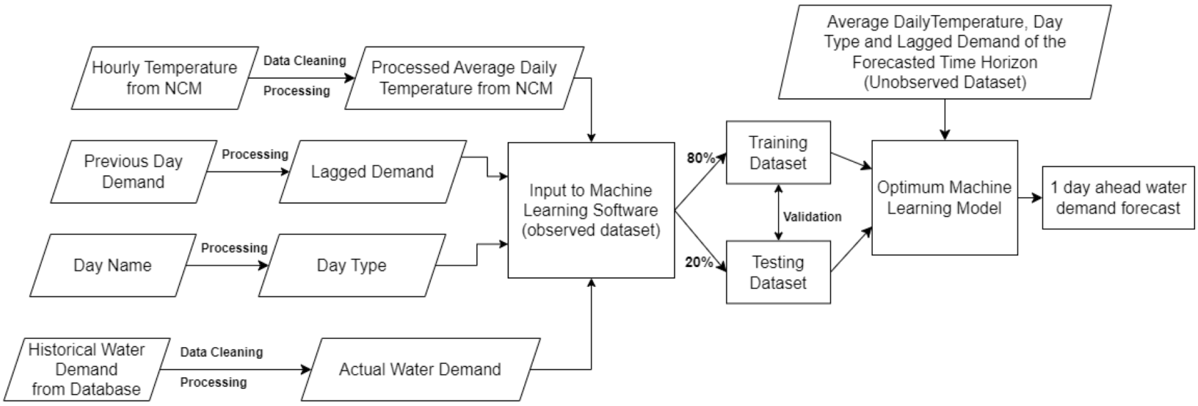

Fig. 1. Machine learning model flow chart.

(20%) datasets. In order to determine the most suitable line that fits the data, the model iterates through various algorithms such as Light GBM Regressor, Elastic Net, Random Forest Regressor, Extra Trees Regressor, Decision Tree Regressor, SGD Regressor, and Pre-fitted Voting Regressor. This iteration continues until the model achieves optimal performance by validating it against the testing dataset. The resulting optimum model is then utilized to forecast water demand for 2018 based on an unobserved dataset that includes the average daily temperature of 2018, the lagged demand, and the corresponding day type.

3. Results and discussion

The results of the AutoML Modeling in Power BI are divided into two main sections: model training details and model performance.

3.1. Model training

The training details shown in Fig. 2 showcase the methodology employed to train the model. It encompasses the total number of sampled rows utilized in the training process, the specific rows on which the model was trained, the total number of iterations executed to

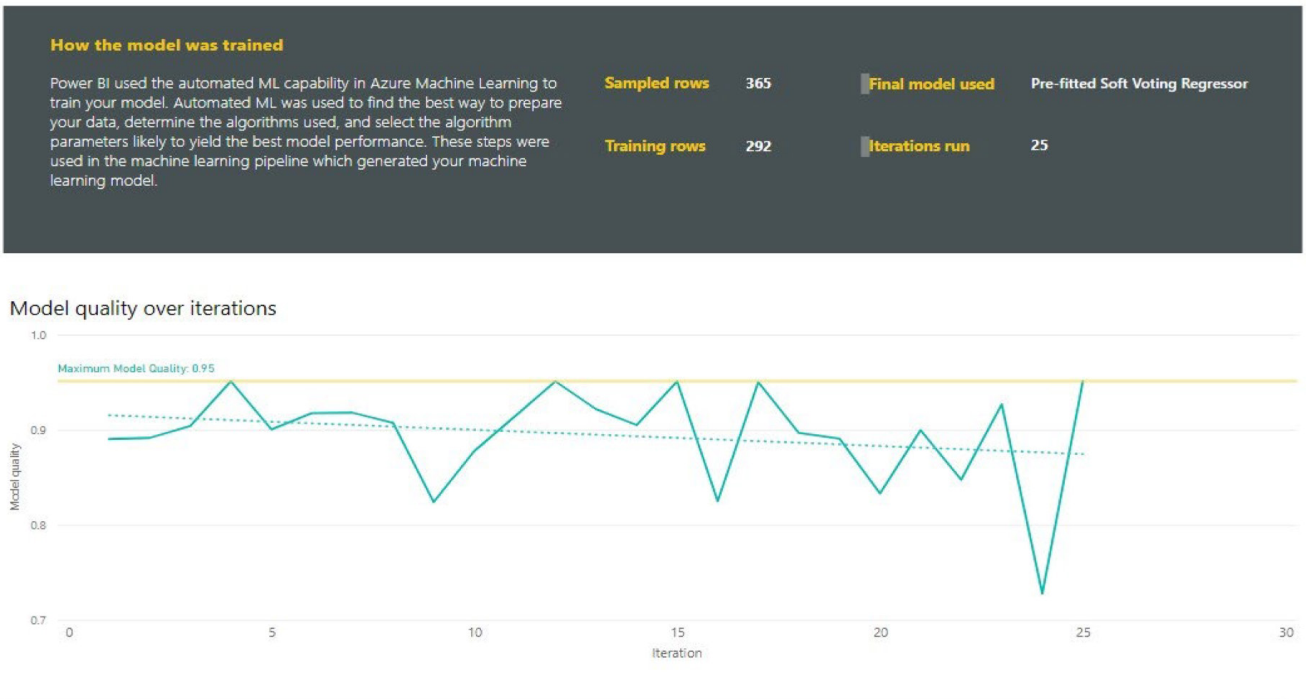

Fig. 2. Model training details.

determine the optimal model, the algorithm employed in each iteration, the model's performance at each iteration, and the ultimate model employed. In our case, the pre-fitted soft voting regressor algorithm yielded the most promising results.

3.2. Model performance

The model performance results shown in Figure 3 illustrate the evaluation of the model's performance. It highlights the total number of rows on which the model was tested and validated, the key predictors, and the overall R-squared (model performance). R-squared is a metric that gauges the proximity of the actual data to the fitted regression model. A higher value indicates a stronger fit of the model to the data. This value, commonly known as the coefficient of determination, represents the proportion of variance in water demand that the model can account for or predict.

3.2.1. Predicted vs. actual demand

In Fig. 3, the chart illustrates the model's predicted value against the known actual values for the validation rows in the dataset. The model's underestimations are represented by values within the blue area, while overestimations are indicated by values within the red area. The error in prediction is measured by the distance from the diagonal. A well-performing model would exhibit test samples clustered near the diagonal.

3.2.2. Residual error by demand

In Fig. 3, in the residual error by demand chart, the distribution of the average error percentage for various values in the sample data set is visualized. The mean of the actual value range is plotted on the horizontal coordinate of the bubble, while the vertical coordinate represents the average residual error within that range. For example, if the average residual error is 5%, it indicates that the model tends to overestimate the value in that range by 5%. The size of the bubble reflects the frequency of values within that range in the validation data set.

3.3. Evaluation of machine learning models

In order to compare the accuracy of predictions from multiple models, the following error metrics were used.

1.1.1 Mean Squared Error (MSE)

The mean squared error is the average of the squared distance between the actual and predicted values.

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}\left[y_i - p_i\right] \tag{2}$$

y_i is the i^{th} observed value, p_i is the corresponding predicted value for y_i, and n is the number of observations.

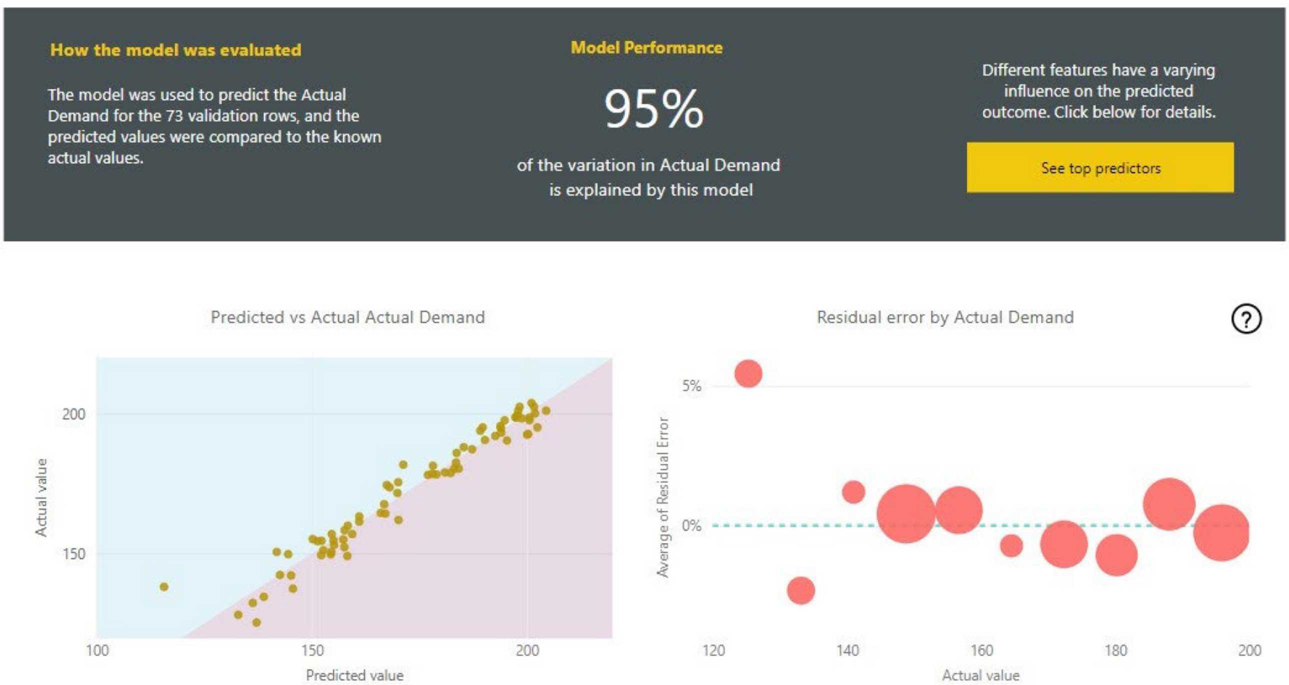

Fig. 3. AutoML model performance.

$\sum$ indicates that a summation is performed over all values of i.

3.3.2. Mean absolute error (MAE)

The mean absolute error is the average of the absolute distance between the actual and predicted values.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left[y_i - p_i\right] \quad (3)$$

3.3.3. Mean absolute percentage error (MAPE)

The mean absolute percentage error is the mean absolute error, converted to a percentage.

$$MAPE = \frac{1}{n}\sum_{(i=1)}^{n}\frac{|y_i - p_i|}{y_i} \quad (4)$$

3.3.4. Root mean square error (RMSE)

The root mean square error is the measure of the average deviation of the estimates from the observed values.

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(y_i - p_i\right)^2} \quad (5)$$

3.4. Model results

The accuracy of the water demand forecast of the developed machine learning model was evaluated by comparing it to the conventional demand forecast of a water utility in the UAE for the year 2018. As can be seen in Figs. 4 and 5. In terms of accuracy, the ML demand forecast outperforms the conventional demand forecast by a considerable margin. Throughout the year, the conventional forecast consistently overestimates the demand, while the machine learning model demonstrates superior predictive capabilities in understanding the network's behavior. Table 1 further highlights the improvement in accuracy. The mean squared error (MSE) decreased from 124 MIGD in the conventional demand forecast to 35.70 MIGD in the machine learning model. The mean absolute error (MAE) also saw a significant reduction, from 8.85 MIGD in the conventional demand forecast to 4.59 MIGD in the machine learning model. Additionally, the mean absolute percentage error (MAPE) decreased from 5.42% in the conventional demand forecast to 2.76% in the machine learning model. The root mean squared error (RMSE) was also reduced, from 11.14 MIGD in the conventional demand forecast to 5.97 MIGD in the machine learning

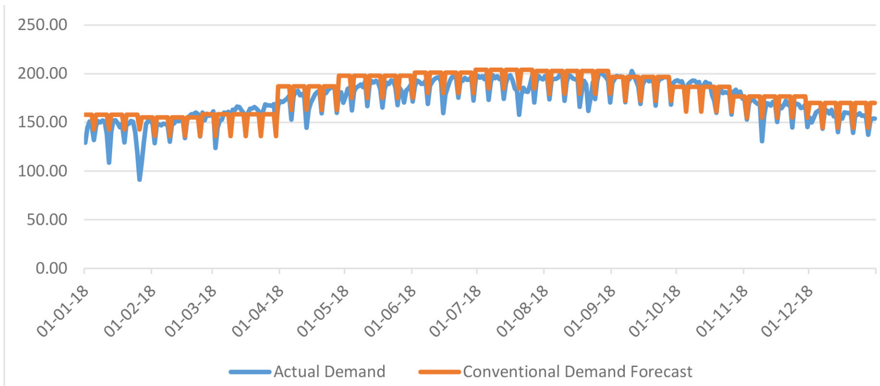

Fig. 4. Actual demand vs. conventional demand forecast.

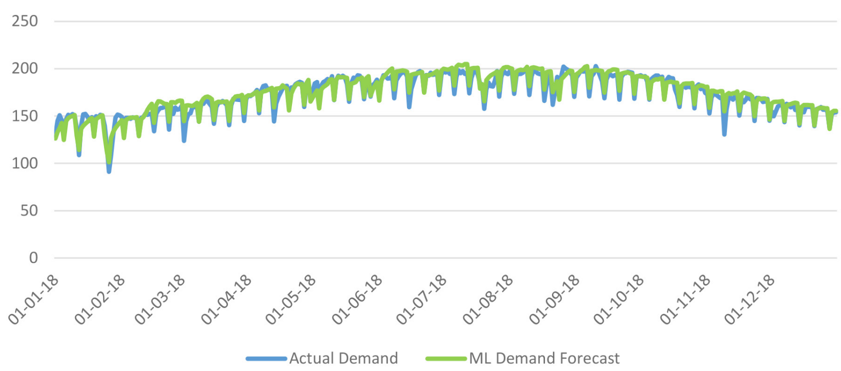

Fig. 5. Actual demand vs. ML demand forecast.

Table 1
Model performance evaluation

Error metric	Conventional demand forecast	Machine learning demand forecast
MSE, MIGD	124	35.70
MAE, MIGD	8.85	4.59
MAPE, %	5.42	2.76
RMSE, MIGD	11.14	5.97
Total difference, y/MIG	2683	900

model. Moreover, the total yearly difference between the actual and forecasted demand decreased from 2683 MIG in the conventional demand forecast to 900 MIG in the machine learning model.

4. Conclusions

By leveraging the AutoML feature in Microsoft Power BI, a machine learning model was created and evaluated for water demand forecasting. The input dataset included the 2017 water demand for a water utility in the UAE, as well as the average temperature, lagged demand, and day type. The optimal model obtained from this process was subsequently employed to predict the water demand for 2018 using unobserved data, which encompassed the average daily temperature of 2018, its corresponding day type, and the demand from the previous day. The outcomes revealed a significant advancement in the accuracy of forecasting when comparing the machine learning demand forecast model to the conventional demand forecast model. The MAPE experienced a reduction from 5.42% in the conventional model to 2.76% in the machine learning model. Moreover, the RMSE decreased from 11.14 MIGD in the conventional model to 5.97 MIGD in the machine learning model. Notably, the conventional model overestimated the water quantity by 2683 MIG, whereas the machine learning model reduced it to 900 MIG, resulting in a savings of 1783 MIG. The surplus million imperial gallons that have been saved can now be effectively utilized to adequately prepare for water production and transmission interruptions, proactively identify potential water supply shortages, and enhance the mitigation procedures undertaken by stakeholders. Additionally, it can be employed to precisely determine the required water reserves and develop optimal operational plans for pumping stations and water production plants. These endeavors will result in a reduction of the disparity between actual and forecasted demand, thereby improving the overall efficiency and performance of the water management system and contributing to the attainment of global water sustainability goals. It is crucial to understand that relying solely on technological progress is not enough to address the challenges associated with water demand forecasting. While advancements in technology hold promise, their successful implementation necessitates the presence of effective policies and regulations.

Acknowledgments

We would like to acknowledge the National Center of Meteorology (NCM) in the UAE for providing the climatic data in a timely manner.

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Balaban Desalination Publications

(2024) 171–179
doi: 10.5004.dsal.2024.700067

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

System dynamics model to study the effect of different policies on Bahrain's hydrological processes

Raed Aljowder, Abrar Habib*

Chemical Engineering Department, College of Engineering, University of Bahrain, Bahrain, email: abr.habib@gmail.com

ABSTRACT

System Dynamics (SD) modeling is a powerful tool for modeling complex interconnected and dynamic systems. It involves representing these systems with blocks and feedback loops defined mathematically. This kind of modeling can be very useful for decision-makers who want to understand the impact of different policies on a particular variable. SD modeling is aligned with the concepts of Integrated Water Resources Management and Water-Energy Nexus because it helps to account for the big picture. In this project, our goal is to conduct a holistic analysis of Bahrain's groundwater system. The effects of different policies in various relevant sectors, such as economic, environmental, and agricultural, among others, on the groundwater volume is studied. To do this, an SD model that represents the groundwater storage volume and its response to natural and artificial recharge, groundwater flow from the head aquifer in Saudi Arabia, abstractions for irrigation, agriculture, and domestic demands, and downstream outflow towards Qatar is developed. The SD model is validated with the help of a validated hydrological model and published information related to groundwater volume, recharge quantities, and abstraction rates, among others. The SD model is lumped for the study area (Bahrain) and ran the simulations for the period 2016–2070. The hydrological model is a semi-distributed model that calculates the water budget using a series of non-linear reservoirs for each catchment at every 30-minute time-step for the simulation period 2016–2021. The hydrological model is validated using regionalization techniques; hence, its results are considered the 'correct' values against which the SD model is validated. The initial results of the study show the effect of artificial recharge and abstractions for different water demands. These results are used as a starting point for the second stage of this work, which involves including socio-economic effects of groundwater abstraction, and implications on food security and energy generation.

Keywords: System dynamics modelling; Sustainable groundwater exploitation; Hydrological modelling; Interconnected systems

1. Introduction

In the realm of water resource management, the creation of comprehensive and exact modeling frameworks is imperative to ensure accuracy and integration. Such models are fundamental for the efficient allocation and utilization of water resources. Given the ongoing expansion of communities and the surge in population, the urgency to fulfill increasing water demands is intensifying, especially against the backdrop of finite water supplies. Consequently, there is an escalating focus on devising strategies to administer

* Corresponding author.

water resources effectively, aimed at accommodating the requirements of growing populations while considering the limitations of existing resources.

Groundwater infiltration, a key element in the hydrological cycle and essential for water security, is subject to substantial influence by the unpredictable characteristics of precipitation and runoff. The inconsistency of rainfall patterns, which varies markedly among diverse geographic regions such as arid and humid zones and through different seasons, plays a significant role in determining the rate and amount of groundwater replenishment. The infiltration process is integral to preserving groundwater levels and securing a sustainable water supply.

The dynamics of this process are increasingly complicated by the effects of climate change. Alterations in precipitation trends, already observable in numerous areas, are modifying the rates of groundwater recharge, affecting both the volume and quality of water in aquifers. Additionally, increased water temperatures, resulting from warmer climates and industrial waste heat discharges, are intensifying pollution challenges. Contaminants like sediments, nutrients, dissolved organic carbon, pathogens, pesticides, salt, and thermal pollution are increasingly infiltrating groundwater. These pollutants pose risks to the ecosystems, human health, and water systems' reliability and operating costs [1].

Hao et al [2] investigated the correlation between precipitation and infiltration depth in the Yellow River and Yangtze-Huaihe River Valley regions, focusing on the primary impact of precipitation and developing quantitative models for different locations in these areas. Markovič G. et al. [3] highlighted the growing need for surface water detention due to increased terrain coverage for construction and other activities, leading to reduced natural rainfall infiltration and ecological issues like floods and soil dehydration, necessitating the development of artificial water regulation for ecological stability. Devia, Gayathri K., et al. [4] reviewed various hydrological models, including VIC, TOPMODEL, HBV, MIKESHE, and SWAT, examining their effectiveness and limitations in different environments and for distinct applications, particularly in the context of climate change and soil heterogeneity's impact on surface runoff.

The dynamic nature of the hydrological cycle renders Integrated Water Resource Management (IWRM) a complex and significant undertaking. This complexity is further heightened by the compounding effects of climate change. Thus, in the pursuit of effective water resource management, it becomes imperative to incorporate both these elements as fundamental aspects in the decision-making framework. Water-resource modeling, therefore, must encompass a diverse array of factors, including hydrological and climatic variables, as well as vital physical, social, economic, and political factors.

The utilization of informed methodologies is crucial for gaining a comprehensive understanding of water infiltration and groundwater conservation. System thinking and system dynamics stand out as vital tools in this area, offering an all-encompassing approach to deciphering the intricate interplays in hydrological systems. These methods enable policymakers to grasp the complex dynamics of water cycles, which include factors like climatic changes, land utilization alterations, and anthropogenic impacts. Particularly, system dynamics allows for the creation of detailed models that can predict the outcomes of various environmental scenarios on groundwater levels and infiltration processes. This integrated approach is essential for formulating policies that are both insightful and effective, considering the broad spectrum of factors affecting water systems. Furthermore, system dynamics capability to simulate the long-term effects of policy choices ensures that water resource management strategies are sustainable and adaptable. Thus, incorporating system thinking and dynamics into the policy development process is a fundamental step toward achieving more knowledgeable, efficient, and sustainable water management practices in an increasingly complex environmental landscape.

Madani [5] reviewed the use of game theory in water resources management and conflict resolution, highlighting how it differs from optimization methods by considering the self-interested behaviors of stakeholders in non-cooperative scenarios, thereby revealing the dynamic nature and evolution of water resource conflicts. Sheikhbabaei et al. [6] introduced a streamflow prediction model for Iran's Aji-Chay watershed using ensemble multi-GCM downscaling and system dynamics, incorporating climate projections, an ANN-based rainfall-runoff model, and various reclamation scenarios, ultimately finding that combining these scenarios achieves socio-environmental sustainability. Haizan et al. [7] examined the escalating water-related challenges in cities. Exploring the potential of systems thinking to address these issues by understanding interrelations and empowering stakeholders to transform urban water sustainability.

Hence, the foremost aim of this study is to introduce a forecasting model that not only predicts future groundwater balance trends but also evaluates the effectiveness of diverse policies and actions through a 'smartness' index. Furthermore, this research endeavors to support policymakers and decision-makers in grasping both the short-term and long-term ramifications of their choices, thereby enhancing their understanding of how their strategies and actions affect groundwater resources and prompting a critical assessment of the wisdom underlying their decisions in this field.

2. Methodology

2.1. Problem description

Beginning in the early 1970s, Bahrain, alongside other Gulf States, has witnessed a significant escalation in developmental progress. This upsurge is largely due to a marked increase in oil revenue, which has substantially bolstered the country's economic infrastructure and improved living standards. This economic boom has precipitated a dramatic increase in Bahrain's population, which grew from 0.2 million in 1970 to 1.46 million in 2021 [8]. Over the last five decades, the combination of a burgeoning population, rapid urbanization, the expansion of irrigated agriculture, and increased industrial activity has led to a significant rise in water consumption. To meet these growing water needs, there has been an increased reliance on groundwater extraction.

Intensive groundwater use has significantly decreased potentiometric levels and altered the pressure gradients between the aquifer's relatively fresh water and the neighboring brackish and saline water bodies. The sustainable yield of Bahrain's groundwater is calculated based on the inflow rate from similar aquifers in eastern Saudi Arabia under equilibrium conditions. This over-extraction has caused saline and brackish waters to intrude into the aquifer, resulting in its salinization and limiting its utility in the affected regions. Presently, a large portion of the original groundwater reservoir, which was previously stable, has become salinized. The current condition of groundwater resources is critical and concerning. Without effective groundwater quality management, there is a risk of complete aquifer loss, leading to expensive solutions for Bahrain's water management authorities [9].

2.2. System dynamics modelling

System dynamics modeling, a field that has significantly benefited from advancements in computer technology, primarily focuses on a systematic approach to understanding complex and dynamic changes. This methodology stems from a fusion of principles from cybernetics, systems science, and information science. It involves constructing and analyzing mathematical models of complex systems to understand how they change over time. By simulating various scenarios, system dynamics provides insights into the behavior of systems under different conditions, allowing for the exploration of potential outcomes and strategies. This approach is particularly useful in fields where systems are characterized by interdependencies, feedback loops, and time delays, making traditional analytical methods less effective. The reliance on computer technology in system dynamics modeling facilitates the handling of large datasets and complex calculations, enabling more accurate and detailed simulations of system behaviors and interactions. This integration of technology enhances the predictive capacity of models and aids in decision-making processes across various disciplines, ranging from economics to environmental management.

In developing a system dynamics model for academic research, adhering to a structured methodology that emphasizes a holistic view of systems is essential. This approach, rooted in systems thinking, involves understanding systems as interconnected wholes rather than isolated components. As Cavana and Maani [10] outlined, this approach employs a set of conceptual and analytical tools for effective systems modeling. The process begins with a comprehensive problem definition, which leads to the creation of causal loop diagrams illustrating the relationships within the system. These diagrams are further developed into stock-flow structures, capturing the dynamic aspects of the system. Scenario planning is also integral to this process, aiding in exploring possible futures and strategies.

To simulate a system dynamics model, the following steps are recommended [11]:

- Define the problem and establish a verbal conceptualization, forming a dynamic hypothesis that explains the issue using causal loops and stock-flow structures.
- Construct an initial causal loop diagram based on this verbal model.
- Expand the causal loop diagrams into detailed system dynamics flow diagrams.
- Convert these flow diagrams into a computational model using tools like STELLA, VENSIM, or a set of differential or difference equations.
- Determine the parameters of the model.
- Conduct validation checks on the model, assess its sensitivity, and evaluate potential policy implications.
- Implement the model in a practical context.

This method is particularly effective for tackling complex problems characterized by intricate interdependencies, historical contexts, the influence of external actions, and coordination challenges among stakeholders. By following these steps, researchers can develop robust system dynamics models that offer valuable insights into complex systems behavior and potential outcomes.

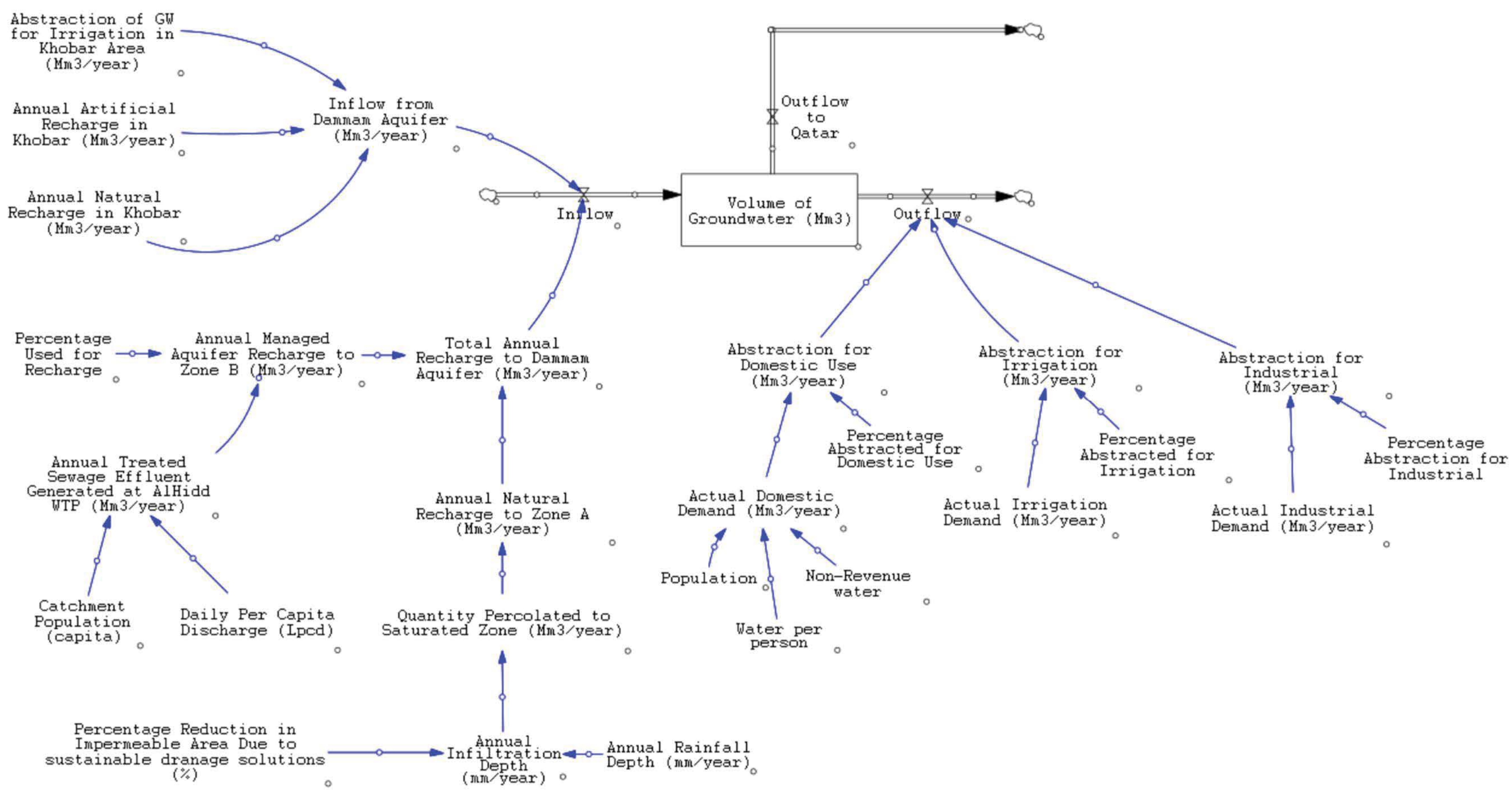

Fig. 1. System dynamics model of Bahrain’s groundwater system. Description of the hydrological Model.

To examine the fluctuations in the volume of groundwater in Bahrain a system dynamics model is developed Fig. 1. In the first stage, the model is designed to include the following:

- Natural recharge to the Alat membrane and artificial recharge to the Khobar membrane. Both form the Dammam aquifer.
- Abstractions for various purposes, in particular, domestic, industrial, and agricultural uses.
- Inflow from upstream in Saudi Arabia
- Outflow towards Qatar.
- Additional variables to allow for flexibility when studying different scenarios are:
    - Changes to the permeability of land surface in Bahrain due to changes in policies
    - Abstraction and recharge in Saudi Arabia
    - Percentages of abstraction and artificial recharge will help control these quantities.
    - Population and per capita water demand.

To ensure an accurate representation of the processes represented in the SD model, we made use of a hydrological model (details in the following section) to represent natural recharge, and observed data for water demand, population, quantities of treated sewage flow (details are in the Data subsection), and GW storage volume and annual inflows and outflows.

For this study, a few scenarios have been studied. The first scenario assumes the continuation of GW exploitation and the remaining scenarios assume changes in policies. The different scenarios are explained below:

- Business as Usual: Unaccounted GW abstraction for irrigation only with no GW recharge.
- GW Replenishment: No GW abstraction and injection of 30 Mm^3 annually at Alhidd Treatment Plant.
- GW for Domestic Demand: Abstraction of GW to meet 5% of domestic and injection of 30 Mm^3 annually.
- GW for Food Security: Abstraction of GW to meet 100% irrigation demand and injection of 30 Mm^3 annually.
- GW for Industrial Activity: Abstraction of GW to meet 50% industrial demand and injection of 30 Mm^3 annually.
- GW for All Demand: this scenario combines scenarios 3, 4, and 5.

A semi-distributed hydrological model developed for Bahrain and validated using regionalization techniques is used for this research. The software used is PCSWMM by CHI [12,13]. The model simulates precipitation along its flow path using a series of processes summarized below and presented graphically in Fig. 2.

- The first main process converts rainfall to runoff. Catchments are considered as reservoirs, with precipitation and evaporation as inputs and runoff, depression storage, and infiltration as outputs. These quantities are updated at every time step.

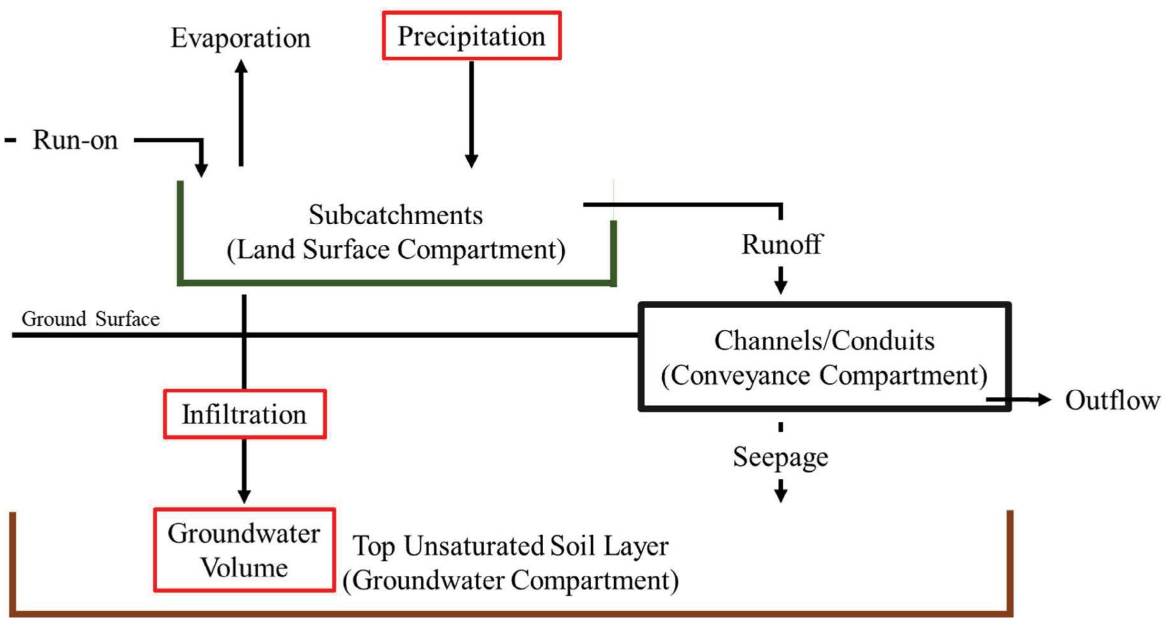

Fig. 2. Conceptual representation of the hydrological model. Components that are of relevance to the SD model are indicated with red boxes.

- The next process transports runoff from the catchments to the conveyance system which is routed using the Saint Venant flow equation.
- The groundwater process consists of two zones: the unsaturated zone and the saturated zone. A mass balance is calculated at every time step to compute how much infiltrated water percolates deeper to the saturated layer and how much evaporates or returns to the conveyance system.

The data extracted from the model to be used in the SD model are the total annual infiltration quantities and total annual groundwater percolation quantities for the period 2016–2021. A linear regression model is used to relate total annual rainfall with infiltration and groundwater and this mathematical relationship is assumed to apply for the period 2021–2070. The linear regressions are presented in Fig. 3.

The average annual natural groundwater recharge quantity is known to be 0.5 Mm^3 [14]. The average storativity of the Alat membrane of the Dammam Aquifer into which natural recharge infiltrates is 0.065 [15]. A specific yield of 0.0325 is computed using an average depth of 50 m [15]. The estimated values result in an average of ~0.5 Mm^3 of recharge.

2.3. Data

Observed population and water demand data are obtained from the Bahrain Open Data Portal. Observed rainfall data are obtained from the Meteorology Directorate and future bias-corrected rainfall projections until the year 2070 are obtained from a regional climate model [16].

3. Results and discussion

3.1. Scenario analysis

Our study explored various scenarios to understand the impact of different groundwater (GW) infiltration scenarios. The scenarios ranged from continued GW exploitation to varied policy shifts focusing on GW replenishment, domestic demand, food security, industrial activity, and a comprehensive approach combining multiple strategies.

- Business as Usual (Scenario 1): This scenario reflects the current trend of unregulated GW abstraction for irrigation without considering GW recharge. It aligns with the 'business as usual' approach observed in many regions. However, this approach risks depleting GW reserves, leading to long-term sustainability issues, especially in arid regions where GW is a critical resource.
- GW Replenishment (Scenario 2): This scenario proposes no GW abstraction and advocates for the injection of 30 million cubic meters (Mm^3) annually at the Alhidd Treatment Plant. This approach prioritizes the replenishment of GW reserves, potentially stabilizing GW levels and mitigating the risks of depletion. The effectiveness of this strategy largely depends on the region's hydrogeological characteristics and the feasibility of such large-scale injection.
- GW for Domestic Demand (Scenario 3): Focusing on meeting 5% of domestic demand through GW abstraction, coupled with the injection of 30 Mm^3 annually, this scenario balances demand and replenishment. It underscores the importance of GW in supporting domestic water needs while maintaining a sustainable approach through recharge initiatives.
- GW for Food Security (Scenario 4): Prioritizing agriculture, this scenario involves GW abstraction to fulfill 100% of irrigation demands, supplemented by the injection of 30 Mm^3 annually. This approach reflects the critical role of GW in ensuring food security. However, it requires careful management to prevent over-exploitation, considering agriculture's significant water footprint.

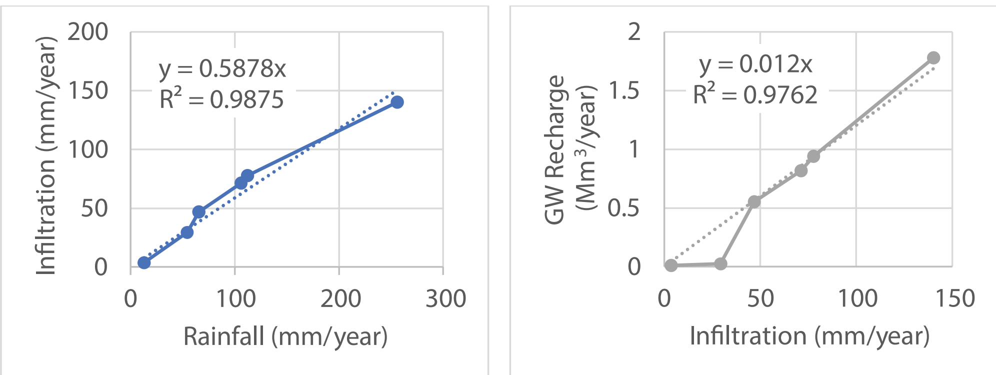

Fig. 3. Left panel: Infiltration vs. total annual rainfall. Right panel: Total annual GW recharge volume vs. infiltration.

- GW for Industrial Activity (Scenario 5): Targeting industrial water needs, this scenario abstracts GW to meet 50% of industrial demands, with an annual injection of 30 Mm^3. It highlights the industrial sector's reliance on GW and the need for balanced exploitation and replenishment strategies to support economic growth without compromising water resources.
- GW for All Demand (Scenario 6): Combining scenarios 3, 4, and 5, this comprehensive approach addresses various demands—domestic, agricultural, and industrial. It embodies a holistic water management strategy, acknowledging the interconnectedness of different water uses and the importance of integrated planning.

The results of the SD model are presented in Fig. 4. For this work, Bahrain's GW reservoir is considered limitless, that is, it is not capped at a maximum value. It is also not restricted from negative values. Nor is I which is not physically correct.

The provided figure illustrates the outcomes of the System Dynamics (SD) model for the various groundwater (GW) management scenarios over time, from 2020 to 2070. The graph's trajectories for each scenario demonstrate the projected changes in GW levels in cubic meters (Mm^3). Notably, the GW reservoir in Bahrain is modeled without a limit, meaning it can theoretically sustain limitless extraction or go into negative values, which is not realistic in physical terms.

3.2. Scenario analysis revisited

The figure presents a stark visual representation of the long-term impacts of each GW management scenario. Notably:

- Business as Usual (Scenario 1) shows a steady decline in GW levels, reflecting the unsustainable nature of current practices. This scenario's trajectory is alarming and suggests a critical need for policy intervention to avoid severe water scarcity.
- GW Replenishment (Scenario 2) maintains a stable GW level, indicating that the injection of 30 Mm^3 annually could offset abstraction, thereby preserving GW reserves. This approach demonstrates the potential effectiveness of GW recharge strategies.
- GW for Domestic Demand (Scenario 3) depicts a slight decline in GW levels, suggesting that meeting 5% of domestic demand through GW abstraction is somewhat sustainable when coupled with the injection strategy.
- GW for Food Security (Scenario 4) shows a significant increase in GW levels, which may indicate that the combined effect of GW abstraction for irrigation and the annual injection of 30 Mm^3 creates a surplus, possibly due to reduced irrigation demand or improved water-use efficiency in agriculture.
- GW for Industrial Activity (Scenario 5) illustrates a moderate decline in GW levels. This could imply that industrial demand is substantial, and while the injections help, they are not enough to fully counterbalance the abstraction.

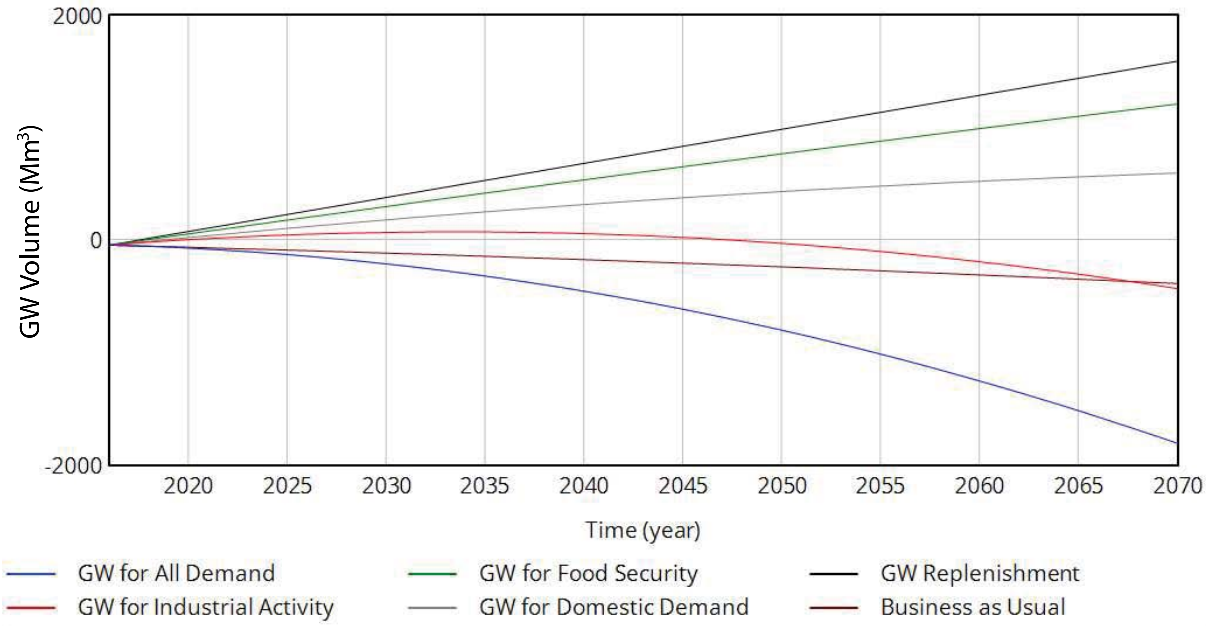

Fig. 4. Results of the SD model showing GW volume in response to different scenarios studied.

- GW for All Demand (Scenario 6), remarkably, shows an upward trajectory, surpassing all other scenarios by 2070. This could suggest that when combining domestic, agricultural, and industrial demands, the GW system experiences greater stress, but the injections are sufficiently large to create an overall positive balance.

4. Reconsideration of implications and recommendations

Considering the model's lack of physical realism (not capping at a maximum or preventing negative values), it is crucial to interpret the results cautiously. The model's assumptions may overestimate the sustainability of certain practices. Despite this, the visual data supports a call for integrated water resources management, emphasizing the need for adaptive strategies that account for actual physical constraints and the potential for GW depletion. Additionally, it is necessary to confirm groundwater response to recharge and abstractions by using a groundwater model.

The upward trajectory in Scenario 4 (GW for Food Security) could be overly optimistic, warranting further investigation into agricultural water use patterns. Similarly, the positive balance in Scenario 6 (GW for All Demand) must be critically evaluated against practical limits to GW recharge capacity.

The model indicates that replenishment efforts are vital across all scenarios to sustain GW levels. The sustainability of GW resources, as reflected in the model, is contingent on the delicate balance between abstraction and recharge. Therefore, while the model offers an encouraging perspective for some scenarios, the real-world application of these strategies requires a pragmatic and scientifically grounded approach to GW management, with robust monitoring and management plans to avoid the pitfalls of over-extraction and resource depletion.

In light of these insights, policymakers should consider the model's implications for GW management and integrate realistic physical constraints into their planning. The overarching goal remains to establish sustainable GW usage patterns that align with Bahrain's socio-economic development plans and environmental conservation efforts.

5. Conclusions and future work

This study has presented a comprehensive System Dynamics (SD) model to evaluate the effect of various groundwater management policies on Bahrain's groundwater resources. The scenarios explored—from the continuation of unregulated groundwater abstraction to strategic replenishment and demand-specific abstractions—highlight the delicate balance required to sustain water resources. Our results suggest that, while replenishment efforts can stabilize groundwater levels to some degree, the 'Business as Usual' approach may lead to unsustainable depletion of groundwater reserves. Moreover, the more optimistic scenarios may require further validation to ensure their feasibility and sustainability given the physical limits of groundwater recharge.

6. Future work

The next stages of this research will delve into the interactions between socioeconomic factors, the agricultural sector, food security, and the energy sector. We aim to:

- Enhance the model by incorporating the impact of socio-economic development on water demand and supply. This will include an examination of population growth, economic expansion, and policy changes on groundwater use.
- Evaluate how different water management strategies affect food security and energy production. This will involve analyzing the potential benefits of increased agricultural production, such as job creation, market expansion, and the export potential of local produce.
- Investigate the impact of taxing groundwater abstraction in the industrial sector and the potential effects of expanding this sector within Bahrain.
- Develop guidelines for policy implementation that consider the SD model's outcomes. This will include a focus on the sustainability of such policies and their alignment with Bahrain's national development objectives.
- Refine the SD model by integrating realistic physical constraints of the groundwater system. This will require adjustments to the model to prevent limitless extraction or the inclusion of negative values, which are not physically plausible.
- Integrating the SD model with a validated regional groundwater model to ensure the accuracy of the model's response to artificial recharge, and changes to inflows from upstream and outflows downstream. This will be vital in refining the model's accuracy and predictive capability.
- Work with local stakeholders, including policymakers, water authorities, and the community, to ensure the model reflects real-world constraints and opportunities.
- Explore the potential for cross-sectoral water management strategies that combine domestic, agricultural, and industrial needs, aiming for a holistic approach to water resource management.

- Investigate the potential of emerging technologies in water conservation, such as advanced irrigation systems, water recycling, and desalination, to be incorporated into future scenarios.

By addressing these aspects, future research will contribute to a more resilient and sustainable water management system in Bahrain, providing a blueprint for other arid regions facing similar challenges.

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Balaban Desalination Publications

The 15th Gulf Water Conference

(2025) 180–201
doi: 10.5004.dsal.2025.700004

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Assessment of the sustainability of water management system in the Sultanate of Oman: a case study of Al-Batha basin

Yasir Said Al-Saadi*

Ministry of Agriculture, Fishers Wealth and Water Resources, Oman
email: ahmed99@squ.edu.om

ABSTRACT

Natural water resources sector in the Sultanate of Oman is one of the sectors that faces many challenges due to the increasing demand for water to meet the various development requirements. In the Sultanate there is an imbalance between water demand and supply, and thus the Sultanate of Oman is working on building many desalination plants to cover the in order to cover this deficit, the Sultanate is building desalination plants and dams, in addition to reusing treated wastewater which contributes in a relatively little to meeting the water deficit. However, this approach, i.e., supply management and maximizing water resources, the Sultanate is currently pursuing has not helped reduce the water deficit, which is estimated at 316 million m^3 (Mm^3). Moreover, seawater desalination is considered very expensive for the government and has negative environmental impacts on the surrounding marine and air environments. This study aims to evaluate the water resources management system in the Sultanate of Oman by using one of the water basins, the Al-Batha basin as a case study, and identify the most important challenges facing the management of water resources in this basin, and propose possible solutions and future scenarios that can contribute to reducing the water deficit in the Al-Batha basin, estimated at about 54.6 Mm^3. The WEAP software was used to build a dynamic mathematical model that simulates the water management system in the Al-Batha basin at the present time in terms of water resources and uses, and then to make future scenarios for future options to reduce the basin deficit during the period from 2020–2040, which is the period of implementation of the Oman 2040 vision. The results showed that if the leakage in the network was reduced by 10%, sewage collection rate was increased, and the irrigation efficiency was raised to 70%, water demands would be considerably decreased. In 2040, the total municipal water demands are calculated at 294 Mm^3 compared to about 317 Mm^3 under the reference scenario. The amount of collected wastewater was about 270,779 m^3 in 2020 and would reach about 318,744 m^3 in 2040. In the agricultural sector, the amount used could be reduced from 6,236 Mm^3 in the reference scenario during to a quantity of 118.3 Mm^3 by the year 2040 if irrigation efficiency measures are implemented. It is recommended that

*Supervisor Prof. Waleed K. Al-Zubari

ISBN 0-86689-078-5

water management priorities be focused on reducing the leakages in the municipal distribution network, increasing the collection of wastewater, and raising the irrigation efficiency in the agricutlrual sector to enhance the sustainability of the water management system in the Sultanate of Oman.

Keywords: WEAP; Integrated management of water resources; Aflaj

1. Introduction

1.1. General

1.1.1. Geography

The Sultanate of Oman occupies the south-eastern corner of the Arabian Peninsula with a total area of about 309,500 km^2. It is bordered in the northwest by the United Arab Emirates, in the west by Saudi Arabia and in the southwest by Yemen. A detached area of Oman, separated from the rest of the country by the United Arab Emirates, lies at the tip of the Musandam Peninsula on the southern shore of the Strait of Hormuz. The country has a coastline of almost 3,165 km from the Strait of Hormuz in the north to the borders of the Republic of Yemen in the southwest, overlooking three seas: the Arabian Gulf, the Gulf of Oman and the Arabian Sea (Ocean, 2009).

1.1.2. Demographics

The total population of the Sultanate of Oman in 2020 reached a total of 4,471 thousand and 148 people, according to the official census of population, housing and establishments. This is compared to 2,773 thousand and 479 people in the 2010 census, where the total population in the Sultanate increased by 61.2% within 10 years.

The population density of Oman reached 14.15 persons/km^2 in the year 2020, and the Governorate of Muscat maintained the lead in the Sultanate's governorates in terms of population. Its total population amounted to 1,302,440 people in the year 2020 AD, compared to the 2010 census, where the population was (775,878) people. an increase rate (68%). It is followed by North Al-Batinah with an estimated 16.5% of the total population, then Al-Dakhiliyah Governorate with 10.1%, Dhofar 10%, then South Al-Batinah, South Al-Sharqiyah, and North Al-Sharqiyah with 9.2%, 6.9%, and 6.1%, respectively. Data from the National Center for Statistics and Information indicate that 45% of non-Omani expatriates are concentrated in the Governorate of Muscat and constitute about 64% of its total population, while approximately 12% reside in the Dhofar Governorate, and 5.9% in Al-Dakhiliyah, and the rest of the expatriates are distributed among the other governorates in %.

1.1.3. Climate

Generally, the climate is considered to be arid and semi-arid but differs from one region to another. It is hot and humid during summer in the coastal areas and hot and dry in the interior regions with the exception of some higher lands and the southern Dhofar region, where the climate remains moderate throughout the year. Potential evaporation varies from 1,660 mm/y on the Salalah plain in the south to 2,200 mm/y in the interior. In the north and centre of Oman rainfall occurs during winter, from November to April, while a seasonal summer monsoon, from June to September, occurs in the southern parts of the country (Dhofar) causing a temperature change (Ocean, 2009).

1.1.4. Water resources management

During the past forty years, there has been rapid development in the use of water resources in the Sultanate. This occurred as a result of growing economy which has brought an increase in urbanisation associated with a demand for high levels of service and quality for water supplies. In addition, associated demand on food has led to a major expansion of agriculture, beyond that of the traditional aflaj areas. As a result, water demand in the agricultural sector has tripled accounting to about 82% of total water consumption (Al Barwani, 2014).

During the Seventh Five-Year Plan (2006-2010), government investment in the water resources sector was approximately US $ 2,044 million in various water projects in the water supply and sanitation sectors. These projects included: Establishing new desalination plants, modernizing existing ones, expanding the existing local water supply, constructing recharge dams and constructing a major retention dam with a maximum capacity of 100 Mm^3 in the Muscat area; Improving the existing sanitation facility and increasing water availability through the construction of new wastewater treatment plants with investments amounting to US$ 58 million (Helmi, 2016). Water is, and will remain, one of the nation's most valuable resources. Optimization and strategic management of the water sector was seen as a key dimension of the Omani Economic Diversification Strategy at the vision "2020" Conference in 1995 (Al Barwani, 2014).

Oman is highly dependent on rainfall for its fresh water supply and groundwater recharge. The main source of water is groundwater. Almost all fresh water in Oman, apart from domestic water supplies obtained from desalination plants, is from rainfall. Nonrenewable fossil groundwater is found in certain localities such as Al-Najd area in Dhofar region. Rainfall is limited and varies considerably throughout the country (Abdelmagid, 2017). The water resources of Oman occur in two forms, the first is in the form of groundwater represented by wells and daudi aflaj, and the second is in the form of surface water represented by the ghaily aflaj, springs, and few perennial wadis.

1.2. Problem statement

The Sultanate of Oman experiences a water deficit between supply and demand estimated 1t 316 Mm^3. On the other hand, there is an increase in the areas of agricultural lands approved by the government, (which will increase the stress on groundwater wells). Rapid population growth during the last ten years caused pressure on water resources, which prompted the government to build dozens of desalination plants to cover the water deficit. Moreover, there is an additional accelerating challenge in the provision of water requirements of the comprehensive development in the Sultanate in the social, economic, tourism and industrial aspects. The strategy of the Sultanate of Oman in the past 30 years to reduce the deficit has been focused on the engineering and supply side management manifested in the construction of desalination plants, and the construction of dams to capture surface water and recharge groundwater, and reuse of treated wastewater. However, these efforts, though strenuous, has not achieved the desired goal towards reducing the deficit despite the costs incurred by the government. Therefore, it is necessary to implement integrated water resources management by complementing the currently practiced management approach by conservation and demand side management approach and investigate its potential and effectiveness in reducing the water deficit in the Sultanate of Oman on a sustainable basis is expected to continue, and probably widen in the future. In the past years, to reduce the deficit the Water Authorities in the Sultanate focused on the supply-side management, management approach represented by expansion in building desalination, increasing groundwater withdrawals, building dams for water harvesting and groundwater recharge. However, this approach is unsustainable and is associated with large economic and environmental costs. A shift towards demand-side management and conservation to complement the existing supply management approach would be needed to address the current and future water deficits.

1.3. Research questions

1. How are the current statures water resources management in the Al-Batha basin?
2. What are the best future scenarios for managing water resources in Al-Batha basin?
3. What are the appropriate recommendation for sustainable water management in the Al-Batha basin?

1.4. Research objectives

This study aims to assess the integrated management of water resources in the Sultanate of Oman, using the Al-Batha Basin in the North and South A'Sharqiyah Governorates, as a case study. The study will use the WEAP dynamic modelling software, as a tool to develop future scenarios to investigate and find appropriate management solutions for balancing the basin supply and demand from an integrated management perspective in the next 20 years. The specific objectives of the study are:
1. Evaluating the current efficiency of water resources management in the Al-Batha basin.
2. Identifying the best future scenarios for managing water resources that are in line with Oman Vision 2040.
3. Make appropriate recommendation for sustainable water management in the Al-Batha basin.

1.5. Research significance

Water is the basis and pillar of life in any society on the globe, and because of the Sultanate's location in arid and semi-arid regions, water is a great and precious wealth that must be preserved and optimally exploited. Therefore, it is important that water resources are efficiently managed to continue to serve the sustainable development of the Sultanate of Oman. In order to optimally manage water, the water situation must be assessed from the administrative and technical aspects, in order to devise appropriate solutions to raise the efficiency of water resources management, reduce the water deficit and reduce costs. Likewise, the problems facing the water resources sector must be identified and solutions are sought and presented to decision-makers in order to take the appropriate decision. One of the methods taken to assess water management is mathematical modeling using a specific model and developing specific scenarios. The importance of this research lies in the fact that it uses management modeling of the water sector in the Sultanate of Oman, specifically in the Al-Batha basin.

1.6. Methodology

1. Evaluation of the current water resources management in the sultanate of Oman will be made using the following steps:
   a. Develop a dynamic mathematical model for the Al-Batha basin using WEAP (collecting data, inputting data, verification of model)
   b. Running model for future scenarios under the

business as usual (using the same management approach and policies)–calculating/observing performance indicators).

2. Identifying best future scenarios
   a. Running model under various potential management interventions and calculating performance indicators
   b. Comparing the performance indicators of the potential management scenarios with the business as usual performance indicators

Make appropriate recommendations for the effective balancing between supply and demand on long-term basis.

2. Literature review

2.1. Introduction

The literature review consists of two important themes. The first is a review of the previous literature about Wadi Al-Batha, and characterizing its watershed, including its topography, geology, water resources both renewable water non-renewable and water uses. The second will be concerned with the topic of using dynamic modeling to evaluate the effectiveness of the current management of water resources in the Al-Batha basin, using the (WEAP) program as one of the widely used tools to serve as decision support.

2.2. Topographical features and terrain

The eastern region is located to the south of the Governorate of Muscat in the southern parts of the Eastern Hajar Mountains and covers an area of about (40,000 km^2). Land altitudes in the region range from more than 3000 m above sea level in the Eastern Al Hajar Mountains to less than 500 m above sea level in the coastal plain of Wadi Al Batha and Sands of A'Sharqiyah, until they reach sea level in the coastal areas.

The governorates of A'Sharqiyah (Northern and Southern) are divided into three geomorphological zones:

- The mountainous region/the mountain plain region, which lies at the top of the catchments and is dominated by ophiolite and basement limestone rocks, and some of its parts are topped by narrow bands of valley pebbles.
- The range of the alluvial plain that extends towards the coast through the middle and lower Ahbas of Wadi Al-Batha.
- A wide range of sand dunes (the A'Sharqiyah Sands) extending south of the alluvial plain until it mixes with the coastal plain from the south and east sides. The northeastern part of the coastal plain is characterized by the presence of extended areas of sabkha deposits.

Precipitation rates vary in the A'Sharqiyah region in each watershed, reaching (196 mm) in Wadi Bani Khaled in the mountainous parts, (110 mm) in the AL-Qabil and Ibra valleys, and (84 mm) in the plain parts in the states of Al-Kamil, and Al-Wafi, Jalan Bani Bu Hassan and Jalan Bani Bu Ali. As for the eastern coastal parts, such as Wadi Rafsa, Wadi Shab and Wadi Tiwi, rainfall rates range between (90–118 mm). In the area of sand dunes (A'Sharqiyah Sands), precipitation rates reach (80 mm).

2.3. Water resources in Oman (Table 1)

Water resources in the Sultanate of Oman are divided into two parts, either conventional or non-conventional. The traditional water resources are surface water and ground water. Unconventional water is obtained from two sources. The first is from desalination processes, and the second is the water produced through sewage treatment plants in the Sultanate of Oman (Mohammed et al., n.d.).

Table 1
Water resources in Sultanate of Oman (Mott MacDonald and Partners Limited, 2013)

Conventional water (1318 Mm^3)		Non-conventional water (238 Mm^3)	
Surface water	Groundwater	Desalination	Treated wastewater
102 Mm^3/y	1216 Mm^3/y	196 Mm^3/y	42 Mm^3/y

2.3.1. Conventional water resources

The total average available traditional resources in the Sultanate of Oman is estimated at about 1318 Mm^3 annually, which represents the actual annual recharge, including renewable surface water estimated at about 102 Mm^3 and renewable groundwater amounting to about 1216 Mm^3. This water is distributed over 1128 Mm^3 used in agriculture and the remaining 88 Mm^3 is used for public water supply, extracted from well fields. Natural water resources include renewable resources, which are currently replenished by the airport and stored in aquifers, and non-renewable resources called fossil water. The total rate of replenishment of renewable resources is estimated at about 1318 Mm^3/y (Alqasmi, 2018).

The annual per capita share of natural water is currently equivalent to about 488 m^3/person, which is close to the state of severe water stress according to international indicators (WaterResourcesManagement-Practices, n.d.).

2.3.2. Non-conventional water resources

2.3.2.1. Desalination

Desalination plays a critical role in filling the gap between freshwater demand and availability in water-scarce Sultanate of Oman since 1976. Installed desalination capacity in the country has almost increased by 60 times that in 1976 with increasing fresh water demand. Even though desalination share is increasing, 80–85% of freshwater demand today is still satisfied with groundwater and natural sources. This is leading to increased soil salinity in recent years affecting the crop production. All the planned and installed desalination plants in the country use conventional fuels for their operation (Bhambare et al., 2018) 80–85% of freshwater demand today is still satisfied with groundwater and natural sources. This is leading to increased soil salinity in recent years affecting the crop production. All the planned and installed desalination plants in the country use conventional fuels for their operation. None of the plants are based on any form of renewable energy source. Consumption of fossil fuels for the operation of these plants is increasing at an average rate of 3-5% affecting the net export for the country. Sultanate of Oman is considered to be one of the most suitable destinations for solar energy applications and solar energy can play a vital and sustainable role in meeting the gap between the demand and supply of fresh water using solar thermal desalination. This paper emphasizes on addressing this aspect for the country. An overview of present desalination status and fresh water demand, fuel requirements, solar energy availability, thermal desalination technologies and solar thermal technologies has been presented in the paper. Conventional thermal desalination technologies and solar thermal technologies have been compared for same capacity on the scale of 1 to 5 for various factors in the context of Sultanate of Oman. Few of the challenges and barriers in the implementation of solar thermal desalination in the country are also discussed in the paper. Fixed focus type Scheffler dish reflectors (SDR.

Total amounts of desalinated water recorded in 2016 are 279.6 Mm^3. This is higher than 2015 by 16.7%. The number of water desalination stations rose as well by 4.0% to reach 52 stations in 2016, but the growth in their capacity was only 0.1% in 2016. The majority of desalination stations use RO technology with the exception of Existing Ghubrah, Barka1 and Sohar, which use other technologies. In 2016, per capita of desalinated water is 173.5 L/d, 10.0% higher than 2015 (Gccstat, 2018). The main four major seawater desalination plants are spread across in Al-Gubrah, Barka, Sohar and Sur region. Further brackish water desalination plants along with natural ground water resources in the inland supply fresh water (Sudhir & Joy, 2016).

2.3.2.2. Wastewater treatment

In the Sultanate of Oman, wastewater treatment has been evolving over the years. Currently, there are more than 400 wastewater treatment in the country. Most of the TWW is being used in landscape irrigation by the municipalities. Oman is putting serious efforts on the treatment and use of wastewater and effluent water. An investment of US$ 2.8 billion has been made to develop, manage, operate and maintain all wastewater networks, and treatment plants throughout the country (Hussain et al., 2019). In Oman, wastewaters collected from domestic and commercial areas are transferred to either wastewater treatment plants (WWTPs) or lagoons via sewer systems (very few) or through tankers from septic tanks (majority).

2.4. Current water demands

Water demand in Oman comes mainly from four sectors: household, industry and municipalities, agriculture (aflaj and farms irrigated with wells), and the environmental requirements of natural plants (Helmi, 2016) (Table 2).

Recent studies show that there is an average water deficit equivalent to 316 Mm^3/y (Mott MacDonald and Partners Limited, 2013).

2.5. Population of study area

The population study area is shown in Fig. 1.

2.6. Study area: Wadi Al-Batha

Wadi Al-Batha in the A'Sharqiyah region is considered one of the largest watersheds in the Sultanate, with a total area of about 5,740 km^2. It and descends from the Eastern Hajar Mountains through several sub-wadis (Al-Qabil – Al-Zahir – Al-Galaji – Al-Nabaa – Ibra – Qafafa – Wadi Bani Khalid) towards the southeast to drain into the Arabian Sea. Wadi Al-Batha passes through many of the wilayats of the A'Sharqiyah region, namely Ibra, Al-Qabil, Bidiyah, Wadi Bani Khalid, Al-Kamil and Al-Wafi, Jalan Bani Bu Hassan, and Jalan Bani Bu Ali. It represents the main source of water used either by

Table 2
Current water consumption in Oman (1872 Mm^3/y) (Mohammed et al., n.d.)

Agriculture (1546 Mm^3)		Drinking water	Industrial and commercial
From wells	From Aflaj		
1060 Mm^3/y	486 Mm^3/y	196 Mm^3/y	130 Mm^3/y

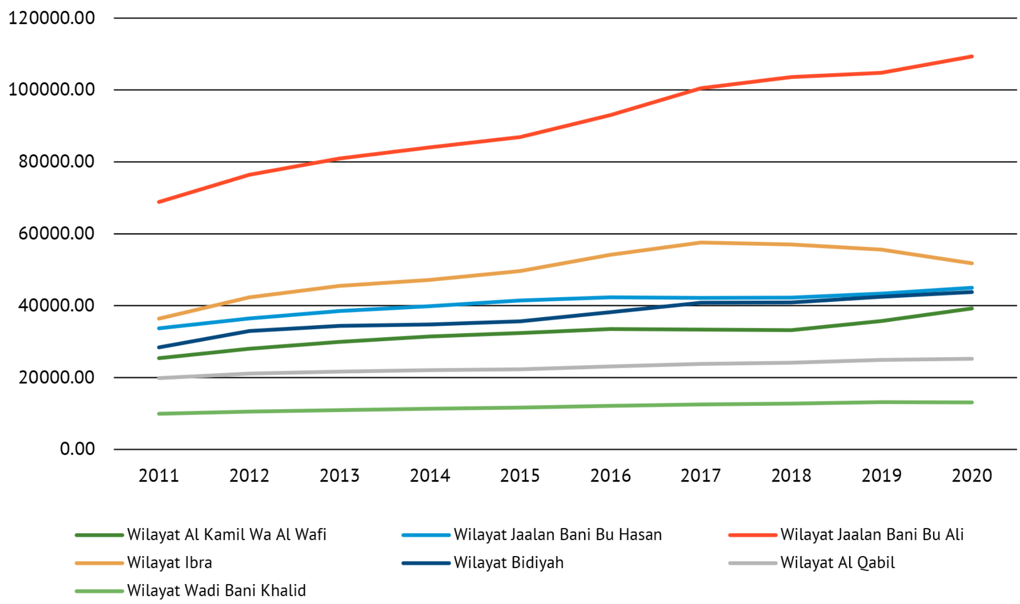

Fig. 1. Population varies for each Wilayat during 2020–2040 (National Center for Statistics and Information data 2020).

wells or aflaj;, there are 2,251 wells used in irrigation purposes, representings about 79% of the total number of wells in the A'Sharqiyah region, in addition to 264 falajs used for irrigation and domestic purposes. These falajs represent about 68% of the total number of falajs in the A'Sharqiyah region. In Wadi Al-Batha, especially its mountainous parts, there are many exploited springs, numbering 62, while there are also many untapped water springs, numbering 33, with most having relatively little flow, with the highest flow reaching 3 L/s, as in Ain Wadi Bani Khalid, one of the sub-wadis of Wadi Al-Batha.

2.7. WEAP applications

Simulation models are tools to assist decision-makers and stakeholders understand the impact of their actions and decisions on outcomes, as well as better understanding water allocation problems by providing a systematic decision-making that indirectly gives a sustainable solution for disagreements (Nandalal and Simonovic, 2003).

One of these models is a WEAP model, which presented by a non-profit research organization, Stockholm Environment Institute (SEI), USA, conduct research and engage with decision-makers on energy, water and climate policy (Adgolign et al., 2016). The WEAP model has been used in many parts of the world to evaluate many water related projects (Jaber, 2018).

The WEAP software is a tool that dynamically models the water management system in an integrated manner (i.e., water resources and water users) to support the decision making process in water planning and management. WEAP allows the simulation of various development scenarios to provide the manager with an understanding of the optimal scenario that can be applied in a specific country, basin or watershed. The model simulates all the components of the water system and allow the investigation of the effectiveness of the demand management policy instruments in balancing supply and demand to ensure that water deficit or poverty is not reached.

Operating on the basic principle of water balance accounting, WEAP is applicable to municipal and agricultural systems, single sub-basins or complex river systems. Moreover, WEAP can address an wide range of issues, e.g., sectoral demand analyses, water conservation, water rights and allocation priorities, groundwater and streamflow simulations, reservoir operations, hydropower generation, pollution tracking, ecosystem requirements, and project benefit-cost analyses (Sieber, 2006).

Jeddah City is expected to experience water supply stress due to rapid population growth and expansion of urban developments. This paper aims to assess the impact of possible water demand on Jeddah water resources in 2030. To facilitate the analyses, a scenario-based modeling is used in conjunction with WEAP to find the best combination of scenarios that meet future water demands. For each scenario, the water resource implications were compared with a 2017 baseline (Al-Juaidi and Al-Shotairy, 2020).

The WEAP model was used to study electricity consumption in the municipal water sector in a water-stressed oil-exporting country: the case of Bahrain, which examined the strong water-energy links in the GCC, which are characterized by water scarcity and energy abundance (Alsabbagh et al., 2021).

3. Current status of water resources system in the Al-Batha basin

3.1. Water resource in Wadi Al-Batha

Oman is the driest country with average rainfall of 62 mm/y (Hussain et al., 2019). A'Sharqiya (north and south) lies 100 km south of Muscat, on the southern flanks of the Al Hajar A'Sharqiya mountain range, and extends over an area of 40,000 km^2. With eleven wilayats and a total population in excess of 300,000. A'Sharqiya (north and south) is the third most densely populated governorate in Oman. The major inland settlements in the region lie on the courses of Wadi Andam and Wadi Al Batha — two long basins which drain from the ophiolite mountains to the Arabian Sea, flanking the western and eastern sides respectively of the A'Sharqiya sands. Both wadis originate from a series of generally south flowing tributaries which rise in the A'Sharqiya Mountains. Very little of the substantial flows generated in these wadi actually reach the sea as a result of high infiltration within upstream alluvial fan and wadi alluvium (Municipalities and Resources, n.d.). Rainfall in the mountains of A'Sharqiya is generally in excess of 200 mm reducing to less than 100 mm in the alluvial plains and in the Eastern Sands. For most of the region the three wettest months are February to April, which account on average for more than 60% of the total annual rainfall. In some areas, a second but less pronounced relatively wet period occurs between July and August, which results from the effects of the khareef/monsoon blowing from the south (Municipalities and Resources, n.d.). Water demand in the northern region (the Interconnected Zone and A'Sharqiya Zone) is projected to increase in the range of 5–7% per year, from 281 Mm^3 in 2015 to a range of 390–440 Mm^3 in 2022 (Bashitialshaaer, 2017).

3.1.1. Conventional water resources

In Oman, non-renewable groundwater reserves largely occur within the Interior Basin where thick Tertiary carbonate formations occur with total thickness of several hundred metres and store vast quantities of water. Groundwater quality tends to be brackish generally deteriorating away from the northern and southern mountains where the rocks are exposed or at shallow depth and where recharge occurred in past times. Nationally, total recharge to groundwater reservoirs is estimated to average about 1,300 Mm^3/y the bulk of which 70% results indirectly from infiltration of surface water flows and the balance from direct rainfall recharge. With settlement and development, the demand for water has led to ever-increasing interception of groundwater flow by, and abstraction from, dug wells and aflaj. Such interception and use have modified the natural balance; in some areas the rate of abstraction now exceeds the rate of replenishment. In such areas, water levels decline signifying a reduction in the volume of water stored in the aquifer. In some coastal areas, the lowering of water levels has reversed the natural groundwater flow direction with consequent movement of sea water inland (Municipalities and Resources, n.d.). In many areas of the Sultanate, withdrawal for water exceeds its availability (Al-Khamisi, 2011).

3.1.1.1. Groundwater resources

Most of the water supplied in Oman comes from groundwater by wells or aflaj systems. However, in major cities such as Muscat, desalination plants provide a portion of the water required for urban use. There are 4,112 falajs in Oman, of which 3108 are live falajs producing water about 680×10^6 m^3/y in which 410×10^6 m^3/y are used. These aflaj irrigate about 26,500 ha (Al-Ghafri, 2004).

3.1.1.2. Aflaj

Aflaj is a traditionally built channel system that collects and transfers the ground and surface waters. It is an ancient heritage in the Sultanate of Oman for more than 2000 years. Among the 4,112 falaj (singular of aflaj) channels, only 3,017 actively supply usable water of 410×10^6 m^3/y (Shaik et al., 2021). Aflaj systems are arranged to fulfil the purpose of domestic use, which is primary followed by agricultural, which is secondary. Of the total aflaj water, 99.8% is used in agriculture. In most cases, aflaj water is first allocated for drinking and then used by mosques, forts, and finally domestic needs. Thereafter, falaj water is used for irrigating the permanently cultivated lands, mostly date palms, and then the seasonally cultivated lands (Al-Ghafri, 2018).

3.1.1.3. Dams

A dam built across an alluvial channel stores water during the flood. The stored and clarified water is then released slowly, so it can infiltrate thick alluvium downstream of the dam and in time be withdrawn for use. In Oman, an additional and very important benefit of storing flood waters underground is the reduction of sea water intrusion in coastal areas, which has become a serious problem in many parts of the country, especially on the Al Batinah plain (Municipalities and Resources, n.d.) (Table 3).

Table 3
Dams located within the study area (above the Al-Batha Valley basin)

Dam name	Dam type	Storage capacity, Mm^3	Spillway length, m	Maximum height, m
Wadi Nam (N1)	Recharge	0.72	333	8
Aleaqida (N2)	Recharge	0.44	1229	5.5
Alrasa (N3)	Recharge	0.78	1097	5

3.1.2. Non-conventional water resources

Non-conventional water sources are those that are obtained with human help, represent by desalinated water and treated wastewater, which has been increasingly relied upon to meet water demands by the rapid population growth escalating socio-economic development and contribute in reducing the Sultanate water deficit.

3.1.2.1. Desalination

Desalination plants make an important contribution to water supplies where natural water resources are unavailable or inadequate. Plants have been installed since the early 1970 s. They are located both on the coast and in the interior, primarily to provide potable water to communities but also to supply industry (Khabouri et al., 2007).

Desalinated seawater has become an essential contributor to water supplies where fresh water resources are limited or unavailable. In general, sea water is used only when fresh water sources are not economically viable, or when there are restrictions on groundwater pumping as in the case of the A'Sharqiah Sands Groundwater Supply Project. The total cost of desalinated water in Oman including treatment (pH, hardness, etc.) is considered to be in the range of 0.700-0.755 OMR/m^3 (equivalent to \$1.81–1.96/m^3) (Al-Khamisi, 2011).

3.1.2.2. Wastewater

Wastewater treatment plants (Table 4) are being installed and commissioned in the main towns in various governorates and regions of the Sultanate to benefit from this renewable resource and to protect the groundwater from contamination. Similarly, there are plants for the industrial cities. In the near future, there will be considerable potential for increasing the use of treated wastewater, particularly for aquifer recharge and irrigation as more advanced wastewater treatment systems are constructed nationally (Al-Khamisi, 2011).

There is one sewage treatment plant in each of the Wilayat located on the Al-Batha watershed. All water extracted from sewage stations in each Wilayat is used to irrigate green areas on main roads, gardens and parks, and so far, treated water has not been used in agriculture. This is because farmers do not accept the idea of using treated water in agriculture also because of customs and religion.

Table 4 shows the quantities of water inflow these stations and the amount of water outflow the stations to be used. It can be concluded that through Table 4 there are very small quantities of water entering the stations, due to the absence of a wastewater network in these areas, except for the Wilayat of Ibra, in which there is a wastewater network in part of this area, about 40% covered by a network sanitation.

Table 4
Wastewater treatment plants in Al-Batha basin

Wilayat	Total year inflow average (m^3/y)	Total year outflow average (m^3/y)
Ibra	23,561	22994
Al Qabil	2405	2309
Bidihya	4529	4221
Al Wafi	1631	1206
Bu Hassan	3505	3196
Bu Ali	4368	4364
Total year average	39,999	38,290

3.2. Water demand management

The need to reduce agricultural water consumption has been established in many areas and the water authorities have a clear policy for demand management in the agricultural sector. A number of measures that could be used to achieve sustainability targets have been evaluated within the development of the Master Plan, which are summarized in the followings (Municipalities & Resources, n.d.).

3.3. Status of the current water resources of the Al-Batha Basin

Data on water uses and water sources in the Al-Batha basin for the year 2020 are collected and a water flow diagram is prepared (Fig. 2) to represent the components of the current water system in the basin. The water system consists of 3 users, municipal, agricultural and industrial sectors, and 3 water sources, groundwater, desalination, reused treated wastewater. The major problems and issues in the current system are:

1. Low irrigation efficiency leading to high agricultural water consumption.
2. Cropping of water-intensive crops such alfalfa and animal feed.
3. Low reuse rate of wastewater.
4. Groundwater deficit.
5. High leakage in the municipal supply distribution network.
6. Random digging inside some homes and farms without official licenses.

Fig. 2 and Table 5 show all the water sources in the Al-Batha basin and where the water goes, where groundwater, desalination and treated water go to the agricultural, municipal and industrial sectors in the areas of the Al-Batha basin. Accordingly, there is a water deficit in the Al-Batha basin estimated at 54.6 Mm^3. There are some problems in the water management system in the aquarium, which are:

- Network leakage = 36%
- Wastewater collection = 0.14%
- Per capita consumption = 65.9
- Irrigation efficiency = 30–40%

4. Modeling the water resources management system in the Al-Batha basin

4.1. Introduction

In this study, the Water Resources Assessment and Planning (WEAP) program was used to simulate and analyze the current water management system in the Al-Batha basin and then to evaluate the effectiveness of future scenarios in providing more sustainable water resources in the Sultanate of Oman in general and the Al-Batha basin in particular.

Fig. 3 shows the location of the Al-Batha basin from the source to the estuary, the administrative model of water in the Al-Batha basin, and the main components of water sources and uses. Data has been entered for water sources (ground water, treated wastewater, and desalinated water), as well as data for water use (agri-

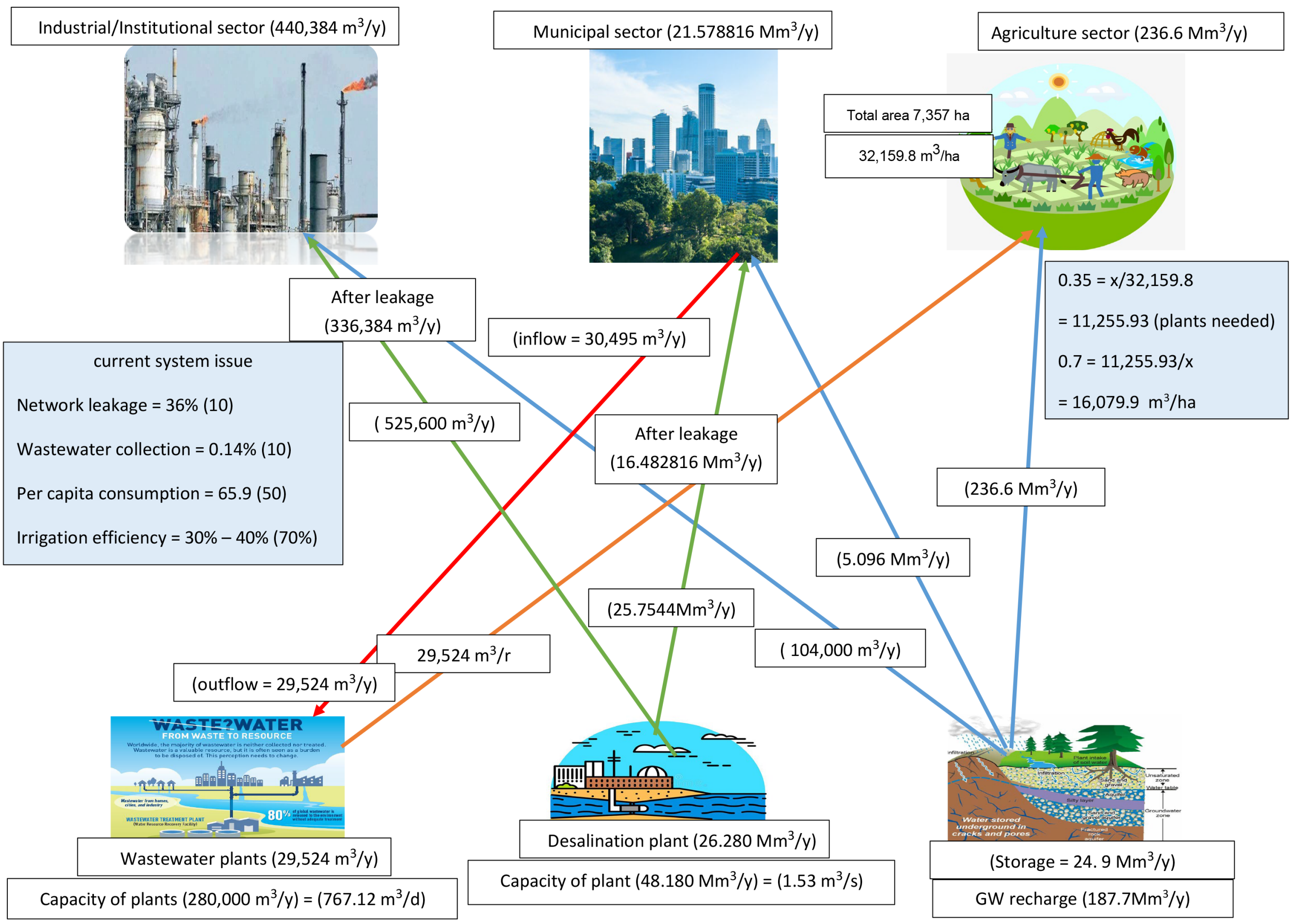

Fig. 2. Current statute water resources in Al-Batha basin.

Table 5
Water resources in the Al-Batha basin. Source: National Center for Statistics and Information (2020), Ministry of Agricultural Wealth, Fisheries and Water Resources (2020), Oman Water and Wastewater Services Company (2018)

Annual population increase rate, %	4.4
Annual population increase	14,404
The population will become in 20 years, in 2040	615,457
The water supply network losses, %	36
The percentage of areas irrigated by modern irrigation systems, %	15
Areas irrigated with modern irrigation systems, ha	1,103.55
Areas irrigated by traditional systems, ha	6,253.45
Irrigation efficiency, %	30–40
Total per capita coms. of produced water (m^3) 2020	79.8 in Oman General (94.2 in Al-Batha)
Water tariff, Bz/m^3	0.990

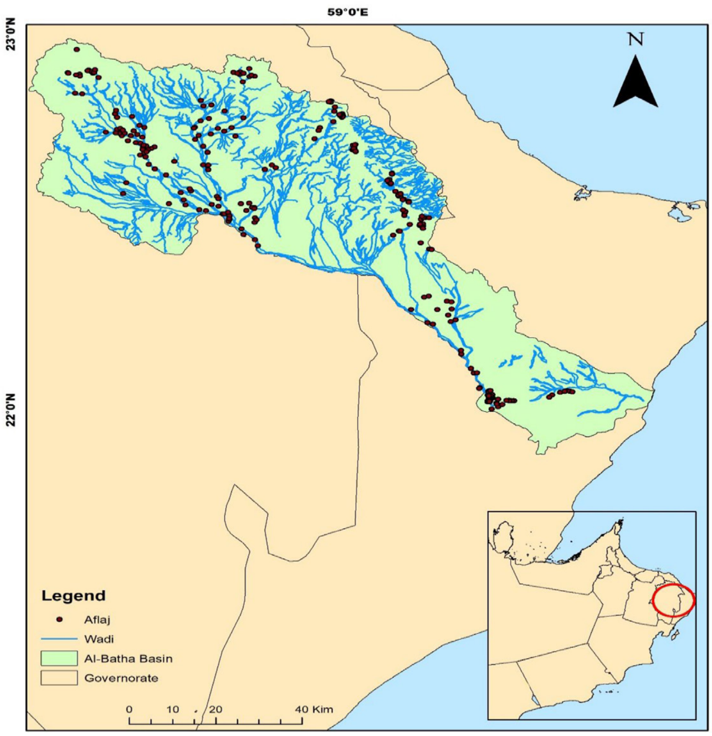

Fig. 3. Location of study area.

cultural sector, municipal sector, industry sector). In addition to entering the number of the population in the study area and its growth rate, the leakage rate from the municipal distribution network and the rate of per capita water municipal water consumption are input. The agricultural sector data entered input consisted the number of hectares irrigated from water sources, the areas irrigated using the traditional system, and the areas irrigated with modern irrigation systems. A reference scenario has been developed for the period (2021–2040).

4.2. Scenarios

In this study, we will analyze a number of scenarios using WEAP. We use the scenarios to explore the best model for water management in the Al-Batha basin in the Sultanate of Oman. By arriving at an ideal model, a set of questions are set, which are as follows:

- What is the impact of the population growth on water resources in Al-Batha basin over the next 20 years?

- What is the impact of the reuse of treated wastewater in the agricultural sector in reducing the deficit and enhancing the sustainability of the water system?
- What is the impact of increasing irrigation efficiency (through the use of modern irrigation system or other demand management means) in reducing groundwater deficit?
- What is the effect of introducing crops that are economically feasible and consume less water?
- What is the impact of changing per capita water consumption on the municipal water demands and in reducing the costs of desalination?

4.2.1. Validation of assumptions

In this study, a mathematical model was built to simulate the water system in the Al-Batha basin, through the water resources and uses of the consuming sectors in the areas that lie within the borders of the Al-Batha basin, during certain periods, as some data were newly collected in 2021 and some during the past years from 2013 to 2020. All data entered into the mathematical modeling system were collected from various parties in the Sultanate of Oman in various sectors (water resources sector, desalinated water sector, wastewater treatment sector). And those data and information were analyzed and processed in an appropriate manner, which is compatible with the mathematical simulation program (WEAP). After that, the validity of building the model was confirmed by comparing the entered and calculated data through the mathematical model. Where the error rate does not exceed 10%, and the aim is to be relied upon in the future prediction with high confidence and can be used in planning and developing strategies for the Al-Batha Basin or in general for all basins in the Sultanate of Oman, and the following assumptions were used in building the model using (WEAP):

- Representing the Al-Batha basin as an independent basin, and entering data for all sectors of demand and the water resources available therein.
- The overall water system was modeled in the Al-Batha basin on an annual basis, and the effects of seasonal seasons, especially the winter and summer seasons, were not taken into account.
- The future scenarios depended on the population census information living in the Al-Batha Basin (North Al-Sharqiyah Governorate and South Al-Sharqiyah Governorate), during the period from 2020-2040 through the data available in the National Center for Statistics and Information (Fig. 4)
- The estimated population increase was adopted based on a specific assumption of the population growth rate of the population of the Sultanate of Oman.
- The system was operated in the reference scenario for the period from 2020-2040 by fixing the per capita consumption rate, the percentage of losses from the network, municipal consumption, industrial consumption, agricultural areas, consumption in the agricultural sector, production from desalination plants, and production from treatment plants.
- The demand sectors were divided into three sections: the municipal sector, the agricultural sector, and the industrial sector (government, tourism and commercial sectors).

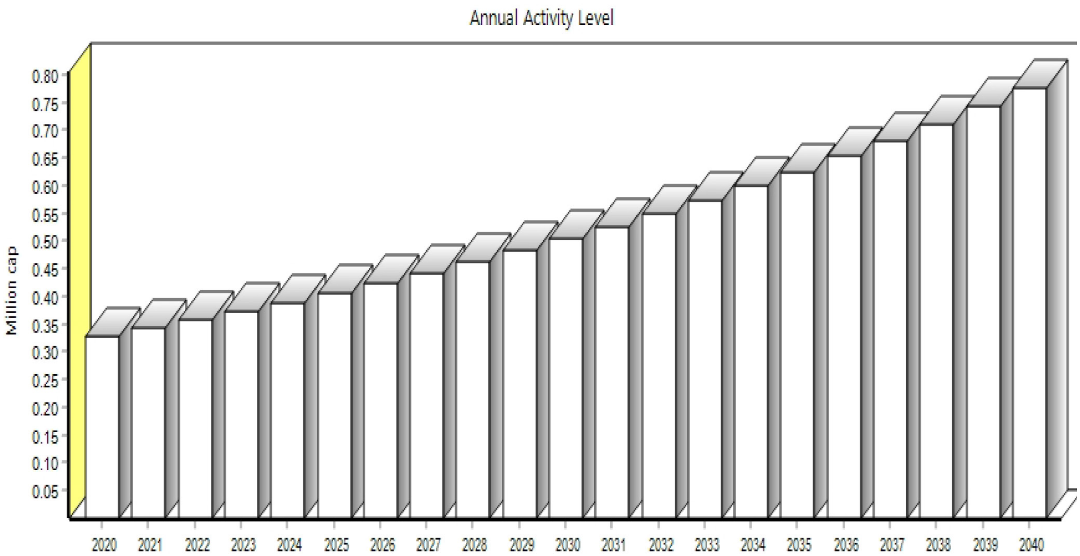

Fig. 4. The population living in the AL-Batha Basin during the current year 2020 and the expected for the period from 2021–2040. (Source: National Center for Statistics and Information).

4.2.2. Reference scenario

This scenario represents the continuation of the current management system for water resources in the Al-Batha basin during the period 2020–2040 and the continuation of the conditions in the previous period, in terms of the consumption rate of the agricultural sector (consumption per hectare), the rate of per capita consumption, and the percentage of network losses, wastewater treatment rates, wastewater recovery rates from the municipal sector, and other water system relationships in the Al-Batha basin.

The main objective of conducting the reference scenario is to obtain reference numbers for comparison with the scenarios that will be developed that represent administrative interventions and evaluate their effectiveness for this scenario by reducing costs and raising the efficiency of water management in order to reach a sustainable water system and integrated management at the lowest costs in the Al-Batha basin.

4.2.3. Municipal water demand

Fig. 5 represents the demand for municipal water in the Al-Batha basin. The demand for municipal water is expected to increase by 136.6%, where it will increase from 21.57 Mm^3 in 2020 to 51.04 Mm^3 in 2040 due to the increase in the population in addition to urban expansion.

4.2.4. Agriculture sector demand

Fig. 6 represents the use of water for the agricultural sector, where it is assumed that there will be no change in the area and practices in the sector in the reference scenario. The total water consumption of the agricultural sector will be constant at 236.6 Mm^3 through all the simulation period.

4.2.5. Industry sector

Fig. 7 represents the scenario for the use of water for the industry sector. Similar to the agricultural sector, the industrial sector water consumption is assumed to be constant in the reference. The industrial sector water consumption is about 440,000 m^3/y.

4.2.6. Wastewater

Fig. 8 illustrates the treated wastewater inflows and outflows of the reference scenario (2020–2040). Because of the anticipated increasing municipal sector demand for water during the next twenty years due to the increase in population, the Sultanate of Oman will build many wastewater treatment plants to protect health and environment. We can understand from the reference scenario that there will be a need for building wastewater treatment plants in the Al-Batha area to accommodate for the generated wastewater in the next 20 years.

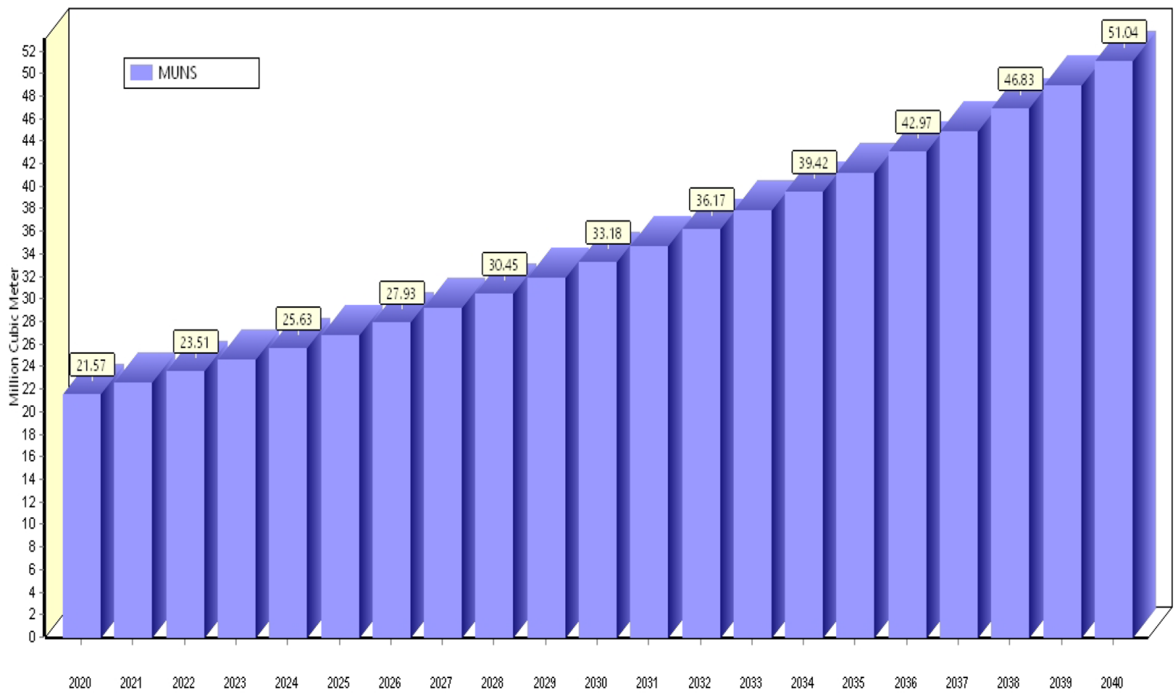

Fig. 5. Reference scenario for municipal water demand (2020–2040).

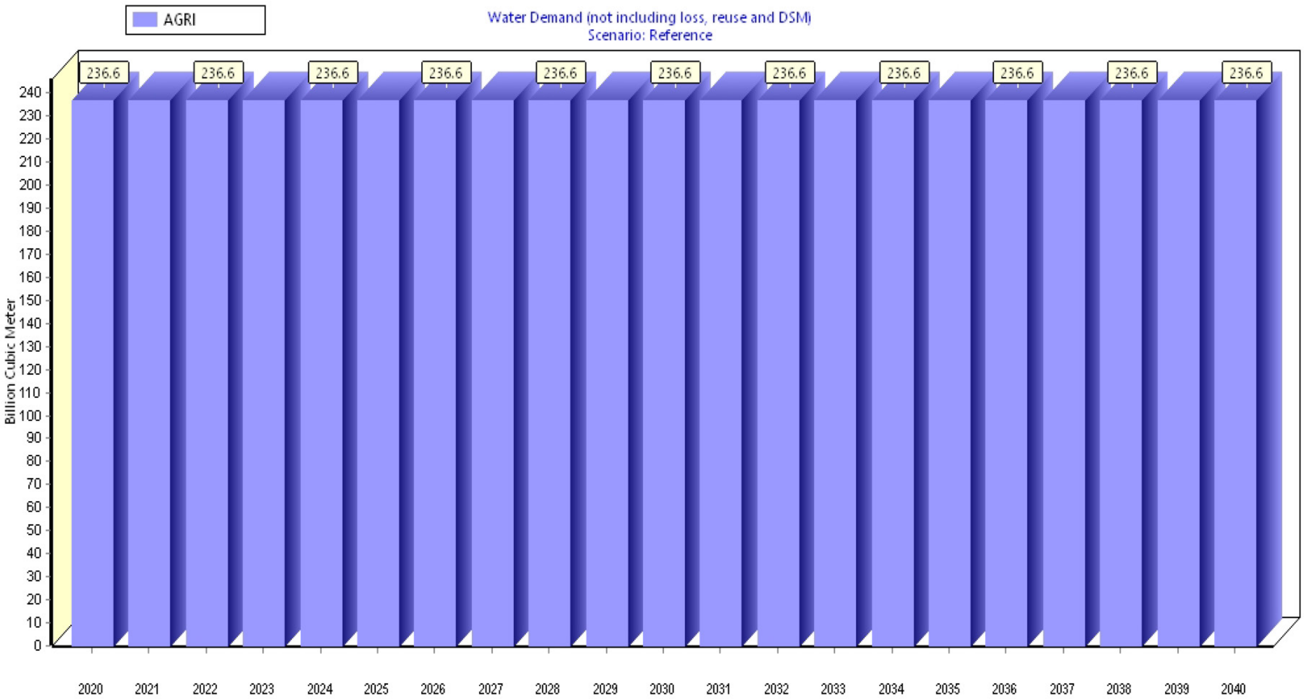

Fig. 6. Reference scenario for agricultural water demand (2020–2040).

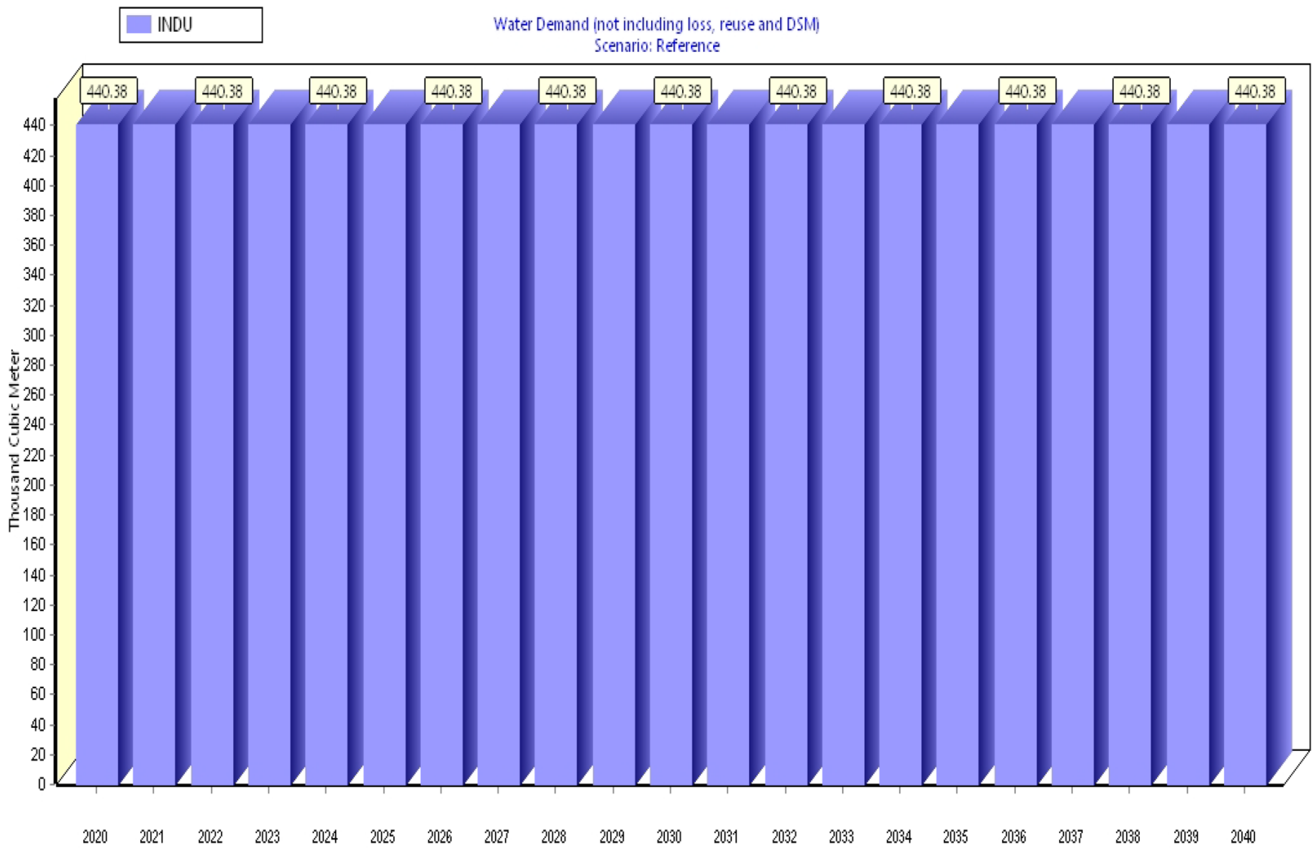

Fig. 7. Reference scenario for industry water demand (2020–2040).

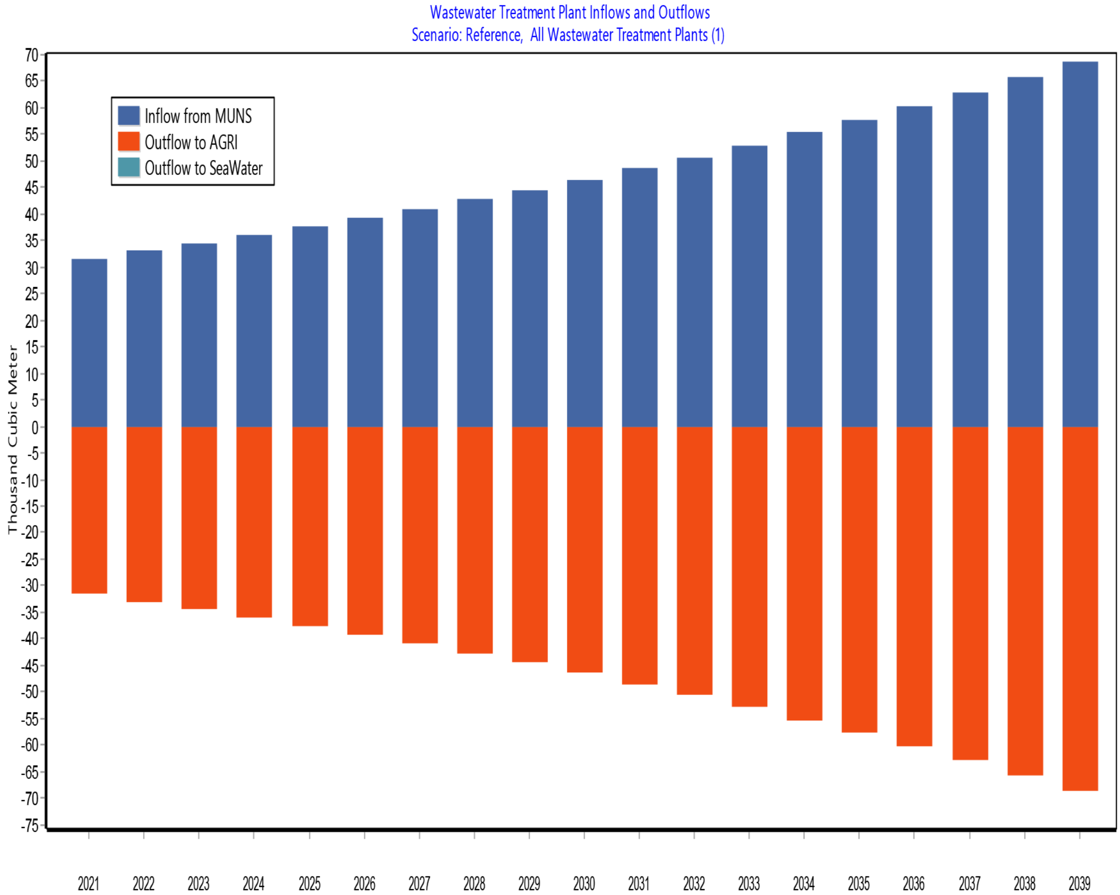

Fig. 8. The quantities of wastewater inflow and outflow treatment plants according to the reference scenario 2020–2040.

5. Strategic options for managing water resources in the Al-Batha basin

5.1. Administrative options scenarios

The reference scenario shows that if the current water management policies and administrative conditions continue in the future unchanged, the water sector challenges and problems in providing water to the consuming sectors in the Al-Batha basin will continue and will be intensified. These challenges and problems are expected to be experienced in all the water basins in the Sultanate of Oman, since the management system of water resources in them is similar to Al-Batha. It can be concluded from the reference scenario (2020–2040) for managing water resources in the Al-Batha basin that the government will tend to increase water supplies by increasing the construction of desalination plants on the Arabian Sea and expanding the increase in wastewater treatment plants or withdrawing from groundwater, which faces an increase in the spatial expansion of agriculture. All of these options will require large financial costs and budget allocation, in addition to their economic and environmental externalities, especially desalination, which is energy-intensive and has negative impacts on the marine and air environments.

The current water management system in the Sultanate, as indicated above, focuses on the supply-side management side, which could not provide high levels of sustainability to the water sector. Hence, there is a need for interventions that focus on demand side management and water efficiency. Such shift, i.e., managing water demands and increasing water efficiency, will result in reducing the financial, economic and environmental costs associated with water management. However, the effectiveness of the management intervention options will need to be evaluated in terms of reducing these costs. They might prove to us that the problem we face is not water scarcity, but inadequate management of water resources.

The GCC Unified Water Sector Strategy (GCC UWS) 2035 was adopted by the Gulf Cooperation Council countries in 2016. It included a number of strategic goals and indicative targets for all the Arab Gulf countries. A number of those administrative options were selected in this study that are commensurate with the existing situation in the Batha basin and the situation of the Sultanate of Oman. In general, these options have been modeled as future scenarios in the developed WEAP dynamic modeling program. The results of implementing these options, individually and all combined, were analyzed and compared with the reference scenario, and then the effectiveness of each option in reducing water demand and increasing supply were evaluated in terms of reducing the associated financial, economic, and environmental costs and impacts.

The future scenarios that have been developed and simulated in a WEAP are:

1. Reducing leakage rate in the distribution network in the municipal sector.
2. Increasing wastewater collection, treatment and reuse in the agricultural sector.
3. Increasing the efficiency of irrigation systems
4. All options together.

5.1.1. Reducing leakages in the water network in the municipal sector

The percentage of losses in the public supply network in the Al-Batha basin is reported at 36% of the total water supply to the public networks of homes, residential and commercial complexes, and others, according to the data of the Omani Company for Water and Sanitation Services for the year 2020. In comparison with the target set by the GCC UWS, which aims to reach a maximum rate of 10% in the network in the year 2035, the percentage found in the Al-Batha basin is considered very high percentage. It indicates that there is a large loss in the network without benefiting any one, which offset large financial losses for the state. Fig. 9 shows the quantities of water leaked from the network when implementing this scenario by gradually reducing the leakage rate in the municipal distribution network to 10% by 2040, compared to the quantities of leaked water in the reference scenario (i.e., 35%).

Fig. 10 shows the total municipal water supplies when implementing this scenario. In 2040 the total municipal water demands are calculated at 294 Mm^3 compared to about 317 Mm^3 under the reference scenario. If this scenario is applied, a cumulative total water volume of about 23 Mm^3 will be saved during the period from 2021–2040, which will be saved from both groundwater and desalinated water. In fact, it is expected that the quality of supplied water will become better since groundwater used for blending will become less.

Fig. 11 shows the comparison between the quantities of municipal water supply, the scenario to reduce leakage and the reference scenario during the period 2021–2040, where it appears that the amount of leakage will decrease compared to the reference scenario.

5.1.2. Increasing wastewater collection and reuse in the agricultural sector

The use of treated wastewater is considered one of the most important strategic options at present to contribute to agricultural development in the Sultanate.

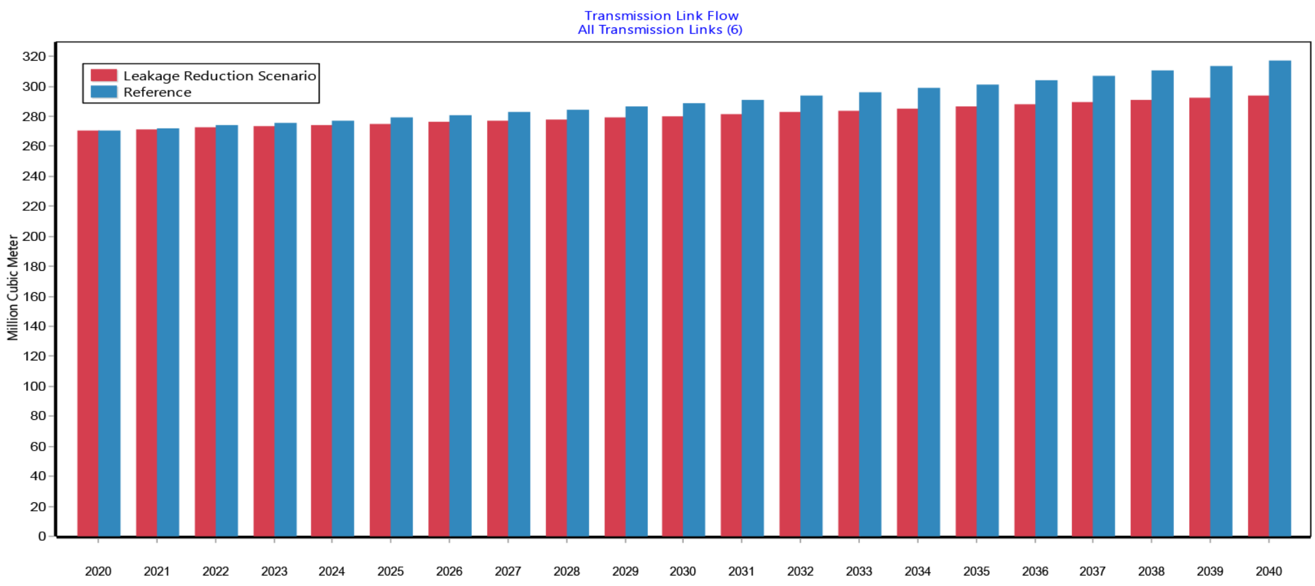

Fig. 9. Comparison of water leakage amounts between the reference scenario and the scenario of reducing leaks to 10% by 2040.

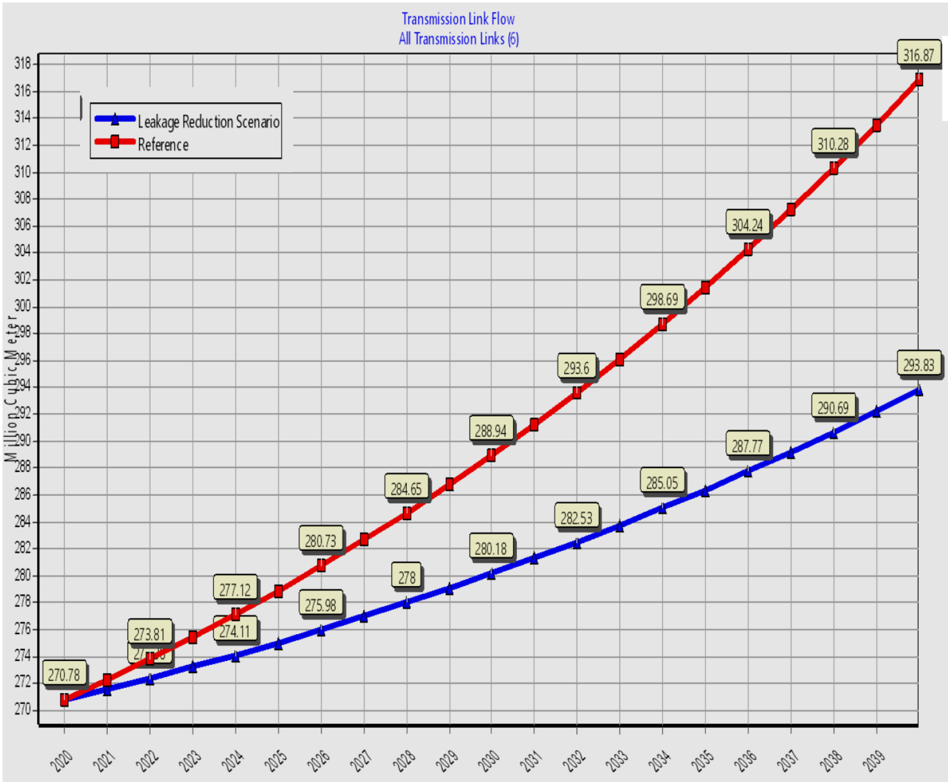

Fig. 10 A comparison of the quantities of water that could be saved in the case of applying the scenario of reducing leakages to 10% by the year 2040 and comparing it with the reference scenario.

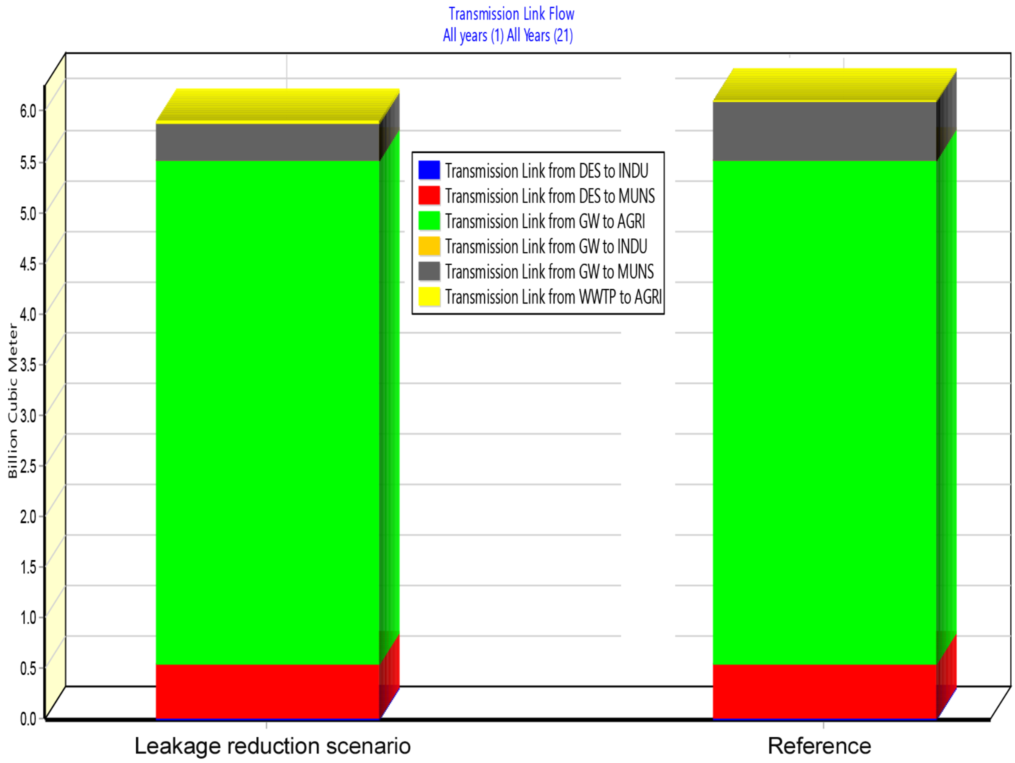

Fig. 11. Comparison of municipal water supply quantities between the leakage reduction scenario and the reference scenario (2021–2040).

This option is considered one of the best alternatives to reduce groundwater withdrawal, especially for various agricultural crops in the Al-Batha basin. Especially those agricultural crops that do not require a high quality water, as this is considered economically feasible, and this is proven by various scientific studies in this regard. Moreover, it is expected that there will be large quantities of treated water resulting from sewage treatment plants during the next twenty years in those plants located on the Al-Batha basin, which will contribute to reducing the pressure that currently exists on desalination plants and the huge withdrawal from underground water. Currently, there are very small quantities of water that are heading towards sewage treatment plants and do not correspond to what is being used. The reason is that there is no network connecting homes and residential, commercial and industrial gatherings with one sewage network, and the outflowing water becomes unknown and some of it is leaked into the ground. Through septic tanks in homes. On the other hand, there is a strategy for the Omani Water and Wastewater Services Company to connect the sewage network to all residential areas during the coming years.

Fig. 12 illustrates the comparison between the quantities of collected wastewater with the reference scenario, as the collected quantity was 270,779 m^3 in 2020 and about 316,866 m^3 in 2040 in the reference scenario compared to the amount of 318,744 m^3 in 2040, as the amount of increase It will be 1,878 m^3.

Fig. 13 shows that the treated wastewater quantities will increase if the collected water quantity is increased, as the collected quantity in the reference scenario is about 26,194 m^3. But if the strategic administrative option is applied, which is to increase the collection rate to 60,000 m^3, the water leaving the treatment plants will be 38,673 m^3.

5.1.3. Increasing the efficiency of irrigation systems

In the Sultanate of Oman, the agricultural sector is one of the largest consumers of groundwater, as the percentage of water used in the agricultural sector reaches 90% of the total water used in the Sultanate. The traditional system is still the most widely used system in most of the agricultural lands in the farms located in the Al-Batha basin, which increases the demand for water due to the low irrigation efficiency, which does not exceed 35%.

This scenario focuses on gradually raising the efficiency of irrigation in the agricultural sector through the use of modern irrigation to a rate of up to 70% (from its current level of 35% by the year 2040; i.e., from a

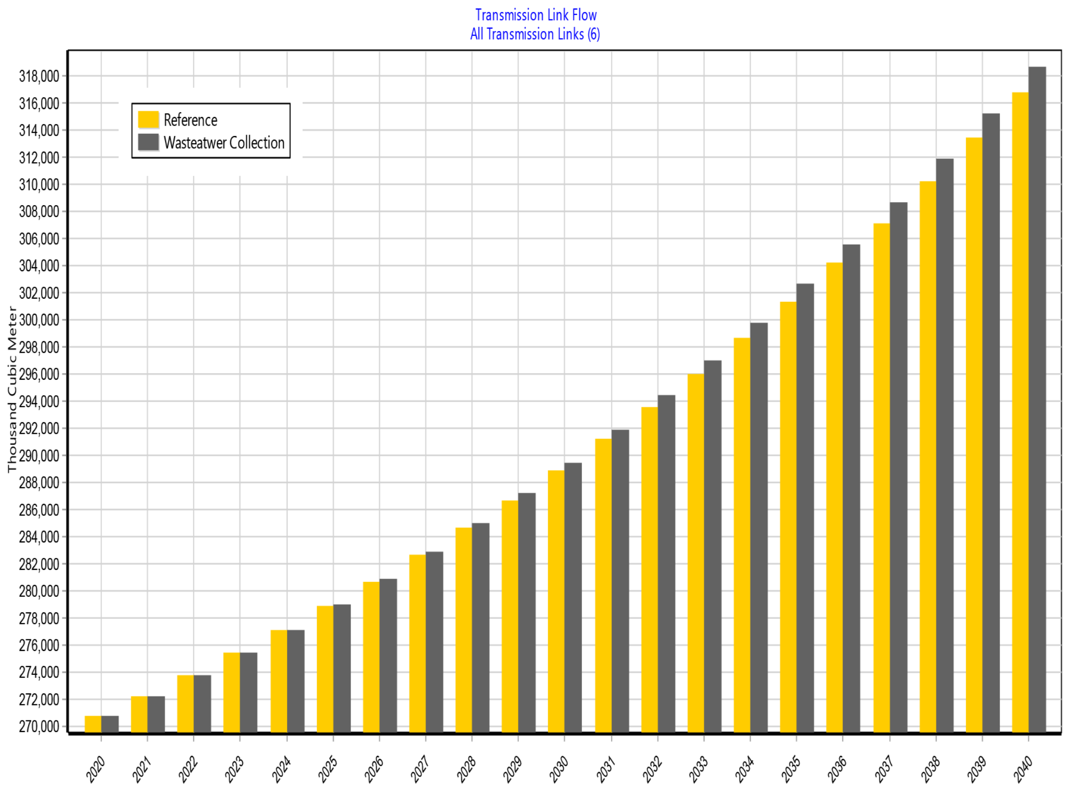

Fig. 12. Wastewater collection comparing with reference scenario (2021–2040).

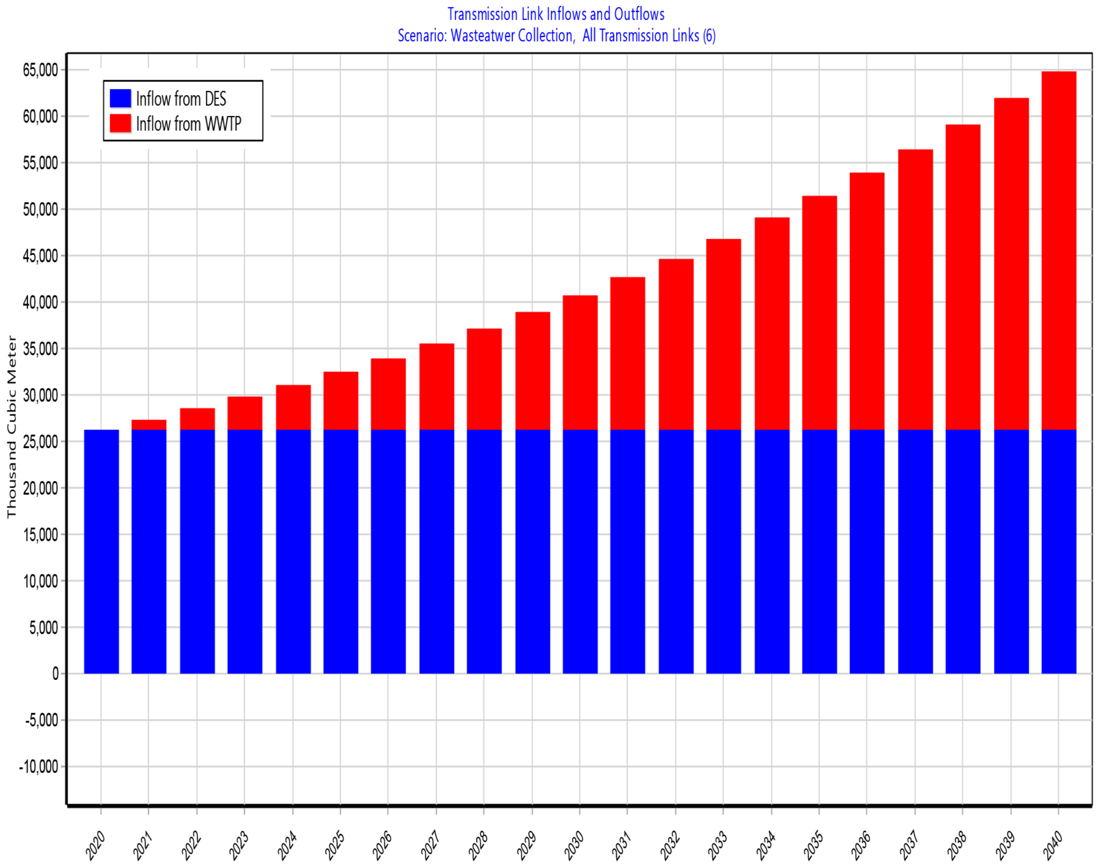

Fig. 13. Inflow water quantity from WWTP (2021–2040).

quantity of 32,159.8 $Mm^3/ha/y$, to 70%, i.e., at a quantity of 16,079.9 $Mm^3/ha/y$. That is, to half the amount used currently. Increasing the efficiency of irrigation to reduce the quantities of water used in agriculture, is among the targets in the GCC UWS 2035.

Fig. 14 shows the difference in the demand for water in the agricultural sector due to the change in irrigation efficiency in the farms located on the Al-Batha basin, from 35% to 70%. Fig. 14 shows that the demand for water used in the agricultural sector can be reduced from 236. 6 Mm^3 in the reference scenario during to a quantity of 118.3 Mm^3 by the year 2040 if irrigation efficiency measures are implemented.

Fig. 15 shows the cumulative water demand during (2021-2040), where the quantity will cumulatively decrease from 4968.59 billion m^3 in the reference scenario to 3726.44 billion m^3 if the irrigation efficiency increase scenario is applied, where the quantity that It will be saved equal to 1242.15 billion m^3. That is, it is possible to obtain water savings that can be used to increase agriculture and produce various crops that could contribute to raising the economic value of the agricultural sector and food security in the Al-Batha basin. It will also contribute to reducing groundwater withdrawals and increasing the strategic water reserve.

5.1.4. All options together

This option applies all administrative options at the same time in order to incorporate the interaction between the sectors and the collective impact of all options on reducing the demand for water. It also studies the quantities of water that can be saved. Fig. 16 shows that in the event that no solutions are taken with regard to groundwater, the aquifer storage will decrease from 24.84 billion m^3 to 23.29 billion m^3.

Fig. 17 shows the amount of water for all scenarios compared to the reference scenario. It can be concluded from Fig. 17 that the quantities of leakage water from network will decrease, and by applying the scenario of improving irrigation efficiency, the amount used in agriculture will be less than what is currently available. Also, compared to the amount of wastewater collected and the reference scenario, the quantity will increase during the coming period, and this is a good thing, but focus should be placed on increasing the collected quantity more and more.

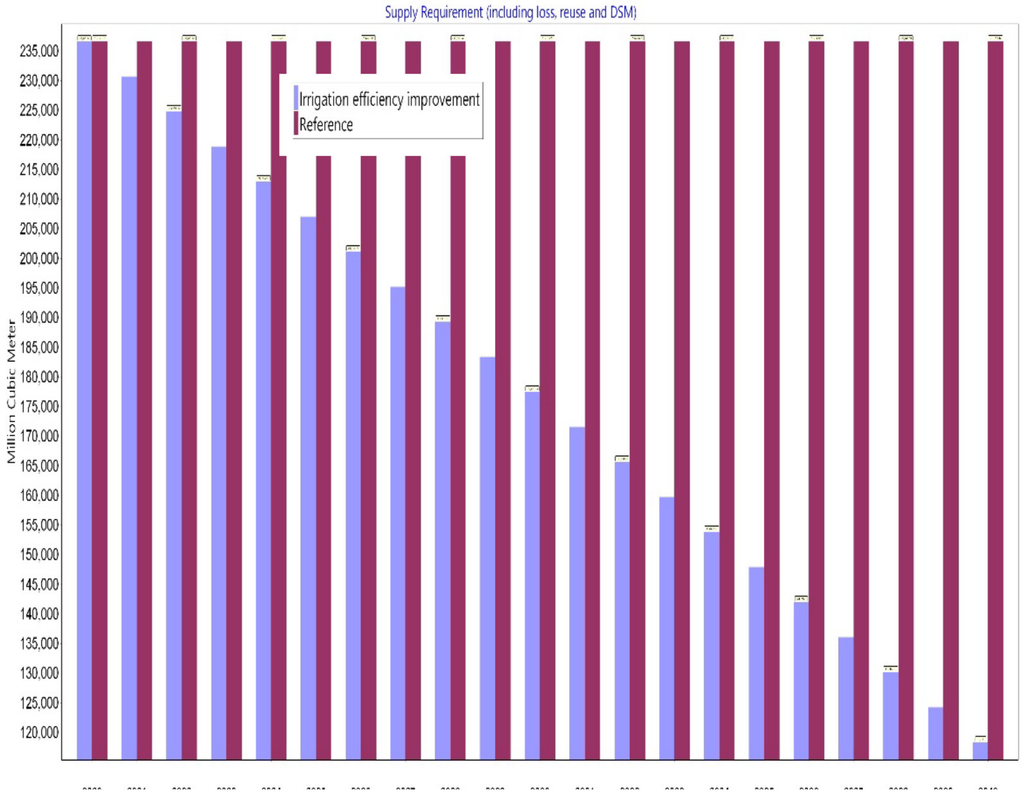

Fig. 14. Comparing the irrigation efficiency scenario with the reference scenario on the demand for water used in agriculture (2021–2040).

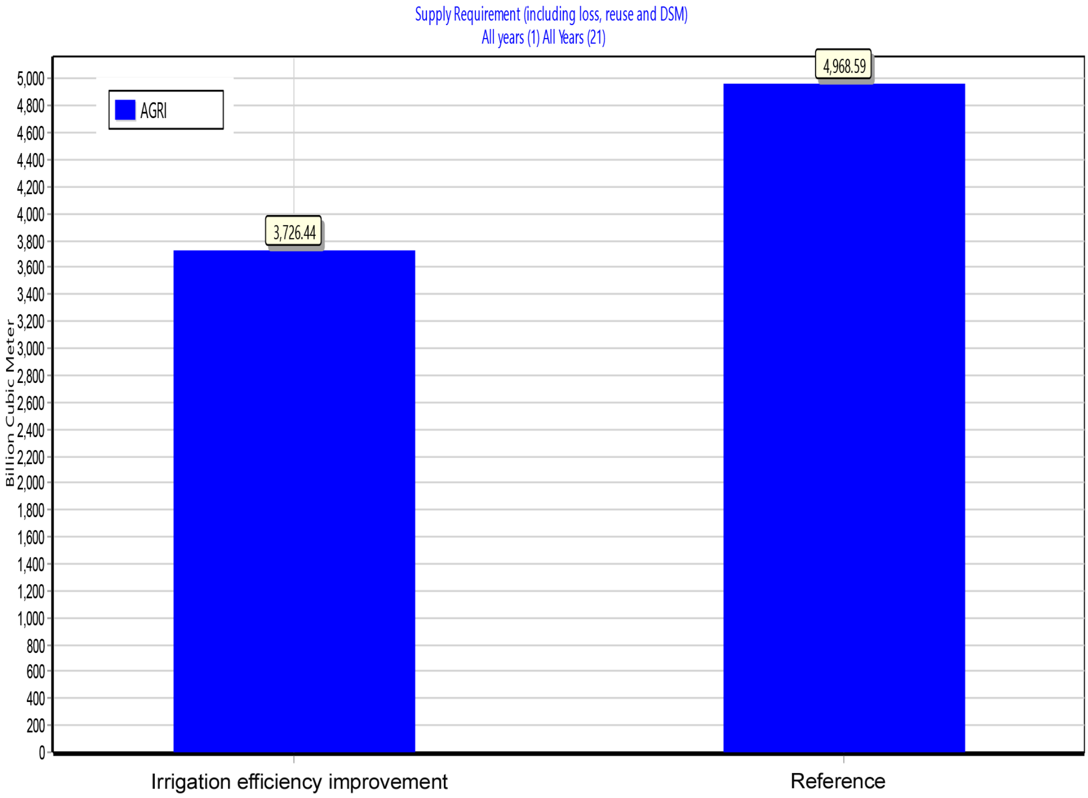

Fig. 15. Comparison of the quantities of water demand used in agriculture (cumulative) between the reference scenario and the scenario of raising irrigation efficiency during the period (2021–2040).

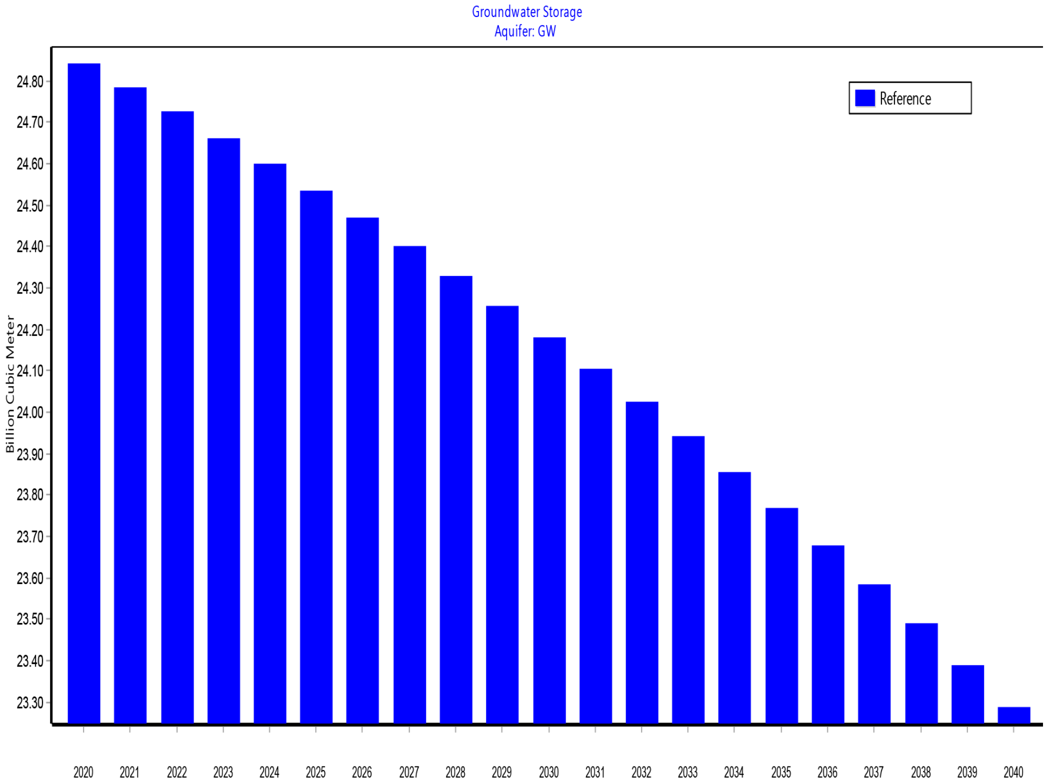

Fig. 16. Comparison between the quantities of water in the aquifer in the reference scenario and the quantity after 20 years.

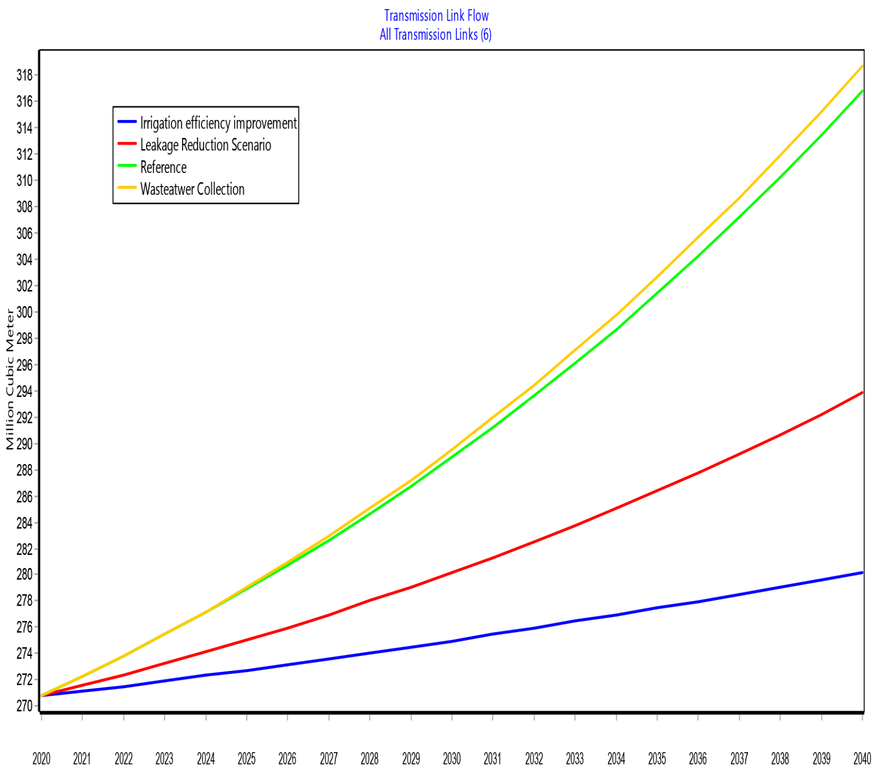

Fig. 17. Comparison between the quantities of water in the reference scenario and the quantity of water in all scenario after 20 years.

6. Conclusion and recommendations

6.1. General

The problem facing the developing countries is the right management of natural resources or the optimum will, due to the scarcity of some natural resources in these countries. The Sultanate of Oman is one of the countries facing challenges in the management and planning of water resources, like other Gulf countries. The biggest challenge is how to provide the expected water needs in terms of quantity, type and water quality in light of the limited water available in the Sultanate of Oman, where the latest water balance study conducted in 2013 shows that the water deficit of the Sultanate is estimated at about 316 Mm^3/y. Among the most important challenges facing the Sultanate of Oman in managing various water resources is the increasing population growth and the change in the way of life in the Omani society, especially in large cities, and the change in water consumption patterns, and the increasing demand for food, in addition to the increase in development projects such as the tourism sector, industry and various trade. Global climate change has also contributed to increasing these challenges. The government in the Sultanate of Oman has taken a set of measures by working to increase and develop the available water resources in several ways, some of which have been applied, such as the traditional measures of enhancing water resources through the implementation of underground recharge dams and surface storage dams, and the work of unconventional measures through reusing Treated sewage water to feed underground reservoirs that suffer from a deficit in their water resources, to enhance groundwater recharge through artificial seeding technology, and to collect fog water in the Dhofar Governorate in the Khareef season.

All those efforts that the Sultanate of Oman is working on is to provide more fresh water to meet the excess water requirements and reduce the water deficit in the Sultanate. Reducing the water deficit by balancing supply and demand, and between the rate of groundwater extraction and the rate of groundwater recharge, is the biggest challenge due to its limitations. However, this balance can be achieved by following a specific approach in managing water demand, through the scenarios that were developed in this study, which were applied to the Al-Batha basin and can be applied to all basins in the Sultanate of Oman.

6.2. Conclusion

In this study, it is clear that the current system used in the Al-Batha basin to manage water resources is not an efficient system, due to the depletion of groundwater, which is considered limited. Also, the Al-Batha basin suffers from a water deficit estimated at about 52 Mm^3 per year based on the latest study of the water balance for the year 2013. That water, which drains heavily in the Al-Batha basin, is relied upon to meet the requirements of the areas located on the Al-Batha basin, especially in the agricultural sector, and there are accelerating requirements for this water due to the large increase in rapid development. In order to confront the imbalance between demand and supply in the Al-Batha basin, a more efficient approach must be taken to balance supply and demand, achieve water abundance, and reduce costs and any environmental impacts. In this study, a number of strategic options were proposed, which are applicable in the Al-Batha basin, and decision-makers can read, understand and apply them because of their importance in raising the efficiency of water resources management in the Al-Batha basin. Those options that have been proposed, worked on and simulated in a dynamic mathematical model focus on the management of water demand and the integration of water resources management in the Al-Batha basin in a correct and efficient manner. Among those options are increasing the collection and treatment of large quantities of wastewater, reducing leakages in the municipal sector network, increasing the efficiency of the irrigation system in the agricultural sector, in addition to putting all the proposed options together in order to see how all options can work together.

6.3. Recommendations

After completing the results and analyzing the data scientifically, this study urgently recommends reconsidering the current water management system in the Batha basin and paying attention to modern programs and methods related to detecting leaks from the public network and controlling leaks in the main and subsidiary pipelines. Also, more attention should be given to reducing the percentage of leaks, as the current rate is high and costs a lot of money. Also, those programs related to maintenance should be compatible with the plans and strategies of the Omani Water and Wastewater Services Company. The study also recommends the need to increase programs related to water demand management in the agricultural sector, especially those that depend on traditional irrigation, through conducting studies to convert traditional irrigation systems by immersion in aflaj into a modern system that contributes to benefiting from the available water, with the need to monitor withdrawals from private wells. citizens in their farms and support them with modern irrigation systems, by installing smart meters on the pumps. This study also recommends focusing on wastewater treatment through increasing wastewater collection and utilization in the agricultural sector.

The study also recommends more modeling and simulation of the water sector in the Batha basin in an integrated manner, where the economic, financial, social and administrative aspects of the current water system are entered with linking them to the supply and demand side, and that costs are calculated for all incoming and outgoing waters. The water sector for the Sultanate of Oman can be fully modeled for ease of reference to the important results for decision makers.

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The 15th Gulf Water Conference

(2024) 202–208
doi: 10.5004.dsal.2024.700053

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Implementation status of integrated water resources management in GCC countries according to UN-SDGs

Mohamed Shamrukh[1,*], Khaled El-Said[2]

[1]*Ministry of Environment and Climate Change, Doha, Qatar (on leave from Minia University, Faculty of Engineering, Civil Engineering Department, ElMinia, Egypt), Tel.: +974 33665784; email: mshamrukh@gmail.com, mshamrukh@mu.edu.eg*

[2]*Chemical Engineering Program, College of Science and Engineering, Hamad Bin Khalifa University, PO Box 23874, Doha, Qatar*

A B S T R A C T

The Gulf Cooperation Council (GCC) Countries are located in arid regions with rare natural freshwater resources and increasing amounts of treated wastewater for reuse or recycling. Therefore, integrated water resources management (IWRM) is essential for water security in the GCC countries. Globally, IWRM is one of the UN Sustainable Development Goals; and UN-Water is the primary international authority for monitoring the IWRM strategic development goal indicators, including indictor No 6.5.1. This indicator tracks the degree of IWRM implementation by assessing the four key components of IWRM: 1) enabling environment, 2) institutions and participation, 3) management instruments, and 4) financing. In this work, the current status of IWRM implementation in the GCC countries according to UN-Water indicators is presented and analysed to assess the level of IWRM implementation in the region. Also, lessons learned from the results of these analyses with respect to implementing the United Nations Strategic Development Goals (UN-SDGs) for IWRM are discussed for each of the GCC countries. Kuwait, Qatar, Oman, and the UAE fall within the very high to high implementation categories. Sustaining momentum and fostering cooperation among the GCC nations could lead them to meet the global target. The findings of this work can contribute to augmenting current efforts toward achieving efficient and sustainable IWRM in the GCC countries.

Keywords: Integrated water resources management; IWRM; GCC; SDGs; Water management

1. Introduction

The Cooperation Council for the Arab States of the Gulf (hereinafter referred to as the Cooperation Council, (GCC)) consists of six countries: Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates. The primary forces shaping the current condition and trajectory of water in the GCC region include: i) rapid population growth; ii) growth of the oil and gas industry; iii) urbanisation; iv); Challenges related to water resource scarcity and sustainability; and v) external pressures, such as climate change. Certainly, global temperature rise, increasing drought incidences, rising sea levels, and other impacts of

* Corresponding author.

climate change will require amplified intervention and investment from both governmental and private sectors in the coming decades to ensure water sustainability. The populations of the area are growing continuously. The GCC region's population in 2021 was 56.4 million per capita (GCC STAT 2022)

With an arid climate and an average annual rainfall as low as 263 mm, all GCC countries, except Oman, are classified under critical water scarcity (GCC STAT 2022; Dawoud 2011). There are no major rivers and few renewable groundwater aquifers (Lupinus 2022). The combination of low rainfall and high rates of evaporation (ranging from 2,500 mm to 4,500 mm/y from coastal to inland areas) makes reliance on the natural water cycle difficult, especially given the high rates of water demand in the GCC countries. The total availability of freshwater per capita in the GCC countries has decreased rapidly from about 1,200 m^3/y in 1950 to less than 325 m^3/y in 2020, compared to a global average of 17,575 m^3, which is far below the extreme water poverty line of 500 m^3/y (Everist 2018). GCC countries are suffering from a significant deficit in their water resources reaching more than 20 billion cubic meters (Bm^3) (Al-Zubari 2021).

The total annual water use of all sectors in the GCC countries increased from about 6 Bm^3 in the 1980s to about 28.5 Bm^3 in 2020 (GCC STAT 2022). Groundwater exploitation, desalination production, and treated sewage effluent (TSE) are 18.5, 6.3, and 3.7 Bm^3, respectively. The reuse percentage of TSE is about 34% of that available quantity. According to the 2018 data, the agricultural sector is the main consumer of water (77%), followed by the municipal sector (18%) and then the industrial sector (5%). The average domestic consumption is 295 L/cap/d (GCC STAT 2022). About 63% of the domestic water supply is met from desalination, which is CapEx/OpEx and energy-intensive, as well as potentially environmentally damaging (Everist 2018). Currently, groundwater extraction rates to meet agricultural demands are increasing and exceed natural recharge rates, leading to depletion and increased salinity. The usage of treated sewage effluent is increasing but contributes to a low share of the region's water demand (Al-Zubari 2003, 2009, 2021). Unless there are changes in water management and practices, annual water demand may reach 50 Bm^3 by 2030 (Al-Zubari 2021). This situation is getting more critical as demand increases beyond sustainable limits, with climate change projected to further stress already scarce resources. Efficient implementation of IWRM can help in creating a sustainable future for water in the GCC region.

The majority of GCC countries have established national water strategies or national water security plans. However, in 2016, the GCC Secretariat drafted the GCC 2035 Unified Water Strategy (GCC UWS 2035), which was approved by the GCC Council in 2016, and approved as "a comprehensive water strategy for all GCC countries (during the 37th Gulf Summit, Manama Summit, December 2016). The overall objective of the strategy is to establish a "sustainable management system for the water sector" in each of the GCC countries by securing long-term water supplies while meeting strict criteria for social, economic, financial, and environmental sustainability, and public health requirements. The vision of the unified water strategy was formulated as "By 2035, the countries of the Gulf Cooperation Council will establish sustainable, efficient, equitable, and safe water resource management systems that contribute to sustainable social and economic development". The enabling factors for this are establishing strong and capable institutions, changing user behavior, and research and development investments in water technology. Proper implementation of integrated water resources management (IWRM) plans in GCC countries are key players for decision makers to achieve this vision. In 2021, Abu Dhabi launched the IWRM which indicates the efforts toward the implantation of IWRM in GCC countries. Although the importance of IWRM, there are few studies about the implementation of IWRM in GCC (Shomar et al. 2014; Al-Saidi 2017; Alshaikh 2018; ESCWA 2019; Alodah 2023).

IWRM is a process that promotes the coordinated development and management of all available water resources and relevant resources to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (IWRM Hub 2023). It is believed widely that the global water crisis is mainly due to poor governance. There are several underpinning factors behind this water governance crisis: IWRM is a paradigm that was designed to replace the traditional, fragmented sectoral management style, that resulted in poor services and unsustainable water resource use. Four key principles of IWRM were adopted at the 1992 Dublin Conference on Water and endorsed at the Rio de Janeiro Summit on Sustainable Development.

The Sustainable Development Goals (SDGs), also known as the Global Goals, were adopted by the United Nations in 2015 as a universal call to action to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity (UNDP 2023). The 17 SDGs are integrated—they recognize that action in one area will affect outcomes in others, and that development must balance social, economic, and environmental sustainability. Countries have committed to prioritize progress for those who are furthest behind. The creativity, know-how, technology, and financial resources from all of society are necessary to achieve the SDGs in every context.

Access to water, sanitation, and hygiene is a human right (SDGs 2023). As more and more countries are experiencing water stress, and increasing drought and desertification are already worsening these trends. By 2050, it is projected that at least one out of four people will suffer recurring water shortages (UNDP 2023). Therefore Goal 6 entitled “Clean water and sanitation” is included. It is to ensure availability and sustainable management of water and sanitation for all and it includes 8 targets with 11 indicators. Target 6.5 of this goal is: By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate. There are two indicators for this target: 6.5.1 Degree of integrated water resources management and 6.5.2 Proportion of transboundary basin area with an operational arrangement for water cooperation (SDGs 2023). UN-Water coordinates the United Nations’s work (30 UN entities and other partners) on water and sanitation including monitoring/reporting of Goal 6. In 2015, the Integrated Monitoring Initiative for SDG 6 was launched by UN-Water with the aim of reporting on progress on water and sanitation in a coherent and coordinated way, shaped by input from UN-Water’s Members and Partners (UN-Water 2023). In 2018, UN-Water produced the first SDG 6 Synthesis Report on Water and Sanitation, presenting the global status of SDG 6 and other water-related targets, and exploring interlinkages within SDG 6 and the wider 2030 Agenda. In 2019, UN-Water created the SDG 6 Data Portal, bringing together data on all the SDG 6 global indicators and other key parameters, and tracks overall progress.

In this paper, the data of UN-Water related to indicator 6.5.1 which measuring the degree of IWRM in GCC countries are presented, assessed, and analysed. Conclusion and recommendations are provided based on this analysis. Priority areas are identified that will help accelerate the full implementation of IWRM in GCC countries.

2. Materials and methods

2.1. GCC setting

The studied regional area in this study is the GCC countries. GCC region is part of the Arabia region and is located in the West Asia regional area (Fig. 1). The GCC region is one of the most water-scarce areas in the world and has identified and studied its water challenges. In this study, an assessment and

Fig. 1. Location map of GCC countries (GCC-SG 2023).

analysis of the implementation of IWRM using the data portal of UN-Water for the six GCC countries is presented.

2.2. UN-Water SDG 6 data portal

The UN-Water SDG 6 Data Portal places all the United Nations' water and sanitation information into one database, designed for decision-makers, advisors, technical professionals, researchers, and students, creating a clear picture of how the world is progressing towards the various SDG 6 targets. The United Nations Environment Programme (UNEP) is the custodian of indicator 6.5.1 which is related to IWRM implementation. The IWRM Data Portal is maintained by UNEP-DHI Centre on Water and Environment, in partnership with UNEP and Global Water Partnership (GWP). The available data is for 2017 and 2020. No closer data is available and data for 2023 might be available in 2024.

2.3. Data source

Data on 6.5.1 are collected through a questionnaire (33 questions) and responses are consolidated through consultations between relevant stakeholders, such as national and subnational line ministries and institutions involved in water resources management, and other stakeholders such as NGOs, academia, and business. The portal hosts more than 185 national reports on SDG indicator 6.5.1.

2.4. IWRM indicator components and scores

Indicator 6.5.1, according to UN WATER, tracks the degree of IWRM implementation, by assessing the four main key components of IWRM:

- Enabling environment.
- Institutions and participation.
- Management instruments.
- Financing.

This methodology takes into account the various users and uses of water, intending to promote positive social, economic, and environmental impacts at all levels, including the transboundary level, where appropriate. Table 1 shows an overview of survey question subjects for the four IWRM dimensions, per level as implemented by UN SDGs.

The indicator on IWRM implementation is measured on a scale of 0 to 100 (100% is the highest/best), based on the degree of implementation of 33 elements. The score is estimated for each component and then the overall average score is calculated. Category, from very low to very high implementation, for estimated score is shown below:

Score %	91 to 100	71 to 90	51 to 70	31 to 50	11 to 30	0 to 10
Category	Very high	High	Medium-high	Medium-low	Low	Very low

Table 1
Overview of survey question subjects for the four IWRM dimensions, per level

IWRM survey	National level	Subnational	Basin/aquifer (and local)	Transboundary	Federal countries only
1. Enabling environment	Policy, Law, Plans	Policy	Basin/aquifer management plans	Management arrangements	Provincial water law
2. Institutions and participation	Authorities Cross-sectoral coordination Capacity Public participation Business participation Gender objectives	Gender objectives	Basin/aquifer organizations Local public participation	Organizational arrangements Gender objectives	Provincial authorities
3. Management instruments	Availability of monitoring Water-use management Pollution control Ecosystem management Disaster management	Data and information sharing	Basin management instruments Aquifer management instruments	Data and information sharing	
4. Financing	Budget for investment Budget for recurring costs	Subnational or basin budget for investment Revenue raised		Financing for cooperation	

3. Results and discussions

It is worth mentioning that the score of the IWRM is related to the management of water resources on both supply and demand sides considering all water resources and all relevant sectors in an integrated framework. It has nothing to do with the quantity and quality of water resources themselves. As said, Fig. 2 shows the IWRM for the six GCC countries in the years 2017 and 2020 as indicated in UN WATER data portal.

3.1. Overall IWRM performance

From the data shown in Fig. 2, it is clear that the last status of all GCC countries shows very high to medium-high scores except for Bahrain. The score for Kuwait is a very high category. Qatar, Oman, and UAE are within the high category. Saudi Arabia is medium-high category, and Bahrain is within the medium-low category. It is noted that Oman has done significant work, which has led to high score in 2020 as compared with that is 2017. Comparing the scores between 2017 and 2020, it is almost the same with negligible change for Qatar, Saudi Arabia, and Bahrain.

3.2. Status of each GCC country

Table 2 shows the scores for each GCC country considering four IWRM dimensions for 2017 and 2020. In the following sections, a brief discussion is given about the status of the IWRM in each country for the four dimensions and changes between 2017 and 2020.

3.2.1. Bahrain

Data for 2020 in the above table shows that Bahrain has a low score in all four dimensions of the IWRM. Enabling environment dimension is the lowest score and the other three scores are almost the same. The score in 2020 is less than the score of 2017 by one percent. Bahrain has the lowest score among the GCC countries. This points to more effort needed to achieve the global target of SDG 6.5.1 for IWRM.

3.2.2. Kuwait

As mentioned earlier, Kuwait is the highest among all GCC countries in IWARM score and is the only state among GCC countries to be in the very high category. In 2020, Kuwait has the full score in two dimensions of IWRM, which are institutions & participation and financing. The score for Kuwait increased from 82% in 2017 to 94% in 2020. The scores of the two other dimensions of IWRM are almost the same. Therefore, there is still a small window for Kuwait to make more progress in these two dimensions and improve its overall very high score in the coming report.

3.2.3. Oman

Oman made a big jump in the overall score between 2017 and 2020, which reflects notable progress in the four dimensions of the IWRM. The highest improvement was in the enabling environment dimension, from 33% to 90%. This indicates a significant effort by Oman to be in the high category of IWRM in 2020.

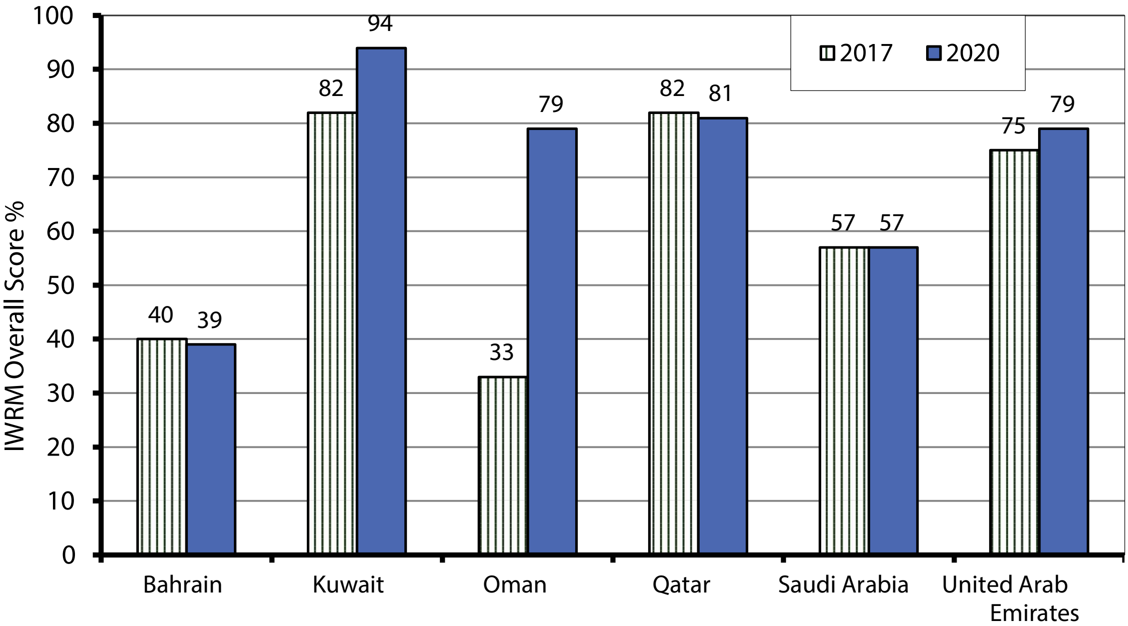

Fig. 2. Overall score of IWRM for GCC countries, 2017 and 2020 (UN Water 2023).

Table 2
Score of each IWRM dimension for each GCC country, 2017 and 2020 (data sources: UN-Water 2023)

	Bahrain		Kuwait		Oman		Qatar		Saudi Arabia		United Arab Emirates	
Year	2017	2020	2017	2020	2017	2020	2017	2020	2017	2020	2017	2020
1. Enabling environment	28	28	84	87	33	90	55	60	42	42	59	69
2. Institutions and participation	48	48	82	100	18	81	100	90	68	69	90	82
3. Management instruments	43	41	80	88	57	86	89	90	71	71	71	73
4. Financing	40	40	80	100	24	60	85	85	46	46	80	93
Overall	40	39	82	94	33	79	82	81	57	57	75	79

3.2.4. Qatar

Recent scores of Qatar in the four IWRM dimensions show very good performance in three categories of the IWRM dimensions. The score of the enabling environment component is the lowest at 60%. However, Qatar achieved a high category in the IWRM overall score. When comparing the scores between 2017 and 2020, it is noticeable that 10% decrease in the component of institutions and participation scores. This has resulted in lowering the overall score in 2020 by one percent compared to that in 2017.

3.2.5. Saudi Arabia

Saudi Arabia has a high score in the management instruments and medium-high score in institutions and participation. The scores of the other two dimensions of IWRM are almost the same with lower values. The latest scores in 2020 for Saudi Arabia in the four IWRM dimensions are similar to the scores in 2017. Saudi Arabia has the highest population and area among GCC countries and this makes IWRM challenging but warranted.

3.2.6. United Arab Emirates

United Arab Emirates (UAE) has a very high score in the financing dimension of IWRM followed by a high score in institutions and participation and management instruments. The lowest score is for the enabling environment. From 2017 to 2020, UAE made good prognoses improving the overall scores of IWRM and the three dimensions with less progress in the institutions and participation.

4. Conclusion and recommendations

This paper provides the first review of the progress in implementing IWRM in the GCC region and identifies priority areas that will help accelerate the full implementation of IWRM. According to 2020 data, Kuwait achieved the highest score of 94% with a very high category. Qatar, Oman, and UAE achieved scores in the high category of IWRM, with scores of 81%, 79%, and 79%, respectively. Saudi Arabia has a score of 57% with medium-high category, with no difference between 2017 and 2020. Bahrain has the lowest score of 39% which makes it in medium-low category. Therefore, based on the published data, significant work is to be done in Bahrain to achieve the global SDGs target of IWRM. It is noted that Oman has made a significant effort to achieve a high score in 2020 compared to the 2017 score. The analysis given in this paper highlights the opportunities for GCC countries to address the gaps in achieving the global target of IWRM. Given the significance of water management for sustainable development in this arid region, IWRM implementation could be accelerated in Bahrain and Saudi Arabia to improve their scores. IWRM scores demonstrate the need for countries to assess their own strengths and weaknesses enhancing cooperation with each other for accelerating implementation. Efficient implementation of IWRM can help in creating a sustainable future for water in GCC region.

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Balaban Desalination Publications

The 15th Gulf Water Conference

(2025) 209–221
doi: 10.5004.dsal.2025.700048

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Using desalination for agriculture irrigation in GCC countries: state of art and future outlook

Mohamed A. Dawoud[1]*, Waleed H. Abou El Hassan[2]

[1]Senior Water Advisor, Environment Agency – Abu Dhabi, UAE, email: mdawoud@ead.gov.ae.
[2]Senior Water Resources Management Officer at Food and Agriculture Organization (FAO) of the United Nations, GCC Regional Office, Abu Dhabi, UAE. email: waleed.abouelhassan@fao.org

ABSTRACT

The Gulf Cooperation Council (GCC) countries are located in an arid and hyper arid region with a scarcity of freshwater resources. Due to limited conventional water resources and deterioration of groundwater, they invested in non-conventional water resources such as desalination and the reuse of treated wastewater. With an area of about 2.6 million km^2, population of 56.4 million in 2021, per capita renewable water of less than 100 m^3 (about 86 m^3 in 2021), and food self-sufficiency ratio less than 15%, using desalination innovative technologies to reduce the cost and energy consumption can be help in using desalinated water efficiently in agriculture production. The current GCC seawater desalination capacity is about 18.2 million m^3/d. Recent studied indicate that the total annual GCC water demand will increase by 40% in 2030 and may reach more than 50 billion cubic meters (BBC). Using innovative technologies in desalination can play an important role in improving the water and food security in GCC if it combined with high efficiency irrigation and agriculture production systems. At present GCC countries use two major desalination technologies in large-scale desalination plants: thermal technologies (about 7.67%) and membrane-based technologies (33%). Among the total contracted and in online desalination plants across the globe in 2021, 47% of them are located in the GCC countries. At present about 20% of the GCC countries desalination production is used in agriculture sector and it is expected to be increased in the near future. As the demand for potable and irrigation water increases in the region, research and development related to innovations in desalination and innovations in agriculture production systems gaining momentum. In this paper the use of sustainable and cost-effective desalination technologies, such as reverse osmosis (RO), membrane distillation, and forward osmosis, in agriculture will be assessed technical, environmentally and economically. This assessment will focus on the current and recent trends in membrane desalination processes used for agricultural purposes. The challenges being faced with desalinating seawater and brackish water will be discussed. A specific focus was placed on the viability of hybrid desalination processes and other advanced recovery systems to obtain valuable irrigation water. A comparison between

*Corresponding author

ISBN 0-86689-078-5

various membrane desalination technologies in terms of efficiency and resource recovery potential will be analyzed. Lastly, concluding remarks and research opportunities of membrane technologies will be discussed.

Keywords: Desalination; Innovations; Food security; Agriculture; Membrane technologies

1. Introduction

The GCC countries boast an annual renewable surface water, desalinated capacity, and wastewater treatment capacity estimated at 1.52, 7.67, and 3.78 billion m^3, respectively. Per capita water consumption average is about 550 L/d, indicating a high-water footprint. The annual per capita renewable water availability less than 100 m^3 compared to the world average of 5400 m^3 (World Bank, 2023). Agricultural water demand, constituting over 75% of total water consumption in GCC countries, heavily relies on groundwater exploitation. The stark imbalance between groundwater discharge (27.8 billion m^3) and recharge (5.3 billion m^3) leads to a concerning decline in groundwater levels and quality deterioration. To address this, the GCC nations are investing significantly in nonconventional water sources, including seawater desalination and treated wastewater. The GCC countries lead globally in water desalination capacity, boasting a net capacity of around 7.67 billion m^3/y in 2023 (Sheriff, et al., 2023). Notably, Saudi Arabia (35%) and the UAE (33%) house the majority of desalination plants. Saudi Arabia alone contributes about 10% to the world's desalination water production, effectively meeting 50% of its domestic water demands. The UAE is also prioritizing the expansion of desalination capabilities. The upcoming Taweelah plant in Abu Dhabi, set for completion in 2024, will reach an impressive capacity of approximately 1.2 BCM annually, making it the world's largest reverse osmosis plant. This underscores the GCC's commitment to addressing water needs through advanced desalination technologies, with notable developments in both Saudi Arabia and the UAE. Given the freshwater resources shortage, GCC countries heavily depend on imports to fulfill the surging food demand for their growing population, importing over 80% of their total food consumption (FAO, 2013). While the literature consistently suggests virtual water as a solution to water scarcity in such countries (Allan, 1997; Hoekstra and Hung, 2002; El-Sadek, 2010; Aldaya et al., 2010; Dalin et al., 2012), few studies have thoroughly investigated the determinants of virtual water flows into the GCC nations. Previous analyses often used aggregated data at higher levels (encompassing developing countries and the Middle-East region), with inadequate coverage and analysis of the GCC countries. This paper stands out by providing a unique perspective, concentrating on the six GCC countries. Using a cross-sectional dataset within a gravity model framework, the study explores the determinants of food imports by the GCC countries from their traditional trading partners, emphasizing the significance of water scarcity-related variables in elucidating their food import patterns. Virtual water refers to the total water used in the production of imported or exported goods. Importing nations, often facing water scarcity and lacking rain-fed systems, contrast with exporting nations that typically enjoy abundant rainfall and surface water resources. The calculation of net virtual water traded involves multiplying the unit water consumption of products by the annual volume of imported crops or livestock, determined through a trade matrix. This concept allows countries to minimize agricultural and industrial water demands through strategic trades. For instance, in 2000, Egypt's maize imports saved about 2.7 BCM of water.

In the GCC countries, water security involves importing water-intensive agricultural and industrial products, making them the highest net importers of virtual water. Saudi Arabia and the UAE lead in net imports, with annual values of 17.1 and 11.95 BCM, respectively. However, Bahrain and Kuwait exhibit the highest water dependency among GCC nations. This challenge is compounded by reliance on energy-intensive desalination and non-renewable groundwater to fulfill internal water footprints. As water demand in the GCC rises, substantial investments are being made to enhance supply capacity and meet the growing needs. Due to the severe water scarcity, about 15% of desalinated water is currently allocated for irrigation. However, considerable research supports the potential future use of desalinated water for agricultural purposes in GCC countries, challenging prevailing limitations. The global desalination capacity is on a continuous growth trajectory and is anticipated to nearly double by 2050 from the 2015 level of 97 million m^3/d (Darre and Toor, 2018). Nevertheless, the perception of large-scale desalination as a solution for urban water scarcity rather than addressing agricultural water shortages and salinity issues persists due to high supply costs, environmental concerns, and agronomic constraints (Burn et al., 2015; Martínez-Alvarez et al., 2016; Sepehr et al., 2017). Recent analyses at field and farm levels, however, suggest that desalination can serve as an economically viable water source for irrigating high-value crops in water-scarce countries such as Spain, Australia, Saudi Arabia, (Reca et al., 2018; Zarzo et al., 2013; Barron et al., 2015; Multsch et al., 2017; Hadas et al., 2016; Kaner et al., 2017). Overlooking the potential contribution of desalination to agricultural productivity in policy and water infrastructure design may lead to suboptimal water management and deadweight loss. Water economies at the basin, regional, or state levels involve multiple water sources with diverse qualities and supply costs (e.g., naturally recharged surface water and groundwater, brackish water, desalinated seawater, and treated wastewater), diverse consumers (e.g., domestic, industrial, and agricultural users) with distinct demands for water quantity and quality, and a complex ensemble of infrastructures that need consideration in achieving sustainable water management.

2. Food security

Historically, food security was not an issue for the GCC states. In fact, GCC states are capital rich and have no foreign exchange limitation for food import (Shahid, 2014). Consequently, due to their robust fiscal position resulting in high buying power, these countries, have been less vulnerable to price risk (i.e., the risk that food is available for import but the importing country may not be able to afford to purchase a sufficient amount for its residents) than other food importers; and able to bridge the shortfall in domestic production (Efron et al., 2018). As a result, in 2018, the six GCC members have been ranked as the most food secure in the Arab world and among the most food secure countries in the world in the Global Food Security Index as shown in Table 1 (EIU, 2018).

Table 1
GCC countries ranking in the Global Food Security Index (2018)

Country	Global rank	Rank in the Arab world
Saudi Arabia	32	5
UAE	31	4
Oman	29	3
Kuwait	28	2
Qatar	22	1
Bahrain	41	6

Source: (EIU, 2018)

The aftermath of the 2007–2008 global food crisis revealed an ongoing challenge to food security in the GCC. Food security holds particular political significance in these countries for various reasons (Lippman, 2010) with food being a commodity of paramount immediacy and political sensitivity, as noted by Lippman (2013). Given their heavy reliance on food imports, the GCC nations are susceptible to price and supply shocks, making the stability and availability dimensions of food security critical issues. Food availability, determined by domestic production, distribution, and imports, is a key factor in assessing food security, especially for countries highly dependent on imports like those in the GCC (Scardigno et al., 2017). It is noteworthy that a nation with low self-sufficiency and high dependence on imports can still achieve food security if it can financially support its imports. The 2007–2008 global food crisis highlighted the GCC states' vulnerability to imports and the absence of clear food security policies. This crisis brought attention to the supply and price risks associated with dependence on the world market (ESCWA, 2017). As the GCC countries navigate these challenges, the imperative for comprehensive and resilient food security policies becomes increasingly evident. The 2007–2008 food price crisis acted as a wake-up call for GCC countries, exposing their vulnerability to food price fluctuations with enduring consequences expected for the next decade. During the crisis, over 30 nations, including Argentina, Russia, India, and Vietnam, imposed export restrictions, causing a profound psychological impact. Despite substantial petrodollar wealth, Gulf countries now grapple with the unsettling prospect of potential challenges in securing ample food imports. This underscores the critical nature of food security beyond market forces. The GCC region faces a significant lack of control and access to its food sources, labeled as a deficiency in food sovereignty. Gulf nations perceive an imminent threat to their food security (Woertz, 2011). Anticipated factors such as population growth, rising incomes, and evolving consumption patterns are poised to drive continuous consumption growth in GCC countries. While per capita consumption in the region is currently lower than in developed economies, it is expected to rise at a comparatively faster rate. In 2018, the GCC region's total population reached 56.65 million, a significant increase from 41.7 million in 2010 and 25.8 million in 2005, with projections indicating further growth. Simultaneously, the forecast for GCC food import demand is expected to reach $53.1 billion by 2020, a substantial increase from $28.4 billion in 2011 as shown in Table 2 (EIU, 2010).

Table 2
GCC food imports (in billion USD)

Country	2010	2015	2020	2025 (estimated)
Saudi Arabia	17.9	24.5	35.2	46.2
UAE	3.8	5.5	8.4	13.1
Oman	2.1	3.3	4.8	6.1
Kuwait	2.5	3.6	5.3	7.4
Qatar	1.3	2.1	3.3	4.5
Bahrain	0.8	1.1	1.6	2.5

Food production in the GCC primarily relied on fishing, animal husbandry, date farming, and small-scale vegetable cultivation. The region, located in one of the world's most arid climates faces constraints on domestic food production due to adverse agroecological conditions, including limited water resources, high temperatures, and poor soils. A mere 19.5% of the GCC's total land area constitutes agricultural land (cropland and pastures), with only 1% being arable (cropland) (Table 3) [41]. This is significantly lower than the global average of 10.6% and falls behind some countries such as the USA (16.6%), the United Kingdom (24.9%), China (12.7%), and India (52.6%). Moreover, ongoing salinization and desertification processes across the entire GCC region are expected to further reduce the availability of arable land (Spiess, 2011).

Table 3. Desalinated water capacity in GCC (2023) (BCM)

Country	Total capacity	Desalination technology			
		MSF	MED	RO	Other
UAE	8.9	6.07	1.07	1.73	0.018
Saudi Arabia	11.4	4.28	1.19	5.65	0.27
Oman	1.1	0.40	0.080	0.61	0.002
Kuwait	2.6	1.90	0.003	0.705	0
Bahrain	0.6	0.10	0.28	0.22	0
Qatar	1.8	1.25	0.36	0.18	0.014
Total	26.4	13.99	2.99	9.10	0.31

Source: Sherif et al., 2023

3. Water resources

Thre are only three sources of water in the GCC countries namely, groundwater, desalinated water and wastewater. Groundwater serves as the primary natural water source in the GCC countries, predominantly found in renewable shallow aquifers nourished by recharge from alluvial deposits along flood plains and main wadi channels. The combined water storage in these shallow aquifers across the GCC countries and Yemen is estimated at 131 BCM, with an average annual recharge of approximately 3.5 BCM. These shallow aquifers play a crucial role in supplying potable water to urban and rural areas, particularly in Oman and Saudi Arabia. However, their sustainability is jeopardized by various human activities, including agriculture, industry, and domestic use. In contrast, non-renewable fossil groundwater resides in sedimentary deep aquifers, mainly found in Saudi Arabia and Oman, with limited occurrences in other GCC countries. This fossil groundwater originated during the Pleistocene and Pliocene geological periods. The water storage in these deep aquifers is around 2175 BCM, with an annual recharge of about 2.7 BCM in outcropping areas. The water quality in deep aquifers varies across different locations and may be suitable for agricultural purposes.

The excessive extraction of groundwater in the GCC countries to compensate for surface water deficiencies has led to a substantial decline in groundwater levels, abandonment of production wells, depletion of springs, and increased intrusion of seawater into coastal aquifers. In 2013, Saudi Arabia alone pumped 22.65 BCM of groundwater (Hassen and El Bilali, 2022). The UAE and Oman pumped approximately 2.013 and 1.30 BCM, respectively, during the same year. The combined pumping from the remaining three GCC countries (Kuwait, Bahrain, and Qatar) was less than 0.65 BCM. Policies such as the "green desert" initiative and achieving self-sufficiency in food production have contributed to the overexploitation of groundwater resources, negatively impacting their sustainability in the region. Recently, Saudi Arabia has taken corrective measures by discontinuing its 30-year food self-sufficiency program after extracting four-fifths of its deep fossil water. The main challenges facing the non-renewable groundwater aquifer systems in GCC are the over abstraction, quality deterioration, drop in water table, and seawater intrusion.

Desalination technology was introduced in the GCC countries during the mid-1950's as a response to water shortages, aiming to reduce reliance on depleting groundwater resources and meet the increasing qualitative water demands for domestic and industrial purposes. The GCC countries primarily employ multi-stage flash distillation (MSF) and multi-effect distillation (MED) technologies for desalination, with power desalination plants consuming a portion of the available fossil fuel. In recent times, more advanced technologies, including reverse osmosis (RO), have been adopted. Over the last two decades, there has been a continuous growth in the reliance on desalinated water. Fig. 1 illustrates the annual capacity and production volume of desalinated water in GCC countries from 2007 to 2019. Both capacity and production exhibited a gradual increase until 2016, followed by a significant upsurge in 2017. The GCC countries boast the highest global water desalination capacity at about 26.4 million m^3/d (MCM/d). Saudi Arabia (35%) and the UAE (33%) host the majority of desalination plants in the region. Fig. 1 highlights that Saudi Arabia alone contributes around 10% to the worldwide production of desalinated water, effectively meeting half of its domestic water demands. The UAE is also actively increasing its desalination capacity, exemplified by the Taweelah plant in Abu Dhabi, set to be completed in 2022 with a remarkable capacity of approximately 9.08 MCM/d, making it the world's largest reverse osmosis plant (Sherif et al., 2023). In terms of consumption, desalination water supports a significant portion of water needs in GCC countries, with 87% in

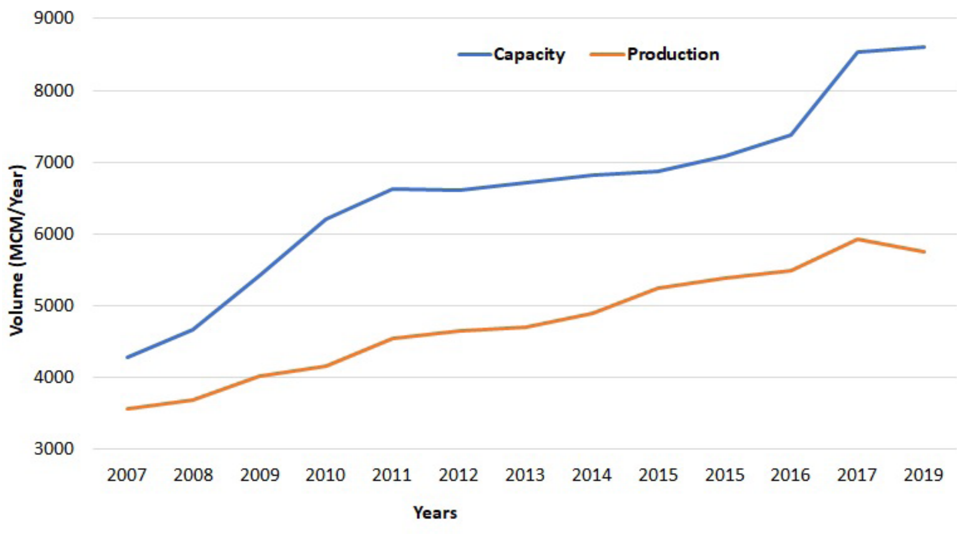

Fig. 1. Desalination capacity and production in GCC countries (2007–2019).

Qatar, 50% in Saudi Arabia, 42% in the UAE, 36% in Bahrain, and 27% in Oman. Oman, in particular, is annually enhancing its desalination capacity by 5%, with 86% of the nation's domestic water sourced from desalination plants. Projections indicate that Oman's desalination capacity will steadily rise to reach 600 MCM/y in the next decade. All GCC countries are making substantial investments to upgrade existing desalination plants and establish new mega plants, aligning with the increasing water demands across various sectors. Table 3 provides a breakdown of water desalination capacity in the GCC countries. The main challenges facing the desalination sector in GCC countries are brine water discharge to environment, high capex and opex costs, and energy consumption.

The desalination has been considered a more expensive option compared to traditional surface or groundwater treatment, with prices hovering around US$1/m^3. However, a significant breakthrough in desalination technology has led to a remarkable improvement in overall costs, encompassing both operational expenditure (OPEX) and initial capital expenditure (CAPEX). Over the past two decades, these costs have seen an impressive 80% reduction, thanks to advancements in technology and equipment. Recent project tenders in Abu Dhabi, and Saudi Arabia have witnessed a milestone, with prices falling below $0.50/m^3 for the first time. Seawater desalination costs have now reached $0.40/m^3, approaching the range of indirect potable reuse, where prices typically fall between $0.30 and $0.40. This trend marks a significant development in making desalination a more economically competitive and viable option for addressing water scarcity challenges.

The treated wastewater metrics in the GCC are intricately connected to the total capacity and production of desalinated water, forming a crucial aspect of regional water management strategies. Among the GCC nations, Saudi Arabia stands out with the highest production of treated wastewater (Qureshi, 2020). The UAE showcases a consistent upward trend in its wastewater treatment production capacity. The efficacy of wastewater treatment is contingent on various factors, including geographical considerations, population density in urban areas, and the strategic location of treatment facilities. For instance, the collection of domestic and industrial wastewater from densely populated regions proves to be more feasible and cost-effective compared to that from low-density and sparsely populated cities. This underscores the nuanced and multifaceted nature of wastewater treatment planning, which is influenced by both geographical and demographic factors in the GCC countries.

4. Irrigation water sources

The agricultural sector in the GCC countries accounts for over 80% of the total available water resources, with the highest consumption observed in Saudi Arabia, the United Arab Emirates, and Oman. However, the economic contribution of the agricultural sector to the region is relatively limited, except for Saudi Arabia, where the gross domestic product (GDP) from the agricultural and fishery sector exceeded $17 billion in 2017. In the late twentieth century, Saudi Arabia allowed the agricultural sector to heavily utilize fossil groundwater to achieve food security, leading to the cultivation of vast areas with water-intensive crops like wheat. Unfortunately, this approach resulted in the depletion of significant non-renewable groundwater reservoirs in Saudi Arabia. The water use efficiency in the agricultural sector of the GCC countries is comparatively low due to challenging climatic conditions, high evaporation rates, and limited monitoring practices in irrigation systems. Consequently, the region is now actively focusing on reducing irrigation consumption through the adoption of efficient, precise, and smart irrigation systems, subsurface irrigation techniques, and the use of soil additives to enhance soil characteristics. Fig. 2 provides a breakdown of water consumption percentages in the agriculture, domestic, and industrial sectors. Recognizing the need for conservation, several GCC countries have recently implemented strict regulations to curtail water consumption in the agricultural sector. For example, the Saudi Food Authority banned wheat cultivation in 2016 to preserve non-renewable groundwater resources. Similarly, the Abu Dhabi Food Control Authority in the UAE decided to replace rhodes grass with more water-efficient crops like buffelgrass. Additionally, some GCC countries are exploring virtual water trade, involving the acquisition of agricultural lands in developing countries to conserve their own limited water resources. Table 4 outlines the land investment initiatives of GCC countries in this regard.

The agriculture is based mostly on open field irrigation methods with a low water use efficiency (WUE) resulting in high losses from evaporation. The average efficiency ratio in the GCC is 54.80% compared to 76.46% in Egypt and 71.69% in Tunisia as shown in Table 5. The overreliance on non-renewable groundwater aquifers for irrigation, accounting for 85% of usage, has led to the excessive exploitation of aquifers beyond their average natural recharge levels. This has resulted in elevated levels of water and soil salinity. In Qatar, for example, the groundwater consumption rate in 2016 (319 million m^3/y) surpassed the recharge rate from natural renewable resources (217 million m^3/y), indicating an annual depletion of 102 million m^3. This over abstraction is depleting aquifer reserves formed over millions of years,

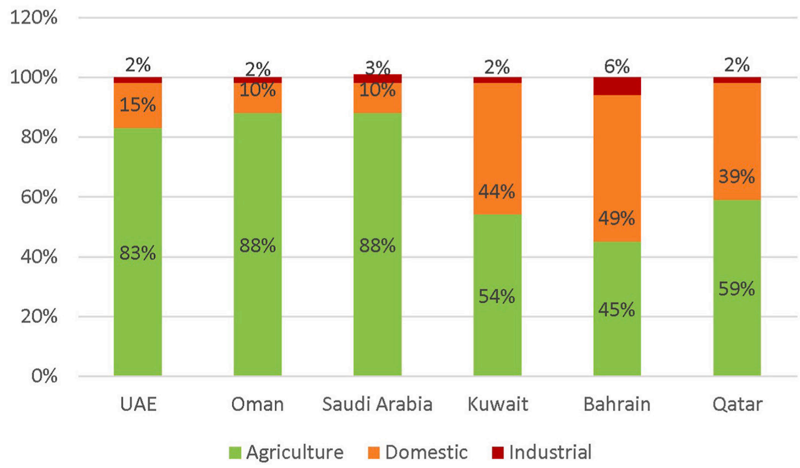

Fig. 2. Water consumption breakdown in GCC countries.

Table 4
GCC land grabbing and investment for agriculture purposes (2020)

Country	Investment location	Produced crops	Area (ha)
UAE	Romania, Pakistan, Indonesia, Tanzania, Ghana, Sudan, Namibia, Egypt, Algeria, and Morocco	Potato, citrus, fodder, rice, sugarcane, alfalfa, cereals, cotton, sunflower, peanuts, and sorghum	1,882,739
Saudi Arabia	Philippine, Mali, Russia, Sudan, Pakistan, Zambia, Argentina, Nigeria, and Ethiopia	Wheat, soybean, poultry items, mango, vegetables, banana, rice, fodder, and pineapple	1,713,357
Oman	Philippine	Rice	NA
Bahrain	Philippine	Rice and banana	NA
Kuwait	Philippine, Cambodia	Rice and maize	NA
Qatar	Australia, Sudan, India, Pakistan, Brazil, Vietnam, Ghana, and Cambodia	Poultry items, meat, wheat, barley, rice, cereals, and citrus	642,630

Table 5
Irrigation water use and efficiency in GCC (2020)

Country	Irrigation water demand (Mm^3/y)	Agriculture water use (Mm^3/y)	Irrigation efficiency (%)
Saudi Arabia	11,599	20,830	55.68
UAE	1,815	3,312	54.80
Oman	721	1168	61.73
Kuwait	721	1,168	61.73
Qatar	76	262	29.01
Bahrain	40	159	25.16

concurrently degrading water quality through seawater intrusion a prevalent issue in the GCC region. The repercussions of such overexploitation, often stemming from inadequate policies and interventions, pose significant hazards to the limited natural resources of water and land (Abdulghafar 2002, Dawoud 2020).

Various strategies exist to enhance water resource availability for irrigated agriculture, encompassing water conservation, infrastructure modernization, implementation of smart irrigation systems, regional water transfers, and treatment of low-quality local water sources. However, these approaches mainly optimize the utilization or relocate existing conventional water resources, rather than expanding their quantity. In regions where these measures are already in place, the utilization of nonconventional water resources, such as desalination and recycling, becomes imperative to augment water supply beyond hydrological cycle limits (Shannon et al., 2002). While recycling and brackish groundwater desalination face constraints related to domestic wastewater production and aquifer exhaustion, seawater desalination emerges as a dependable solution, playing a crucial role in addressing the global challenge of water scarcity in sustaining agricultural production (Elimelech and Phillip, 2011). Desalinated seawater (DSW) emerges as a plentiful and consistent water source, free from the climatological and hydrological limitations associated with traditional water resources, such as droughts. Its use avoids the social opposition and conflicts often linked to river regulation through dam construction and long-distance inter-basin water transfers. These inherent qualities position DSW as an appealing alternative for high-return agriculture, particularly in arid coastal regions where clear alternative water sources are scarce. While brackish water desalination for agriculture has gained global traction, its cost, typically less than half of DSW, has contributed to its increased adoption. Despite DSW historically being more expensive, it is now emerging as a viable option for crop irrigation in Spain. Assessments or plans for DSW agricultural application are underway in some U.S. states like Florida and California. DSW is predominantly utilized as a supplementary source for crop irrigation, often blended with conventional sources.

5. The potential of using desalinated water in irrigation

Initially managed as a supplementary source for crop irrigation, desalinated water is increasingly being considered a primary water source for agriculture, with direct irrigation practices observed in GCC countries. This trend is expected to persist and intensify in the near future. Originally utilized for domestic and industrial needs, desalinated water application is expanding as desalination technology advances and costs decrease. The Food and Agriculture Organization's (FAO) report on water desalination for agricultural applications (FAO, 2006) suggests that although desalination costs

Table 6
Average chemical composition of desalinated water for crop irrigation compared with brackish groundwater (2020)

Parameter	Average chemical composition	
	Desalinated water	Brackish groundwater
EC (dSm^{-1})	0.16–0.32	4.51 ± 0.98
Ca^{2+} ($mg\ L^{-1}$)	29.0–32.0	229.5 ± 39.3
Mg^{2+} ($mg\ L^{-1}$)	4.3–5.8	99 ± 17
SO_4^{2-} ($mg\ L^{-1}$)	5.8–6.8	980 ± 364
Cl^- ($mg\ L^{-1}$)	125–147	972 ± 608
Na^+ ($mg\ L^{-1}$)	86–102	573 ± 153
B^{3+} ($mg\ L^{-1}$)	0.56–0.63	1.36 ± 0.54
Alkalinity as $mg\ L^{-1}\ CaCO_3$	—	—
Langelier index (LI)	—	—
SAR	4.0–4.3	15.4 ± 10.6
pH	7.8–8.3	7.4 ± 0.5

remain high for most irrigated agriculture, its economic feasibility is growing, especially for high-return crops. Reverse osmosis (RO) has become the leading technology for seawater desalination plants (SWDPs) due to its relatively low energy consumption compared to other technologies (Greenlee et al., 2006). RO is widely considered the most adaptable technology for agricultural use, as evidenced by its use in current agricultural experiences in Spain and Morocco. However, challenges such as nutrient deficiencies, compliance with stringent standards for agricultural irrigation, sodium accumulation in soil, energy requirements, greenhouse gas emissions, and environmental impacts need to be addressed when using desalinated water produced through RO. Despite these concerns, advancements in RO technology make desalinated water a technically and economically feasible solution for high-return agriculture, especially in regions where the costs of surface water and groundwater are on the rise. Given desalinated water potential in meeting global water demands amid growing water scarcity, this paper aims to review and analyze key issues revealed by current experiences in crop irrigation with desalinated water. The focus is primarily on agronomical aspects, excluding discussions on desalination and post-treatment processes, which have been extensively covered in other reviews (Burn et al., 2015). The information gathered will be valuable for water planners and managers in water-scarce coastal regions with highly technical agriculture, where a significant portion of crop water requirements is expected to rely on seawater desalination in the future.

5.1. Desalinated water quality for crop irrigation

When considering irrigation with desalinated water, addressing agricultural water quality becomes paramount. Desalinated water, distinguished by its unique composition compared to brackish groundwater sources used for irrigation at present in GCC countries. Despite having lower salt content than brackish groundwater, desalinated water heightened concentrations of phytotoxic ions like sodium (Na^+), chloride (Cl^-), and boron (B^{3+}). Conversely, crucial nutrients vital for plant growth, such as magnesium (Mg^{2+}), calcium (Ca^{2+}), and sulfate (SO_4^{2-}), exhibit unusually diminished levels. To assuage agronomic apprehensions surrounding desalinated water utilization in crop irrigation, a meticulous assessment of its chemical makeup, as provided by the major desalination plants in GCC countries, is imperative. This evaluation involves a thorough comparison with the standards delineated by Ayers and Westcot (1985), predicated on soil and crop protection criteria, thereby ensuring the judicious utilization of desalinated water resources in agricultural practices.

5.2 Irrigation water salinity

The impact of irrigation water salinity on crop yield becomes evident when specific concentrations are exceeded. Typically, crop salt tolerance is illustrated through a model depicting yield decline across varying salt concentrations, measured as irrigation water electrical conductivity (EC). This model is often characterized by an EC 'threshold' value below which yield remains unaffected, alongside a 'slope' describing the rate of yield decline with increased EC beyond the defined threshold. This threshold–slope model, specific to crops and varieties, serves as a fundamental tool in crop irrigation management. Notably, the EC values for desalinated water range from 0.46 dSm^{-1} to 0.54 dSm^{-1}, approximately half the EC thresholds values for the crops listed in Table 6. Table 7 presents threshold-slope values for the most prominent irrigated crops in GCC countries. Consequently, from a salinity perspective, the supply of desalinated water ensures the absence of any detrimental effect on crop yield a statement applicable across the board, as the threshold for the most salinity sensitive crops in GCC countries is EC = 0.7 dSm^{-1}. The introduction of desalinated water can yield varied agronomic outcomes contingent upon the quality of the replaced irrigation water. In instances where high-quality waters are replaced, the low salinity of desalinated water doesn't inherently translate to agronomic benefits, as theoretically anticipated in irrigation districts supplied by the T-S aqueduct, where water is characterized by low EC values around 0.85 dSm^{-1}. However, if desalinated water replaces waters with an EC surpassing the salinity threshold for a specific crop, an increase in productivity and quality of crop yields becomes foreseeable, owing to reduced salinity stress. This scenario is commonplace in the SRB, even in T-S irrigation districts, where persistent water deficits necessitate farmers to incorporate low-quality groundwater into their on-farm ponds, subsequently blending it with T-S supply to achieve EC values ranging from 1.5 to 2.5 dSm^{-1}, generally above the EC threshold values for crops. The final column in Table 7 offers an example of the quality of this supplementary groundwater supply. Thus, the judicious blending of desalinated water in collective or individual on-farm ponds empowers farmers to manage lower EC in irrigation water, thereby enhancing crop yields and potentially conserving water, given that the additional irrigation water required for salts leaching significantly diminishes as EC decreases. Several instances of these advantageous effects have already been documented in GCC countries, where desalinated water replaced both T-S aqueduct supply (EC = 1.2–2.2 dSm^{-1}) and brackish groundwater (EC = 5–7 dSm^{-1}) in a citrus orchard, resulting in production increases of approximately 10% and 50%, respectively, alongside a 20% reduction in irrigation requirements.

Table 7
Salt tolerance parameters and maximum permissible concentrations of chloride, sodium and boron

Crop	Salt tolerance parameters of crop yield response functions values for irrigation water (1)		Maximum chloride concentration (mgL^{-1}) in irrigation water without yield reduction (2)	Maximum sodium concentration (mgL^{-1}) in soil water without yield reduction (3)	Maximum boron concentration (mgL^{-1}) in soil water without yield reduction (4)
	Threshold (dSm^{-1})	Slope (% per dSm^{-1})			
Lettuce	0.9	19.6	—	—	1.3
Broccoli	1.6	13.9	—	—	1.2
Peach trees	1.1	31.2	251	—	0.5–0.75
Orange trees	1.2	23.5	354	315	0.5–0.75
Lemon trees	1.0	24.5	341	321	<0.5
Cucumber	1.3	25.3	312	310	1.2

It should be noted that tolerances vary, depending upon variety and rootstock (in tree crops), climate, soil conditions, and cultural practices.

(1) Adapted from the lists of crop salt tolerance parameters published by Maas and Grattan (1999) and Ayers and Westcot (1985).
(2) Adapted from the list of crop chloride-tolerance limits published by Hanson et al. [23]. Vegetable crops are notably less sensitive than tree crops and their values are generally not provided.
(3) Sodium toxicity is often modified or reduced if enough calcium is available in the soil. Therefore, toxicity guidelines usually consider SAR as the indicator of the potential for sodium toxicity. Values for citrus trees were recommended by Grattan et al. (2015).
(4) Adapted from the lists of boron tolerance parameters published by Hanson et al. (1999).

5.3. Concentrations of essential nutrients

When considering the use of DSW for crop irrigation, it's essential to account for the low concentrations of Mg^{2+}, Ca^{2+}, and SO_4^{2-}. Typically, these ions play a secondary role in crop fertilization due to the ample concentrations provided by natural waters in the SRB and soil mineral content, adequately meeting crop requirements. As a result, tree crops and open-air vegetable crops generally do not require additional nutrient supplementation, while only greenhouse crops, particularly those in soilless systems, necessitate extra fertilization to achieve concentrations in irrigation water of 80–120 mgL^{-1} for Ca^{2+}, 24–36 mgL^{-1} for Mg^{2+}, and 100–150 mgL^{-1} for SO_4^{2-}. Table 6 illustrates how the concentrations of these nutrients in the T-S aqueduct water supply align with or exceed the aforementioned concentrations, especially with blending with brackish water. However, the concentrations of Mg^{2+}, Ca^{2+}, and SO_4^{2-} in desalinated water vary considerably lower, ranging from 14.9 to 29.0 mgL^{-1}, 1.4–4.3 mgL^{-1}, and 4.0–6.6 mgL^{-1}, respectively, well below the required values for greenhouse crops. Consequently, significant amounts of Ca^{2+}, Mg^{2+}, and SO_4^{2-} must be added to greenhouse crop fertilization if transitioning to desalinated water, incurring increased operational costs for farmers. This challenge has been highlighted in Spain, where an additional cost of fertigation with Ca^{2+}, Mg^{2+}, and SO_4^{2-} amounted to \$3500/ha (equivalent to \$0.50/m^3 of irrigation water) for a greenhouse pepper crop. To address this deficiency in essential nutrients and its impact on fertilization requirements, the common practice in the SRB involves blending DSW with surface water, groundwater, or both, until EC values range from 1.5 to 2.5 dSm^{-1}, depending on T-S aqueduct water availability and the threshold salt tolerance of each crop.

5.4. Soil sodicity risk

Aside from direct phytotoxicity, the elevated concentration of Na^+ in desalinated water can induce soil physical impairment through sodicity, indirectly affecting plant growth and significantly impacting crop yield. Sodicity detrimentally alters soil physical properties by causing clay dispersion, resulting in structural collapse of soil aggregates, reduced soil hydraulic conductivity, erosion issues, soil compaction, and diminished soil aeration. The risk of soil sodicity diminishes when multivalent cations, primarily Ca^{2+} and Mg^{2+}, are present in the irrigation water, thus necessitating a thorough assessment of soil sodicity hazard using the sodium adsorption ratio (SAR), following Ayers and Westcot criteria. For mid to long-term analysis, both SAR and EC values must be considered, delineating three regions with varying sodicity risk, as depicted in Fig. 3. The chemical composition of desalinated water supply in the SRB exhibits minimal Ca^{2+} and Mg^{2+} concentrations alongside high Na^+, yielding SAR values ranging

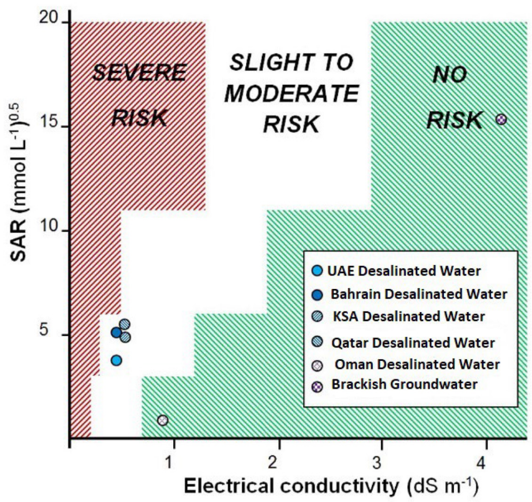

Fig. 3. Mid-long term soil sodicity potential risk.

from 4 to 5.6 as shown in Table 6. These values plotted in Fig. 3, along with the EC of each desalinated water supply, signify moderate soil sodicity hazard across all seawater desalination plants, potentially leading to decreased soil infiltration rates and hindering infiltration drainage and diffused atmospheric oxygen flux through soils in the mid-term. This sodicity hazard associated with desalinated water contrasts sharply with the water supply from the T-S aqueduct and brackish groundwater in GCC countries, depicted in the no-risk region of Fig. 1. Consequently, water blending management strategies are advisable to alleviate or mitigate concerns regarding soil sodicity risk. Nonetheless, at the very least, seasonal soil monitoring is prudent to detect any deterioration in soil structure when DSW is employed for crop irrigation, particularly in soils with high clay content, where sodicity hazard is more pronounced.

5.5. Irrigation water chemical stability

The chemical stability of water in distribution schemes is primarily governed by two parameters: first, the buffering capacity of the water, which denotes its ability to withstand significant pH changes when exposed to strong acids or bases; and secondly, the tendency of the water to precipitate or dissolve $CaCO_3$. Alkalinity serves as a standardized measure of water's buffering capacity, with low alkalinity indicating heightened sensitivity to pH changes, while increased alkalinity enhances the water's resistance to pH fluctuations. The potential for carbonate precipitation or dissolution can be assessed using various quantitative and qualitative indices, such as the Langelier Index (LI), which signifies the pH shift required to attain equilibrium; negative values indicate water's ability to dissolve $CaCO_3$, while positive values suggest the potential for $CaCO_3$ scales to precipitate. LI values close to zero are recommended for distribution schemes. Adequate buffering capacity in desalinated water is particularly crucial for agriculture in GCC countries, given prevalent practices like fertigation, cultivation on low-buffering substrate, and soil-less crop cultivation in its high-tech agriculture sector. In fertigation, desalinated water often undergoes mixing with liquid fertilizers, making sudden pH changes potentially detrimental to crop nutrient availability and, consequently, agricultural productivity. Hence, Spain quality criteria for combined agricultural and municipal desalinated water use advocate for a minimum alkalinity level of 80 mgL^{-1} as $CaCO_3$. Notably, alkalinity is typically omitted from chemical analyses governing desalinated water production in GCC countries, with only the minor sweater desalination plants providing a value of 52 mgL^{-1} as $CaCO_3$, falling below Spain's recommended threshold. Moreover, high alkalinity values are advised for corrosion minimization in distribution systems and prevention of pipe rusting. The control of carbonate precipitation or dissolution potential in irrigation water is equally vital in GCC countries, where irrigation districts have historically relied on the T-S aqueduct supply, characterized by high water hardness and carbonate precipitation potential (LI>1, Table 6). Consequently, $CaCO_3$ scale deposition is commonplace in their pipeline systems, and a shift to negative LI waters could dislodge existing scales, impeding the operation of valves, filters, flowmeters, and leading to pipe blockages. However, GCC countries desalinated water agricultural supplies exhibit LI values very close to zero (ranging from –0.06 to –0.18, as shown in Table 6), ensuring the absence of new carbonate scale precipitation or the release of existing scales, thereby maintaining efficient system functioning.

6. Desalination energy consumption and greenhouse gas emissions

The production of desalinated seawater involves considerable energy consumption and CO_2 emissions, particularly evident due to the high specific energy requirements compared to other water sources, accentuating the water-energy nexus. For agricultural purposes, desalinated seawater supply can be even more energy-intensive than for potable use due to post-treatment necessities for B^{3+} removal, allocation to irrigation districts, and utilization in pressurized irrigation systems. Table 8 delineates the specific energy consumption of the major desalination plants in GCC countries supplying agriculture, categorizing it into desalinated water production, conveyance to irrigation districts, allocation within districts, and irrigation system operation. The specific energy consumption for desalinated water production in GCC countries ranges from 4.50 to 5.30

kWhm^{-3} in RO plans and 13.20–19.70 kWhm^{-3} in thermal plants. Additionally, the specific energy required for conveying desalinated water to nearest irrigation demand centers (farms) ranges from 0.59 to 1.00 kWhm^{-3}. This additional energy compensates for head loss in the piping system and the altitude difference between the desalination plants and the irrigation demand centers. Notably, the specific energy consumption at desalination plants far exceeds that of traditional agricultural water supplies in GCC countries pumping brackish groundwater (0.48 kWhm^{-3}) and reusing treated wastewater (0.72 kWhm^{-3}) and desalinated brackish groundwater (3.01 kWhm^{-3}). The average specific energy required for water allocation within GCC countries irrigation demand centers is about 0.16 kWhm^{-3} and for pressurizing drip irrigation systems is 0.17 kWhm^{-3}, resulting in a total specific energy consumption for agricultural desalinated water use ranging from 4.46 to 5.15 kWhm^{-3}. Consequently, replacing brackish groundwater sources with desalinated raises significant environmental concerns due to increased greenhouse gas (GHG) emissions, counteracting the perceived benefits of desalinated water use in agriculture, such as reliability and independence from climatic conditions. Some authors (Rogers et al., 2002) even regard desalination as a misguided adaptive strategy to climate change, as elevated GHG emissions may exacerbate water scarcity processes. From an agricultural standpoint, analyzing GHG emissions associated with intensive desalinated water use is crucial, as heightened energy consumption could shift the CO_2 balance of irrigated crops from sink to source, exacerbating climate change. Fig. 4 illustrates the impact of desalinated water supply on the CO_2 balance of representative irrigated crops in the SRB under current farming practices, assuming traditional water sources are entirely replaced with desalinated water. This assessment, following the approach by Martin-Gorriz et al. (2014), underscores how GHG emissions linked with irrigation would increase proportionally to crop irrigation requirements, becoming the most significant component of total GHG emissions in farming activities. Thus, agriculture's resilience in water-stressed regions through desalinated water substitution may inadvertently intensify climate change processes.

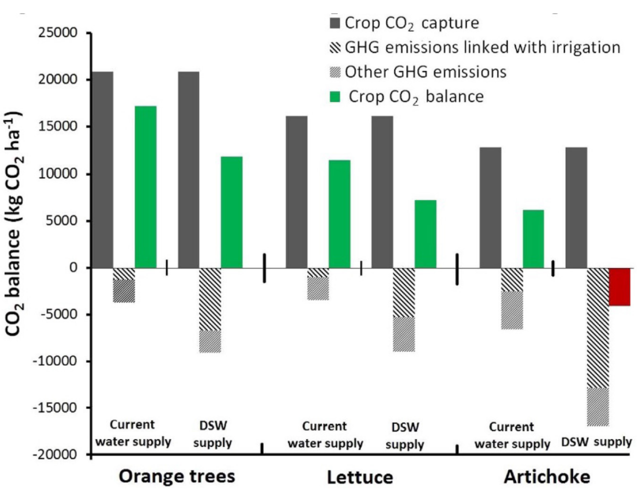

Fig. 4. Main CO_2 balance components for three irrigated crops.

7. Economic analysis for using desalination in irrigation

The total costs associated with desalinated seawater production in GCC countries can be delineated into two main components: capital costs (Capex), encompassing the initial investment in seawater desalination plants, and operational and maintenance costs (Opex), which persist continuously throughout the operational period. Firstly, Capex are typically calculated under the assumption that desalination plans operate at their projected capacity over their lifespan. However, desalinated water demand is immediately influenced by the availability of cheaper alternative water supplies (brackish groundwater and treated wastewater). Secondly, Opex are heavily reliant on energy consumption, with energy costs typically constituting around 53–61% of Opex expenses. Consequently, these costs exhibit a direct correlation with energy prices, as observed. In general, the Capex cost ranges between US$1200–1400/m in thermal desalination and US$900–1200/m in membrane (RO) systems. The desalinated water production cost ranges between US$1.2–2.1/m in GCC countries.

The selling price of desalinated seawater to farmers falls below the total costs of the production across all desalination plants (subsided by governments), indicating the presence of indirect subsidies in agricultural production. This phenomenon persists mainly due to the fact that Capex do not consistently factor into the selling price and even in some countries such as UAE it lower than Opex (water price for agriculture sector is 3.1 AED which the cost is about 1.6 AED). In addition to indirect subsidies, direct subsidies were implemented by some GCC governments as an extraordinary measure to alleviate the impacts of the prevailing water scarcity on the T-S aqueduct supply. Collectively, these direct subsidies, significantly contributing to the current surge in demand for desalinated water for crop irrigation. There are many plans and recent studies on the future increase of using desalinated water in irrigation and crops production in GCC countries.

8. Conclusions and recommendations

In response to intensifying water scarcity driven by climate change and deterioration of groundwater used in irrigation, GCC countries is pioneering an agricultural paradigm, amalgamating extensive seawater desalination, advanced agronomic techniques, and high-value crop cultivation to increase their self-sufficiency and food security which is less than 15% at present. This innovative model aims to bolster the resilience of irrigated agriculture. The evolution of desalination for crop irrigation in GCC countries starting in 2020, offering theoretical insights and practical assessments of their merits and drawbacks. Noteworthy strengths include:

(1) desalinated water potential as an agricultural water source, offering invaluable buffering against drought risks;
(2) the substitution of present brackish groundwater sources with desalinated water opens avenues for novel water policies and on-farm management strategies;
(3) its low salinity can substantially enhance both the quality and quantity of crop yields, especially when replacing or blending with inferior water supplies.

However, principal concerns loom over:

(1) the substantial energy consumption of desalination, resulting in higher costs compared to alternative water sources, potentially undermining the economic viability of major irrigated crops;
(2) prevailing B3+ concentrations in desalinated water exceeding toxicity thresholds for many tree crops in GCC countries, posing a significant risk of crop damage; and
(3) the exacerbation of the water-energy nexus in desalinated water production, leading to elevated greenhouse gas emissions that exacerbate climate change.

While further research is imperative to foster reliable and sustainable agricultural desalinated water utilization, the growing expertise in agricultural desalinated water management in Spain and Morocco holds promise for overcoming agronomic challenges in the foreseeable future. This trajectory could position desalinated water as a pivotal water supply for irrigated agriculture in coastal regions grappling with escalating water scarcity.

From an economic standpoint, the complete replacement of traditional water sources with desalinated seawater is currently feasible only for greenhouse crops, while blending with more affordable water sources is imperative to render its utilization economically viable across a broader spectrum of crops. Water blending emerges as the most prudent management approach, even for greenhouse crops, as it not only offsets high costs but also mitigates significant agronomic concerns stemming from the unique chemical composition of desalinated seawater. These concerns include nutrient deficiencies impacting fertilization requirements, toxicity risks from elevated B^{3+} concentrations for many irrigated tree crops, and the potential for soil sodicity and subsequent soil physical degradation. Hence, both agronomic and economic considerations underscore the advantages of integrated planning and management of desalinated seawater alongside other available water resources within each irrigation area, necessitating meticulous assessments regarding blending ratios and associated costs. Blending strategies should be intricately modeled and scrutinized for each irrigation district or farming scenario, considering factors such as the chemical makeup of supplied desalinated seawater, the quality of alternative water sources, crop-specific nutrient requirements including Mg^{2+} and Ca^{2+}, ion toxicity thresholds, and the implications for agricultural greenhouse gas emissions and crop CO_2 balance. In cases where blending with multiple water sources is standard practice, the implementation of real-time water-quality monitoring systems is highly recommended to ensure a consistent supply of high-quality water to crops over time. The case of GCC countries underscores the importance of prudence in the development of large-scale desalination initiatives, given that agricultural desalinated seawater demand correlates inversely with the availability of alternative, cheaper water supplies. To address this, the establishment of long-term take-or-pay contracts between desalination plants and farmers' associations is suggested, mirroring practices in Spain and Morocco where such policies ensure that the government commits to paying for the agreed-upon volume of water supplied by desalination plants annually, thereby guaranteeing that facilities operate at their intended capacity.

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Balaban Desalination Publications

(2025) 222–224
doi: 10.5004.dsal.2025.700107

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Climate change and water scarcity: strategies for sustainable agricultural water use in the Arab Region

Kamel Mustafa Amer

Water Resources Advisor, Arab Organization for Agricultural Development (AOAD), 11 Al Islah Al Zeraie St., Co-Operative of Agricultural Reform Building, Dokki, Giza, Egypt
email: kamel.mostafa.elsayed@gmail.com

ABSTRACT

Climate change represents a profound and ubiquitous challenge with particularly acute consequences in the Arab region. In this area, inhabitants confront escalating temperatures, shifting rainfall patterns, and increasingly frequent and intense meteorological phenomena. These alterations exacerbate the pre-existing critical issue of water scarcity. The arid climate, burgeoning populations, and brisk economic development intensify the pressure on water resources. The region's susceptibility to climatic shifts presents substantial hazards to the vital water supplies necessary for agriculture, potable use, and hygiene purposes. Studies indicate that the Arab region is warming at a rate surpassing the global average, jeopardizing the water security of over 360 million individuals. This predicament necessitates prompt action to alleviate the impacts and preserve water resources for future generations.

Keywords: Water scarcity; Climate change; Arab region; Agricultural water use; Sustainability; Innovative water management; Policy framework

1. Current state of water resources

In the Arab region, the allocation and accessibility of water resources are markedly inconsistent and frequently subjected to intense pressure. Central challenges encompass significant groundwater depletion, pervasive contamination, and escalating salinization, all of which contribute to a fragile state of water security. Groundwater serves as a vital water source in over 11 Arab nations, yet it is being exhausted at rates significantly surpassing natural replenishment rates, with certain regions experiencing annual declines in groundwater levels exceeding two meters. Moreover, agricultural endeavors, which account for the highest water usage—often surpassing 85% in several countries—are hindered by inefficiencies that are compounded by antiquated irrigation techniques and suboptimal water management strategies, all further aggravated by the effects of climate change.

2. Agricultural water use

In the scope of agriculture, a pronounced divergence exists between the water requirements of crops and the water supplies available, fostering pervasive inefficiencies and unsustainable farming techniques. This dis-

ISBN 0-86689-078-5

crepancy often arises from deficient water management strategies and reliance on outdated irrigation methods that fail to integrate contemporary water-conservation technologies. To mitigate these issues, it is crucial to implement a combination of more effective irrigation technologies, select crop varieties that demand less water, and embrace advanced water management approaches. These enhancements have the potential to boost water use efficiency by as much as 40% in certain regions, thus narrowing the existing chasm between water demand and availability. Furthermore, the selection of crop varieties that can withstand dry conditions and the adaptation of irrigation schedules to leverage real-time data can significantly advance the alignment of agricultural operations with the objectives of sustainable water management.

3. Challenges and opportunities

The environmental predicaments facing the Arab region are intensifying, with escalating threats of drought, desertification, and the deterioration of soil quality. These complications are magnified by climatic shifts anticipated to heighten the frequency and severity of extreme weather conditions. The threat of desertification is notably severe, impacting specific zones with profound consequences for land utilization and agricultural productivity. Socioeconomic dynamics, including the swift population growth observed in numerous Arab nations and increasing urbanization, exacerbate the demand for water. In some areas of the Arab region, the pace of population expansion places immense pressure on existing water and agricultural infrastructures. Nonetheless, these difficulties also present significant prospects through the lens of technological progress. Cutting-edge developments in water management and agricultural methodologies provide viable strategies to boost water efficiency and promote environmental sustainability.

4. Innovative water management strategies

Using innovative water management strategies is essential to reducing the grave problem of water scarcity, particularly in the agricultural sector—which uses a lot of water. Innovative irrigation techniques, including drip and precision irrigation systems, have demonstrated a critical role in increasing water use efficiency. These methodologies can engender considerable conservation of water, with research suggesting that smart irrigation could curtail water consumption by a considerable percentage. This is achieved by channeling water directly to the plant's root zone, thereby curtailing evaporation and runoff. Such a pinpointed modus operandi not only preserves water but also fosters more robust crop development by ensuring plants receive the precise volume of water at the requisite junctures. Water reclamation, which entails the reconditioning of wastewater for its subsequent employment in agricultural irrigation, represents another tactic that has demonstrated the potential to diminish dependence on unadulterated freshwater sources. Through the reuse of water, the agricultural domain can access a steady supply, a boon for regions where water scarcity is intensified by seasonal fluctuations. In certain scenarios, the implementation of water recycling has been capable of slashing the demand for freshwater by as much as 50%, contingent upon the sophistication of the treatment process and the variety of crops irrigated.

An auxiliary strategy, rainwater harvesting, involves the accumulation and storage of rainwater for future application. This technique can significantly bolster water conservation efforts, particularly in arid and semi-arid locales where precipitation is sporadic yet can be torrential when it does transpire. Rainwater harvesting apparatuses can range from diminutive rooftop contrivances to expansive infrastructural undertakings. In some cases, rainwater harvesting has been able to furnish up to 70% of the water requisites for crop irrigation throughout the parched season, thus markedly alleviating the burden on traditional water sources.

The amalgamation of these pioneering water management strategies can usher in a more sustainable and robust agricultural sector. By amalgamating smart irrigation with the strategic repurposing of water and the systematic collection of rainwater, it is feasible to engender a cumulative effect that amplifies water conservation and guarantees a more steadfast supply of water for agricultural purposes. For example, the integration of sophisticated sensors and meteorological prognostication in intelligent irrigation systems can be synchronized with the strategic reserve of recycled and harvested rainwater to fine-tune water usage across the calendar year.

5. Role of technology and research

The significance of technology and research in enhancing water management tactics cannot be overstated. Sophisticated monitoring frameworks and analytics-based decision-making processes enable more accurate allocation of water resources, optimizing utilization while reducing excess. Investigative pursuits into cutting-edge technologies, including the refinement of desalination methodologies or the integration of renewable energy for irrigation purposes, are pivotal in the progressive evolution of water management techniques. Moreover, cooperative initiatives, especially in the dominion of research and development, are vital for catalyzing innovation and deploying technological solutions tailored to the unique challenges of the Arab region.

6. Policy and regulatory framework

In the quest to address the dual challenges of water scarcity and climate change, the establishment of a comprehensive policy and regulatory framework is paramount. This framework must be conducive to the sustainable utilization of water resources. The enactment of well-conceived policy initiatives is indispensable for steering the integration and adoption of water-saving practices and technologies, thereby ensuring the prudent stewardship of water resources. The escalating pressures of burgeoning demand in the face of dwindling supplies underscore the imperative for pioneering policy interventions or substantial revisions to extant regulations. Such policies ought to extend beyond mere water conservation; they must weave climate change mitigation strategies into the fabric of water resource management planning to secure enduring resilience and sustainability.

To surmount the obstacles of water scarcity in the Arab region, a concerted approach is necessary—one that encompasses the augmentation of technological prowess, the introduction of progressive water governance frameworks, and the fortification of robust policy structures. These endeavors should be buttressed by persistent research and cooperative ventures, tailored to the dynamic environmental and socio-economic terrains.

7. Future directions and recommendations

In the Arab region, the formulation of strategic frameworks for water management is imperative, requiring the creation of comprehensive, long-term objectives and the integration of these plans with broad-based climate mitigation tactics. This strategic methodology should encompass measurable targets, such as reducing water usage by predetermined percentages or boosting the employment of recycled water in agricultural activities by a designated year. The critical importance of stakeholder involvement in this endeavor is paramount—it is essential for the effective execution of sustainable practices. Involving a varied array of stakeholders, including community groups, governmental bodies, and private sector actors, guarantees the incorporation of diverse insights and expertise into water management strategies. Furthermore, international collaboration is vital in this domain, offering a venue for the exchange of knowledge, resources, and exemplary practices across national boundaries. Such international engagement is essential for tackling the transboundary nature of water resources and the effects of climate change. Collaborative initiatives should strive to cultivate a sense of ownership and accountability among all parties involved, ensuring that water management efforts are comprehensive and successful. For example, international alliances could concentrate on advancing technology sharing and expertise, as well as procuring financial backing for water management endeavors, with the objective of enhancing water efficiency in the region by 30% by 2030.This strategy underscores the need for collective decision-making and the synchronization of governance norms across various societal and institutional strata. Employing participatory methods can fortify more robust and flexible water management systems, as they integrate local insights and preferences at the onset of the planning stage, thus potentially elevating the success rates of the policies and projects implemented.

Conclusion

A comprehensive strategy is necessary to effectively address the intertwined challenges of water scarcity and climate change in the Arab world. This plan should incorporate cutting-edge technology applications, sound policy frameworks, and global cooperation. Water sustainability will be advanced throughout the region and agricultural productivity will rise by giving priority to cutting-edge water management strategies and research-based solutions. It is imperative that an all-encompassing policy environment that promotes the adoption of sustainable practices and technologies underpins these strategies. Furthermore, accomplishing the primary objectives of increased water efficiency and climate resilience requires developing international partnerships and encouraging the sharing of expertise. By putting these measures into place, the area will ensure a prosperous and sustainable future by meeting present demands while also protecting water resources for future generations.

Balaban Desalination Publications

مؤتمر الخليج الخامس عشر للمياه
The 15th Gulf Water Conference

(2025) 225
doi: 10.5004.dsal.2025.700108

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Economics of water under climate change in Arab countries: a policy perspective

Mohamed A. Abdrabo

Alexandria Research Center for Adaptation to Climate Change (ARCA), Alexandria University, Egypt
email: mabdrabo@alexu.edu.eg

ABSTRACT

The Arab region is one of the driest regions in terms of water availability, as the region is located in arid and sub-arid regions with low rainfall and high temperatures in summer, they are vulnerable to drought. and climate change is expected to heighten water stress in the region, with a reduction in precipitation and increased demand from competition users, particularly with rapid population growth and improving living standards. Water scarcity, particularly from an economic perspective, a very complex multidimensional issue due to the same resource may have different targets to attain including being a human right, socio-cultural, supporting ecosystems functioning, and being input to most economic activities. The diversity of uses as well as sources of water creates complex interlinked issues, especially when considering the energy, food, and environment, that need to be addressed simultaneously. From a policy perspective, water scarcity is typically dealt with in Arab countries by attempts to augment water resources using traditional and non-traditional sources. Water demand management still lags with limited efforts, with the classical focus of potable water pricing, for instance, is cost recovery, meaning trying to cover the cost of the process of water treatment and pumping, which implicitly assumes that the economic value of water as a natural resource is zero. The paper in hand intends to examine the implications of climate change on the economics of water security in Arab countries, attempting to identify potential management actions. It was found that there is a need to have a significant shift in policymaking concerning water management. Such a shift would require:

- Adopting a holistic integrative framework for sustainable development and water management.
- Incorporating economic valuation into water-related decision-making to resolve some of the resourcing and capacity issues challenges.
- Integrating various economic instruments, e.g., abstraction charges, water markets, tradable pollution permits, subsidies, and payments for environmental services, into water policies.

Such actions should be utilized to attain efficiency and equity among different water users including socio-cultural, economic, and environmental purposes.

Keywords: Arid and sub-arid regions; Water stress; Water scarcity; Human right; Socio-cultural; Energy; Food; Environment; Water demand management; Framework; Potable water; Climate change

ISBN 0-86689-078-5

Balaban Desalination Publications

(2025) 226–228
doi: 10.5004.dsal.2025.700109

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Harnessing biosaline agriculture for food security in the arid GCC

Rachyd Zaabol

International Center for Biosaline Agriculture, UAE, email: r.zaaboul@biosaline.org.ae

EXTENDED ABSTRACT

Water scarcity is a prominent challenge threatening efforts to achieve food security in the GCC. A predominantly arid region characterized by scant and erratic rainfall combined with high potential evaporation rates exacerbates the profound and widespread impacts of accelerating water scarcity on local agricultural sustainability. The increasing demand for freshwater to meet the growing need for food to sustain the growing population remains a pressing concern amidst the constrained freshwater supply. Agriculture, consuming over 70% of the available water resources in the GCC, faces a forecasted 50% increase in water demand by 2050, intensifying competition with other essential water sectors.

Climate change's present and anticipated impacts on agriculture and water resources suggest a worsening situation for arid regions such as the GCC. Rising temperatures, variable rainfall, and increased occurrences of extreme droughts and floods are set to exacerbate water scarcity, jeopardizing vulnerable farming communities and food security. Global warming is expected to lead to higher temperatures across many regions, including the Middle East. Higher temperatures can intensify evaporation rates, potentially leading to increased water loss from soils, wadis, oasis, and reservoirs. North Africa is predicted to get drier, with an annual rainfall deficit reaching more than 50% by the end of this century under a high-emission scenario. The annual rainfall predictions for the GCC are more optimistic, with a potential increase in the annual rainfall reaching more than 50% by the end of this century under a high-emission scenario. However, this rainfall increase is insufficient to meet the growing demand for freshwater.

Soil and water salinization also present a growing concern in the MENA, the GCC region, and globally, posing a threat to some of the most productive lands currently utilized for irrigated agriculture. Rapid soil degradation due to salinization and soil sodicity has emerged as a significant challenge in recent decades, leading to substantial risks to global food security and environmental sustainability.

These mounting pressures severely undermine the region's capacity to ensure equitable access to water and food for all. The agr-innovative programs the International Center for Biosaline Agriculture implemented provided locally suited solutions for increasing food production in arid conditions with limited freshwater availability. This research for development programs focused on four main thematic areas of research. The first program is climate-smart crops that are heat, drought, and salt tolerant. These crops can grow under harsh, arid environments, where a range of crops that can tolerate different levels of salinity were provided to many farmers in these arid regions. For example, for low soil and water salinity levels ranging from 5 to 8 ds/m, Amaranth, Sorghum, Pearl millet, Mustard, and Sunflower produced a significant yield increase of 30% compared to conventional varieties or crops. Similarly, for higher salinity levels up to 30 ds/m, important forages, fruits, and crops such as Salicornia, Sporobolus virginicus, distichlis Spicata, date palm trees, and quinoa were

ISBN 0-86689-078-5

grown. In addition to selecting and introducing these crops, ICBA provided a holistic solution through farms' best practices of inputs and fertigation, irrigation, and enhancing the value chain from the farm to the fork.

The second program is land and water, providing smart solutions for improving water use efficiency and agricultural water productivity. On-farm management practices utilizing water-saving and fertigation technologies have proven effective in conserving water and maximizing farmers' benefits per unit of water used. Scaling up these best practices through field extension projects and training initiatives can enhance the quantity and quality of food production, meeting market demands while minimizing environmental impact.

Watershed management using GIS and remote sensing techniques helped to manage the available water resources at the basin and sub-basin levels. Land use and land cover mapping were used to delineate the change in the agricultural areas needed to track and monitor agricultural production and productivity, and it also allowed the calculation of the actual water use of selected crops. In addition to brackish water, other non-conventional water resources such as treated wastewater, desalinated water, and its valuable by-product, the brine, were used in ICBA's research and development projects. These water resources are crucial in averting food crises and sustaining food production. ICBA promoted using non-conventional water resources in agricultural production because they are crucial for addressing water scarcity. Fortunately, many countries in the GCC region have incorporated non-conventional water resources into their national water balance and strategies, encompassing policies, institutional frameworks, regulations, and more.

Improving soil health through mixing with suitable soil amendments such as biochar helped to achieve a better crop yield, saved water up to 30%, and allowed for carbon sequestration. Adding the soil amendment improved the soil water retention near the crop roots. The rehabilitation of degraded soil due to salinity and sodicity showed significant improvement in agricultural production, bringing degraded lands to be productive again. Many farms are abandoned due to increasing soil salinity or degrading the water quality. Best practices to improve the soil health provided to the farmers through demonstration farms, farmers' field schools, and extension works improved the farms' yield and protected the environment from further degradation.

With the emergence of big data, the data-driven program succeeded in modeling the effect of climate change on agricultural production using several global and regional climate and emission scenarios, which helped the countries monitor and plan their water resources to adapt to or mitigate its effect. The Center built the staff capacity in four countries in the MENA region, Morocco, Tunisia, Jordan, and Lebanon, by developing decision support tools to allow them to monitor the drought events and make the right decision at the right time.

Remote sensing and satellite images integrated with in situ field sensors controlled by the Internet of Things (IoT) provided more precise estimates of crop water requirements and appropriate irrigation scheduling by irrigating the right volume of water at the right time. High-resolution satellite images were downscaled from global databases and used with less than 30 meters resolution. Several applications and tools were developed using machine learning and AI, and they benefited from these open-source images.

Significant innovative solutions were provided under the novel production program, which focused on improving Controlled Environment Agriculture (CEA) by developing desert-type CEA in collaboration with a Korean program. The research addressed significant issues of greenhouse cooling, new structural designs, growing media, and relevant materials. The water saved from irrigation and cooling was about 30% compared to the conventional CEA. Alternative water sources for cooling were tested at ICBA's farm, such as brackish water and treated wastewater. The results showed the potential to use these alternative water resources in cooling, but further research is still needed on their technical and financial feasibility.

The Integrated Agri-Aquaculture Approach showed realistic results and was considered a relevant agricultural solution for the arid environment. The approach incorporated circular economy concepts by using brine as a water source instead of considering it a waste. This provided additional benefits to the farmers by growing fish in the fish tanks using brine water, and sequentially, the aquawater is used to irrigate halophytic crops. The experiment's results showed a potential to scale out this approach for many farmers using small-scale RO units on their farms.

In conclusion, in the face of increasing water scarcity and the challenges posed by aridity, harnessing biosaline agriculture emerges as a promising strategy for securing food production in the arid GCC region. The extensive efforts of the International Center for Biosaline Agriculture underscore the potential of innovative agricultural practices tailored to thrive in harsh environments characterized by limited freshwater availability and high salinity levels.

ICBA's multifaceted approach, spanning climate-smart crops, efficient land and water management, and integrating non-conventional water resources, exemplifies a holistic strategy toward sustainable food production. Significant yield increases have been achieved by introducing heat, drought, and salt-tolerant crops suited to the region's conditions, offering a viable alternative to conventional varieties. Moreover, optimizing water use efficiency through on-farm management practices and adopting water-saving technologies contributes to conserving precious freshwater resources while maximizing agricultural productivity.

The utilization of non-conventional water sources such as treated wastewater and desalinated water, coupled with innovative irrigation techniques, not only mitigates water scarcity but also enhances the resilience of agricultural systems against climate variability. ICBA's emphasis on improving soil health through soil amendments and rehabilitation techniques boosts crop yields and rejuvenates degraded lands.

Moreover, ICBA's pioneering initiatives in harnessing big data, remote sensing, and IoT technologies enable precise monitoring of agricultural systems, facilitating informed decision-making amidst changing climatic conditions. By leveraging cutting-edge advancements in Controlled Environment Agriculture (CEA) and integrated agri-aquaculture approaches, ICBA pioneers sustainable farming practices that promote resource efficiency and circular economy principles.

As the GCC region navigates the complex interplay of climate change, water scarcity, and food security, the transformative potential of biosaline agriculture becomes increasingly evident. The GCC can unlock new pathways towards resilient, sustainable, and food-secure futures in the arid landscape by scaling up these innovative solutions and fostering collaboration between research institutions, governments, and farmers. Through concerted efforts and strategic investments in biosaline agriculture, the GCC can transcend the challenges of aridity, ensuring food security for generations to come.

Keywords: Water scarcity; Food security; Agricultural sustainability; Global warming; ICBA; Water resources; Climate change; Agri-aquaculture approach; Remote sensing; IoT technologies

Balaban Desalination Publications

The 15th Gulf Water Conference

(2024) 229–238
doi: 10.5004.dsal.2024.700088

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Developing a sensor-based agricultural water management system for irrigation scheduling, automation, and optimization

Farhat Abbas[1,*], Salem Al-Naemi[1], Aitazaz A. Farooque[2,3], Rachid Benlamri[1], Hassan Ali[1], Jose Emmanuel L. Ventura[1]

[1]*University of Doha for Science & Technology, P.O. Box 24449, Doha, Qatar, Tel.: +974 44952263, email: farhat.abbas@udst.edu.qa,*

[2]*Canadian Centre for Climate Change and Adaptation, University of Prince Edward Island, Charlottetown, C1A 4P3, PE, Canada,*

[3]*Faculty of Sustainable Design Engineering, University of Prince Edward Island, Charlottetown, C1A 4P3, PE, Canada,*

ABSTRACT

The role of agriculture has been marked significantly in sustaining societies throughout the globe. Its relevance to dry arid regions like GCC (Gulf Cooperation Council) region countries is more particular due to food security, sustainability, and climate change. Qatar's efforts in safeguarding food security have been witnessed greatly in recent years due to the country's increased food demands, caused by its rapid population growth and economic development. The blockade imposed on Qatar in 2017 also raised a serious concern for food security and self-sufficiency. This situation emphasizes the need to explore options for precision irrigation water management through climate-smart farming in Qatar to meet its food security and sustainability targets as a part of the National Food Security Program and Qatar's National Vision 2030 (QNV-2030). An automated irrigation system can assist in irrigation scheduling for precision water conservation and natural resource (water) optimization through enhancing irrigation water use efficiency. A scientific and smart-agriculture approach is being adopted as a work package of an applied research project, "Development of Smart Agricultural Technologies to Optimize Resource Allocation to Ensure Food Security – A Pathway Towards Sustainable Vegetables and Date Palm Production in Qatar" funded by the Qatar Research, Development and Innovation (QRDI) Council — Qatar. This novel approach involves developing and testing a sensor-based smart and sustainable irrigation system to irrigate date palm trees and agricultural fields cultivating vegetables in Qatar. As a first step, a laboratory experimental setup was developed consisting of A) a wireless SM-100 soil moisture sensor B) an irrigation solenoid valve controller, C) a single channel relay, D) a solenoid valve, E) a step-down transformer 240/24VAC (volts, alternating current), and F) soil state representations. The system was tested to mimic soil moisture conditions for wilting point and field capacity to respectively start and stop irrigation via controlling a solenoid valve of an irrigation system wirelessly connected with a soil moisture sensor. In its second step and after a successful laboratory trial, the system is prepared to be installed and tested in the field under real conditions of GCC region countries to irrigate date palm orchards and greenhouse crops. The system will operate with

* Corresponding author.

a soil water characteristics curve to be established as part of this step. With the successful use of artificial intelligence in various fields of system automation, the automation of irrigation systems can benefit from these modern approaches to system automation. The novel system thus developed will help ensure GCC region countries address challenges of food security, sustainability, and climate change.

Keywords: Irrigation scheduling, system automation, soil moisture monitoring, water characteristics, water management, precision irrigation, artificial intelligence.

1. Introduction

The world population will be over 8 billion people by 2025 posing challenges to the world's food security, environment, and water availability (Ungureanu et al., 2020). Food insecurity leads to poor physical and cognitive development and ultimately to hunger and low productivity. Since the beginning of the current century, societies have paid attention to the food security systems realizing that global poverty, from food insecurity, prevents sustainable development and rapid growth (Guo et al., 2021). Specifically, The Government of the state of Qatar is investing in and encouraging research and development initiatives related to food security and sustainability (Ben Hassen et al., 2020).

Food security is undeniably linked with water, which supports life on Earth (Hordon, 2023). Water is an essential ingredient for agricultural production. Qatar is no exception; it is known for being a high water-stressed country, where its developing agricultural sector greatly relies on the supplies of desalinated brackish groundwater (Lawler et al., 2023). Despite Qatar's water scarcity, and geographic, and climatic conditions, the Government has launched a Strategic Food Security Project for 2018 to 2023, right after the country was exposed to the 2017 blockade. The plan focused on four pillars: 1) international trade and logistics; 2) domestic self-sufficiency; 3) strategic reserves; and 4) domestic markets. The 2nd pillar of the program aims to boost the country's self-sufficiency by efficiently cultivating crops, meat, and fish locally. By 2023, the program aims to have 70% of greenhouse vegetables produced domestically and develop 110 hectares with high-tech greenhouses (Ministry of Municipality & Environment, 2020).

The Qatar National Vision 2030 envisions transforming Qatar by 2030 into a modernized nation equipped with the ability to independently sustain its growth and ensure a prosperous quality of life (General Secretariat for Development Planning, 2008). The first National Development Strategy 2011–2016, formulated to achieve the QNV 2030, recognizes that to ease the heavy demands on Qatar's valuable water resources, changes in the agricultural sector should made, particularly in: 1) water consumption patterns; 2) irrigation methods; and 3) crop fixes. As an example, inefficient irrigation practices in Qatar due to high levels of evaporation include flood irrigation of open fields (Qatar General Secretariat for Development and Planning, 2011). Moreover, the Second National Development Strategy 2018–2022 also mentions that most of the farms in Qatar are still not equipped with modern agricultural and drip irrigation, leading to lower efficiency of plant production systems and whole agricultural sectors' productivity. The latter strategy states that agricultural research will assist in replacing traditional methods (Planning and Statistics Authority, 2018).

Developing a smart irrigation water management system has been a topic of interest for researchers worldwide. For example, Suma et al., 2021, presented a project for farmers in rural areas that incorporates IoT with various features comprising GPS-based controlled monitoring, moisture and temperature sensing, leaf water content, and irrigation facilities. In this study, various sensor nodes are adjusted at multiple places in the farm and monitored via an interfacing sensor, Wi-Fi (wireless fidelity), and a camera with a microcontroller. Abioye et al. (2022) discovered that the effective implementation of sustainable precision irrigation management plays a crucial role in promoting food security and mitigating the risk of water scarcity. These parameters are controlled with internet service or any other device. Abbas et al. (2023a) suggested that a comprehensive consideration of water dimensions, security, governance, and climate change impacts can lead to the sustainable use of water resources and the community's well-being. The future approaches and strategies to enhance food security and address the growing demand for food should be combined with effective initiatives aimed at conserving water resources in the agricultural industry (Lawler et al., 2023). Water conservation is crucial to the survival of ecosystems of GCC (Gulf Cooperation Council) region countries including Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates which rely on desalination to produce water for domestic use (Abbas et al., 2023b).

1.1. Statement of the problem and research objectives

Like for the rest of the world, climate change has impacts on GCC (Gulf Cooperation Council) region countries. Eventually, agricultural sustainability is at stake due to land degradation, water scarcity, and environmental pollution induced by climate change. The water, energy, and food requirements continue to increase with population increases in addition the climate change. Realizing the impact of climate change on food production, the GCC region prioritizes sustainable agricultural production. A well-researched and careful planning and policy adaptation is required for supplemental irrigation from the water pools of treated resources or from groundwater withdrawal lest the environmental impacts outweigh the agricultural benefits. Climatic and non-climatic uncertainties and diminishing profit margins thereof in agriculture have disincentivized conventional farming. Therefore, climate-smart agriculture is gaining popularity worldwide but is at an exploratory stage in GCC region countries.

Unfortunately, research for resource conservation such as precision water management has not touched the levels of importance in GCC region countries despite clear needs and pointed out problems of water scarcity. Therefore, aligned with Qatar's goal of sound water management in the agricultural sector and food security initiatives, this study aims to design and develop a system equipped with a wireless network of moisture sensors to monitor relevant variables, such as soil moisture content, for precise supplemental irrigation of crops inside a greenhouse and date palm orchards out in the field. The study covers one of the six work packages of an applied research project, "Development of Smart Agricultural Technologies to Optimize Resource Allocation to Ensure Food Security – A Pathway Towards Sustainable Vegetables and Date Palm Production in Qatar" funded by the Qatar Research, Development and Innovation (QRDI) Council and the Ministry of Municipality and Environment cycle 3 (MME3) in 2022.

2. Methodology

The objective of work package 3 of the QRDI-MME3 project (MME03-1121-210025) was to develop and apply a sustainable sensor-based irrigation system to optimize the quantity and timing of water allocation (smart irrigation) for sustained water productivity/crop production in Qatar. This activity has focused on developing and promoting sustainable smart irrigation practices for tomatoes, eggplants, and date palms. A detailed review of current irrigation practices and water availability helped to set the basis for the development of sustainable sensor-based smart irrigation in Qatar. Accurate estimation of crop water requirements can help to implement site-specific irrigation practices to avoid under and/or over-application of water and promote water savings and sustainable practices in Qatar.

Five tasks to achieve the project objectives were to i) investigate smart and sustainable irrigation systems to produce dates and vegetables in Qatar, ii) develop weather-based models to predict crop water requirements using artificial intelligence forecasting, iii) install soil moisture sensors to capture the water content in the root zone for vegetable and date palms in real-time, iv) develop, test, and evaluate sensor and crop water requirements based on sustainable (solar-operated) irrigation methods (drip/sprinkler) to accomplish site-specific irrigation strategies based on crop needs, and v) evaluate the productivity and water savings benefits of the developed system. The proposed system is shown in Fig. 1.

2.1. System design

The design of a soil moisture sensing system comprises a capacitive soil moisture sensor, i.e., SM100 WaterScout soil moisture sensor (Source: Spectrum Technologies; Aurora, Illinois, USA) connected to the ESP32 microcontroller (Espressif Systems Co. Ltd, Brno, Czech Republic) that is widely used for IoT applications such as robotics, industrial automation, and high-performance sensor networks (Fig. 2a). It was selected to be the main board for this project since its powerful chip includes Wi-Fi and Bluetooth connectivity, as well as a dual-core processor. The SM-100 sensor (Fig. 2b) consists of a pair of electrodes acting as a capacitor, where the soil surrounding it acts as the dielectric material. An 80 MHz oscillator powers the capacitor, and a signal that corresponds to the soil's dielectric permittivity is transformed into the output signal. Any changes in the water content of a soil sample can be easily detected by the sensor circuitry and these changes can be correlated to the soil's moisture content since the dielectric permittivity of water is significantly greater than organic matter, air, and soil minerals (Spectrum Technologies, 2019). Relative dielectric permittivity quantifies a certain material's polarization capability under an electric field, expressed as the ratio of its absolute permittivity to that of free space (Ledieu et al., 1986). Therefore, permittivity gauges the ease with which an electric field can travel through a substance, in this case, soil.

2.2. Soil water characteristics curve

A soil water characteristics curve helps determine available water (θ_{AW}), which is the quantity of water content (θ) between field capacity (θ_{FC}) and wilting

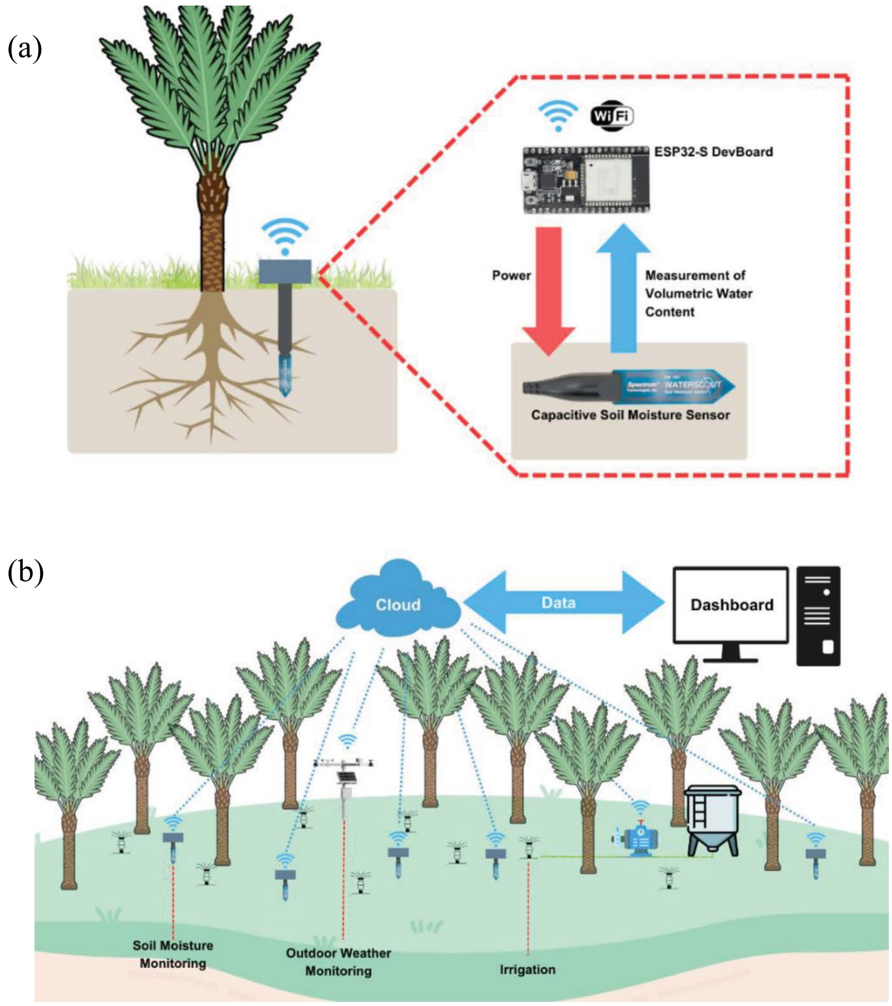

Fig. 1. (a) Planned on-site implementation of a wireless moisture sensor for a single tree system and (b) Planned system network wireless moisture sensors for an orchard.

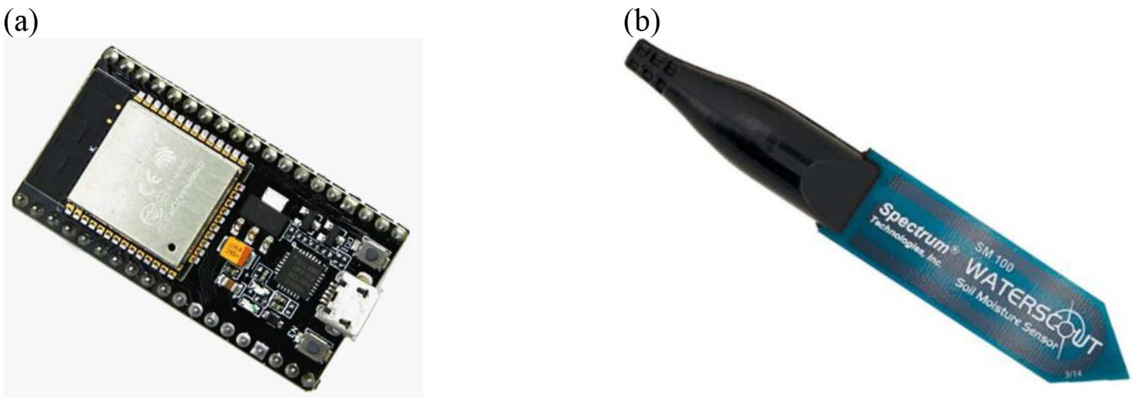

Fig. 2. (a) ESP32-S development board, retrieved from QuartzComponents, and (b) SM-100 Soil Moisture Sensor (Source: Spectrum Technologies, 2019).

point (θ_{WP}) as $\theta_{AW} = \theta_{FC} - \theta_{WP}$. Plants can use θ_{AW}; therefore, an irrigation system must operate between θ_{FC}–θ_{WP}. Soil moisture sensors need to be calibrated to read soil water levels at θ_{FC} and θ_{WP} for soils supporting horticulture (growing date palms or vegetables in the field or a greenhouse.

3. Main results

3.1. Design testing

Fig. 3a shows the wiring diagram of the SM-100 sensor with the ESP32 microcontroller. This setup was used to test the reading accuracy and create the calibration curve of the soil moisture sensor while the sensor was in extreme dry and wet conditions. The GIOP 36 (general-purpose input-output pin) is channel 0 of the ADC (analog-to-digital converter) module 1 of the ESP32. This channel can receive the output signals of a soil moisture sensor. The ESP32 board is powered through the micro-USB port (Fig. 3a), while the soil moisture sensor receives its excitation voltage from GIOP 17. This connection also serves as the communication port to see the soil moisture readings through the serial monitor of the Arduino Integrated Development Environment (IDE). The Arduino IDE offers multiple functions such as sketch creation, code editing, compilation, and serial monitoring. In this report, the messages about the soil moisture readings were printed onto the serial monitor of the Arduino IDE. The Serial Monitor is a separate pop-up window that acts as a separate terminal that communicates by receiving and sending serial data of a sensor.

A program code was written to read the soil moisture readings and display the corresponding digital value and voltage value in the serial monitor of the Arduino IDE (Fig. 3b). The sensor was tested in two scenarios: Scenario A is when the sensor is exposed to air, while Scenario B is when the sensor is fully submerged in water respectively mimicking total dry and total wet conditions for the sensor's operation.

As shown for scenario A, the digital readings and voltage readings, when the sensor was exposed to air, are around 825 and 0.66 V, respectively. As for scenario B, the corresponding readings when the sensor was fully submerged in water are around 1770 and 1.43 V, respectively. These generated sensor values from the test are very close to the output specifications set by the manufacturer which indicates that with 3 V excitation, the expected output signal should range from 0.5 to 1.5 V, where 0.5 V is the reading when the sensor was in air and 1.5 V when the sensor is in a fully saturated (Spectrum Technologies, 2019). This difference in reading is due to the reason that the excitation voltage used for the test is 3.3 V, an available voltage pin on the microcontroller close to the 3 V excitation limit provided by the manufacturer. A few other reasons for the difference in readings might be due to the non-linear response and electrical noise present in the ADC (analog to digital converter) module.

3.2. Overcoming electrical noise

Using the programming code and the serial monitor of the Arduino IDE, fluctuations in the sensor readings caused by electrical noise in the ADC module were observed. The program took 400 sample readings (opted by the programmer to have enough representations) while the soil moisture sensor was fully submerged in a glass of water for observation purposes (Fig. 4). The figure shows a scatter plot of sensor readings with a sample size of 400, where the y-axis is the digital value and the x-axis is the sample number. As seen in Fig. 4a, while the sensor is submerged in water, the sensor output readings are mostly fluctuating in the 1776 to 1770 digital range. There are also a few readings that spike or fluctuate way above and below the expected reading. These readings were recorded from

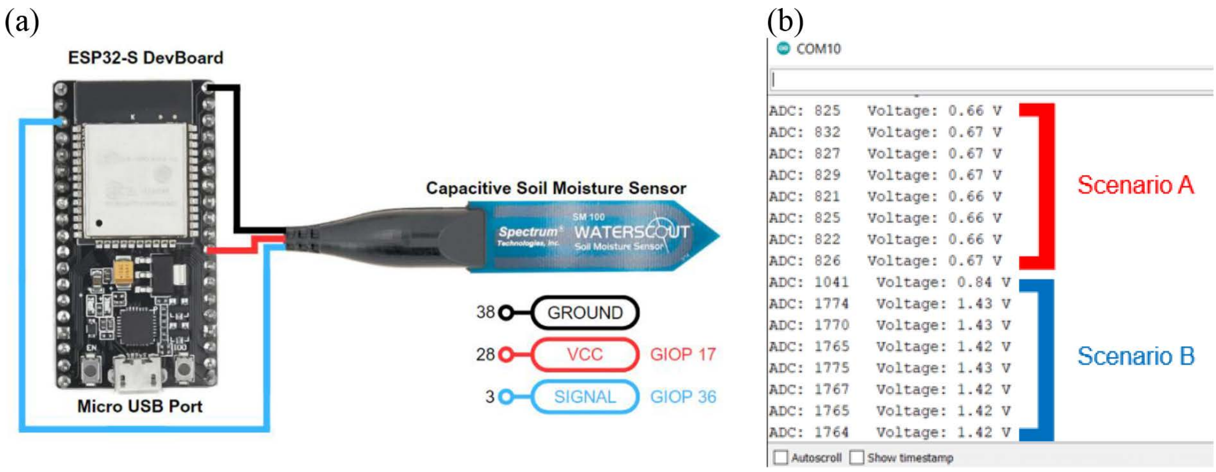

Fig. 3. (a) Initial wiring diagram of the soil moisture sensor with the ESP32 microcontroller and (b) Digital value and equivalent voltage readings for scenarios A (extreme dry conditions) and B (extreme wet conditions). This image is a screenshot taken from the Serial Monitor of the Arduino IDE (internal development environment).

the serial monitor of the Arduino IDE, as programmed. A way of minimizing noise has been uploaded to the Espressif documentation website (Espressif Systems Co. Ltd., 2022). The recommended solution to mitigate electrical noise is by adding a bypass capacitor, preferably a 100 nF ceramic capacitor, to the ADC input pad being used and by implementing multisampling of the program code. Fig. 4b shows a graph of the ADC noise comparison with no capacitor, with capacitor, and with capacitor and multisampling as borrowed from Espressif Systems Co. Ltd., 2022 site.

3.3. Mitigating the effect of electrical noise

The proposed design to mitigate the effect of electrical noise involved adding a bypass capacitor to the circuit of ESP32-S (Fig. 5a). This updated wiring diagram with a bypass capacitor was added to the circuit to mitigate the effects of electrical noise. A photo of the physical wiring circuit can be found in Fig. 5b. So, a bypass capacitor, a ceramic 100 nF capacitor exactly, was connected across channel 0 of the ADC module 1 and the ground pin of the soil moisture sensor. Compared to the previous wiring diagram, the soil moisture sensor is now receiving its excitation voltage from the 3.3 V VCC pin of the ESP32 board. Implementing a bypass capacitor and multisampling in the program code can achieve the best results in mitigating the effects of electrical noise; i.e., lesser fluctuation in the readings. As seen in Fig. 6a, there is an obvious improvement when compared to the previously generated plot in Fig. 4a. Further improvements in the code writing reduced electrical noise with bypass capacitor and multisampling technique Fig. 6b.

3.4. Communication through cloud database

For a real-time operation of an irrigation system in an agriculture field the soil moisture sensor has to

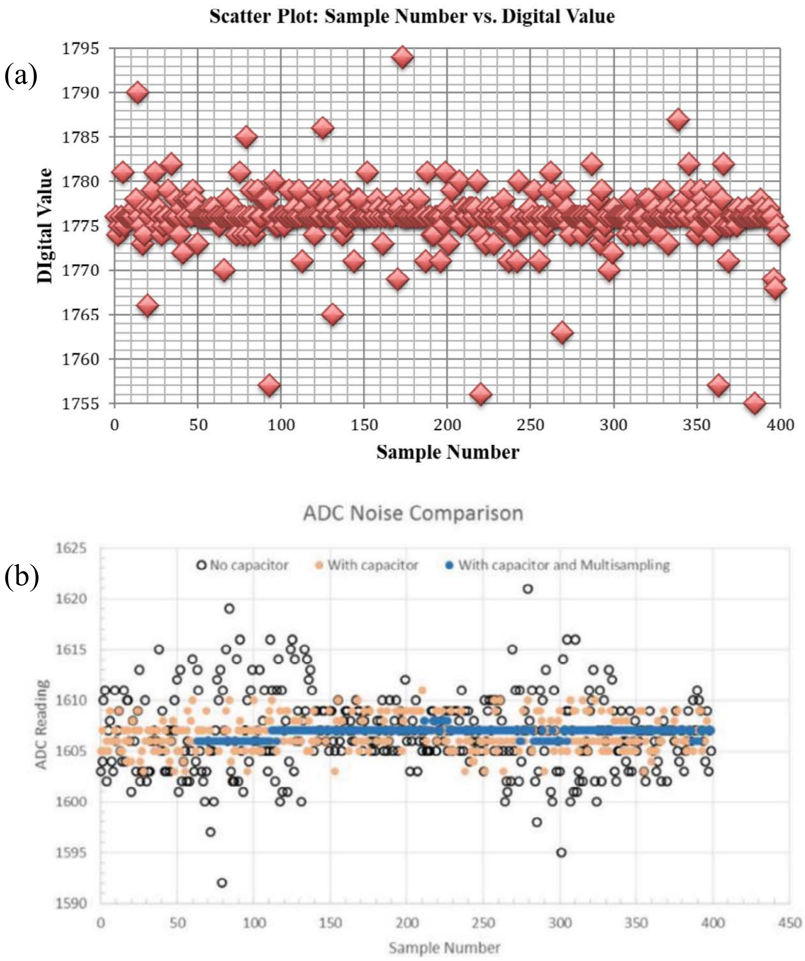

Fig. 4. (a) Observed measurement fluctuation reflected by digital values for various sample numbers. This image is generated using an MS Excel spreadsheet. (b) ADC Noise Mitigation using Capacitor and Multisampling of 64 Samples (retrieved from Espressif, 2022).

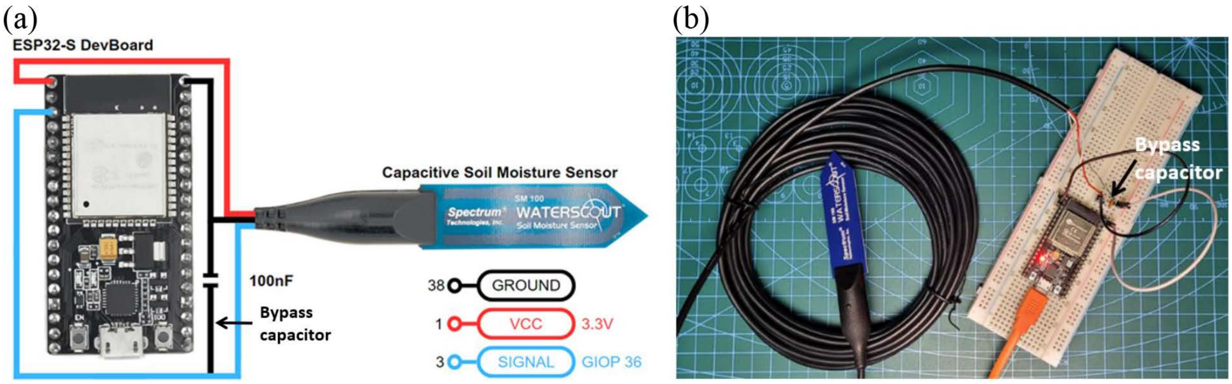

Fig. 5. (a) Addition of bypass capacitor (black lines) and (b) Wiring Diagram- added bypass capacitor (orange color).

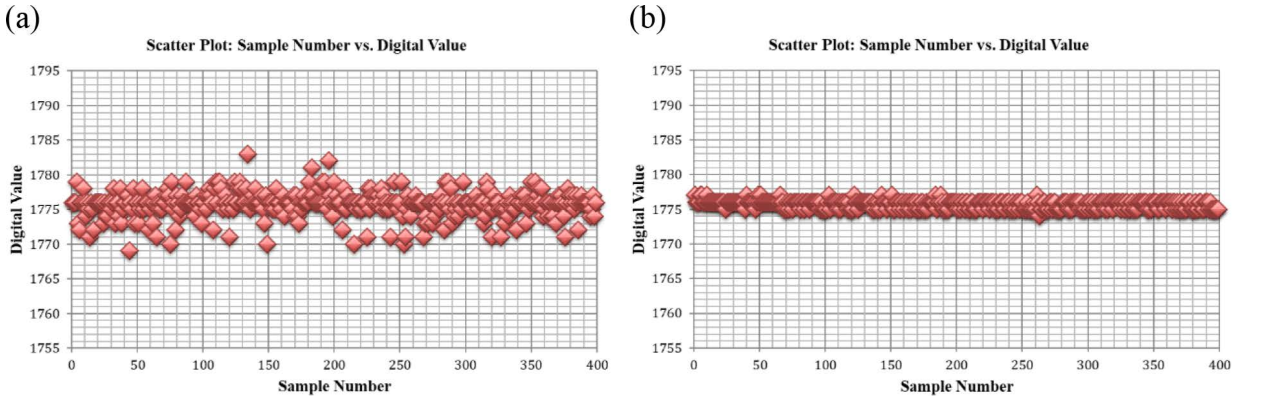

Fig. 6. (a) Electrical Noise Mitigation with Bypass Capacitor and (b) Electrical noise mitigation with bypass capacitor and multisampling technique.

work smartly. A smart irrigation system comprises water supply lines coming from a water tank or freshly pumped source, connected via a solenoid valve, with drip irrigation lines having emitters or popup sprinklers installed at specified lengths wirelessly integrated with soil moisture sensors installed in the field of vegetables or fruit tree orchards.

The wireless soil moisture sensor developed for this study uses Google's Firebase to store real-time sensor readings of volumetric water content. The irrigation solenoid valve controller takes the readings from the database and processes the data to determine the control action, i.e., either to turn ON or OFF the solenoid valve. The volumetric water content values set for the wilting point and field capacity of the concerned soil are used to turn ON or OFF the solenoid valve, respectively.

The laboratory experimental setup of this study consisted of (A) a wireless SM-100 soil moisture sensor (B) an irrigation solenoid valve controller, (C) a single channel relay, (D) a solenoid valve, (E) a step-down transformer 240/24VAC, and (F) soil state representations (Fig. 7). The wireless soil was programmed to send data every 15 s to the Firebase Database, while

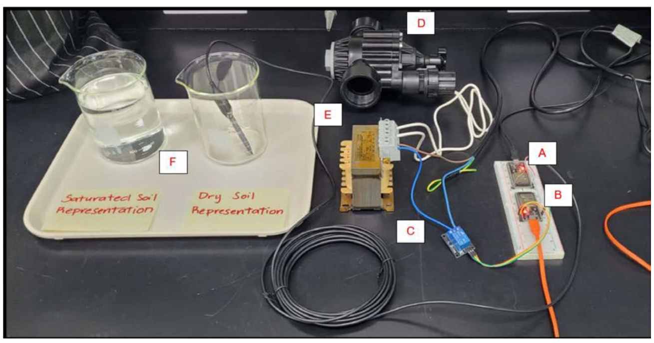

Fig. 7. Laboratory experimental setup showing its contents labeled as (A) a wireless SM-100 soil moisture sensor (B) a wireless irrigation solenoid valve controller, (C) a single channel relay, (D) a solenoid valve, (E) a step-down transformer 240/24VAC, and (F) soil state representations.

the solenoid valve controller was programmed to read the volumetric water content from the database every 15 s. After reading the data, it decides whether to turn ON or turn OFF the solenoid valve. For the sandy loam soil of the UDST landscape, the wilting point was assumed at 30% volumetric water content of the soil, and the field capacity was assumed at 70% volumetric water content of the soil. The program codes were written to turn ON the solenoid valve at the volumetric water content of the wilting point and turn OFF the solenoid valve at the volumetric water content of field capacity.

Components A and B in Fig. 7 are the two microcontrollers. Microcontroller A is for wireless soil moisture sensing while microcontroller B is for wireless irrigation control. The two microcontrollers are powered with Micro USB cables (black for A and orange for B). There is no physical wiring between microcontrollers A and B, they communicate wirelessly. A provision of Wi-Fi systems enables the two microcontrollers to communicate regardless of the distance between them. Therefore, the provision of a Wi-Fi connection is essential to this prototype design.

For sending and reading volumetric water content wirelessly to and from the cloud database, both the soil moisture sensor and solenoid valve controller were provided with a Wi-Fi connection to be able to store and read data from the Firebase database. Fig. 8a below shows the solenoid microcontroller connecting to a Wi-Fi hotspot. When the soil sensor was placed in the dry soil representation soil wilting point conditions, it sent and stored its corresponding volumetric water content readings to the Firebase database (Fig. 8b). Eventually, the solenoid valve controller took the reading and sent an ON signal to the relay, which closed the path of electricity to the solenoid valve, ultimately powering it ON to operate the irrigation system (Fig. 8c). The turned-o red LED indicates that the valve is switched ON. Likewise, when the soil sensor detected the soil field capacity conditions, it sent and stored its corresponding volumetric water content readings to the database. The solenoid valve controller read the volumetric water content values and sent an OFF signal to the relay, which opened the path of electricity to the solenoid valve, ultimately powering it OFF and stopping the operation of the irrigation system. The turned-off red LED indicates that the valve is switched OFF (Fig. 8d).

3.5. Recommendations

3.5.1. Construct a volumetric water content calibration curve

The collected soil will be packed in an experimental vase for a known bulk density and total porosity. The packed soil medium will be saturated gradually from low water content levels to high levels. The volumetric water content of the soil samples will be determined using the FieldScout TDR-150 (Spectrum Technologies, Aurora, Illinois, USA) for the known

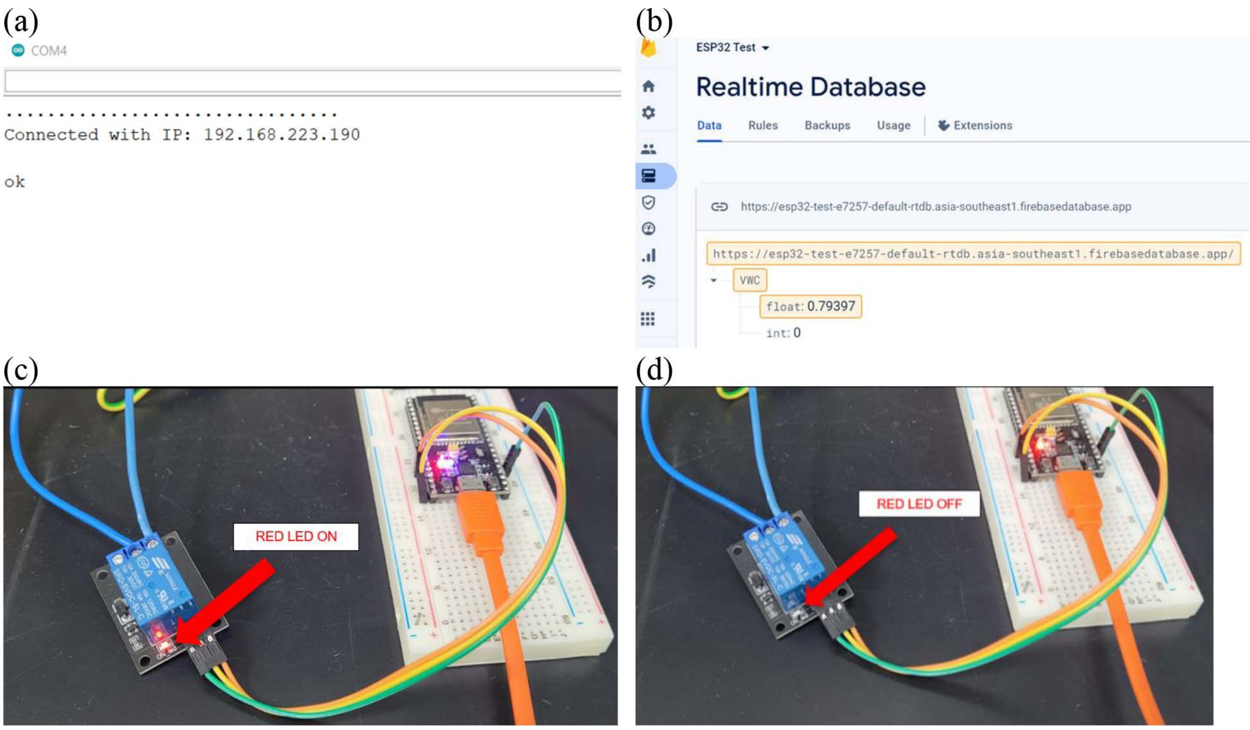

Fig. 8. (a) ESP32 controller connecting to Wi-Fi, (b) storing of the dry soil state volumetric water content readings to the database, (c) the resultant switching ON the solenoid valve through the relay shown by the red LED on, (d) the resultant switching OFF the solenoid valve through the relay shown by the off LED.

soil samples intermittently saturated for a range of levels between the permanent wilting point to the field capacity of the soil samples. TDR volumetric water content readings will be assumed to serve as the reference for the actual volumetric water content readings. Starting from dry to saturated conditions (going beyond permanent wilting points and field capacity saturation levels), scenarios of soil sample saturation will be created by adding a measured quantity of distilled water in a soil-packed vase of known porosity and bulk density. The meter readings will be simultaneously read using TDR-150 (for volumetric water content) and SM-100 soil moisture sensors (for voltage) followed by converting the SM-100 voltage readings to volumetric water content by establishing a regression equation between the data of TDR-150 and SM-100. The regression equation, to be termed a volumetric water content calibration curve, will be used to convert analog voltage readings to the volumetric water content of the soil to percent volumetric water content. This will be done by plotting the SM-100 soil water content sensor's readings (y-axis) against the actual soil moisture levels, measured with TDR-150 (x-axis) by using a regression line drawn in an Excel spreadsheet. The x-axis had the actual soil moisture levels, and the y-axis had the sensor readings. The goodness of fit of the coefficient of correlation (R^2) will be used to determine the best fit when R^2 is close to 1. For a linear relationship, the equation will take the form $y = mx + b$, where y will represent the sensor readings, x will represent the actual soil moisture levels, m will be the slope of the line, and b is the y-intercept. For a nonlinear relationship, a more complex equation may be formulated and used depending upon a satisfied value of R^2.

3.5.2. The use of artificial intelligence in irrigation automation

With the successful use of artificial intelligence (AI) in various fields of system automation, the automation of irrigation systems can benefit from this new technique of deep learning (DL) and machine vision (MV) in addition to the Internet of Things (IoT) (Alvim et al., 2022). Precision irrigation water management can conserve precious water for agriculture that according to the World Bank consumes about 70% of all water withdrawals across the globe. AI-based efficient irrigation can prevent the over-application of irrigation water that often infiltrates below the plant root zone leading to groundwater pollution, water logging, and soil salinity.

Soil water sensors are operated and controlled by IoT and the soil water content data generated thereby provides foundation stones for the use of AI in agriculture water management. The AI and/or sensor-based irrigation scheduling techniques can replace the current destructive methods of soil water content determination that have been conventionally used to determine the next schedules of crop irrigation. Thus, AI and/or sensor-based irrigation scheduling can be termed as a non-destructive practice of agriculture to emotionalize agriculture management practices as climate-resilient, labor-saving, energy-efficient, and smart (Parihar et al., 2021).

The DL and MV components of AI-based irrigation automation involve the use of data analytics with the support of real-time data generated from soil moisture and/or thermal sensors and cameras (Saggi and Jain, 2022). For this purpose, the next step would involve collecting digital and image data about dry and saturated conditions of soil substrate, labeling it with relevant information, and training the machines (i.e., those used to operate an irrigation system) for controlling opening and closing of the system solenoid valve OFF and ON at θ_{FC} and θ_{WP}, respectively. The needed digital data could be the soil water content values and the image data could be the camera photos of soil substrate saturated/dried at different soil water content levels representing θ_{FC} and θ_{WP} of the respective soil (Gu et al., 2020, 2021).

4. Conclusion

A Qatar-specific sensor-based automated irrigation system was designed and developed to provide precision irrigation to greenhouse crops and date palm trees. Designing, developing, and lab testing tasks of the system have been achieved. Calibration of the irrigation sensors is underway for their installation in the real soils or soil substrates for wilting point and field capacity levels of soil water contents. The two levels will be used to turn the solenoid valve of the irrigation system ON and OFF, respectively for water conservation and optimization of water use efficiency during crop production. The only limitation of the designed system is the availability of the Wi-Fi system. Since the microcontrollers A and B communicate wirelessly as there is no physical wiring between them, a provision of Wi-Fi systems is a crucial part of this system to enable the two microcontrollers to communicate regardless of the distance between them. Therefore, the provision of a Wi-Fi connection is essential to this prototype design.

Acknowledgments

Funds for this work were provided by the QRDI (Qatar Research, Development, and Innovation) Council under project # MME03-1121-210025.

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Balaban Desalination Publications

مؤتمر الخليج الخامس عشر للمياه
The 15th Gulf Water Conference

(2025) 239–250
doi: 10.5004.dsal.2025.700072

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

دور تكنلوجيا المعلومات في معالجة تغدق وتملح الترب في محافظة ديالى (جمهورية العراق) 2023

الاستاذ الدكتور محمد يوسف حاجم الهيتي
استاذ جغرافية التنمية & GIS,
العراق – -جامعة ديالى - وحدة الابحاث المكانية

The role of information technology in addressing soil logging and salinization in Diyala Governorate (Republic of Iraq) 2023

Prof Dr. Muhammad Yousif Hajim Al-Hiti

Professor Development Geography and GIS, Spatial Research Unit - Diyala University – Iraq (009647709277046), email: Drmyhsn64@gmail.com

Agricultural Water Management: AGR-72: CONFERENCE SESSIONS

التغدق والتملح هو انخفاض أو تدهور قدرة الانتاج البيولوجي مما يؤدي في النهاية إلى وجود أوضاع صحراوية في المنطقة. وهو أحد جوانب التدهور الشائع الذي تتعرض له النظم البيئية من تحديات وبالتالي تدمير الإمكانات البيولوجية من الانتاج النباتي والحيواني وتدهورها.

إن المشكلة الأساسية التي يعاني منها القطاع الزراعي هو مشكلة تملح التربة وتغدقها أو ما يشوب التربة ولمساحات كبيرة في وسط وجنوب العراق من تحديات بيئية, وبحسب التقديرات الرسمية فأن اكثر من (100) ألف دونم من الأراضي الصالحة للزراعة سنوياً ,تعاني من هذه المشكلة التي باتت تهدد اغلب محافظات العراق.

وهنا تجدر الاشارة ان المناطق الرطبة في محافظة ديالى تتباين في مظهرها من حيث وجود البرك المالحة اوالأراضي المتغدقة والتجمعات المائية الصغيرة الدائمة عند مصبات الأنهر إلى الخزانات المائية التي يقوم الانسان بإنشائها كمحطات المياه ، اذ يعد أي تجمع مائي في هذه المنطقة, ذو أهمية كبيرة لبقاء الطيور المائية والمهاجرة, وينظر إلى جميع المسطحات المائية على أنها مصدر للاستعمالات الحضرية والزراعية والصناعية وقد تؤثر وتتاثر عدد من المسطحات المائية بزيادة الملوحة ،وتغدق الترب

اولاً: ـ المشكلة :-

تعاني ترب محافظة ديالى من عدة مشاكل تؤثر على الانتاج الزراعي في مقدمتها مشكلة تغدق وتملح الترب التي أصبحت مشكلة عالمية تعاني منها أغلب دول العالم وتسعى إلى ايجاد حلول لها وعلى ضوء ذلك تم صياغة مشكلة البحث بما يلي

1. ما هو مدى تأثر مشكلة التغدق والتملح في ترب محافظة ديالى ؟
2. هل توسعت مشكلة تغدق وتملح الترب لنطاق واسع وباتت تأثر على النشاط الزراعي؟
3. هل لتكنلوجيا المعلومات دور في الكشف ورسم خارطة توزيعات مكانية لتغدق الترب وتملحها ؟

ثانياً: ـ فرضية البحث :-

1. تعاني ترب المحافظة من مشكلة التغدق والتملح وأصبحت تؤثر في انخفاض خصوبة التربة.
2. هناك أثر واضح لتملح الترب على تذبذب الانتاج الزراعي في المحافظة
3. تكنلوجيا المعلومات اداة فاعلة للكشف عن التحديات المرتبطة بالترب كما تساهم تطبيقلت sig في تمثيل المشكلة ونطاقها .

* Corresponding author.

ISBN 0-86689-078-5

ثالثا: ـ هدف البحث

1. اعتبار التغدق والتملح مشكلة واقعة ولها آثار اقتصادية واجتماعية وبيئية في منطقة وجدت.
2. أن أكثر البلدان تأثراً بالتصحر هي النامية .وتحتاج لادخال تقنيات كشف حديثة كنظم المعلومات الجغرافية كحلول لمتابعة تغير الظاهرة المدروسة وعلاقتها بالعوامل المناخية.

ان تأثيرمشكلة التغدق والتملح ,باتت واحدة من التحديات التي تؤثر بشكل مباشرعلى مناطق معيشة السكان والمزارعين بمحافظة ديالى الواقعة في القسم الأوسط من شرق العراق, والتي ترتبط بالحدود الدولية مع ايران من جهة الشرق, وتحدها محافظة السليمانية من الشمال الشرقي, ومحافظة صلاح الدين من الغرب والشمال الغربي, ومحافظة بغداد من الغرب والجنوب الغربي, وتحدها محافظة واسط من جهة الجنوب, اذ .تحتاج المحافظة إلى دعم كبير تكنلوجيا وماديا, وبدون هذا الدعم سيصبح من المستحيل مواجهة متطلبات مكافحة التصحروالأنشطة ذات الصلة باستصلاح الاراضي الجافة.

الجانب النظري :(المفاهيم وتكنلوجيا ادارة المياه في الزراعة الحديثة)

يؤدي سوء ادارة الانسان لموردي التربة والمياه الى تزايد نشاط عملية التملح والتغدق للتربة اذ يؤدي اهمال البزل وعدم تنظيف مشاريع المبازل المخططة ـ الى رفع مستوى الماء الارضي الحامل للاملاح الى منطقة المجموع الجذري مما يسبب تدهور صفات التربة الفيزياوية والكيمياوية والمعدنية مما يؤثر على الخصوبة.

يشير تقرير الامم المتحدة FAOالى ان 60-70%من ترب وسط وجنوب العراق متاثرة بدرجة خطيرة بعمليات تراكم الاملاح التي يكون مصدرها بدرجة رئيسة المياه الجوفية, لقد اشار العديد من الباحثون ان اهم واجبات الجغرافي هو اعداد مسوحات ميدانية للترب في المناطق المتاثرة بعمليات التراكم الملحي بفعل الماء الارضي لتحديد احصاء المساحات المتدهورة واعداد خرائط لاهم المؤشرات التي تبين مقدار التدهور فيها واستخدام تكنلوجيا المعلومات المتوفرة في البلد. وهذا يتطلب وصف مكاني وتجريبي بتكنلوجيا حديثة من خلال:-

مشاهدة واقع واسباب التملح والتغدق بالاراضي الزراعية بمنطقة الدرسة:

تمتلك المحافظة اراضي شاسعة و صالحة للزراعة تتميز معظم اراضي المحافظة بخصوبة التربة وانبساطها مع بعض المرتفعات، كما في سلاسل جبال حمرين و زاكروس، وبحيرتي حمرين والعظيم وبساتين النخيل والفواكه ,والخضر والحبوب وانتشار المصانع والمعامل، وتربية الماشية)خاصة الأغنام والدواجن(وكذلك يتم تربية الأسماك من خلال البرك الاصطناعية) وانتشار ما مجموعه (33) مزرعة سمكية, تجاوزت اعداد شركات الدواجن العاملة والمنتجة على 300 حقل، ، بالاضافة الى تربية النحل تعد محافظة ديالى من المناطق ذات الصيغة الزراعية, حيث يعمل اغلب سكانها في الزراعة وتبلغ مساحة الاراضي الزراعية في المحافظة 2959225 دونم بينما تبلغ) مساحة الأراضي الديمية غير مضمونة الأمطار مساحة 1470237 دونم والمتبقي مساحات غير مستصلحة،وتعتمد مساحة 1524604 دونم على طريقة الري التقليدية سيحا وبضمنها مساحات الغابات والبساتين بينما تعتمد مساحات 114549 دونم على طريقة الري بالواسطة)الابار(. غير ان ما مستغل منها لايزال قليلا وبالاضافة الى ذلك فان ثمة تحديات[1] ترافق استغلال هذه الاراضي وتعيق من الاستفادة منها بشكل سليم وكما يأتي :

أ. التغدق والملوحة في ترب وسط وجنوب المحافظة.؟

1. تفتت الملكية الزراعية وصغر الحيازات اذ تعيق تطوير العمليات الزراعية واستخدام المكننة والتقنيات الحديثة؟
2. انتشار الترب الجبسية في مناطق واسعة وهي عقبة في مسار التنمية الزراعية فتحتاج الى خبرة وعناية ؟
3. انتشار الكثبات الرملية والتعرية الحاصلة نتيجة العوامل الطبيعية فهي تعد تهديد على الزراعة ؟

الدراسات السابقة

شهدت الآونة الأخيرة تطورات سريعة غير مسبوقة في كافة نواحي الحياة، و أبرزهذه التطورات التي ميزت وقتنا الحالي هي الديناميكية التي عرفها المجال التكنولوجي خاصة تلك المتعلقة بمعالجة المعلومات و بثها والذكاء الاصطناعي ، أو بما أصبح يعرف بتكنولوجيا المعلومات.واستخدم الخرائط الرقمية. لقد أصبحت التكنولوجيا تاخذ دورا مهما في النهوض بإقتصاديات الكثير من الدول وخاصة الدول التي تهتم بالشان الغذائي والانتاج الزراعي باعتبار الزراعة نفط دائم والتكنلوجيا تمثل مفتاح للتنمية المستدامة وذلك من خلال الفهم والتنبؤ والضبط للظاهرة المدروسة .ومن اهم ما تم اطلاع عليه هو[2][3][4][5]:

- جاسم شهاب حمد العتابي، وعبدالحليم علي سليمان، وأحمد عدنان الفلاحي، دراسة التغاير المكاني لملوحة التربة لترب مشروع شيخ سعد باستخدام تقنيات الاستشعار عن بُعد RS ونظم المعلومات الجغرافية GIS.
- أوراس محي طه الوائلي، وأحمد مهدي عبدالكاظم، دراسة اثر العمق وبعض الخصائص الكيميائية للماء الأرضي في ملوحة وصدوية التربة باستخدام الإحصاء الجيولوجي وبيانات التحسس النائي.
- محمد يوسف حاجم، وهالة محمد سعيد، الجفاف وآثاره المكانية في انخفاض مناسيب البحيرات في محافظة ديالى.
- منذر صائل محمد، خصائص تربة ناحية المنصورية وعلاقتها بالبيئة.

2-الجانب التطبيقي:((المواد وطرائق التحليل المختبري والكمي والكارتوكرافي))

المبحث الاول : موقع محافظة ديالى وموضع تجربة البحث (منصورية الجبل) انموذجا :

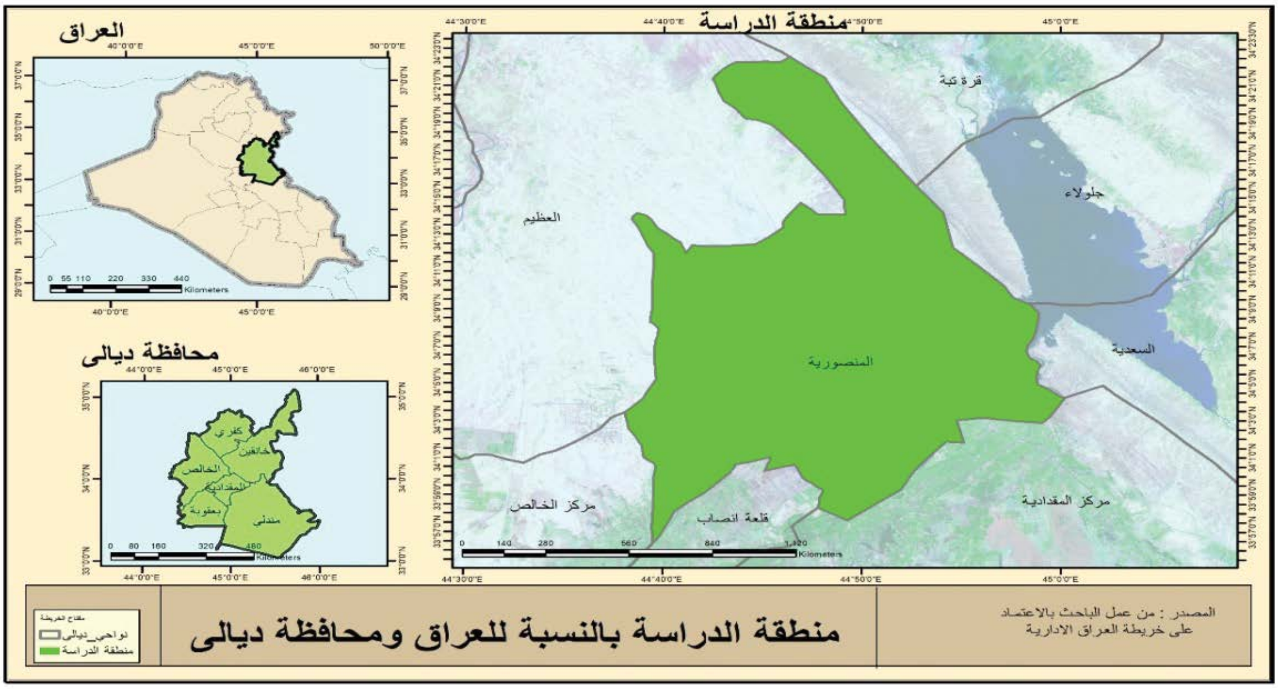
تقع المحافظة في الجزء الشمالي الشرقي من العراق اما الموقع الفلكي فهي تقع بين دائرتين عرض هي ((33,3 -35,60)) شمالا وخطي طول ((44,22 -45,56)) شرق خط كرينتش وهذا يعني انها تقع ضمن نطاق العروض المعتدلة الدفيئة في النصف الشمالي[6].

ان توسط المحافظة الجزء الاوسط من شرقي العراق وقربها من العاصمة بغداد جعلها ذات موقع متميز يحدها من الشمال والشمال الغربي كل من محافظة السليمانية وصلاح الدين على التوالي من شرقها إيران ومن الغرب محافظة بغداد ومن الجنوب محافظة واسط (الخريطة رقم (1)).

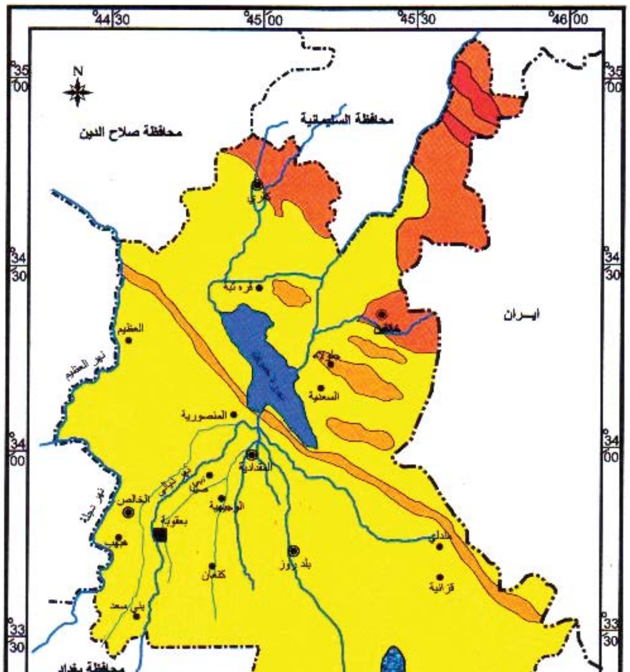
تبلغ مساحة محافظة ديالى (17,685 كم2) وتمثل نسبة (4,1%) من مجموع مساحة العراق البالغة (434,128 كم^2) وتضم المحافظة ستة أقضية من ضمنها مركز المحافظة قضاء بعقوبة وثلاثة عشر ناحية (2) وتم اختيار ناحية منصورية الجبل للتحليل الجغرافي للظاهرة المدروسة قيد البحث .ينظر الخريطة رقم (1و2)

مظاهر السطح ـ تتنوع مظاهر السطح في محافظة ديالى وقد تم اختيار منطقة منصورية الجبل التي تتركز فيها هذه الظاهرة بوضوح لاجراء التجربة من المحافظة : حيث شكلت السهول الغرينية اجزائها الجنوبية الغربية، فيما تتحول مظاهر السطح الى الشكل المتموج كلما اتجهنا نحو الشرق والشمال الشرقي وتخللهُ بعض المرتفعات والهضاب الواطئة ثم تزداد هذهِ المرتفعات ارتفاعاً كلما تقدمنا اكثر من الشرق والشمال. ويمكن اعتبار مرتفعات حمرين حداً فاصلاً بين المنطقة السهلية والمنطقة المتموجة. (ينظر خريطة (3)

هناك مرتفعات قليلة الارتفاع يطلق عليها محلياً روابي السعدية التي تمتد بموازاة مرتفعات حمرين. كما توجد مرتفعات (دروايشكه) جنوب غرب حمرين



الخريطة (1) و(2) منطقة دراسة



خريطة (3) تضاريس محافظة ديالى

المصدر : جمهورية العراق :خريطة العراق الطبوغرافية ، الهيئة العامة للمساحة ، 1990، مقياس الرسم 1000000/1

يصل ارتفاعها الى (700 م) عند قمة جبل (قرة داغ) ثم تأخذ الأرض بالارتفاع كلما نتجه نحو الشمال الشرقي حتى تصل جبل (بمو) الذي يبلغ ارتفاعه (1000 م) وتمر من خلاله حدود محافظتي ديالى والسليمانية بينما يشكل جزئهُ الشرقي حدود العراق وايران. (راجع خريطة (2) كما تمتد سلسلة جبال زاجروس بمحاذاة الحدود الشرقية مع ايران وهي تشرف على الأراضي العراقية بعدها تأخذ بالانخفاض من الشرق نحو الغرب حيث توجد بعض المرتفعات بالغرب من الحدود العراقية الإيرانية وهي اورزانه وميماك.

أولاً : البنية الجيولوجية : تقع منطقة الدراسة ضمن الرصيف غير المستقر وضمن نطاق الطيات الواطئة منه, تحديداً في جبال حمرين والسهل الرسوبي[7], ومن خلال التكوين الجيولوجي للمنطقة نتعرف من خلاله على بنية التربة وتركيبها ونوعية المادة الام المكونة لها (Parent material) وتأثير تلك المادة على الخصائص الفيزيائية والكيميائية للتربة. والمهم في هذه الدراسة هو التكوينات التي ترسبت في أواخر الزمن الثالث وخلال الزمن الرابع وتشمل هذه التكوينات ما يأتي : خريطة (4)

الخريطة الطوبغرافية والكنتورية :-تتصف منطقة الدراسة بنوعين من المظاهر الطوبغرافية والكنتورية, الأولى المنطقة المتموجة التي تغطي الأجزاء الشمالية والشمالية الشرقية, والثانية السهل الفيضي وهي منبسطة تغطي الأجزاء الشمالية الغربية والأجزاء الجنوبية الغربية والجنوبية من منطقة الدراسة ينظر الخريطتين (5 و6) التي تمثل المنطقة المتموجة وهي المتمثلة بسلسلة جبال حمرين, التي يتراوح ارتفاعها بين (100-175)م فوق مستوى سطح البحر في منطقة الدراسة, وهي تلال قليلة الارتفاع ويقل الارتفاع تدريجياً كلما اتجهنا نحو الجهة الغربية من منطقة الدراسة بحيث يكون الارتفاع(75) م في الجهة الشمالية من المنطقة و(50)م في الجهة الجنوبية الغربية منها[8]. تؤدي عوامل التعرية المائية التي تنشط بفعل تساقط الامطار بعد فصل الجفاف الى ضحالة سمك التربة في المنحدرات, والتي تقع ضمن هذه السلسلة الجبلية مقاطعة 28/ منصورية الجبل الشمالي, وهي أراضي مهملة متروكة تقع خارج الأراضي الصالحة للزراعة بسبب طبوغرافيتها غير الملائمة للإنتاج الزراعي[9].

اما السهل الفيضي هو جزء من السهل الرسوبي, إذ تغلب عليه صفة انبساط السطح شأنه شأن جميع المناطق المكونة من ترسبات الأنهار, وهو التواء مقعر تحيط به أراضي مرتفعة من الشمال والغرب والشرق, الامر الذي ساعد نهري دجلة والفرات والوديان القادمة من الشرق والغرب على تفريغ حمولتها فيه[10]

أ- تكوينات الزمن الجيولوجي الثالث :-

1. تكوين الفتحة Fatha Formation:

2. تكوين انجانة Inaja Formation

3. تكوين المقدادية. Mukdadiyah Formation

4. تكوين باي حسن Bai Hassan Formation

ب– الترسبات الحديثة(ترسبات الزمن الرباعي) Quaternary deposits

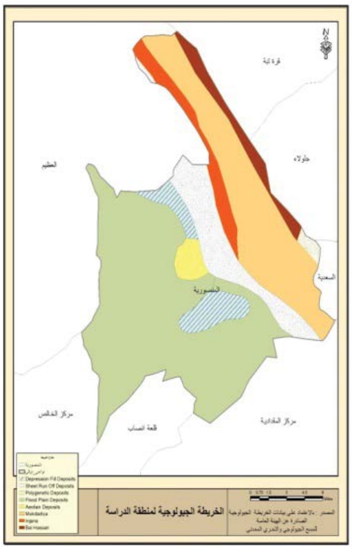
1-ترسبات المصاطب النهرية (River Terraces Depositions)

2ترسبات الوديان والمنخفضات (Valleys Deposits)

3ترسبات السهل فيضي (Flood Plain Deposits)

4-الترسبات الريحية (Aeolian Deposits)

5 -ترسبات متعددةالأصول (Polyfentic deposits



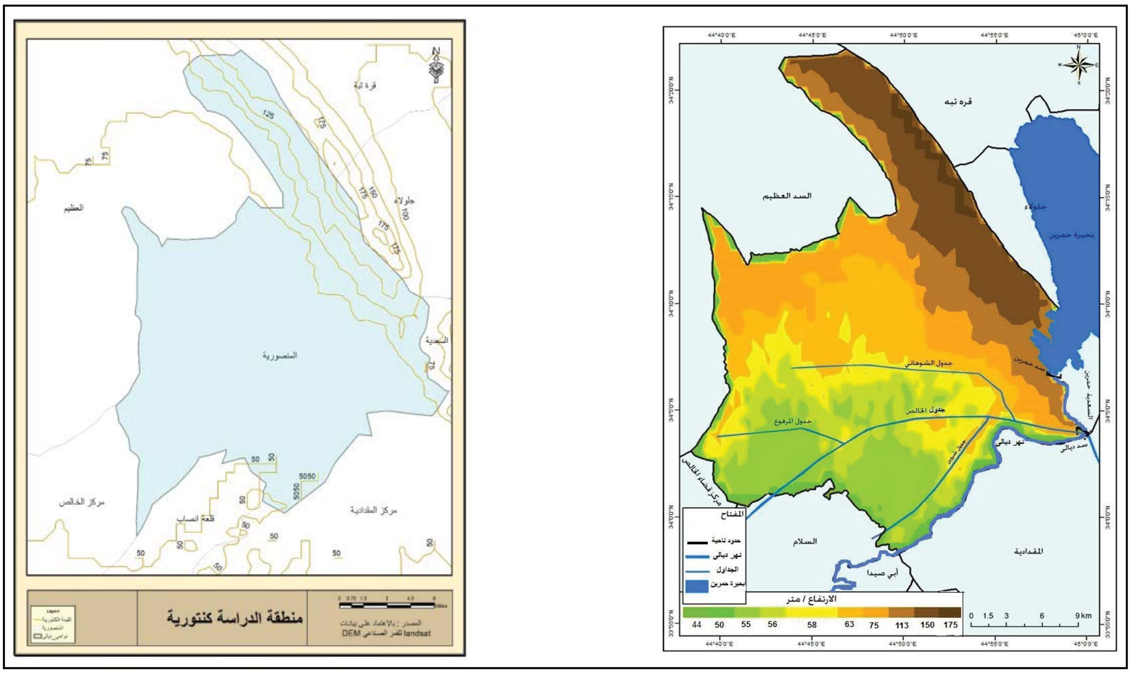
خريطة رقم (4) جيولوجية منطقة الدّراسة

المصدر : خريطة الاساس :جمهورية العراق ,خريطة العراق الطبوغرافية، الهيئة العامة للمساحة، 2020 ، مقياس الرسم 1000000/1

والخريطة (4) التي توضح الارتفاعات ضمن منطقة الدراسة إذ تأخذ الأرض بالانحدار التدريجي كلما اتجهنا نحو الجنوب الغربي.

انبساط السطح وانحداره التدريجي ساعد الأنهار على بناء ضفافها إثناء فترة الفيضانات فأصبحت ضفاف الأنهار أكثر ارتفاعاً من الأراضي المجاورة, كما إن ذرات تربتها اكبر حجما ، لأنها أول ما تترسب من المواد العالقة ، وذلك لقربها من النهر ، أما السهول البعيدة عن ضفاف الأنهار فتكون منخفضة وتربتها ذات ذرات دقيقة (صلصالية) [11].

الخصائص المناخية العامة :- يعد المناخ من أهم العوامل الضرورية لتكوين التربة, فالتربة هي المرآة العاكسة لاثر الظروف المناخية السائدة بالمنطقة[12], فأذا توفرت العوامل المناخية المناسبة من حرارة ورطوبة وإشعاع شمسي وإمطار فقد تتاح إمام التربة جميع العوامل المناسبة لنمو النباتات, ويمكن ملاحظة هذه العلاقة بين العوامل المناخية ونوعية الترب من خلال الاطلاع على توزيع الترب على سطح الأرض, فكلما كانت العو امل المناخية تميل الى القساوة سواء كان ذلك في المناطق الباردة او الحارة كانت الترب بحاجة الى عمليات



الخريطة رقم (5و6) الخريطة التضاريسية و الكنتورية لمنطقة الدّراسة

المصدر : خريطة الاساس :خريطة العراق الطبوغرافية –والكنتورية ،جمهورية العراق : الهيئة العامة للمساحة، 1990 ، مقياس الرسم 100000/1

استصلاح لتزويدها بالخصوبة[13], ولا يقتصر دور المناخ على كمية الرطوبة او الإشعاع الشمسي بل يتعداه الى التأثير المباشر على خصائص التربة الفيزيائية والكيميائية كالتهوية والمسامية ودرجة الحموضة وعلى نسبة المواد العضوية ويمكن ان تعطي الجداول المناخية (1-2-3-4) انعكاس لمناخ المنطقة من خلال استخدام محطتين مناخيتين احاطت بنطاق منطقة الدراسة وهي (محطة خانقين) التي تقع شمالها و(محطة الخالص) جنوبها لعدم توفر محطة مناخية خاصة بالمنطقة. مع الاشارة بشكل اكثر تركيز على عامل تساقط الامطار وشرح ابعاده الزمكانية.

الامطار : ان الأمطار تمد التربة بالماء, وبدونه لا يمكن ان تتم العمليات الكيميائية والإحيائية, إلا إن غزارة تساقط الإمطار يؤدي الى غسل التربة, وتعرف عملية هجرة مكونات التربة عن طريق الماء المتغلغل الى الأسفل, ويحدث ذلك تعرض الطبقة السطحية او أفق (A) من التربة بالغسل, وفي المناطق الجافة والشبه جافة يزيد التبخر عن التساقط, وتجف التربة لفترات طويلة ويرتفع الماء الأرضي ببطء نحو السطح بفعل الخاصية الشعرية, ويتبخر الماء من التربة تاركاً خلفه الأملاح الذائبة على سطح التربة[14].

تبدأ فترة سقوط الإمطار في منطقة الدراسة في شهر تشرين الأول (13,8ــ 9,2) ملم في محطتي خانقين والخالص على التوالي, يتضح من الجدول (4) والشكل (3), وتتصف بالزيادة التدريجية لتصل أقصاها في شهر كانون الثاني(53,1 – 32,3)ملم في محطتي خانقين والخالص على التوالي, ثم تتناقص تدريجياً لتصل في شهر مايس الى (5 – 3)ملم في محطتي خانقين والخالص وتنعدم بشكل نهائي في شهر حزيران الى أيلول, يبلغ مجموع كمية الإمطار السنوية (280,8 – 152,7)ملم في محطتي خانقين والخالص.

ان منطقة الدراسة تنحصر بين خطي المطر المتساوي (100 – 300)ملم أي ان خط المطر (200) ينصفها وهي منطقة غير مضمونة الامطار وتتباين من شهر الى أخر خلال السنة, كما يتضح من الخريطة (5) وبما إنها إمطار متذبذبة وغير منتظمة في مواعيد سقوطها وتتباين كميتها من سنة الى أخرى, فأنها تؤثر بشكل مباشر على خصائص التربة في منطقة الدراسة, إذ تنخفض كمية التساقط فضلاً عن انخفاض نسبة الرطوبة في التربة مما يعني تعرض تماسك تجمعاتها للتفكك بسبب طول فترة الجفاف بالتالي يؤدي الى قلة النبات الطبيعي وبالتأكيد يعرض التربة الى التعرية الريحية, اذ يظهر اثر ذلك على التربة في أجزاء واسعة من منطقة الدراسة[15].

مواصفات نسجة التربة لمقاطع الفحص لمنطقة الدراسة والبنية الداخلية للتربة:-

تمثل نسجة التربة التوزيع الحجمي لأحجام مفصولات التربة الرئيسة (Soil disperses) والتي تتمثل بالرمل Sandوالغرين silt والطين clay والعلاقة النسبية بينهما[16]. ويقصد بها أحياناً التناسق النسبي بين الأحجام المختلفة للذرات التي تتكون منها التربة، وفي العادة لا يتضمن نسيج التربة المواد الخشنة جداً التي يزيد حجمها على (2ملم)[17].

اولا :تحليل نسجة التربة:-

يمكن تحديد نسجة التربة بعدة طرائق منها حقلية تقليدية تعتمد هذهِ الطريقة بالأساس على اللمس حيث يتم فرك التربة الرطبة بين أصابع اليد, فإذا كان ملمسها ناعماً وكانت لزجة ومطاطيتها عالية, دل على زيادة نسبة الطين فيها, أما الرمل فيكون خشناً وليست له لزوجة ولا مطاطية ، الغرين يكون طحيني الملمس ولزوجته ومطاطيته قليلة, وتعتمد دقة النتائج بدرجة كبيرة على الخبرة العملية, أما الطريقة الثانية فهي المختبرية المرتبطة تكنلوجيا باجهزة فحص متقدمة, التي يتم بواسطتها تحديد نسجة التربة تسمى بالتحليل الميكانيكي (mechanical

جدول (1) المعدلات الشهرية لعدد ساعات الإشعاع الشمسي الفعلية(ساعة /يوم) لمحطتي خانقين للمدة (1982 – 2021) والخالص (1991 – 2021)

اسم المحطة	الاشهر												
	كانون الثاني	شباط	آذار	نيسان	مايس	حزيران	تموز	آب	ايلول	تشرين الاول	تشرين الثاني	كانون الاول	المعدل السنوي
خانقين	5,6	6,0	6,9	7,5	8,8	10,8	10,7	10,4	9,4	7,6	6,7	5,3	8,0
الخالص	5,7	6,5	7,6	8,2	9,5	11,4	11,3	11,2	10,1	8,1	7,0	5,6	8,5

المصدر :جمهورية العراق الهيئة العامة للأنواء الجوية والرصد الزلزالي, قسم المناخ, 2021 ,(بيانات غير منشورة)

جدول (2)المعدل الشهري والسنوي لدرجة الحرارة العظمى والصغرى لمحطتي الخالص وخانقين (1991-2021) والمعدل السنوي

اسم المحطة	ك2	شباط	اذار	نيسان	مايس	حزيران	تموز	اب	ايلول	ت1	ت2	ك1	المعدل السنوي
الخالص	9.5	10.8	15.1	21.8	26.5	30.6	33.1	32.3	28.5	24.2	15.0	11.2	21.5
خانقين	10.2	12.1	16.2	22.2	28.8	34.0	36.2	35.6	31.0	25.2	16.9	12.0	24.1
الشهر	ك2	شباط	اذار	نيسان	مايس	حزيران	تموز	اب	ايلول	ت1	ت2	ك1	المعدل السنوي
الخالص	4.0	5.6	9.3	14.11	19.1	22.6	24.7	24.2	20.4	16.0	9.5	5.5	14.6
خانقين	5.1	6.2	9.5	14.9	21.3	24.6	26.7	26.2	22.1	17.7	10.6	6.5	16.0

المصدر :جمهورية العراق الهيئة العامة للأنواء الجوية والرصد الزلزالي, قسم المناخ, 2021 ,(بيانات غير منشورة)

جدول (4) معدلات المجاميع الشهرية والسنوية للإمطار الساقطة (ملم) لمحطتي خانقين للمدة (والخالص للمدة (1991 – 2021)

الشهر	ك٢	شباط	اذار	نيسان	مايس	ت١	ت٢	ك١
الخالص	30.9	26.5	18.1	18.0	3.5	8.7	21.9	25.2
خانقين	54.6	40.2	42.0	30.4	6.1	20.1	52.9	44.1

لمصدر : جمهورية العراق : الهيئة العامة للأنواء الجوية والرصد الزلزالي, قسم المناخ, 2021,(بيانات غير منشورة)

analysis) وهي التي استخدمت في الدراسة من أجل تحديد أصناف النسجة اعتمادا على نتائج تحليل حجوم المفصولات (الرمل, الغرين, الطين) وباستعمال مثلث تعيين نسجة التربة المعروف لدى الباحثين و المقترح من قبل وزارة الزراعة الأمريكية[18].

لقد اظهرت فيه نتائج التحليل كما في الجدول (6) إن نسجة التربة في منطقة الدراسة, تبدو متباينة وفي أعماق مختلفة وكما يأتي:-

نسب المفصولات و صنف النسجة للتربة حسب مقاطع التربة في منطقة الدراسة:

المقطع الاول (شروين) :-يحتوي هذا المقطع على صنفين من النسجة وهما مزيجية امتدت في عمقين من (0– 30) سم و(31– 60) سم والنسجة الثانية مزيجية غرينية في العمق الثالث (60– 100) سم.

المقطع الثاني (الكوام) :- يحتوي هذا المقطع على صنف واحد من النسجة وهي النسجة مزيجية طينية غرينية في جميع الأعماق للتربة.

- المقطع الثالث (المرفوع) :- يحتوي المقطع على صنفين من النسجة هما النسجة الطينية وامتدت في عمقين : الأول (0– 30سم) والثاني (31– 60سم) والنسجة مزيجية طينية غرينية في العمق الثالث (61- 100سم).
- المقطع الرابع (الشوهاني) :- يحوي هذا المقطع على صنف واحد من النسجة وهي النسجة مزيجية غرينية وامتدت في جميع أعماق التربة .
- المقطع الخامس (المشروع2) :- يحتوي هذا المقطع على صنف واحد من النسجة وهي النسجة المزيجية الطينية وامتدت في جميع أعماق التربة .
- المقطع السادس (منصورية الجبل) :- يحتوي هذا المقطع على صنف واحد من النسجة هي النسجة المزيجية الرملية وامتدت في جميع أعماق التربة.
- المقطع السابع (المشروع1):- يحتوي هذا المقطع على صنفين من النسجة هما النسجة المزيجية الغرينية وامتدت في عمقين الأول (0-30سم) والثاني

جدول (6) ارقام المناطق والمقاطعات التي تم فيها فحص التربة بمنطقة الدراسة (منصورية الجبل)لتحديد صنف النسجة

رقم المقطع واسم المنطقة	الأعماق / سم	رمل %	غرين%	طين %	صنف النسجة	الرمز
الاول /شروين	0- 30	54	40	17	مزيجية	L
	31-60	40	48	15	مزيجية	L
	61-100	44	57	5	مزيجية غرينية	SIL
الثاني /الكوام	0- 30	24	44	35	مزيجية طينية غرينية	SICL
	31-60	25	47	35	مزيجية طينية غرينية	SICL
	61-100	28	47	37	مزيجية طينية غرينية	SICL
الثالث /المرفوع	0- 30	18	38	45	طينية	C
	31-60	18	36	49	طينية	C
	61-100	23	50	37	مزيجية طينية غرينية	SICL
الرابع /الشوهاني	0- 30	24	53	28	مزيجية غرينية	SIL
	31-60	27	53	27	مزيجية غرينية	SIL
	61-100	25	55	23	مزيجية غرينية	SIL
الخامس /المشروع(2)	0- 30	30	43	34	مزيجية طينية	CL
	31-60	42	43	29	مزيجية طينية	CL
	61-100	32	35	32	مزيجية طينية	CL
السادس /منصورية الجبل	0- 30	60	35	7	مزيجية رملية	SL
	31-60	66	25	7	مزيجية رملية	SL
	61-100	65	29	10	مزيجية رملية	SL
السابع /المشروع(1)	0- 30	35	60	8	مزيجية غرينية	SIL
	31-60	42	50	7	مزيجية غرينية	SIL
	61-100	60	37	9	مزيجية رملية	SL
الثامن /منصورية الجبل الشمالي(2)	0- 30	60	30	8	مزيجية رملية	SL
	31-60	70	25	5	مزيجية رملية	SL
	61-100	78	19	6	مزيجية رملية	SL
التاسع /التجداري	0- 30	25	59	18	مزيجية طينية غرينية	SICL
	31-60	29	65	18	مزيجية غرينية	SIL
	61-100	21	54	26	مزيجية طينية غرينية	SICL
العاشر/منصورية الجبل الشمالي(1)	0- 30	61	29	10	مزيجية رملية	SL
	31-60	55	35	7	مزيجية رملية	SL
	61- 100	54	30	6	مزيجية رملية	SL

المصدر :- تم تحديث الفحوصات لنفس المناطق والمواضع في عام 2023 –اعتمادا على : منذر صائل محمد, خصائص ترب ناحية المنصورية وعلاقتها بالبيئة, رسالة ماجستير غير منشورة, جغرافية, كلية التربية للعلوم الانسانية. 2014.

(31-60سم) والنسجة المزيجية الرملية في العمق الثالث (61- 100سم).

- المقطع الثامن (منصورية الجبل الشمالي2) :- يحتوي هذا المقطع على صنف واحد من النسجة هي النسجة المزيجيه الرملية وامتدت في جميع أعماق التربة.
- المقطع التاسع (التجداري) :ــ يحتوي هذا المقطع على صنفين من النسجة هما النسجة المزيجية الطينية الغرينية في العمقين الاول (0 – 30)سم والثالث (61 – 100)سم والنسجة المزيجية الغرينية في العمق الثاني (31 – 60)سم .
- المقطع العاشر (منصورية الجبل الشمالي1) :ــ يحتوي هذا المقطع على صنف واحد من النسجة هي النسجة المزيجية الرملية وامتدت في جميع أعماق التربة.

فمن خلال هذا التصنيف حددت خريطة (9) ووزعت عليها أصناف نسجة التربة. إذ يلاحظ أن تربة منطقة الدراسة تتوزع فيها أصناف النسجة وذلك تبعاً للعوامل الطبوغرافية, إذ تتميز المناطق المرتفعة بأنها ذات تربة خشنة المتمثلة بمقاطعة منصورية الجبل (17) ومنصورية الجبل الشمالي, أما ترب كتوف الأنهار التي تتميز بترب متوسطة الخشونة المتمثلة في الجانب الأيمن من نهر ديالى ,اما اغلب الترب الباقية فهي من نوع الترب ذات النسجة الناعمة وخليط من الرمل والغرين.

تعد نسجة التربة إحدى الصفات الفيزيائية المهمة التي تؤثر على نمو النبات بصورة مباشرة وذلك عن طريق تأثيرها في تعميق ونمو الجذور وبصورة غير مباشرة عن طريق تأثيرها على جاهزية الماء والعناصر الغذائية[19].

وتعد الترب الرملية ذات قيمة زراعية واطئة, ولكن يمكن استصلاحها بإضافة المادة العضوية إليها وتكون أكثر دفئاً وملائمة لإنتاج بعض الغلاة الزراعية, كالبصل والبطاطا والثوم والخضراوات بأنواعها[20].

ثانياً :ــ تحليل الكثافة وعلاقتها بتغدق تربة منطقة الدراسة هي كتلة المادة الصلبة من التربة لحجم معين منها, وتختلف كثافة التربة بحسب تركيبها المعدني والعضوي ونسبة الفراغات بين جزيئاتها اذ تساعد معرفة كثافة التربة على تحديد مساميتها[21],ويعبر عنها بطريقتين هما:ــ

الكثافة الظاهرية :هي النسبة بين كتلة التربة الجافة وبين حجمها الكلي ,(المتضمنة كل من حجم المادة الصلبة وحجم الفجوات). اي ان الحجم في هذه الحالة يشمل حجم الدقائق وحجم المسامات الموجودة بينهما[22].

اذ تتباين قيم الكثافة الظاهرية لتربة منطقة الدراسة للأعماق الثلاثة فبالنسبة للعمق الاول (0 – 30)سم تراوحت قيم الكثافة الظاهرية بين(1,29 – 1,55) غرام/سم^3 في المقطع الاول منطقة شروين والمقطع الثاني الكوام, والعمق الثاني (31– 60)سم تراوحت بين (1,38 – 1,71) غرام/سم^3 في المقطع الاول منطقة شروين والمقطع التاسع التجداري, اما العمق الثالث (61 – 100)سم تراوح بين (1,44– 1,75) غرام/سم^3 في المقطع الاول منطقة شروين والمقطع العاشر منصورية الجبل الشمالي[23].

ويمكن القول إن قيم الكثافة الظاهرية في العمقين الأول والثاني تبدو اقل منها في العمق الثالث كون الطبقات السطحية معرضة للعمليات الزراعية والعوامل المؤثرة في الكثافة الظاهرية مثل البناء ونسبة الرطوبة ونوع معدن الطين فضلاً عن احتوائها على المادة العضوية, وعلى هذا الأساس فإن الكثافة الظاهرية تعكس خصائص التربة الفيزيائية التي تؤثر في درجة إنتاجيتها, فالتربة المرصوصة ذات الكثافة الظاهرية العالية تتصف بقابليتها على الاحتفاظ بالماء وانخفاض درجة نفاذيتها ورداءة تهويتها, لذا تكون إنتاجيتها قليلة[24].

ثالثاً : المسامية وعلاقتها بتغدق وتملح التربة في منطقة الدراسة :- تتراوح مسامية التربة بين (30% - 60%) على الرغم من انخفاضها في أنواع التربة الصلصالية وارتفاعها في التربة العضوية, وتنخفض المسامية في الترب الخشنة القوام الرملية عنها في الترب الطينية ناعمة القوام[25].

اذ تباينت قيم المسامية في تربة منطقة الدراسة من مكان الى أخر وحتى على مستوى العمق الواحد, اذ وجد ان القيم للعمق الأول تتراوح بين (41,72-54,95)% وتم ملاحظته في (المقطع الثاني منطقة الكوام والمقطع الثامن منصورية الجبل الشمالي), فيما تراوحت القيم للعمق الثاني بين(36,69-50,69)% وتم ملاحظته في (المقطع العاشر منطقة منصورية الجبل الشمالي والمقطع الثامن منصورية الجبل الشمالي), إما في العمق الثالث تراوحت بين (33,82-47,59)% وتم ملاحظته في (المقطع العاشر منطقة منصورية الجبل الشمالي والمقطع الاول شروين) [26].

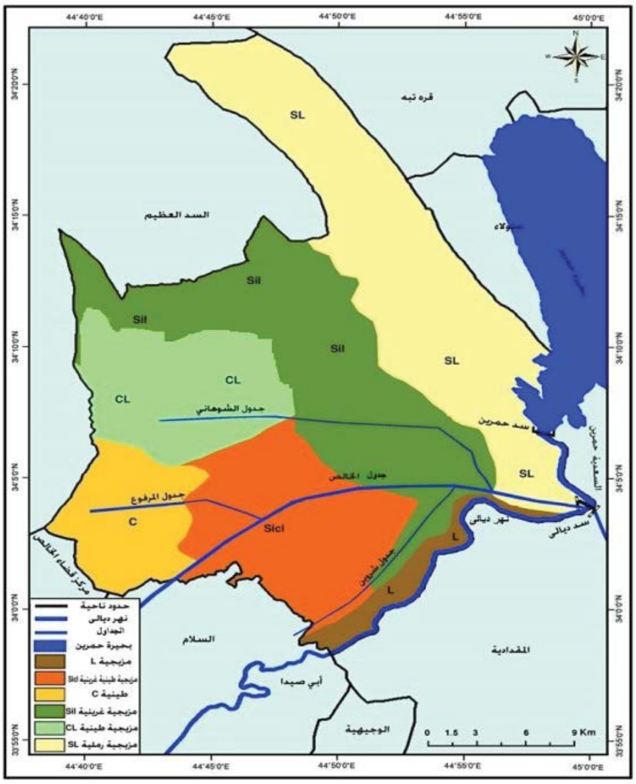
نستنتج مما سبق ان مسامية تربة منطقة الدراسة ذات معدل أعلى في العمق الأول ويليه العمق الثاني فالعمق الثالث, ويعود ذلك لتأثر مسامية التربة بالعديد من العوامل منها نسجة وتركيب التربة ونسبة المادة العضوية وطريقة إدارة التربة كالحراثة والتسميد ونوع المحصول المزروع ومقدار تعرض التربة الى عملية الانضغاط[27].

رابعاً:بناء التربة وعلاقته بتغدق وتملح التربة في منطقة الدراسة:ـ

لكي نعطي صورة واضحة ومفصلة على بناء التربة في أفق معين وجد أنهُ من الضروري أن يكون الوصف مرتكز على[28]: حجم البناء :Class of structure حيث هناك هناك خمسة حجوم وهي ناعمة جداً (very fine) ناعمة fine ، متوسطة medium ، خشنة coarse، خشنة جداً very coares. فضلا عن مراعاة مسالة معينة وهي نوع البناء Type of structure:ـ اذ يقسم الى:ـ

- الطبقي (الصفائحي) platy :ـ وهو على سبيل المثال موجود في الترب الطينية المترسبة حديثاً ، وهو بناء غير مرغوب فيه لقلة مساميته وهذا النوع يوجد في المقطع العاشر منصورية الجبل الشمالي في العمق الثالث.
- موشوري أو عمودي (prismatic or columnar): ــ

يتكون هذا البناء أثناء عملية جفاف الأرض المحتوية على طين صودي غروي حيث تتشقق الأرض في شقوق طويلة تختلف في أعماقها ، وهذا البناء شائع في أفق B من الترب الطينية ولاسيما في المناطق الشبة الجافة ، وعندما



خريطة (9) تصنيف ترب حسب النسجة في ناحية المنصورية

المصدر/ خريطة الاساس : نتائج التحاليل المختبرية في الجدول (6) جامعة ديالى 2023 بالاعتماد على موائمتها مع نتائج دراسة منذر صائل محمد – تطابق نسبي كبير

يكون الجزء العلوي مسطحاً فأن هذهِ المجاميع العمودية تسمى موشورية prismatic- وأذا كانت مدورة فتسمى عمودية columnar,ويوجد هذا النوع من البناء في المقطع الثالث المرفوع في العمق الثالث وكذلك في المقطع الثامن منصورية الجبل الشمالي في العمق الثالث أيضاً.

- كتلي Blocky:- تربة ذات كتل شبيهة بالمكعبات لحد 10سم^3 في الحجم ، وتكون بعض الأحيان ذات زوايا وأوجه محددة وواضحة، أن هذهِ التركيبات تحصل بصورة عامة في الجزء العلوي من الأفق (B), وهو سائد في منطقة الدراسة في كل من المقاطع الآتية (الاول شروين ,الثاني الكوام الرابع الشوهاني ,الخامس المشروع (2).
- كروي Spherical :- مجاميع مدورة بصورة عامة ليست أكبر من 2 سم بكثير وغالباً ما تتواجد في حالة مفككة في أفق (A)، وتسمى مثل هذهِ الوحدات حبيبات فتاتية وهي مسامية[29], ويوجد هذا النوع من البناء في المقطع السادس منصورية الجبل والمقطع السابع المشروع1 بشكل كامل اما في المقطع الثامن منصورية الجبل الشمالي2 في عمق الاول والثاني كما هو الحال في المقطع العاشر منصورية الجبل الشمالي1 ويتواجد في المقطع التاسع التجداري في العمق الثاني

إنَّ بناء ترب منطقة الدراسة يبدو انها من أنواع مختلفة ، إلا أن البناء الكتلي هو السائد في منطقة الدراسة ويتضح ذلك من الوصف المورفولوجي لترب منطقة الدراسة. أما من حيث درجة البناء فيلاحظ انها تراوحت بين عديمة البناء في المقطعين السادس والسابع في العمقين (الثاني والثالث) كونها ترب رملية وقليلة المادة العضوية, أما البناء الضعيف فتمثل في المقاطع السادس والسابع في العمق (الأول) على التوالي والمقطع الثامن والعاشر في العمقين (الأول والثاني). أما المعتدل فهو السائد في منطقة الدراسة والبناء القوي حيث تمثل في المقاطع الثاني والثالث والرابع في العمق (الأول) على التوالي ، لذا يجب محاولة تحسين بناء التربة في منطقة الدراسة عن طريق عملية الحراثة التي تعمل على تكسير الكتل الكبيرة والقوية الى كتل أصغر واستعمال الأسمدة العضوية التي تعمل على تماسك مكونات التربة مع بعضها البعض.

خامسا : اللون وعلاقته بتغدق وتملح التربة في منطقة الدراسة

تتغير الوان الترب بتغير المخزون المائي ونوع مصادر المياه, اذ توجد عدة طرق لتحديد لون التربة بصورة تقريبية أهمها :ـ (طريقة منسل Mansell [30], ان نسبة اللون مختلفة من منطقة الى أخرى وأحيانا في المنطقة نفسها

جدول (8)الوصف المورفولوجي لبناء التربة حسب مقاطع التربة في منطقة الدراسة

رقم المقطع واسم المنطقة	العمق/سم	درجة بناء التربة	صنف البناء	نوع البناء
	0- 30	معتدلة	متوسط	كتلي غير حاد الزوايا
الاول /شروين	31-60	معتدلة	متوسط	كتلي غير حاد الزوايا
	61-100	معتدلة	متوسط	كتلي غير حاد الزوايا
	0- 30	قوية	متوسط	كتلي غير حاد الزوايا
الثاني /الكوام	31-60	معتدلة	متوسط	كتلي غير حاد الزوايا
	61-100	معتدلة	خشن	كتلي حاد الزوايا
	0- 30	قوية	خشن	كتلي حاد الزوايا
الثالث /المرفوع	31-60	معتدلة	خشن	كتلي حاد الزوايا
	61-100	معتدلة	خشن	منشوري
	0- 30	قوية	خشن	كتلي حاد الزوايا
الرابع /الشوهاني	31-60	معتدلة	متوسط	كتلي غير حاد الزوايا
	61-100	معتدلة	متوسط	كتلي غير حاد الزوايا
	0- 30	معتدلة	خشن	كتلي غير حاد الزوايا
الخامس /المشروع(2)	31-60	معتدلة	خشن	كتلي غير حاد الزوايا
	61-100	معتدلة	خشن	كتلي حاد الزوايا
	0- 30	ضعيفة	متوسط	كروي فتاتي
السادس /منصورية الجبل	31-60	عديم البناء	ناعم	كروي حبيبي
	61-100	عديم البناء	ناعم	كروي حبيبي
	0- 30	ضعيفة	متوسط	كروي حبيبي
السابع /المشروع(1)	31-60	عديم البناء	ناعم	كروي حبيبي
	61-100	عديم البناء	ناعم	كروي حبيبي
	0- 30	ضعيفة	ناعم	كروي حبيبي
الثامن /منصورية الجبل الشمالي(2)	31-60	ضعيفة	ناعم	كروي فتاتي
	61-100	معتدلة	متوسط	منشوري
	0- 30	معتدلة	خشن	كتلي غير حاد الزوايا
التاسع /التجداري	31-60	معتدلة	خشن	كروي حبيبي
	61-100	معتدلة	خشن	كتلي غير حاد الزوايا
	0- 30	ضعيفة	متوسط	كروي حبيبي
العاشر /منصورية الجبل الشمالي(1)	31-60	ضعيفة	خشن	كروي حبيبي
	61- 100	معتدلة	خشن	صفائحي

المصدر : اظهرت نتائج الدراسة الميدانية الجديدة عدم تغير المؤشرات البنيوية التي اوجدتها الدراسة السابقة والوصف المورفولوجي الحقلي لمقدات التربة منذر صائل محمد, مصدر سابق ,-ص99 – فحص التربة لعام 2023

وذلك حسب التباين في الأفاق والأعماق ويرجع ذلك الى الاختلاف عناصر الالوان وهي التدرج والقيمة والصفاء لكل عينة من العينات, ان كل ترب المنطقة تسودها (Hue l0 yR) مع قيمة (لمعان اللون) كان بين (6 – 4) بينما الصفاء (نقاوة) فقد كان بين (6 – 3), يتضح من الجدول (9) بان اللون البني المصفر(Yellowish brown) هو السائد فإنه يرجع الى نقص المادة العضوية بالتربة, واللون البني (brown) يدل على تراكم كميات كبيرة من اكاسيد الحديد, ان البني المصفر الفاتح (Light Yellowish brown) يوجد في المقطع الرابع في العمق(الثاني) والبني المصفر غامق (Dark Yellowish brown) يتواجد في المقطع التاسع في العمق(الثالث) والمقطع العاشر في العمق(الثاني), واللون البني الرمادي (Grayish brown) يتواجد في المقطع التاسع في العمق (الثاني) ان اللون الشائع في ترب منطقة الدراسة هو اللون الفاتح في الطبقة السطحية والذي يشير الى ضعف الغطاء النباتي وعدم تراكم المادة العضوية[31].

نستنتج من ذلك ان المناخ السائد جاف وحار قليل الإمطار اذ ان سيادة هذا النوع من المناخ أدى الى قلة النبات الطبيعي من جهة وسرعة تحلل المواد العضوية القليلة من جهة أخرى, ان الاختلافات الأفقية بين الترب والعمودية ضمن التربة الواحدة يدل على سيادة تأثير كل من المادة الأصلية (نوع الترسبات) والجيومورفولوجيا (التضاريس) وما ينجم عنها من اختلافات في مستوى الماء الارضي وفي تكوين ترب المنطقة.

تحليل ووصف جغرافي لاسباب التملح والتغدق بالمحافظة

ان تأثيرمشكلة التغدق والتملح ,باتت واحدة من التحديات التي تؤثر بشكل مباشرعلى مناطق معيشة السكان والمزارعين بمحافظة ديالى التي تقع في القسم الأوسط من شرق العراق, , اذ .تحتاج المحافظة إلى دعم كبير تكنلوجي ومادي, وبدون هذا الدعم سيصبح من المستحيل مواجهة متطلبات مكافحة التصحروالأنشطة ذات الصلة باستصلاح الاراضي الجافة.

ونظرا لاهمية الزراعة وما تمثله المحافظة من اهمية استراتيجية ,كونها تعد سلة العراق الغذائية و مصدر مهم لتزويد سكانها بالمحاصيل الزراعية الضرورية والتي ترتبط بالامن الغذائي فكان لزاما الوقوف على معالجة التحديات التي تظهر على التربة وبالطرائق التكنلوجية الحديثة.

فرغم ان الملح يعد العنصر الطبيعي للتربة والحياة. فالأيونات المســـؤولة عن التملـــــح هي : (الصوديوم, البوتاسيوم, الكالسيوم, المغنيسيوم والكلور) وبما أن الصوديوم هو العنصر السائد فتصبح التربة (صوديومية) ,اذ تواجه التربة المليئة بالصوديوم تحديات خاصة بالمنطقة الجغرافية لأنها تكون مهيكلة بشكل سيء للغاية, مما يحد أو يمنع من ارتشاح الحياة. ومع مرور الزمن, فأن معادن التربة بالمنطقة وتفاعلها مع عوامل التهوية وجدناها تطلق هذه الأملاح, ثم تتدفق أو تترشح إلى سطح التربة في منطقة الدراسة مع ارتشاح الحياة في المناطق ذات الأمطار الغزيرة, بالإضافة إلى ذلك فالمعادن ترسب الاملاح أيضاً عن طريق الغبار والأمطار في المناطق الجافة وقد تتراكم الأملاح مما ادى إلى تربة مالحة ,

فعلى سبيل المثال في أجزاء كبيرة من استراليا يمكن للممارسات البشرية أن تزيد من ملوحة التربة من خلال اضافة الأسمدة في حياة الري بشكل صحيح ويمكن أن تحول دون تراكم الملح عن طريق تصريف الحياة بشكل كاف لتصفية الأملاح في التربة. كمل لوحظ ان الملوحة تاتي بزيادة تركيز الأملاح في محلول التربة بنسبة أكثر من الأملاح اللازمة لنمو النبات, وتعد مشكلة الملوحة مشكلة واقعة وفي توسع غير مسيطر عليه.

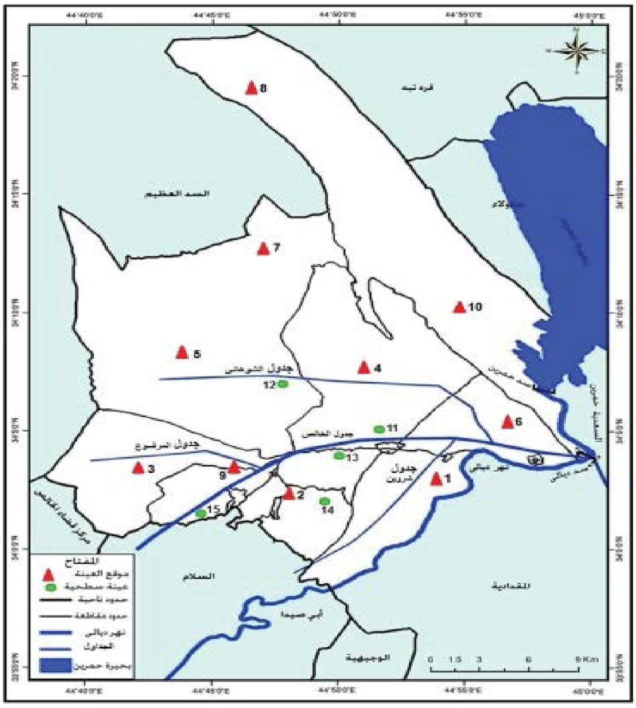
ناهيك عن التملح الثانوي الذي يحدث في الترب المتكونة والمتطورة بسبب ارتفاع مستوى المياه الجوفية المالحة أو التضاريس التي تلعب دوراً مهماً في تملح التربة أيضاً. فالأملاح تتجمع أو تتراكم عندما لاحظنا وجود مصدر لها أو امكانية نقل هذه الأملاح الى الجزء العلوي لمقدار التربة[32].وهذا ماتم ملاحظته في الدراسة الميدانية فالتغدق وتشبع التربة بالماء خلال المواسم الرطبة من السنة بعد سقوط الأمطار بكميات وفيرة في الطبيعة ولفترة زمنية طويلة على تلك الرطوبة التي تكون أعلى من رطوبة ماء الاجتذاب وهذه الأمطار وذوبان الثلوج وجريان الماء لا ينفذ إلى الاعماق وذلك بسبب قلة نفاذية الطبقة السفلى مما يؤدي إلى تجمع الماء على السطح .

أن ظاهرة التغدق السطحي تظهر بشكل جلي في مساحات الأراضي التي ليس فيها منحدر أو ذات منحدر بسيط وغير مستوي, عندما تكون هناك صعوبة في إزالة ماء الاجتذاب وتمثل في مناطق محافظة ديالى في كل من قضاء المقدادية وناحية الوجيهية وقضاء بلدروز ..بشكل عام وواضح بشكل دقيق في منصورية الجبل بالمنطقة رقم 6

ثانياً – مناقشة النتائج والتوصيات المقترحة:

من خلال البحث والتقصي والتحليلات المختبرية لوحظ الاتي:-

- تراكم الامـلاح وتركيزها:-اظهرت النتائج ان الترب بالمنطقة تتصف بالتملح وفي الغالب تتكون املاح الصوديوم بشكل يتم عن ذوبان كلوريدات – كبريتات – بيكربونات تحتوي على كلوريدات – كبريتات الكالسيوم والمغنيسيوم معاً ولكن بشكل أقل عندما تتطور التربة بوجود المحتوى العالي من ألاملاح ,وفي العادة والأهم يكون تملح التربة تملح أولي باختلاف طبيعة عمليات تكون التربة, أما الثاني يعتمد على صفات التربة وباطن الأرض على الخصائص المناخية وعلى توفير مياه الأرض أي مياه الري وعلى الدورة الزراعية وعلى التكنولوجيا الزراعية التي تمارس من قبل المزارعين بالمنطقة.
- توصيف مقاطع التربة :-عند التعامل مع السطح الأفقي وعند المقاطع الصغيرة تم التوصل والملاحظة خلال الحراثة ان التربة المتشبعة الاعماق المتباينة مع عمق المقاطع يحدث فيها تفكك في التربة تحت السطح الى الاعلى (مع الاخذ بالاعتبار ان لا يؤدي الوصول إلى الأفق A الذي يكون سمكه الى تسوية التربة ويعطي مقدمات منطقية مما يزيد من كثافة الانتاج الزراعي في منطقة الدراسة)
- النظام المائي للري:- فالموازنة المائية السالبة خلال فترات التبخر كانت السبب الرئيسي لنقل الأملاح إلى الطبقات العليا للتربة وعند تغير الظروف



خريطة (10) موقع اختيار العينات للترب حسب النسجة ولتحديد اللون في ناحية المنصورية

المصدر/ خريطة الاساس لمراجعة الباحث المواقع نفسها التي فحصت التربة بها عام 2014 وزيارتها عام 2023

جدول (9) لون التربة حسب مقاطع الفحص في منطقة الدراسة

رقم المقطع واسم المنطقة	العمق/سم	Chroma	Value	Hue	اللون التربة في الحالة الرطبة
الاول /شروين	30 -0	4	5	10YR	Yellowish brown
	60-31	3	5	10YR	brown
	100-61	3	5	10YR	brown
الثاني /الكوام	30 -0	3	4	10YR	Dark brown
	60-31	3	4	10YR	Dark brown
	100-61	4	5	10YR	Yellowish brown
الثالث /المرفوع	30 -0	4	5	10YR	Yellowish brown
	60-31	6	5	10YR	Yellowish brown
	100-61	4	5	10YR	Yellowish brown
الرابع /الشوهاني	30 -0	3	5	10YR	brown
	60-31	4	6	10YR	Light Yellowish brown
	100-61	4	6	10YR	Light Yellowish brown
الخامس /المشروع(2)	30 -0	4	5	10YR	Yellowish brown
	60-31	4	5	10YR	Yellowish brown
	100-61	4	5	10YR	Yellowish brown
السادس/منصورية الجبل	30 -0	4	5	10YR	Yellowish brown
	60-31	6	5	10YR	Yellowish brown
	100-61	6	5	10YR	Yellowish brown
السابع /المشروع(1)	30 -0	6	6	10YR	Brownish yellow
	60-31	4	5	10YR	Yellowish brown
	100-61	4	5	10YR	Yellowish brown
الثامن /منصورية الجبل الشمالي(2)	30 -0	3	5	10YR	brown
	60-31	3	5	10YR	brown
	100-61	4	5	10YR	Yellowish brown
التاسع /التجداري	30 -0	3	5	10YR	brown
	60-31	2	5	10YR	Grayish brown
	100-61	4	4	10YR	Dark Yellowish brown
العاشر /منصورية الجبل الشمالي(1)	30 -0	4	5	10YR	Yellowish brown
	60-31	6	4	10YR	Dark Yellowish brown
	100 -61	4	5	10YR	Yellowish brown

المصدر :,-اظهرت نتائج الدراسة الميدانية الجديدة عدم تغير المؤشرات اللونية التي اوجدتها الدراسة السابقة منذر صائل محمد, مصدر سابق ص102. بالاعتماد على أطلس الألوان (لمنسل) ,والوصف المورفولوجي الحقلي لمقدات التربة- فحص التربة 2023

والذي يتم ذلك بمساعدة مجموعة من العمليات التي تعرف بتقليل عملية التبخر من السطح خلال آيار. فالنباتات ذات النظام العميق تمثل الجزء الأساسي للنظام الجذري وهي تمتص الرطوبة من الطبقات الأكثر عمقاً.

اما عن أسباب التغدق:-

فعند ملاحظة خصوصية بناء ترب الجيرنوزيم الطينية في منطقة الدراسة .

- بالنسبة الى الأرض المستوية, التي تتصف بانحدار الأرض من 1,2 – 6 % هذا الانحدار لا يكفي لجريان الماء السطحي بشكل طبيعي مما يعني تباطؤ حركة المياه وتشبع و حصول تغدق في التربة.
- بالنسبة للظروف المناخية, التي تتصف الزيادة بكمية الأمطار على سرعة تبخر الماء خلال فصول الخريف ـ الشتاء والربيع .ساعدت على زيادة التغدق بالمقاطعة 6 بالذات وهي الاكثر تاثرا بهذه المشكلة.
- اما النشاط الانتاجي للإنسان, فالتوسعات كبيرة في انشاء المصانع والمعامل والطرق مما تكون على حساب المساحات الزراعية وبالتالي تساهم الى تركز وتوجيه المياه الة المناطق الاقل منسوب ارضي مما يؤدي الى تراكم الاملاح وتغدق التربة.

ولذلك يمكن حل هذه المشكلة في المنطقة او المناطق المشابهة بهذه المشكلة من خلال استخدام تكنلوجيا التشغيل او التحليل الاقتصادي الرقمي وهو"مجموعة المعارف والمهارات والخبرات الجديدة التي يمكن تحويلها لمعادلة إنتاج تتعامل مع السلع والخدمات وتسويقها وتوزيعها، أو استخدامها في توليد هياكل تنظيمية إنتاجية". تنطلق من تطبيق الإجراءات المستمدة من البحث العلمي والخبرات العلمية لحل المشكلات الواقعية، ولا تعني التكنولوجيا هنا الأدوات والمكائن فقط بل أنها الأسس النظرية والعلمية والبرمجيات التي ترمي إلى تحسين الأداء البشري في الحركة التي تتناولها وهي تعتمد على ثلاث مرتكزات هي:-

- أساس مستوى درجة التحكم في تصريف المياه :وتشمل التكنولوجيا الأساسية : وهي التكنولوجيا التي تمتلكها أغلب المؤسسات المرتبطة بتنظيم الري وتتميز بدرجة تحكم كبيرة فضلا عن الارصـاد الجوي للتنبؤ بالامطار

الغزيرة وتنظيم السدود والتدفق المائي لمجاري السيول .سيما وجود بحيرة سد حمرين المجاورة للمنطقة.

- أساس مستوى تكنولوجيا التسيير في حركة المياه على سطح الارض : وهي التي تستخدم في تسيير تدفقات الموارد المائية ،والتحكم بالمشاريع الاروائية وشبكات مياه الري بالمحافظة ومن أمثلتها البرامج والتطبيقات التسييرية .او تكنولوجيا التصميم : وهي التي تستخدم في نشاطات التصميم في المؤسسة كالتصميم بمساعدة الحاسوب .او تكنولوجيا أسلوب فتح وغلق البوابات المائية الكترونيا عبر الاشارات اللاسلكية للمشاريع الزراعية المرتبطة بها ، وعمليات التركيب والمراقبة او تكنولوجيا المعلومات والاتصال و تستخدم في معالجة المعلومات والمعطيات ونقلها للحد من صرف المياه وتقنين وترشيد الاستهلاك المائي.
- اساس مستوى تكنولوجيا التعقيد في الري : وهي التكنولوجيا الاكثر في التعقيد، والتي من الصعب على المؤسسات الوطنية في الدول النامية تحقيق إستغلالها إلا بطلب من صاحب البراءة او صاحب المزرعة باعتماد تكنولوجيا اعتيادية اذ تعد اقل تعقيدا من سابقتها، حيث بإمكان المختصين المحليين في المحافظة إستيعابها غير أنها تتميز أيضا بضخامة تكاليف الإستثمار.ومثال ذلك هو استخدام المستشعرات المرتبطة بجذور النبتة لحاجة النبات للمياه عبر الاشارات والمتحسسات فتقوم بالاداء دون تدخل المزارع

ولذا تعد المعلومات والبيانات الاساس المعرفي لبناء نظم تكلنولوجية حديثة تواكب الظاهرة وتتابع التغيرات الحاصلة عليها عن بعد او قرب ويعتمد هذا الامر على ركيزيتين هما توفير برمجات مناسبة وتقانات حديثة لفهم حركة الظاهرة زمانيا ومكانيا وهذا الامر لايتم الا عن طريق توفر مايسمى (بالمعلومات الرقمية الدقيقة) التي تحمل الخصائص الاتية وتوفرها من حيث:

أهمية دقة المعلومات:

- من خلال إثراء البحث العلمي و تطور العلوم والتكنولوجيا في مجال الهندسة الزراعية. ونظم المعلومات الجغرافية والتحسس النائي والبرمجيات الحديثة مثل استخدام برنامج Hydrus-2D الذي يحاكي المتغيرات الزراعية لحاجة النبتة الى الرطوبة الفعلية. ودعم العنصر الأساسي في إتخاذ القرر لحل المشكلات المرتبطة بتقنين الري في الوسط الذي تنمو عليه النباتات
- لها دور في التوقيت المناسب من خلال دورة المعالجة و الإدخال وتسليم التقارير الرقمية عند الطلب
- تساعد المعلومات في نقل الخبرات للآخرين و على حل المشكلات التي توجه المزارع و على الاستفادة من المعرفة المتاحة لسكان المنطقة من المزارعين والقائمين على ملف ادارة ملف المياه وتطبيق الخطة الزراعية ونجاحها في كل موسم زراعي.

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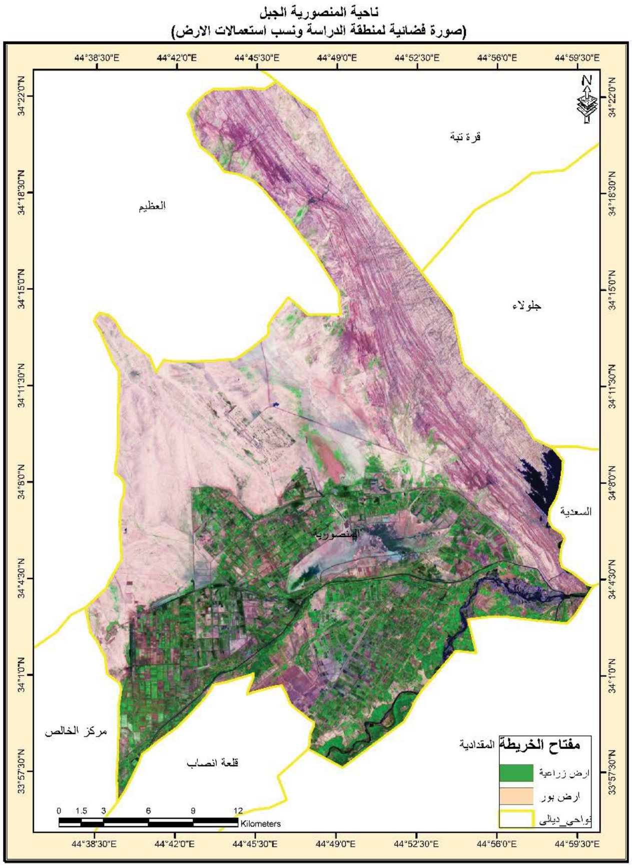

خريطة (11)خريطة استعمالات الارض في ناحية منصورية الجبل 2023 والتصحر الناتج من الاثر البيئي
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Balaban Desalination Publications

The 15th Gulf Water Conference
مؤتمر الخليج الخامس عشر للمياه

(2025) 251–262
doi: 10.5004.dsal.2025.700007

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Treated wastewater application in urban agriculture

Ahmed Al-Busaidi[1]*, Mushtaque Ahmed[1], Wenresti Gallardo[2], Waad Al-Aghbari[1]

[1]*Department of Soils, Water and Agricultural Engineering, Sultan Qaboos University,*
[2]*Department of Marine Science and Fisheries, College of Agricultural & Marine Sciences,*
P.O. Box 34, Al-Khoud 123, Muscat, Oman
email: ahmed99@squ.edu.om

ABSTRACT

Waste management is one of the most crucial challenges for the governments to control the worst impacts in terms of public health, environmental resources (water and food) and climate change. Therefore, in order to achieve Sustainable Development Goal (SDG) 12, water deficit countries need to look for innovative and sustainable production of food using integrated circular approach (reduce, reuse, recycle) in modern agriculture such as hydroponic and aquaponics systems. Circulating water in a close hydroponic system with fish and vegetable production (aquaponics system) using treated wastewater will contribute to sustainable consumption and production (SCP) in the region. Therefore, the objective of the study was to evaluate the effect of tertiary treated wastewater on plant growth and production using aquaponics system. This approach will enhance the saving of freshwater and used fertilizer in similar agriculture systems. Nine tanks with dimensions of 80×40×40 cm were filled either with freshwater or a mixture of freshwater and treated wastewater at (50:50 and 75:25% ratios). Each tank was stocked 25 pieces of Tilapia with an initial body weight of 49 g. Each tank was connected with another tank of same dimensions that was used to grow lettuce and bean crops on the top layer. Water was circulating between two tanks. No fertilizer was added to all treatments and all tanks got similar amount of fish feed. It was found that tanks with treated wastewater got higher values of metal content due to minerals added from treated wastewater compared to fresh water alone. Therefore, lettuce and bean growth were much better and got higher values of chlorophyll content compared to control tanks. For heavy metal analysis, all waters got similar values with small increase in some elements found in treated wastewater. For the edible part, lettuce grown in treated wastewater got higher value of Fe and Ba compared to control. Similar concentrations were found with bean plants with higher values in treated wastewater compared to freshwater. However, low concentrations of heavy metals were found in the edible parts of all treatments and it was within the international standards. Fish analyses showed that all tested heavy metals were within the safe limit. However, applying this technique in the farming system will help the environment by utilizing treated wastewater and reducing fertilizer applications. Moreover, farmer income will increase since both fish and crops will be produced with minimum resources.

*Keywords***:** Hydroponics; Aquaponics; Fish; Heavy metal; Plant quality

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*Corresponding author

ISBN 0-86689-078-5

1. Introduction

Responsible consumption and production is the stated goal of the Sustainable Development Goal 12 (SDG 12 of the United Nations 2030 Agenda for Sustainable Development). Striving for such a stated goal will ultimately lead to sustainable consumption and production in all sectors of economy and will lead to conservation of energy and water and reduce concerns in achieving food security. In the GCC countries, water is in short supply leading to production of potable water at very high cost using the desalination technology. Because of high standard of living water consumption is among the highest in the world. Food security is achieved through importation of food as the countries are rich. One of the obvious choices for these countries would be to use recycled water (treated wastewater) multiple times for food production in controlled environment. A system using treated wastewater for growing fish and crops (commonly known as aquaponics) achieves the goal of sustainable consumption and production as it involves both water and food. In this paper we will provide details of a research project undertaken at Sultan Qaboos University in Oman which if adopted in a large-scale will result in the realization of SDG 12.

An increasing number of countries are facing economic and physical water scarcity, leading to a growing incapability in feeding their people (WWAP, 2012). On average, global agriculture uses around 70% of the available freshwater resources. In arid climate zones such as the Middle East and North Africa, the agricultural water consumption can even be up to 90% (FAO, 2005). Compared to conventional agriculture, aquaponics uses less than 10% of water, depending on the climatic conditions (Bernstein, 2011). Aquaponics can reduce fresh water depletion associated with irrigation whilst guaranteeing safe encouraging sustainable farming and food production practices, which in turn reduces the freshwater consumption in countries facing water stress. System related water losses that occur in evaporation, plant transpiration and the water content of the agricultural products can be compensated for by capturing water from air humidity (Fraunhofer, 2009) or by reverse osmosis desalination plant in coastal areas (Greenlee et al., 2009).

Global demand for water is expected to grow by 50% in year of 2030. Most of this demand will be in cities and will require new approaches to wastewater collection and management (Arnell, 2004). Indeed, reused wastewater may help address other challenges including food production and industrial development. Treated wastewater is a good source of different plant nutrients for agricultural lands. It can improve soil fertility and crop productivity and minimize the inputs of fresh water and synthetic fertilizers.

In Oman, "Nama Company" is a government company that is responsible for building, operating, and managing wastewater projects in Oman. Disposing of treated wastewater in an environmental friendly way is a major concern for Nama Company and relevant authorities in the country. Furthermore, reusing of treated wastewater produced from the current treatment plants and the future ones in sustainable, economic and environmental friendly ways are very important in country like Oman. Therefore, there is a need to implement comparative and comprehensive studies on potential reuse options for the treated wastewater produced by Nama Company. These options include: urban reuse, agriculture reuse, industrial reuse, ground water recharge, and energy generation. Moreover, there is a gap of knowledge that might affect the public's perception towards wastewater, treatment and reuse and associated risks. Therefore, there is a need to shed light on the level of knowledge and community perceptions about treated wastewater reuse. This is followed by public awareness that can be done through meetings with farmers, home gardeners, and other community groups either by field or site visits, schools visits or through the different media outlets.

In general, use of treated wastewater in agriculture could help in improving the fertility of Oman coarse soil, increasing the yield of different crops and reduce usage of fresh water resources. However, it may contain high concentrations of salts, heavy metals, pathogens, and emerging pollutants with unknown fate and effects on the ecological system. The guidelines did not count for emerging pollutants and limited studies were done to evaluate the presence of pathogens, heavy metals and emerging pollutants in cash crops (such as cucumber and tomato) irrigated by treated wastewater. Therefore, there is a need to evaluate the possible health risks associated with application of treated wastewater in agriculture, aquaculture and home gardeners so clear message and with supported data can be transferred to decision makers, public and different farmers.

Oman lies in an arid region and rainfall is limited and irregular over much of the country which makes fresh water an expensive commodity. Thus, despite an increasing demand for fresh fish the development of fresh water aquaculture is slow, and it needs to be further expanded. In recent years the Oman aquaculture industry has been ginning attention from both public and private sectors. The Ministry of Agriculture, Fisheries Wealth and Water Resources has issued 19 licenses to investors who have met the technical criteria to set up aquaculture projects and the total investment in these projects is valued at OMR 128.8 million (Zafar, 2014).

Aquaculture has been identified as sector that could further diversify the Omani economy beyond primarily hydrocarbons. Oman Government has made the development of aquaculture sector a top priority over the past five years (Prins, 2014). Considering that aquaculture may cause environmental pollution if not done properly, the government is promoting the integrated system which includes aquaponics. In Oman, aquaponics will help to preserve our heritage, while integrating it with the technology to sustain natural resources by minimizing water used in aquaculture and production of fish and crop.

Aquaponics is the combination of aquaculture and hydroponics. It allows the production of fish and plants in one system with big reduction in overall water uses. The two main components of the system are the fish tank and the grow beds with small pump moving water between the two. The water passes through the roots of the plants before draining back into the fish tank. The plants absorb the water with different nutrients coming from fish waste cleaning the water for the fish. There are number of different styles of grow bed designs. The most common designs are flood and drain, and floating raft style (Diver, 2006; Goodman, 2011).

In general, aquaponics system incorporates recirculating aquaculture with the soilless production of plants. The recirculating systems are designed to raise large quantities of fish in relatively small volumes of water by treating the water to remove waste products and then re-using it. As water is recycled beneficial nutrients and organic materials accumulate. These are then channeled into secondary crops in an integrated system. Plants grow rapidly with dissolved nutrients that are excreted by the fish or generated by the microbial breakdown in fish wastes (Rakocy et al., 2006). There are a number of benefits linked to aquaponics. These include: 1) reduced water requirement for intensive fish and plant production, 2) the daily supply of feed to the fish supplies a steady flow of nutrients, which are recovered, after treatment, from the fish tank effluent and used to irrigate crops, 3) shared infrastructure and operating costs, 4) reduced land requirement (Rakocy, 1997).

In recent years, aquaponics has gained popularity in many countries including Saudi Arabia, Oman, Egypt and Algeria. Currently, Sultan Qaboos University is involved in FAO project on the use of non-conventional water in support to sustainable agri-aquaculture development in desert and arid lands in the Near East and North Africa region, particularly in Algeria, Egypt and Oman (Gallardo, 2019). The survey in Oman shows that are already several aquaponic farms that can be categorized into: 1) large-scale commercial farm, 2) medium-scale commercial farm, 3) small-scale (hobby/family) farm, 4) research/demonstration farm.

Tilapia (*Oreochromis niloticus*) is the most commonly used fish in aquaponics systems due to their high availability, fast growth, stress and disease resistance and easy adaptation to indoor environment (Popma and Masser, 1999; Yildiz et al., 2017; Stathopoulou et al., 2018). Treated wastewater (Nama) was tested as a potential replacement for tap water in the future. Lettuce and beans are good vegetables to be grown in aquaponics systems because they grow fast in response to high levels of nutrients in aquaculture water (Rakocy et al., 1997).

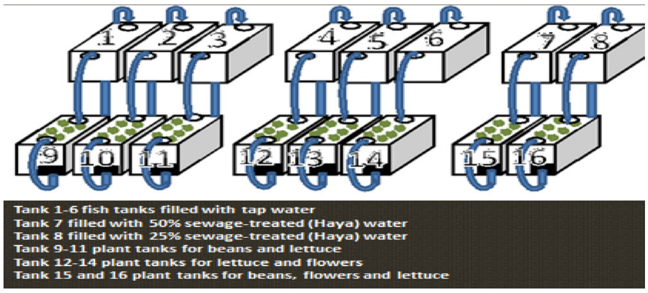

Fig. 1. Simple diagram of the system.

Fig. 2. The aquaponic system.

From other side, in water-scarce regions like Oman, the use of treated wastewater in agriculture will free up, and prevent the contamination of good quality water resources for the use in urban centers and industry. Although the use of treated wastewater in agriculture is encouraged and promoted (Abdelrahman et al., 2011; Alkhamisi et al., 2016). Therefore, the objective of the study was to evaluate the effect of treated wastewater on fish life and later on the effect of the produced effluent coming from fish tank on grown crops.

2. Materials and methods

2.1. System design and operation

The study was done in shade house in college of Agricultural and Marine Sciences at Sultan Qaboos University. The aquaponics system consisted of 16 rectangular tanks with length of 80 cm, width of 40 cm and height of 40 cm and capacity of 100 L as shown in Figs. 1 and 2. The important elements of this aquaponics system were the fish rearing tanks, solid removal filter, a Styrofoam (to cover the tanks and as raft for the plant seedlings), PVC pipe to connect the fish tanks with the solid removal filter tanks (plants tanks). Air stones connected to air blower were installed in the culture tank to supply oxygen for the fish.

The fishes were distributed at density of 25 fish per tank which filled either with tap water or tertiary treated wastewater (treated black water) in ratio of 50:50% or 75:25%. Fish densities of 20 and 30 fish per tank were also used as a comparison for other study. Holes were made in the Styrofoam raft and plant (lettuce and beans) seedlings were planted in them as shown in Fig. 2.

Cotton was used to wrap the roots of the seedling of lettuce and beans in order to aid absorption of the water from the tanks. Moreover, seedlings of flowers were also used as a comparison for other study. A total of 108 seedlings were planted into the 8 tanks. Evaporation was minimized by using Styrofoam to covers each tank. A submersible pump was installed in each tank to return the filtered water back to fish tank.

Constant aeration was provided at fish tank. No water was added or removed during the study. The fish was fed three times a day and water was circulated between each two tanks. Weekly analyses were done for water salinity, dissolved oxygen and pH. Plant growth was monitored and data for chlorophyll using CCM-200 devise was taken. At the end of the study, plants were harvested and different parameters were measured such as: ammonia, nitrate, nitrogen, microbiological analysis and other metal analysis using ICP machine.

3. Results and discussion

3.1. Fish growth

Initial average weight of 40 randomly selected tilapia was 49.4 g and the final average weights of tilapia in both treatments (tap water and treated wastewater) are shown in Figs. 4 and 5. Fig. 3 shows the average weight of fish grown during the 6 weeks of experiment. The weight of fish increased significantly among weeks but the final weight was not significantly different ($P > 0.05$) among densities. According to Roy (2002) and Rashid (2008) the relationship between weight gain and stocking density is inverse but our results show no significant difference which indicate that in aquaponics system, higher fish densities can be used. Many studies confirmed that tilapia performed well in the aquaponic system (Rakocy et al., 2004).

The weight of fish increased significantly among weeks in all treatments but there was a significant difference ($P < 0.05$) between two systems (tap water and treated wastewater) in term of weight gain. We clearly observed that fish weight in treated wastewater was greater than tap water tanks (Fig. 4). This needs further investigation on the elements available in treated wastewater that may enhance fish growth.

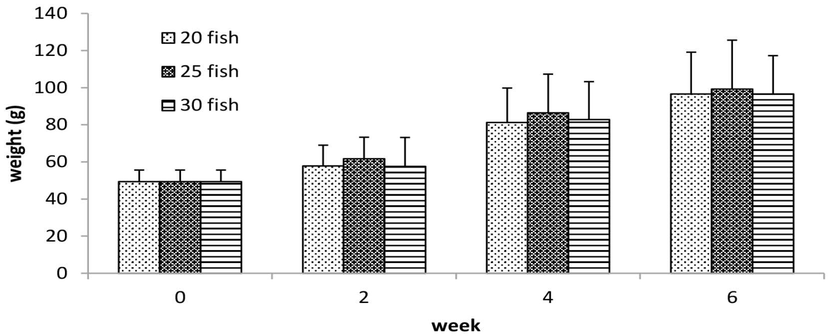

Fig. 3. Growth of fish at densities of 20, 25, and 30 fish/tank during the 6 weeks experiment period. Bars show the average weight and error bars are standard deviation.

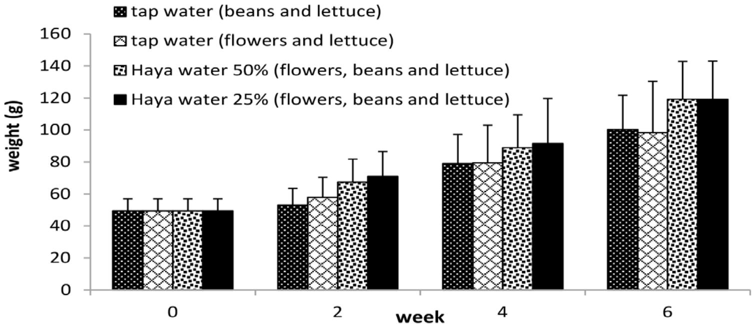

Fig. 4. Growth of fish at densities of 25 fish/tank in different culture systems: 1) tap water with beans and lettuce, 2) tap water with lettuce and flowers, 3) 50% treated wastewater with beans, lettuce and flowers, 4) 25% treated wastewater with beans, lettuce and flowers. Bars show the average weight and error bars are standard deviation.

The final weight of fish grown with beans and lettuce was found to be the highest (100 g) in 25 fish/tank and the lowest (87.08 g) in tank 20 fish/tank (Fig. 5). Whereas, the final weight of tilapia grown with lettuce and flowers was found to be the highest (106.18 g) in 20 fish/tank and the lowest (98.26 g) in 30 fish /tank. On other hand, the final weight of fish in treated wastewater was higher than in tap water which was 119 g in both tanks. The final weight of fish in tap water was not significantly different among fish density but there was significant difference between tap and treated wastewater.

The present study demonstrated that the aquaponics system used in this study was effective in fish waste treatment and water conservation in the period of 6 weeks. Growth of fish was high in all fish densities even at the treatment of treated wastewater which can be a potential replacement for tap water.

The percentage weight gain of fish grown in combination with beans and lettuce was 100% in tank 2 (50.5 g) and lowest in tank 1 (70%). The percentage weight gain of tilapia grown in combination with flowers and lettuce was highest in tank 4 (115%) and lowest in tank 6 (98.9%). On other hand, it was observed that the treated wastewater resulted in higher weight gain than tap water (Fig. 6).

The average specific growth rate (SGR) of fish in tap water was 1.2 with the highest in rearing tank 4 (1.4) and the lowest in tank 1 (0.9) but the treated wastewater had the highest specific growth rate compared to tap water (Fig. 7).

3.2. Water quality

Oxygen is essential for all three organisms involved in aquaponics; plants, fish and nitrifying bacteria all need oxygen to live. Dissolved oxygen (DO) level describes the amount of molecular oxygen within the water, and it is measured in milligrams per liter. It is the water quality parameter that has the most immediate and drastic effect on aquaponics. Indeed, fish may die within hours when exposed to low dissolved oxygen within the fish tanks. Thus, ensuring adequate dissolved oxygen levels is crucial to aquaponics. Whenever the dissolved oxygen gets down that mean it may contain some microbes or contaminants and it is un-healthy water for the fish. For Fig. 8, it can be seen that dissolved oxygen level was vary with time and almost all treatment got similar concentrations. However, some time it was found that treatments that had treated wastewater got higher values of dissolved oxygen and that due to algae growth that was enhancing production of dissolved oxygen through photosynthesis. From other side and sometimes, high density of algae blocked some pipelines and reduced water circulated between tanks which affect dissolved

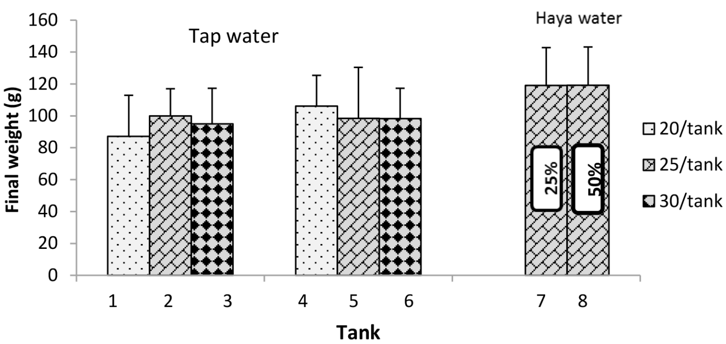

Fig. 5. Final average weight of fish in each tank after six weeks. Bars show the average weight and error bars are standard deviation. Bars show the average weight and error bars are standard deviation.

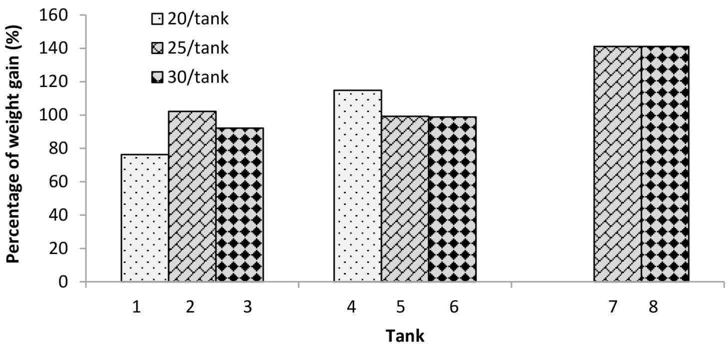

Fig. 6. Percentage of weight gain of fish after 6 weeks in each tank (final-initial/initial weight ×100).

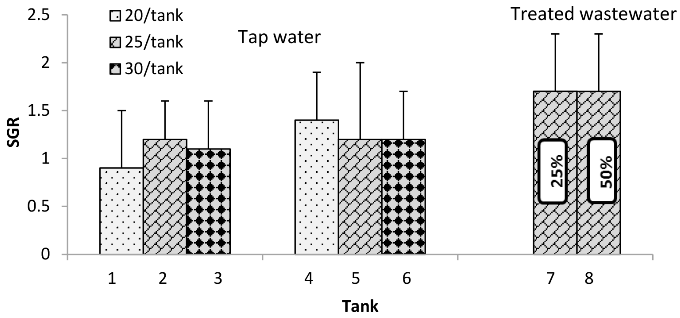

Fig. 7. Specific growth rate (SGR) of fish in 42 d at different fish density. Bars show the average SGR and error bars are standard deviation.

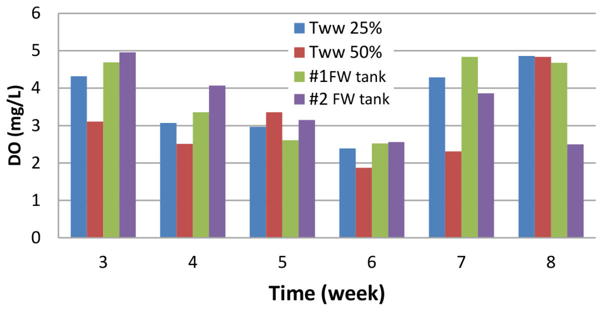

Fig. 8. Weekly changes in dissolved oxygen of all treatments.

oxygen values and that was happening in tank with 50% treated wastewater.

Optimum levels of dissolved oxygen are 4–8 mg/L. Nitrification will decrease if dissolved oxygen concentrations drop below 2.0 mg/L. Moreover, without sufficient dissolved oxygen concentrations, another type of bacteria can grow, one that will convert the valuable nitrates back into unusable molecular nitrogen in an anaerobic process known as denitrification (Munguia-Fragozo, et al., 2015).

Oxygen is essential for all three organisms involved in aquaponics; plants, fish and nitrifying bacteria all need oxygen to live. The dissolved oxygen level describes the amount of molecular oxygen within the water, and it is measured in milligrams per liter. It is the water quality parameter that has the most immediate and drastic effect on aquaponics. Indeed, fish may die within hours when exposed to low dissolved oxygen within the fish tanks. Thus, ensuring adequate dissolved oxygen levels is crucial to aquaponics. Although monitoring dissolved oxygen levels is very important, it can be challenging because accurate dissolved oxygen measuring devices can be very expensive or difficult to find. It is often sufficient for small-scale units to instead rely on frequent monitoring of fish behavior and plant growth, and ensuring water and air pumps are constantly circulating and aerating the water (Timmons and Ebeling, 2010; Munguia-Fragozo, et al., 2015).

Water quality in aquaponics including carp and tilapia, can tolerate dissolved oxygen levels as low as 2–3 mg/L, but it is much safer to have the levels higher for aquaponics, as all three organisms demand the use of the dissolved oxygen in the water (Timmons and Ebeling, 2010).

Water salinity should be constant with small increase due to evaporation process or salts coming from fish food or fish waste. Moreover, treated wastewater is rich of many nutrients so it could add some extra salts to the tanks. As it was expected and shown in Fig. 9, water salinity was increasing until plants start to utilize those salts as nutrients for its growth. However, the original values were close to the third week data with small increase with time (FW: 0.4 mS/cm and Tww 5%: 0.45 mS/cm).

There are many biological and chemical processes that take place in an aquaponics system that affect the pH of the water, some more significantly than others, including: the nitrification process; fish stocking density; and phytoplankton (Timmons and Ebeling, 2010, Zou, et al., 2016).

It can be seen from Fig. 10 that water pH ranged from 6 to 8 then it starts to decrease in week 7. The fresh water tanks had higher values of pH compered to treated wastewater tanks. However, tank of 25% treated wastewater reached the lowest values of pH 5 in week 8, which almost acidic condition that could affect the

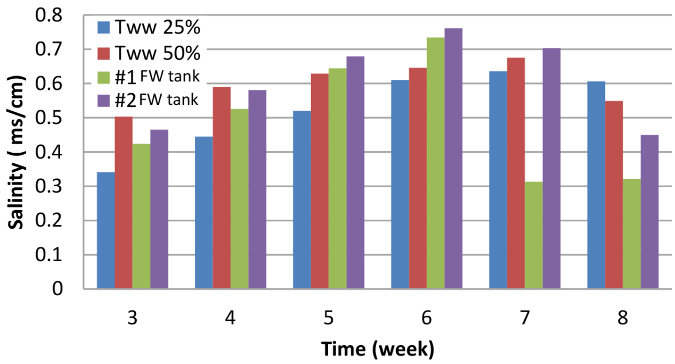

Fig. 9. Weekly changes in water salinity of all treatments.

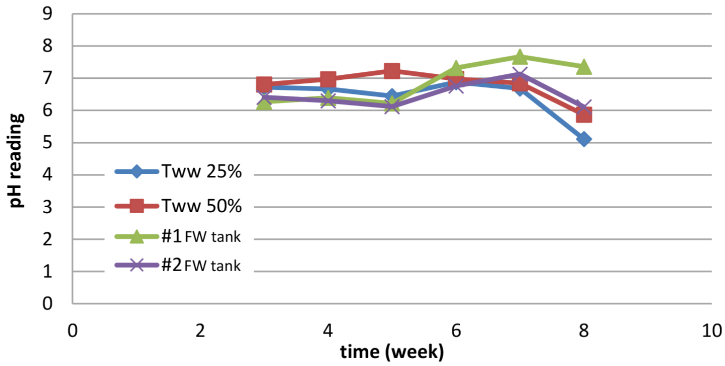

Fig. 10. Weekly changes in water pH of all treatments.

absorbance of some plant nutrients. In all cases, no big changes in water pH in the excited short study.

Most plants need a pH value between 6 and 6.5 in order to enhance the uptake of nutrients. The fish species Tilapia (*Oreochromis*) is known to be disease-resistant and tolerant to large fluctuations in pH value with a tolerance between pH 3.7 and 11, but achieves best growth performance between pH 7.0 and 9.0 (McAndrew et al., 2000). The ideal pH value for the system is between 6.8 and 7.0. Although root uptake of nitrate raises pH as bicarbonate ions are released in exchange (Kaiser et al., 2011), the acidity producing nitrification process has a higher impact on the overall system pH, leading to a constant and slight decrease in the pH-value.

It was reported by Zou et al. (2016) that water pH has a major impact on all aspects of aquaponics, especially the plants and bacteria. For plants, the pH controls the plants' access to micro- and macronutrients. At a pH of 6.0–6.5, all of the nutrients are readily available, but outside of this range the nutrients become difficult for plants to access. In fact, a pH of 7.5 can lead to nutrient deficiencies of iron, phosphorus and manganese. This phenomenon is known as nutrient lock-out. Nitrifying bacteria experience difficulty below a pH of 6, and the bacteria's capacity to convert ammonia into nitrate reduces in acidic, low pH conditions. This can lead to reduced biofiltration, and as a result the bacteria decrease the conversion of ammonia to nitrate, and ammonia levels can begin to increase, leading to an unbalanced system stressful to the other organisms. Fish have specific tolerance ranges for pH as well, but most fish used in aquaponics have a pH tolerance range of 6.0–8.5. However, the pH affects the toxicity of ammonia to fish, with higher pH leading to higher toxicity.

In general, the ideal aquaponic water is slightly acidic, with an optimum pH range of 6–7. This range will keep the bacteria functioning at a high capacity, while allowing the plants full access to all the essential micro- and macronutrients. pH values between 5.5 and 7.5 require management attention and manipulation through slow and measured means. However, a pH lower than 5 or above 8 can quickly become a critical problem for the entire ecosystem and thus immediate attention is required (Timmons and Ebeling, 2010; Zou, et al., 2016).

Ammonia analysis of last day of the study (Table 1) showed that treated wastewater (25%) had the highest value of Ammonia. Whereas, treated wastewater (50%) got the highest values of phosphate. It was expected since treated wastewater is rich of different nutrients that can move and transform form one compound to another. However, ammonia is toxic to fish. It is one of the major enemies for aquaculture where it is considered to be lethal even at low concentrations (Goddek et al., 2019; Su et al., 2020). Tilapia and carp can show symptoms of ammonia poisoning at levels as low as 1.0 mg/L. Prolonged exposure at or above this level will cause damage to the fishes' central nervous system and gills, resulting in loss of equilibrium. Other symptoms include red streaks on the body, lethargy and gasping at the surface for air. At higher levels of ammonia, effects are immediate and numerous deaths can occur rapidly. However, lower levels over a long period can still result in fish stress, increased incidence of disease and more fish loss.

In our case the level of ammonia was above than 1.0 mg/L but no bad effects were observed in fish life. It could be due continuous aeration and good plant growth which act as a filter and reduce the side effect of high ammonia. From other side, ammonia could be converted to nitrate (NO_3^-) that is less toxic to aquatic life as shown in Table 1.

Table 1
Ammonia, phosphate and nitrate in aquaponics tanks (mg/L)

Sample	Ammonia	Phosphate	Nitrate (NO_3^-)
Treated wastewater 25%	1.34	3.55	380
Treated wastewater 50%	1.11	3.78	260
Fresh water #1	0.03	1.82	150
Fresh water #2	0.14	3.07	180

Nitrate is a far less toxic than the other forms of nitrogen. It is the most accessible form of nitrogen for plants, and the production of nitrate is the goal of the biofilter. Fish can tolerate levels of up to 300 mg/L, with some fish tolerating levels as high as 400 mg/L. High levels (> 250 mg/L) will have a negative impact on plants, leading to excessive vegetative growth and hazardous accumulation of nitrates in leaves, which is dangerous for human health. It is recommended to keep the nitrate levels at 5–150 mg/L and to exchange water when levels become higher (Timmons and Ebeling, 2010; Zou, et al., 2016; Khiari et al., 2020).

The equilibrium in the aquaponic system can be compared with balancing scale where fish and plants are the weights standing at opposite arms. The balance's arms are made of nitrifying bacteria. It is thus fundamental that the bio-filtration is robust enough to support the other two components. This corresponds to the thickness of the lever in note that the arms were not strong enough to support the amount of fish waste and that the arm broke. This means that the biofiltration was insufficient. If the fish biomass and biofilter size are in balance, the aquaponic unit will adequately process the ammonia into nitrate. However, if the plant component is undersized, then the system will start to accumulate nutrients. In practical terms, higher concentrations of nutrients are not harmful to fish nor plants, but they are an indication that the system is underperforming on the plant side (Timmons and Ebeling, 2010; Zou, et al., 2016).

High values of heavy metals are not recommended especially in the edible part of the plant. It can be seen in Fig. 11 that all measured values had low concentrations except for B, Fe and Zn. There were higher in treated wastewater compared to fresh water. However, all concentrations for all treatments were close from each other which mean the source of those elements could be fish food or waste but not treated wastewater only. Therefore, monitoring is required to make sure that used water is not casing any health problem to fish or grown plants which later will be reflected in human health. The proportions of the elements in the water used

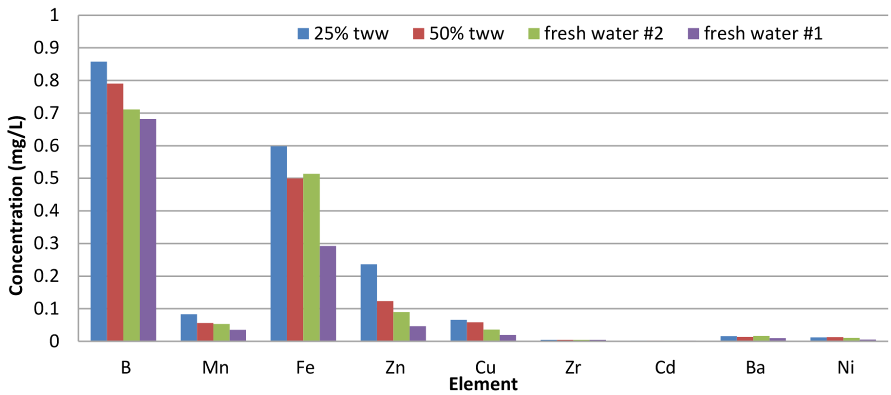

Fig. 11. Average elements concentrations of all treatments

Table 2
Microbial analysis

Sample	Coliforms	Most probable number (MPN) of the Coliform bacteria	E-Coli
Treated wastewater 25%	50	200.5	0
Treated wastewater 50%	50	200.5	0
Fresh water #1	50	200.5	0
Fresh water #2	50	200.5	0

in hydroponics and aquaponics may vary according to several opinions of scientists (Moaed, 2022).

Usually, biological analyses are direct indicators for microbial contamination. In this study, Coliform bacteria was expected to be found because it is existed in fish waste (Table 2). However, E-Coli was not found and that was a good indicator for good quality of all used waters.

3.3. Plant analysis

Chlorophyll data is a good indicator for nitrogen values in plant tissues. It can be seen from Fig. 12 that all measured data for all treatments had good values of nitrogen and even higher with treated wastewater treatments which also confirmed by measured nitrogen shown in Table 3. This can be explained by nitrogen provided to the plants from fish waste and treated wastewater.

Table 3
Nitrogen values on lettuce plant

Treatment	Nitrogen %
Treated wastewater 25%	3.82
Treated wastewater 50%	3.70
Fresh water	3.56

Since no chemical fertilizer was add to all treatments so plants were relaying on nutrients coming from fish waste and available in treated wastewater. Therefore, it can be seen from Fig. 13 that treated wastewater treatments gave better growth for lettuce plants compared to fresh water treatment.

Nitrogen is supplied to aquaponic plants mainly in the form of nitrate, converted from the ammonia of fish waste through bacterial nitrification. Some of the other nutrients are dissolved in the water from the fish waste, but most remain in a solid state that is unavailable to plants. The solid fish waste is broken down by heterotrophic bacteria; this action releases the essential nutrients into the water. The best way to ensure that plants do not suffer from deficiencies is to maintain the optimum water pH 6–7 and feed the fish a balanced and complete diet, and use the feed rate ratio to balance the amount of fish feed to plants (Hu, et al., 2015).

The most sensitive part for human consumption in each crop is the edible part. It can be seen from Fig. 14 that both crops lettuce and bean got similar values for all measured elements which is a reflection for what was found in irrigation waters. Elements of B, Fe were found in high concentrations for all treatments which could be a limited factor for crop consumption. However, other elements such as Ni, Zn and Cu can be found in higher concentrations in treated wastewater compared to fresh water but in general, the difference was small. In Selem et al. (2000) study, they observed an increase in Fe, Zn, Cu, Mn, Pb and Co with land irrigated with treated wastewater as compared to untreated soil. The accumulation of heavy metals in the edible part of some plants could adversely affect human and animal health (Abd-Elfattah et al., 2002). In present study, the increase

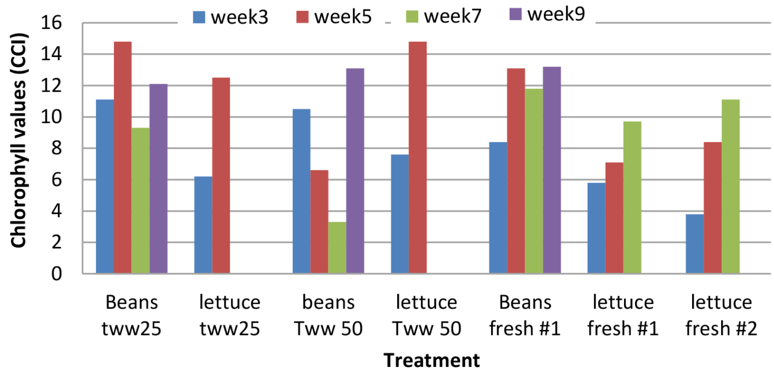

Fig. 12. Chlorophyll content of all treatments.

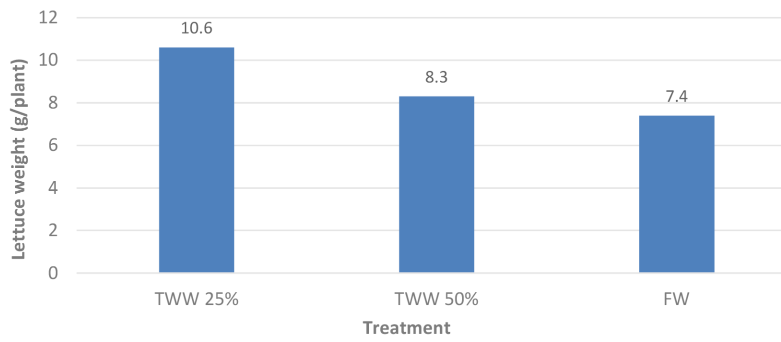

Fig. 13. Lettuce growth as affected by different treatments.

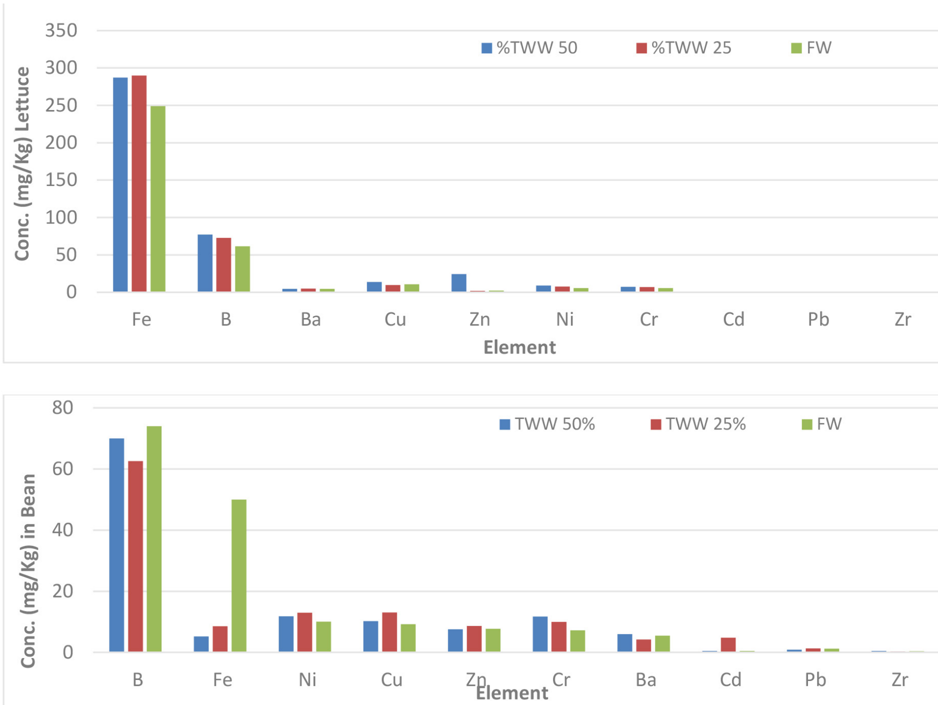

Fig. 14. Average elements concentrations in lettuce and bean shoots.

in heavy metals with treated wastewater was small compared to fresh water and nothing was reflected in plant and fish lives. In addition to that, the grown fishes were tested and measured values related to health issues were within the acceptable limit of international standards. However, monitoring is required to avoid any health problems.

Tyson et al., (2011) reported that plants need macronutrients (e.g., C, H, O, N, P, K, Ca, S and Mg) and micronutrients (e.g., Fe, Cl, Mn, B, Zn, Cu and Mo), which are essential for their growth. In aquaponics systems, plant nutrient input from the fish tanks contains dissolved nutrient rich fish waste (gill excretion, urine and faeces), comprising of both soluble and solid organic compounds that are solubilized to ionic form in the water and assimilated by the plants. To sustain adequate plant growth the concentrations of micro- and macronutrients need to be monitored. Aquaponic systems need to be able to host different microorganism communities that are involved in fish waste processing and solubilization. Ammonia (NH_4^+) from fish urine and gill excretion can build up to toxic levels if not removed from the system. This can be done by step-wise microbial conversion to nitrate. One of the most important microbial components is the nitrifying autotrophic bacteria consortium that is established as a biofilm on solid surfaces within the system and is principally composed of nitroso-bacteria (e.g., *Nitrosomonas* sp.) and nitro-bacteria (e.g., *Nitrospira* sp., *Nitrobacter* sp.). The ammonia within the system is converted into nitrite (NO_2^-) by nitroso-bacteria, before being transformed into nitrate (NO_3^-) by the nitro-bacteria (Tyson et al., 2008). The final product of this bacterial conversion, nitrate, is considerably less toxic for fish and due to its bioconversion, is the main nitrogen source for plant growth in aquaponics systems (Endut et al., 2014).

Finally, it is clear that aquaponics is most appropriate where land is expensive, water is scarce, and soil is poor. Examples are: deserts and arid areas, sandy islands and urban gardens are the locations most appropriate for aquaponics because it uses an absolute minimum of water. There is no need for soil, and aquaponics avoids the issues associated with soil compaction, salinization, pollution, disease and tiredness. Similarly, aquaponics can be used in urban and peri-urban environments where no or very little land is available, providing a means to grow dense crops on small balconies, patios, indoors or on rooftops. Aquaponics food products are chemical-free with zero use of hormones, pesticides/fungicides or antibiotics (Berillis et al., 2018).

4. Conclusion

The project described the possibility of producing crops in aquaponics system using both fish waste and treated wastewater. Both sources enriched the media with many nutrients needed for the plant growth. Some heavy metals were accumulated in the irrigation water which was reflected in grown crops. The concentrations of heavy metals in fresh water and treated wastewater were close from each other indicating that diluted wastewater can be used safely in aquaponics system. Therefore, the system used in this study can provide plants with needed nutrients and produce safe crops with minimum risk. The system is simple and can be implemented in small area. It is environment friendly, help in saving fresh water and maximizing the application of treated wastewater with no or minimum need for chemical fertilizers. However, monitoring with good managements is required to avoid any health issues.

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Balaban Desalination Publications

The 15th Gulf Water Conference

(2024) 263–271
doi: 10.5004.dsal.2024.700090

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Towards sustainable water management: Leveraging soil moisture sensors for smart irrigation in the GCC

Hassan Ali[1,*], Rachid Benlamri[1], Aitazaz A. Farooque[2,3], Farhat Abbas[1], and Raziq Yaqub[4]

[1]*Centre of Excellence for Food Security and Sustainability, University of Doha for Science and Technology, Doha, Qatar, email: hassan.ali@udst.edu.qa,*

[2]*Canadian Centre for Climate Change and Adaptation, University of Prince Edward Island Charlottetown, Canada,*
[3]*Faculty of Sustainable Design Engineering, University of Prince Edward Island Charlottetown, Canada,*
[4]*Department of Electrical Engineering and Computer Science, Alabama A&M University, USA.*

ABSTRACT

Efficient water management in agriculture is paramount in the arid and semi-arid regions of the Gulf Cooperation Council (GCC) countries. Soil moisture sensors-based irrigation scheduling has emerged as a crucial tool for optimizing irrigation practices, conserving water resources, and improving crop yields. This paper delves into the application of soil moisture sensors for smart irrigation scheduling in the GCC, discussing their types, benefits, challenges, and relevant research and development (R&D) efforts demonstrating their successful implementation in this region. The authors identify several key areas of concern and provide a roadmap for future research endeavors in maximizing the potential of soil moisture sensors for efficient water management and smart irrigation in the GCC region.

Keywords: Soil moisture sensors, soil moisture monitoring, irrigation scheduling, smart irrigation, precision agriculture, water management, GCC

1. Introduction

The Gulf Cooperation Council (GCC) is a regional intergovernmental political and economic union of six Arab states in the Persian Gulf: Bahrain, the Sultanate of Oman, Kuwait, Qatar, Saudi Arabia, and the United Arab Emirates (UAE). The GCC nations grapple with formidable water scarcity challenges due to their arid climate and limited freshwater resources [1]. Efficient water management is critical, particularly in agriculture, which consumes a substantial portion of available water.

Soil moisture sensors [2–4] represent a significant advancement in agricultural technology, enabling continuous monitoring of soil moisture levels and providing valuable insights into dynamic water dynamics crucial for crop health. By leveraging real-time data from these sensors, stakeholders can establish precise moisture thresholds aligned with the water demands of various crops, optimizing irrigation timings and mitigating risks associated with inadequate or excessive watering. The adoption of soil moisture sensors not only conserves water resources and enhances agricultural productivity but also leads to energy savings and reduced ecological footprints.

Despite their predominance in regions like the United States, Australia, and Canada, the use of soil moisture sensors for smart irrigation scheduling is steadily growing in the GCC states. This paper explores the role of soil moisture sensors in addressing water challenges through soil moisture sensors based smart

*Corresponding author.

irrigation scheduling in the GCC region, examining relevant research and development efforts, identifying challenges and gaps, and proposing recommendations for advancing efficient water management practices.

2. Smart irrigation

A soil moisture-based smart irrigation system represents a cutting-edge solution for optimizing water usage in agriculture. These systems integrate soil moisture sensors with wireless communication and IoT technologies to precisely determine and deliver water where and when it's needed most. By harnessing real-time data, these systems ensure optimal plant health while minimizing water wastage.

Soil moisture sensors, strategically placed at various depths in the soil, accurately measure moisture content using capacitance or resistance-based technologies. Connected to a wireless network, typically Zigbee, LoRa, Wi-Fi, or Bluetooth, these sensors transmit data to a central control system. This system, acting as the hub of the irrigation network, collects sensor data and autonomously makes decisions regarding irrigation timing and volume.

Utilizing cloud-based platforms accessible via the internet, farmers and irrigation managers can remotely access and analyze data collected by the sensors. Advanced algorithms, coupled with analytics and additional parameters like weather forecasts and crop water requirements, optimize irrigation schedules in real-time. Machine learning algorithms further refine these schedules based on historical data and evolving conditions.

Irrigation is triggered automatically when soil moisture levels dip below predefined thresholds, ensuring plants receive water precisely when necessary. Some systems incorporate solar-powered components for enhanced energy efficiency.

Accessible through mobile apps or web interfaces, users can monitor soil moisture levels, adjust irrigation parameters, and receive alerts for system anomalies or extreme weather events. The system's scalability allows for adaptation to different field sizes, with the flexibility for farmers to remotely fine-tune irrigation settings.

3. Soil moisture sensors

Soil moisture sensors are divided into two categories based on the technology they use: 1) Volumetric water content soil moisture sensors and 2) Soil water tension or matric potential sensors.

3.1. *Volumetric water content soil moisture sensors*

Volumetric water content (VWC) represents the volume of liquid water per unit volume of soil, typically expressed as a percentage. Generally, crops experience stress when soil water depletion reaches 30%–50% of the available water holding capacity (AWC), termed as Management Allowable Depletion (MAD). Irrigation should commence when the

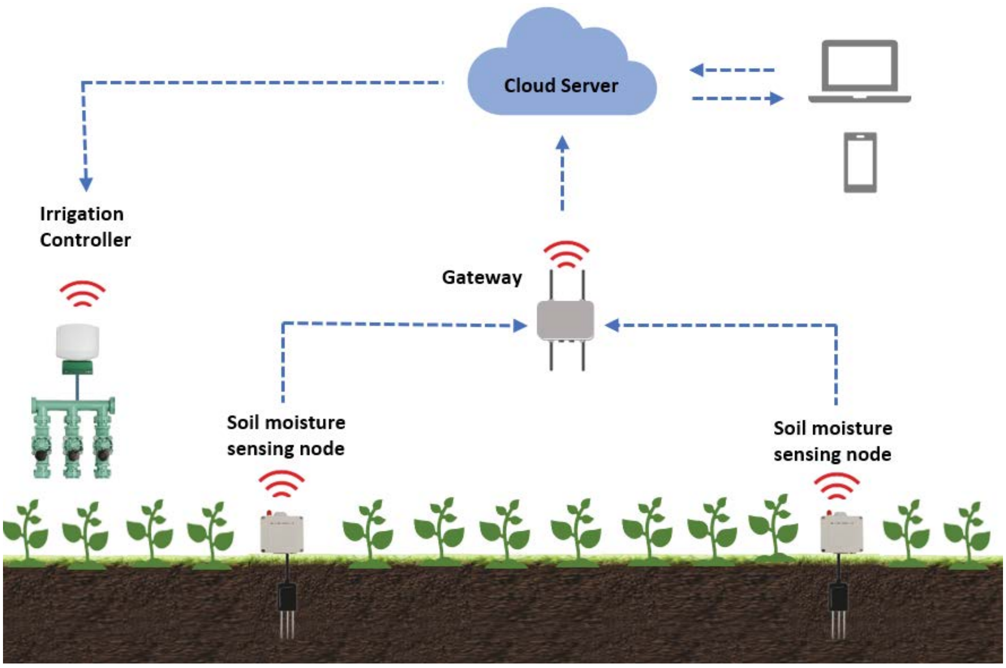


Fig. 1. A smart irrigation scheduling system.

percentage of soil water depletion aligns with or nears the MAD threshold.

Volumetric water content (VWC) serves as a basis for calculating the percentage of soil water depletion using the following formula [5]:

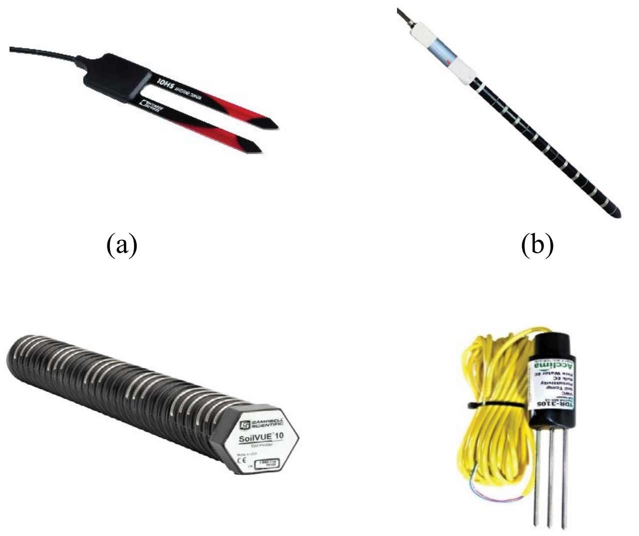
$$\% \text{ Soil water depletion} = \left[1 - \left(\frac{\text{Sensor VWC}(\%) - \text{PWP}(\%)}{\text{FC}(\%) - \text{PWP}(\%)}\right)\right] \times 100 \quad (1)$$

where PWP is a permanent wilting point and FC is field capacity.

The most common types of VWC sensors in use are capacitance sensors, also known as Frequency Domain Reflectometry (FDR) sensors [10], and Time Domain Reflectometry (TDR) sensors [11]. These sensors employ indirect methods to assess VWC by analyzing the soil's dielectric and electrical properties, such as soil bulk permittivity or soil dielectric constant.

3.2. Soil water tension or matric potential sensors

Soil water tension represents the energy needed by plant roots to draw water from soil particles. As soil water diminishes, tension within the soil increases. This tension is typically quantified in centibars or bars of atmospheric pressure, with minimal tension occurring when the soil is saturated with water. Two prevalent types of soil tension sensors are tensiometers and electrical resistance sensors [12–14].



(a) (b) (c) (d)

Fig. 2. VWC sensors: (a) a capacitance sensor [6], (b) a multi-depth capacitance sensor [7], (c) a SoilVue 10TDR soil moisture and temperature profile sensor [8], (d) a TDR sensor [9].

(a) (b)

Fig. 3. Matric potential sensors: (a) tensiometer with vacuum gauge and (b) watermark granular matrix electrical resistance sensor [15].

An extensive range of soil moisture sensors have been commercialized for irrigation scheduling. Table 1 presents the summary list of the most commonly used commercially available VWS and soil tension moisture sensors, including their advantages disadvantages, and costs.

4. Methodology

Several successful R&D initiatives demonstrate the effective implementation of soil moisture sensors for irrigation scheduling in the GCC region. To search for relevant R&D work in the Gulf countries, the methodology largely depended on major contributions from scholarly literature. We conducted a pilot search based on the specific keywords, and we decided to use soil moisture sensors, smart irrigation, irrigation scheduling, and country names in the search string. Internet research has been performed by using Google scholar to collect information, MDPI, Elsevier, and IEEE Xplore. The obtained results were compiled manually to get the best sources for literature search, review, and further analysis.

5. R&D efforts

5.1. Smart irrigation in the Kingdom of Saudi Arabia

The irrigation sector in the Kingdom of Saudi Arabia (KSA) faces numerous challenges, including limited water resources, high salinity and alkalinity of irrigation water, inefficient practices, and competition for water resources across sectors [16]. These challenges have resulted in reduced agricultural yields and abandonment of arable lands. Soil moisture sensors offer a promising solution to these issues by enabling more efficient irrigation practices. Efforts have been made to manage irrigation water more effectively, with studies highlighting the critical role of soil moisture sensors, particularly in implementing smart irrigation scheduling practices within KSA.

Table 1
Summary list of commercially available soil moisture sensors

Types	Commercial sensors	Advantages	Disadvantages	Cost
Capacitance or frequency domain sensors	Spectrum SMEC300, SM100 Sentek Enviroscan, Diviner 2000 METER 5TE, 5TN	Rapid response time Lower cost compared to TDR Remote accessibility Suitable for high saline soils High accuracy with site calibration	Small sensing area Preferential site/soil-specific calibration Affected by soil conditions: salinity, clay content, temperature, bulk density	$250–400 per sensor
TDR	Acclima true TDR 315, 315L,310 S Spectrum Field Scout TDR; CS 655, 650	Very accurate Remote access of data available Soil/site calibration usually not required	Expensive technology A very small area of influence	$250–400 per sensor
Tensiometers	Irrometer tensiometers	Inexpensive Available in various lengths Unaffected by salinity	Limited operative range for fine-textured soils Requires frequent maintenance Slow response time to soil water changes Manual readings and data collection Not suitable for cold temperatures	$80 per sensor $150 - $170 for transducer
Granular matrix sensors	Irrometer watermark sensors	Good accuracy in medium to fine soils Remote data logging and retrieval Large soil tension range Inexpensive Continuous measurement at the same location	Sensitive to temperature and salinity Less accurate in sandy soils Relatively slow response time Requires calibration for each soil type	$40–60 per sensor

One notable initiative, the RIWA project initiated in 2010 by the National Agricultural Development Company (NADC) and Dacom in collaboration with the Ministry of Agriculture of Saudi Arabia, monitored soil moisture at various farms across the country [17]. This project resulted in significant water savings of 30%–75% and yield improvements of 10%–25%.

A study [18] conducted by the Department of Soil Sciences at King Saud University and Al-Mohawis's Agriculture Farm investigated the influence of different factors on soil moisture measurements using ECH2O-5TE sensors. These sensors performed well under specific soil salinity and temperature conditions, with acceptable results obtained within certain ranges. An empirical equation was proposed to correct for the influence of salinity and temperature, taking soil texture into account.

In Ragheid et al. [19], presented a wireless automated irrigation system based on soil moisture sensors for wheat crops, demonstrating improved plant growth and soil condition while achieving a 25% increase in water use efficiency.

King Abdullah University of Science and Technology (KAUST) developed a high-tech soil moisture sensor using a metal-organic framework (MOF) that exhibited excellent water capture capabilities [20]. Field tests are planned to further evaluate its performance.

In [21], the authors designed and calibrated a low-cost capacitive soil moisture sensor for use in controlled greenhouses, demonstrating reliable performance in clay soils. Future research aims to expand its applicability to different soil types and develop an automated irrigation system using deep learning.

Shabana et al. [22] proposed an IoT-based automated wastewater irrigation system capable of real-time soil and atmospheric temperature measurement and data transmission via Wi-Fi and IoT servers.

These initiatives underscore the transformative potential of soil moisture sensors in addressing irrigation challenges in KSA, paving the way for more sustainable and efficient agricultural practices.

5.2. Water management and food security in Qatar

Qatar faces significant challenges as a water-scarce and arid region, compounded by demographic and socio-economic pressures. Cultivating food crops is particularly challenging due to limited water supply and arable land availability. The heavy reliance on imported grains and food items makes the country vulnerable to fluctuations in international commodity markets, exacerbating concerns about food security and self-sufficiency.

The Qatar National Strategy for Food Security 2018–2023 [23] consolidates efforts across authorities to optimize natural resources, strengthening food security resilience against emergencies, trade shocks, and supply chain disruptions. The Ministry of Municipality and Environment (MME) supports research and development in food production, while educational institutions like the University of Doha for Science and Technology (UDST) and Qatar University have established centers and programs focusing on food security, sustainability, crop production, soil improvement, and water reuse.

The Qatar National Research Fund (QNRF), in collaboration with the MME, has launched joint initiatives, including funding sustainable smart irrigation practices for key crops under the 3rd Cycle of the Food Security Call [24] - UDST project "*Development of smart agricultural technologies to optimize resource allocation to ensure food security*". The project integrates soil moisture sensors, data loggers, and AI-based crop water requirements to optimize water management. Comparative studies against traditional irrigation methods aim to quantify water savings without compromising crop productivity.

Various types of soil moisture sensors have been deployed in commercial settings, with studies, such as [25], demonstrating the efficacy of standalone fuzzy logic-based smart irrigation systems for crops like cucumbers.

The state of Qatar is investing in centralized smart irrigation systems to reduce water wastage in urban gardens and parks [26]. These systems utilize real-time weather and soil moisture data for precise irrigation scheduling, contributing to water efficiency and environmental sustainability.

Additionally, innovative concepts like the smart sustainable greenhouse model [27], powered by solar energy and incorporating soil moisture sensing, showcase Qatar's commitment to sustainable agriculture practices.

5.3. Precision irrigation management in the UAE

The United Arab Emirates (UAE) faces challenges due to its climate characterized by high temperatures, low rainfall, and limited freshwater resources. This has resulted in increasing demands from domestic, industrial, and agricultural sectors, leading to a sharp decline in groundwater resources. Water scarcity poses significant obstacles to agriculture, landscaping, and maintaining green spaces. Conventional irrigation methods often contribute to excessive water usage and inefficiency. In response, smart irrigation systems have emerged as a promising solution [28].

An example of smart irrigation technology is the smart irrigation management system deployed in Abu Dhabi's Masdar City. This system utilizes AI algorithms to monitor and regulate irrigation based on weather forecasts, soil sensors, and plant requirements. By doing so, it reduces water consumption, promotes optimal plant growth, and contributes to sustainable water management practices [29].

In [30,31], researchers evaluated the potential water savings achievable through smart irrigation compared to conventional irrigation systems used in Warsan Nursery in Dubai, UAE. The study focused on comparing a Smart Irrigation System (SIS) with a timer Controlled Irrigation System (CIS) to assess their impact on irrigation water consumption and vegetation health. The SMRT-Y system utilized in this research incorporated a smart soil moisture sensor to measure soil moisture levels. The SIS, based on these measurements, determined the timing and quantity of irrigation water required to conserve water and improve vegetation health. The results demonstrated changes in water consumption ranging from –26.48% to +23.47%, with an overall reduction of 5.76% over the experiment's duration. Additionally, the SIS contributed to enhancing the health of the vegetation, particularly the grass [30].

In [31], researchers evaluated a wireless capacitive sensor's effectiveness in irrigating greenhouse tomato and cucumber crops in Abu Dhabi to develop an irrigation scheduling program. The study compared irrigation amounts, yields, and water use efficiency between the capacitive sensor system and three other irrigation methods derived from the FAO Penman-Monteith method. Results indicated that the capacitive sensor provided accurate irrigation amounts and yielded the best crop yields. Furthermore, data from the sensor system aided in devising suitable irrigation schedules for the two crops in Abu Dhabi.

5.4. Smart Irrigation in Oman

Oman, situated in the southeastern part of the Arabian Peninsula, experiences a climate characterized by low rainfall and high temperatures for most of the year.

The study [32] outlined the design and implementation of an automated irrigation system for small to medium-scale farms in Oman's Batinah region. This system aimed to reduce water over-pumping while ensuring essential water requirements for plants. The authors conducted theoretical analyses based on two models to assess variations in irrigation requirements under different environmental and soil conditions in the region, investigating the hypothesis that soil moisture-based irrigation methods contribute to water savings.

In another study [33], authors introduced an irrigation system utilizing wireless and GSM technology to send notifications when soil moisture levels are low, enhancing the efficiency of the irrigation process. The system employs a soil moisture sensor to determine if the field requires watering, automatically activating or deactivating the pump based on signals received from the sensor.

6. Results and discussion

Research in the GCC region has extensively examined the utilization of soil moisture sensors, focusing on several pivotal areas. Firstly, studies highlight the integration of advanced sensor technologies, offering farmers a spectrum of options based on accuracy, depth measurement, and response time. Secondly, these investigations underscore the significant impact of soil moisture sensors on data-driven decision-making in agriculture, empowering farmers to optimize irrigation schedules, conserve water, and enhance crop yields through real-time and precise soil moisture data. Furthermore, there is a noticeable shift towards smart irrigation in the region, where soil moisture sensors, in conjunction with weather data and IoT technologies, are playing a crucial role. Lastly, the research delves into the feasibility of smart irrigation scheduling systems, enabling farmers to access sensor data via mobile applications, thereby enhancing convenience and facilitating timely responses to soil conditions, irrespective of geographical distances.

6.1. Challenges and considerations

The studies presented demonstrate the effectiveness of soil moisture sensors in optimizing irrigation scheduling within GCC countries, however, GCC farmers face several below-listed challenges and issues in their adoption and effective use:

Cost constraints: Acquisition, installation, and ongoing maintenance costs can be prohibitive for small-scale farmers, straining financial resources. Although initial costs may pose obstacles, the long-term benefits typically outweigh these investments.

Data interpretation: Successful implementation requires a nuanced understanding of data interpretation, as farmers and agronomists must be adept at deciphering sensor data and translating it into practical irrigation decisions to optimize the overall efficacy of these technologies. The complexities of interpreting sensor data necessitate training and technical support to maximize their effectiveness.

Calibration and placement: Ensuring accurate readings and effective irrigation management requires proper calibration and placement of sensors in diverse soil types.

Salinity and soil variability: Soil moisture sensors may need adjustments to accommodate saline soils and varying compositions, impacting their accuracy.

Energy availability: Access to reliable power sources for sensor operation and data transmission is a challenge, particularly in remote areas. While solar-powered options offer potential solutions, they have limitations.

Knowledge and awareness: Enhancing farmer awareness and understanding of the benefits and usage of soil moisture sensors is crucial, necessitating outreach and education initiatives.

6.2. Gaps and opportunities

Several gaps and opportunities for further research and implementation have been identified. Addressing these gaps can contribute to a more comprehensive and inclusive approach to expedite soil moisture-based efficient water management and sustainable agriculture in the region.

Limited focus on smallholder farming: Smallholder farmers in the GCC region often lack resources, including access to technology and capital. Future research and implementation efforts could focus on tailoring soil moisture sensor solutions for small-scale agriculture.

Geographic coverage: Existing studies predominantly focus on countries like Saudi Arabia, UAE, and Qatar, overlooking other GCC nations with diverse climates and agricultural practices. Future research should explore sensor adoption across a broader range of GCC countries, with comparative studies aiding in identifying factors influencing sensor effectiveness.

Crop diversity: While some studies address soil moisture sensor applications for vegetables, there is a gap in considering staple crops like date palms and other commonly grown crops in the region. Research should prioritize developing crop-specific irrigation strategies incorporating soil moisture data for staple crops, promoting efficient water use.

Data sharing and collaboration: Collaborative efforts and data sharing among GCC countries are essential for collective water management. Future research should explore mechanisms for regional collaboration, data-sharing agreements, and technology transfer initiatives to support efficient water management practices.

Cost-benefit analysis: Detailed cost-benefit analyses, especially considering initial investments, are lacking. Future studies should assess sensor adoption costs and benefits across various crop types, farm sizes, and regional contexts to provide practical insights for decision-makers.

Technology accessibility: Accessibility of soil moisture sensor technology, particularly for small and resource-limited farms, requires attention. Research and development efforts should focus on technology adaptation, cost reduction strategies, and policy recommendations to ensure affordability and accessibility.

Climate change adaptation: Evolving climate patterns pose challenges to water availability and soil conditions. Future studies should explore how soil moisture sensors can be integrated into climate-resilient agricultural practices, incorporating predictive modeling and adaptive management strategies.

Policy integration: The role of government policies in promoting sensor adoption is underemphasized. Future research should investigate policy alignment with sustainable irrigation practices and potential incentives for sensor adoption.

Scalability: Existing studies demonstrate scalability in countries like Qatar and Saudi Arabia, showcasing the technology's capacity to address water scarcity across broader regions. Future efforts should focus on replicating successful implementations and scaling sensor adoption across diverse agricultural practices.

7. Conclusions

In this paper, we have thoroughly examined the indispensable role of soil moisture sensors in addressing the complex water management challenges encountered by the GCC countries, particularly in agriculture. These sensors have demonstrated remarkable versatility and effectiveness within the region. Through an exhaustive investigation covering technological insights, benefits, challenges, and exemplary R&D efforts, several crucial insights and future directions have emerged.

The presented research underscores successful implementations of soil moisture sensors across various GCC nations, including Qatar, Saudi Arabia, UAE, and Oman. These studies highlight the transformative potential of intelligent irrigation scheduling systems driven by soil moisture data, optimizing irrigation practices, conserving water resources, and enhancing crop yields. Real-time data provision through smart irrigation scheduling empowers farmers to make informed decisions, fostering water conservation, improving crop quality, and realizing economic savings.

However, significant challenges and gaps persist in their adoption and utilization. These obstacles include the need for precise calibration, initial cost constraints, complexities in data interpretation, and the necessity for customized solutions to address prevalent soil variability and salinity in the region. Addressing these challenges is crucial to ensure that soil moisture sensors are accessible and feasible for a broader spectrum of farmers, including smallholders.

Looking ahead, numerous opportunities for further research and implementation have been identified.

These opportunities include a heightened emphasis on smallholder farming, broader geographic coverage encompassing all GCC countries, formulation of crop-specific irrigation strategies, facilitation of data sharing and regional collaboration, meticulous cost-benefit analyses, enhancement of technology accessibility for resource-constrained farmers, adaptation to climate change dynamics, policy integration, and scalability and adaptability of sensor technology.

In conclusion, the GCC region has witnessed a growing interest in soil moisture sensors as invaluable tools for mitigating water scarcity challenges and reinforcing agricultural sustainability. With sustained research, innovation, and collaborative efforts, these sensors hold promise in playing a pivotal role in fostering sustainable and resilient agricultural practices in the region.

Acknowledgement

This research was supported by the Qatar Research, Development, and Innovation (QRDI) Council through Grant No. MME03-1121-210025.

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Balaban Desalination Publications

The 15th Gulf Water Conference

(2025) 272–274
doi: 10.5004.dsal.2025.700110

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Electricity generation and industrial wastewater treatment using microbial fuel cell

Abdullah Al-Matouq*, Mohd Elmuntasir Ahmed, Mishari Khajah, Hussain Abdullah, Rashed Al-Yaseen, Mariam Al-Jumaa, Farah Al-Ajeel, Noura Alayyadhi, Ahmed Shishter

Kuwait Institute for Scientific Research, KISR, Water Research Centre, Kuwait
**email: amatouq@kisr.edu.kw*

ABSTRACT

Due to the rapid increase in population and industry sectors, the consumption of energy from fossil fuels is increasing rapidly, as a result, carbon emissions have increased, which negatively affects the environment. Currently, the electrical energy plants in Kuwait serve around 70,085 M.kWh and this is expected to increase in the future, which will increase the strain on the budget of the Kuwaiti government [1]. Most of the energy consumption was concentrated in the water and electricity sector, oil sector, transportation sector, and household sector. Furthermore, the industrial sector is another important sector that consumes a significant amount of energy on a daily basis [2]. In Kuwait, there are now more than 18 industrial areas and most of these industries are located mainly in Shuaiba, Mina Abdullah and Mina Al-Ahmadi. Those areas mainly contain the following industries: refineries, dairy factories, detergents factories, and soft drinks factories. Kuwait Environmental Protection Authority (KEPA) has divided industrial wastewater into two main categories: industrial wastewaters that meet KEPA's standards and can be treated off-site at municipal wastewater treatment plants, and industrial wastewaters that do not meet KEPA's standards and can be treated on-site or at special treatment plants. Thus, it is important to find an effective and sustainable way to treat industrial wastewater on-site and then transfer it to the treatment plant. Generally, wastewater contains a huge amount of energy, approximately 3–10 times more energy than the energy required for treating wastewater [3]. Each gram (g) of chemical oxygen demand (COD) contains 14.7 kJ, which means that there is a massive amount of energy in wastewater [3]. Using conventional wastewater treatment processes are expensive and consume huge amounts of energy, especially with the restrictive regulations prior to discharge where most of the energy is used for aeration and recirculation. Microbial fuel cells (MFCs) are bio-electrochemical devices that utilize electrochemically active bacteria (The microorganisms that are capable of exocellular electron transfer) as catalysts to convert the chemical energy of organic substrate into electricity [4]. MFCs are able to recover energy by degrading organic and inorganic matter in wastewater and produce less sludge. MFC offers a promising waste-

*Corresponding author

ISBN 0-86689-078-5

water treatment technology with great environmental friendly benefits, such as a source of energy, wastewater treatment process, biosensor system, and low carbon emission process [4]. MFCs have many advantages, such as being easy to handle, not being toxic, the ability to extract 90% of electrons from organic compounds, and self-sustaining systems. MFC produces around 0.5 to 0.8 V working voltage (0.02 – 0.07 kWh/kg-COD), which considers low for real applications but very efficient in wastewater treatment. The generated energy is a function of wastewater type, COD concentration, MFC design, and the selected design materials. In addition, the generated electricity can be promoted by connecting many individual MFCs in parallel, series, or hybrid stacks.

Keywords: Microbial fuel cell; Industrial wastewater; Electricity; Sustainability; Treatment

Methodology

Eight tubular MFCs (approximately 5 L each, dimensions: length 50 cm and diameter 12 cm) will be designed, installed and operated at Sulaibiya Research Plant (SRP). The MFCs will be divided into 4 groups. Each group contains two MFCs and will be operated individually using industrial wastewater from one of the industries (dairy, refinery, detergents, and soft drinks). The MFCs will be operated to assess the efficiency of MFCs to treat industrial wastewater and to generate electricity. The MFC contains a carbon brush anode and a carbon cloth cathode contained a platinum catalyst. The anode and cathode will be connected by titanium wires with an external resistance. The cathode electrode will be exposed to air on its outer surface, as well as being in contact with the membrane. A cation exchange membrane (Nafion 117#) will be wrapped around the tubular anodic chamber to separate the anodic and cathodic chambers, and then a layer of carbon cloth will be wrapped around the CEM to function as the cathode. The generated voltage across the external resistance of 1000 Ω was recorded every 10 min using an ADC-24 data logger system. Real activated sludge from Kabd Wastewater Treatment plant will be used to inoculate the anode chamber. The anode chamber will be inoculated with a 1:1 mixture of activated sludge and anolyte medium (containing in (g/L): Sodium acetate 3.28 + ammonium chloride 0.31 + potassium chloride 0.13 + sodium phosphate anhydrous monobasic 2.69 + disodium hydrogen phosphate 4.33 + 10 mL of vitamins solution + 10 mL of a trace element solution).

The following parameters will be analyzed at the inlet and outlet of the MFCs; temperature, pH, conductivity, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), total solid (TS), total suspended solids (TSS), and heavy metals such as, (Hg, Zn, Cu, Fe, Ni, Cr, Ag, Cd, Pb, Cn, As, B).

Results

All the MFCs were continuously operated for more than 90 d, and the generated electricity varied depending on the industry. The MFCs that operated with dairy wastewater achieved the highest maximum open voltage of 0.625 V, followed by detergent wastewater at 0.495 V, soft drinks at 0.468 V, and finally petrochemical wastewater at 0.165 V, which achieved a low electrical energy output of 0.165 V (Fig. 1). In addition, an extra MFC (control MFC) was operated simultaneously with the eight MFCs using domestic wastewater collected from the inlet stage at Kabd WWTP. The control MFC achieved a maximum open voltage of 0.5 V. All types

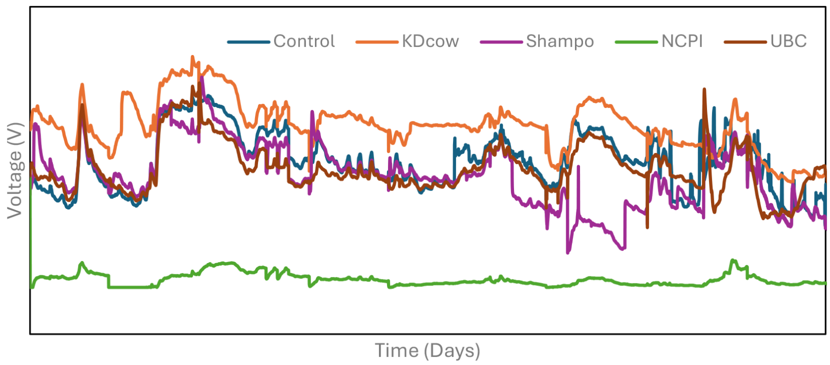

Fig. 1. Change in output voltage over time in the MFCs units using wastewater from the selected factories.

of industrial wastewater have generated electricity; however, the amount of energy varies depending on the wastewater type. Generally, the MFCs that operated with dairy wastewater generated the highest current density (73 mA/m^3) throughout the study. The second industry that generated high electrical energy is the detergent industry (69 mA/m^3), followed by domestic wastewater (64 mA/m^3) and then soft drinks (62 mA/m^3).

Furthermore, the MFCs achieved a maximum CE of 2.9% using soft drink wastewater. The second greatest CE was for domestic wastewater, followed by detergent wastewater and then dairy wastewater. Finally, the CE in petrochemical wastewater was the lowest of all MFCs. The CEs in all MFCs in this study were low and similar results were obtained in different studies. The low CE in his study indicates that most of the released electrons in the oxidation reactions are not used in electricity generation; however, it has been consumed in other electron acceptors such as NO_3 and sulfate. In addition, the MFC design including reactor volume and catalyst layer leads to high electron losses. Also, the complex characterization of the used industrial wastewater leads to deterioration in the oxidation reactions.

In terms of treatment efficiency, all MFCs had COD removal efficiencies of >70% (Fig. 2), except detergents and petrochemical MFCs. Detergents and petrochemicals had the highest influent COD concentration, and it might require more HRT to improve the treatment efficiency. Therefore, the HRT dose has been increased to understand the effect of HRT on treatment efficiency. Increasing the HRT in detergents and petrochemical MFCs from 7 to 14 d increased the treatment efficiency from 44 to 62% and from 7 to 14%, respectively. Increasing the HRT led to an increase in the contact time between the substrate and the microbial community, which provides more time for the bacteria to degrade the organic matter. Generally, MFCs achieve high COD removal compared to many other treatment technologies, and the operational cost is low. MFCs can theoretically generate around 0.004 kWh/kg COD, which can be used to compensate for any energy consumed in the process. On the other hand, activated sludge, which is the main process in wastewater treatment, consumes around 0.6 kWh/kg COD, which is considered an expensive process. Besides the operational cost, MFCs can be used to recover multiple products, such as P, ammonia, and heavy metals, from wastewater. There was no significant correlation between the removed COD and the generated electricity (P>0.05), as low CE (<2%) was obtained in all MFCs. Most of the COD removed was not used in energy generation and was consumed by other microbial consortiums.

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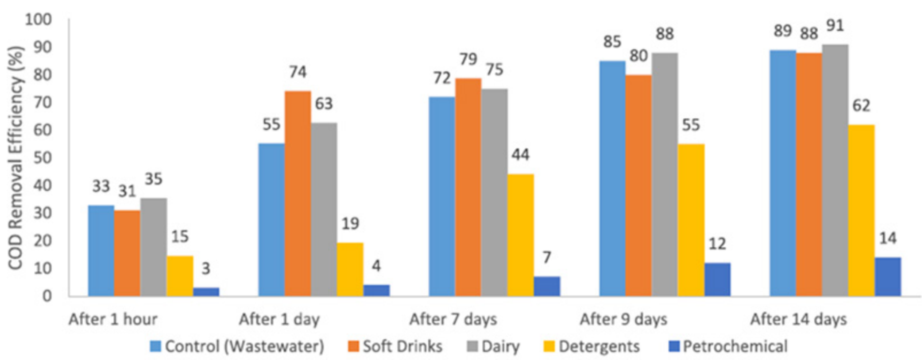

Fig. 2. Comparison of COD removal efficiency over time using wastewater from all four selected factories.

Balaban Desalination Publications

(2025) 275–276
doi: 10.5004.dsal.2025.700111

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Advanced wastewater treatment using functionalized membranes

Mohammed Z. Al-Abri[1,2]

[1]*Nanotechnology Research Center, Sultan Qaboos University, Oman*
[2]*Petroleum and Chemical Engineering Department, College of Engineering, Sultan Qaboos University, Oman*
email: alabri@squ.edu.om

ABSTRACT

Membranes play a crucial role in water treatment and desalination, offering an essential solution to meet the increasing global demand for clean water. The versatility of polymeric membranes in terms of fabrication processes, membrane properties, and applications makes them incredibly well-suited for various wastewater treatment applications. Their adaptability allows for tailored designs and optimization to specific water treatment challenges. Moreover, the recent advancements in electrospun nanofiber polymeric membranes (ENMs) have revolutionized membrane technology, presenting exciting opportunities to enhance the performance of membranes in produced water treatment greatly. The development of ENMs has opened up new avenues for improved filtration efficiency, enhanced water permeability, and increased resistance to fouling, addressing the unique challenges posed by wastewater treatment. These innovative membranes hold significant promise in overcoming the limitations of conventional membrane technologies and advancing the field of water treatment.

Oil and gas-produced wastewater, or oilfield wastewater, is the wastewater generated during oil and natural gas extraction and production. It is a byproduct that emerges alongside the hydrocarbons during drilling, well stimulation, and production processes. Oil and gas-produced wastewater is a complex mixture that contains various contaminants, including hydrocarbons, heavy metals, salts, suspended solids, organic compounds, and naturally occurring radioactive materials (NORMs). The composition of produced water can vary depending on the characteristics of the oil or gas reservoir, the extraction methods used, and the geological formations in the area. Due to its composition and potential environmental impact, the treatment and disposal of oil and gas-produced wastewater present significant challenges for the oil and gas industry. Effective treatment methods must remove or reduce contaminants before safe disposal or potential water reuse.

Additionally, conventional water treatment infrastructure is confronted with a growing challenge stemming from higher living standards, an expanding pharmaceutical industry, and the proliferation of personal care products, micro and nano-plastics, and various human-made chemicals. These persistent contaminants pose a serious threat to water systems as they find their way into natural water bodies, necessitating advanced treatment strategies beyond the capabilities of conventional methods.

ISBN 0-86689-078-5

Nanotechnology, with its precision in manipulating matter at the atomic and molecular levels, emerges as a transformative force in overcoming these challenges. It offers modular and efficient solutions for general wastewater treatment. Nano-adsorption, photocatalysis, and functionalized membranes are key processes targeting diverse contaminants. This multifaceted approach ensures high wastewater treatment efficiency, modularity, and cost-effectiveness.
The utilization of nanofiber membranes incorporating nanomaterials for produced water treatment has gained considerable attention. Specific emphasis has been placed on nanofiber membranes with surface characteristics exhibiting superhydrophobic/superoleophilic or superhydrophilic/superoleophobic properties. Generally, nanoparticles such as iron oxide (Fe_3O_4), titanium dioxide (TiO_2), and silica (SiO_2) have been employed to improve the properties of ultrafiltration (UF) membranes. Incorporating nanoparticles can significantly enhance the hydrophilicity of the membrane surface, thereby improving water permeability and resistance against fouling when treating domestic or industrial wastewater. Nanomaterial-enhanced membranes possess not only superwetting properties but also exhibit photocatalytic capabilities. Commonly used metal oxide nanoparticles like TiO_2 and ZnO are photocatalysts for various water applications. Photocatalysis utilizes visible light or UV to degrade organic contaminants and disinfect bacteria through oxidation or reduction reactions.
Despite nanotechnology's promise, translating these advancements into large-scale industrial applications has encountered hurdles, primarily due to the complexity of system design. Bridging the gap between cutting-edge research and practical implementation is essential for the widespread adoption of nanotechnology in water treatment. This study provides valuable insights into the latest developments, challenges, and opportunities in nanotechnology-based approaches, paving the way for sustainable and responsible water management practices amid evolving environmental concerns.

Keywords: Membranes; Nanofibers; Functionalization; Produced water; Emerging contaminants; Water treatment

Balaban Desalination Publications

The 15th Gulf Water Conference

(2024) 277–285
doi: 10.5004.dsal.2024.700083

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management 28–30 April 2024, Doha, Qatar

Wastewater industrial database for total nitrogen in Shuaiba area in Kuwait

A. Al-Haddad*, M.E. Ahmed, H. Abdullah, A. Al-Matouq, A. Abusam

Kuwait Institute for Scientific Research, Safat, Kuwait, email: ahadad@kisr.edu.kw

ABSTRACT

A research study was carried out to collect data on the quality and quantity of 17 petroleum industrial wastewater from different sources in Kuwait over a period of one year as well as developing a database of such characteristics and attributes using the geographic information system (GIS) technique. During the field visits, specially designed field surveys were submitted to the owners of industrial facilities in Shuaiba industrial areas in Kuwait. In this study, Wastewater samples were collected and analysed on a monthly and biweekly basis from 17 petroleum factories in Shuaiba industrial areas. This paper targeted assessment of total nitrogen in the raw wastewater for factories of the Shuaiba industrial area. The field wastewater data indicated the presence of slightly acid to slightly alkaline (5.7–12.9), reduced to oxidized environment (–410 mv–538 mv) and freshwater to brackish water (333 µS/cm–33,090 µS/cm). The laboratory results revealed that total nitrogen concentrations for wastewater of 17 factories ranged between 0.003 mg/l and 150 mg/l. The mean values of total nitrogen concentrations for wastewater of 17 factories except Kuwait Lube Oil Company meet the maximum limit (65 mg/l) set by KEPA for irrigation water purposes. The mean value of quantities of wastewater generated from 17 factories was found 62,280 m^3/week. The large quantities of raw wastewater generated from these factories can be used safely as irrigation water with respect to total nitrogen concentrations.

Keywords: Wastewater; Field survey; Laboratory results; Petroleum and nitrogen; Sample collection

1. Introduction

Kuwait is one of the five water-stressed countries in the world. The main source of water supply for municipal uses is the costly desalinated seawater. Kuwait is producing approximately 682.8 million imperial gallons (MIG) per day of potable water from a number of seawater desalination plants (MEWRE, 2022). Groundwater supply in the country is depleting at 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

* Corresponding author.

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 (Al-Haddad, et al., 2022). 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. The Gulf Corporation Council (GCC) countries mostly depend on seawater treatment technologies to produce potable water. Also, these countries mostly depend on ground water and domestic treated wastewater for agricultural purposes. Data related to utilization of industrial wastewater for agricultural usage are limited in the GCC countries due to the absence of an industrial wastewater database. Accordingly, this study was initiated to collect data on the quality and quantity of petroleum and non-petroleum industrial wastewater from different sources in Kuwait over a period of one year. Additionally, the study aims to develop a database on the above-mentioned attributes using the geographic information system (GIS) technique. The study is a continuation of a previous project (Shahalam et al., 2008) 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. The GIS technique is a very important tool to determine the concentration, distribution, and statistical analysis of each wastewater parameter for each industrial area in the country. Also, a research study was conducted to establish an industrial wastewater database for the determination of total petroleum hydrocarbon concentration at Sabhan area, Kuwait (Al-Haddad et al., 2022). This paper aims to evaluate the concentrations of different total nitrogen (TN) in raw wastewater generated from 17 petroleum factories in Shuaiba industrial area, to determine quantities of wastewater generated, and to draw distribution maps for total nitrogen 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. The questionnaire includes the coordination of the factories, quantity of freshwater consumed and wastewater generated from each factory, type of products produced by each factory, and if there is treatment technology was used by the factory. 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. A total of 17 factories were selected to determine the quality and quantity of wastewater from the Shuaiba industrial area. Fig. 2, represents location maps for these factories. A summary of the factory names, sampling codes along coordinates is presented in Table 1.

2.2. Industrial wastewater sampling and laboratory analysis

Based on the field surveys of the targeted industries, wastewater sampling and associated measurements were 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 the 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. Before 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 collected and analysed according to standard methods for the examination of water and wastewater (APHA, 2017). In the data analysis section, the laboratory results of the wastewater samples were compared with local standards (KEPA, 2017) for irrigation water standards.

2.3. Wastewater quantities

The quantities of freshwater consumption inside each plant were measured near flow meter gage, and these data were collected from owners of the factories while the raw industrial wastewater was measured by calculating the number of sewage takers (each tanker with a capacity of 5,000 gallons) discharged per week from each factory.

3. 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 abbreviation PT was used to

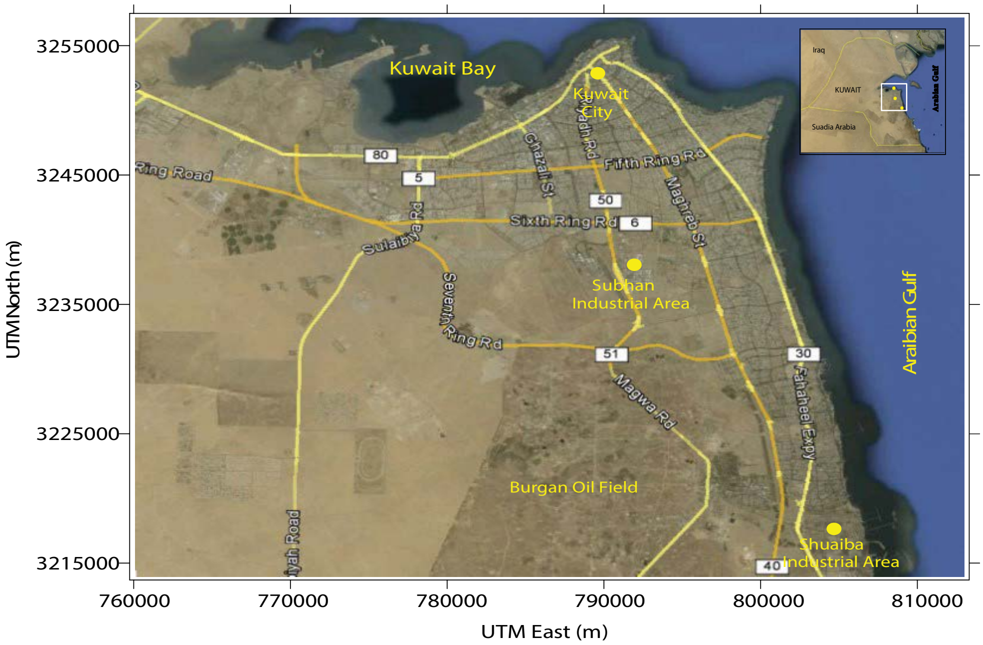

Fig. 1. Location map of the study area.

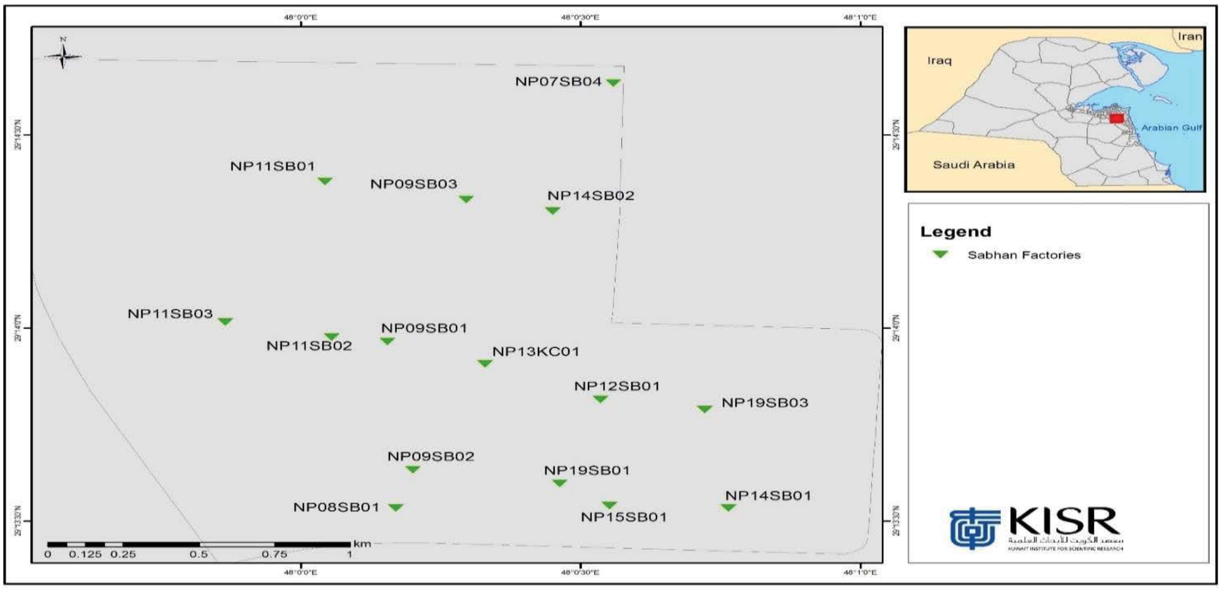

Fig. 2. Location map of selected factories in the Shuaiba industrial area.

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. The coordination of the industrial site studied was measured in the Universal Transverse Mercator (UTM) system, North and East. Table 1 shows the codes and the UTM coordinates of the 17 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.

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

Serial No.	Factory/Site Name	Sample Code	Factory/Site Coordinates (UTM)	
			North	East
1	ACICO Construction Company	NP03-SH01	29.001353	48.127914
2	ACICO Industries Company	NP03-SH02	28.985778	48.126397
3	Al-Khat Packaging Company	NP15-SH02	28.986341	48.130486
4	AQUASAN Company	NP16-SH01	29.002925	48.130212
5	Gulf Glass Company	NP02-SH01	28.993068	48.132995
6	Gulf Paper Manufacturing Company	NP12-SH01	28.992502	48.130495
7	Hempel Paints Company	PT03-SH01	28.996074	48.129608
8	Kuwait Insulating Material Manufacturing Company	NP01-SH02	28.992772	48.134731
9	Kuwait Gypsum Ceiling Company	NP04-SH01	29.012163	48.125629
10	Kuwait Gypsum Manufacturing and Trading Company	NP04-SH02	28.993843	48.1263
11	Kuwait Lube Oil Company	PT01-SH02	28.990565	48.130554
12	National Chemical Petroleum Industries Company	PT02-SH02	28.990364	48.12927
13	National Industries Company	PT02-SH03	29.013721	48.123287
14	National Industries for Ceramic Company	NP16-SH02	29.016453	48.11492
15	United Oil Projects Company	NP10-SH01	28.990886	48.126334
16	United Paper Industry Company	NP12-SH02	29.002925	48.130212
17	United Steel Industries Company	NP05-SH03	28.987705	48.12811

Note: UTM-Universal Transverse Mercator

4. Results and discussions

The quantities of freshwater consumption and wastewater generated from each industry were presented in Fig. 3. The maximum, mean, and minimum values of freshwater consumption for 17 factories of Shuaiba industrial areas were found to be 20,833,250 m^3/week, 62,28 m^3/week, and 1,226,130, respectively. The highest freshwater consumption was found with Gulf Paper Company. A total of 20,844,223 m^3/week of freshwater was consumed by 17 factories. On the other hand, the maximum, mean, and minimum values of wastewater produced by 17 factories in Shuaiba industrial areas were found to be 200 m^3/week, 42 m^3/week, and 20 m^3/week, respectively. The highest wastewater generated was found with Kuwait Lube Oil Company. A total quantity of 720 m^3/week of raw wastewater was generated by 17 factories (Fig. 3).

The pH is a field parameter that provides information about wastewater environment if it is acidic, neutral, or alkaline media associated with certain dissolved gases in that media. A lower limit (6.5) and upper limit (8.5) were set for the pH parameter of wastewater by Kuwait EPA for irrigation water purposes. The maximum, average, and minimum values of wastewater pH for 17 factories in the Shuaiba area were plotted in Fig. 4. Except four factories (ACICO Construction, ACICO Industries, National Ind. For Ceramic and National Industries) where wastewater pH values were found alkaline, the wastewater pH for the remaining factories represent acidic environment. The mean values of pH of wastewater for the remaining thirteen companies were meeting the lower or upper limits set by KEPA for irrigation water standards.

The 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 from 17 factories were found to be 294 µS/cm and 33,090 µS/cm, respectively (Fig. 5). The average values of electrical conductivity (lower than 5000 µS/cm) of wastewater for all factories categorized as freshwater type except the mean values of electric conductivity (above 2000 µS/cm) of wastewater of ACICO Construction, Al-Khat Packaging and Gulf Paper Company which characterized as brackish water type.

The oxidation-reduction potential values of the wastewater ranged between –431.0 mv and 617.0 mv for the 17 factories. The ORP values of the wastewater of a total of 16 factories indicated reduced environments while the ORP values (below 0.0 mv) except for the wastewater of Kuwait Gypsum Manufacturing factory indicated oxidized environments (above 0.0 mv) as shown in Fig. 6. The negative values of ORP values might be due to presence of a number of reduced gases such as ammonia, methane, hydrogen sulfide and volatile organic compounds in the raw wastewater.

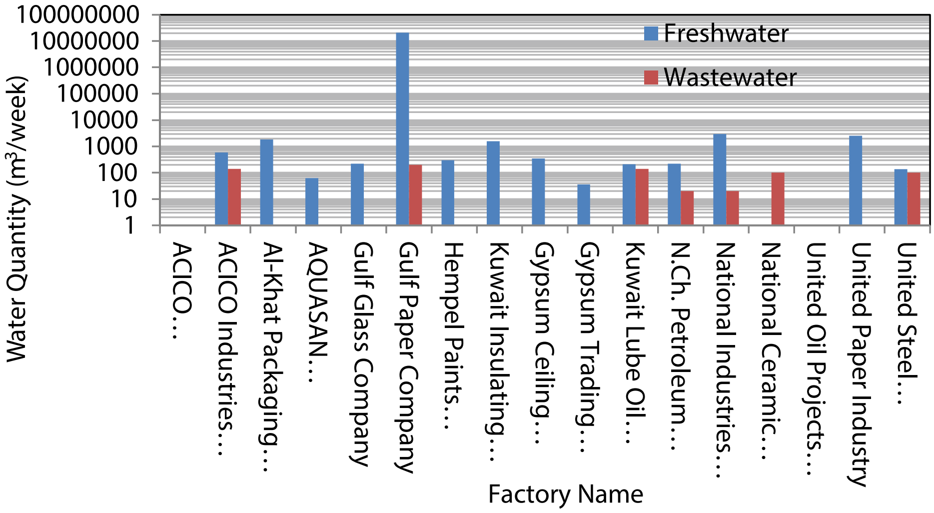

Fig. 3. Quantities of freshwater and wastewater for each factory of the Shuaiba industrial area.

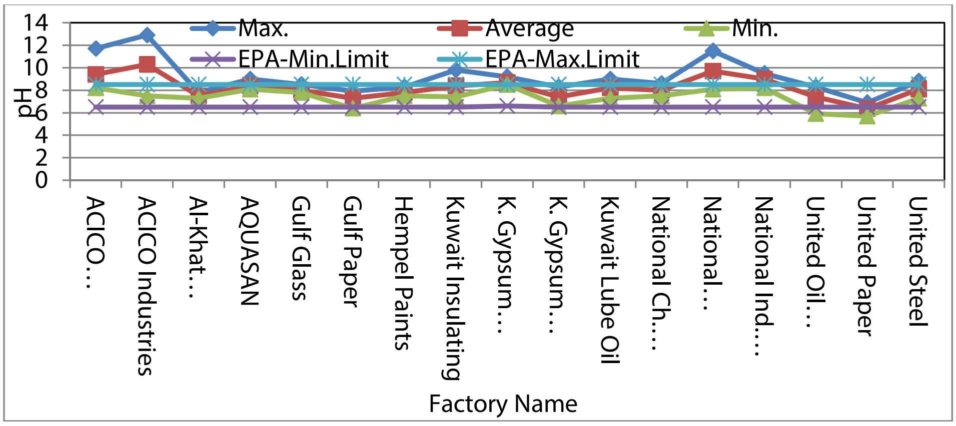

Fig. 4. Changes in pH values of wastewater for Shuaiba factories.

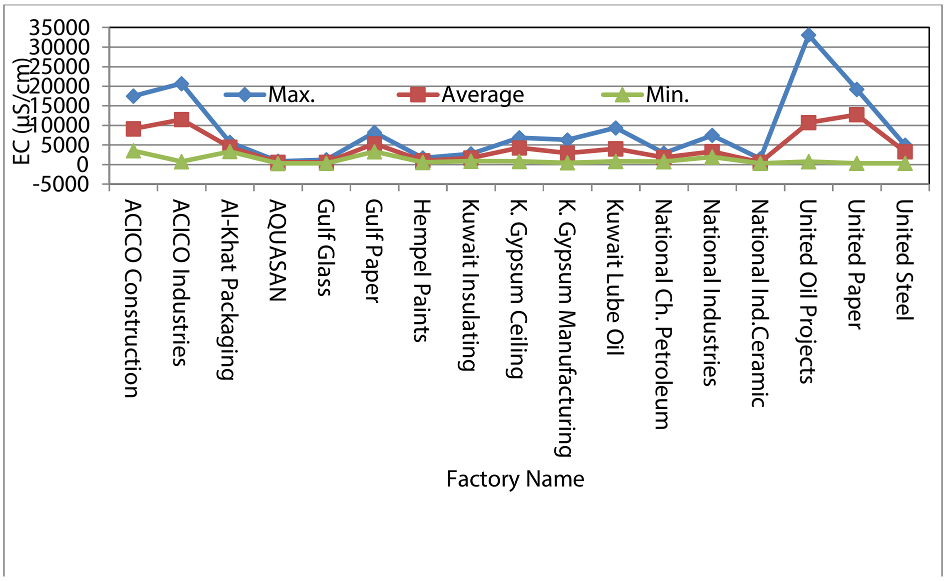

Fig. 5. Changes in electrical conductivity values of wastewater for Shuaiba factories.

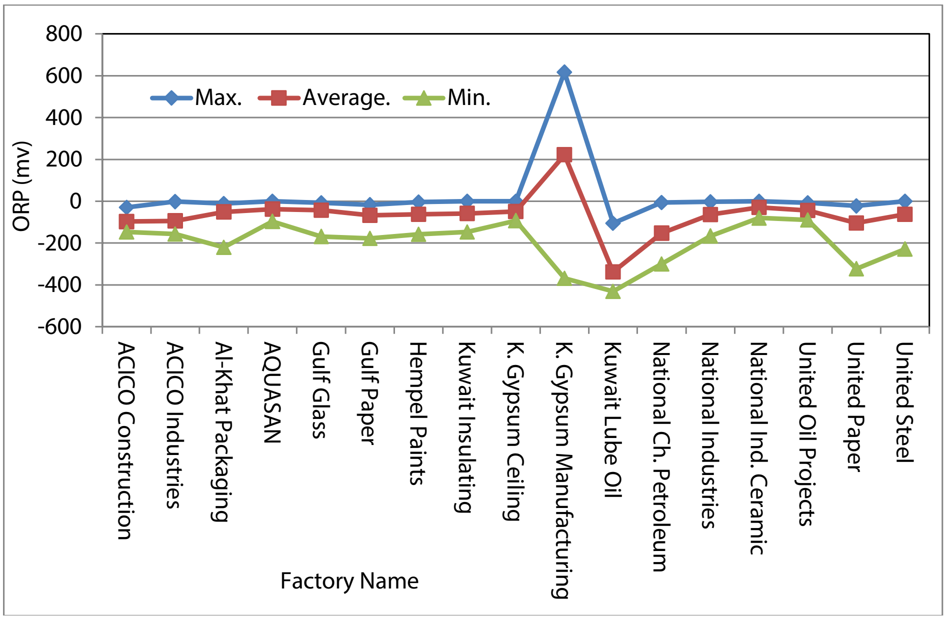

Fig. 6. Changes in oxidation-reduction potential values of wastewater for Shuaiba factories.

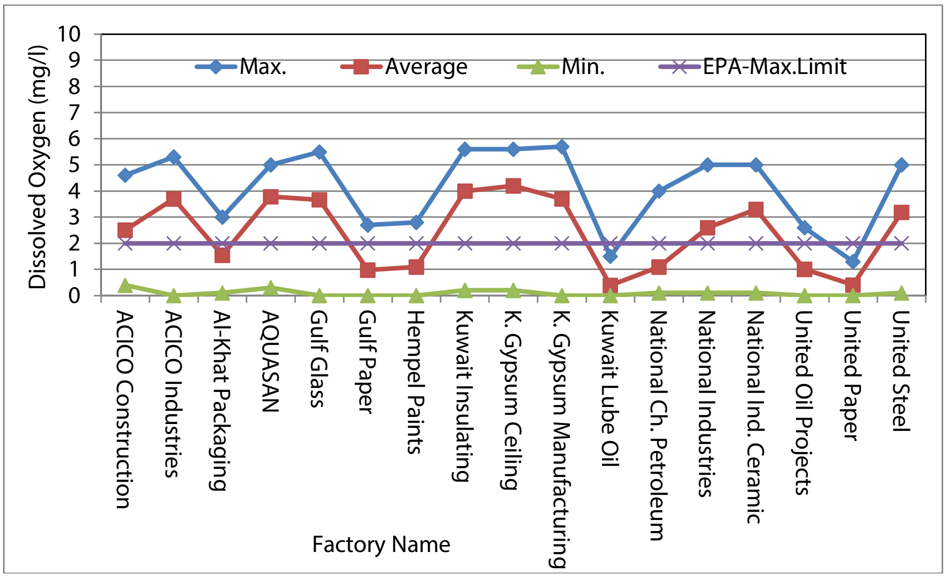

Fig. 7. Changes in dissolved oxygen values of wastewater for Shuaiba factories.

The dissolved oxygen (DO) values of the wastewater ranged between 0.0 mg/l and 5.7 mg/l for the 17 factories. The same factories with reduced ORP values of the wastewater had 0.0 mg/l DO while the DO values (above 0.0 mv) for the wastewater of the remaining indicated oxidized environments as shown in Fig. 7. The mean values of DO of wastewater for ten companies do not meet the maximum limit (2 mg/l) set by KEPA for irrigation water standard. On the other hand, only seven factories meet the KEPA standards with respect to DO parameters.

The total nitrogen value of 65 mg/l was set by KEPA as the maximum limit for irrigation water (KEPA, 2017). Nitrogen also is considered a nutrient and an essential element for plant growth. The total nitrogen values of the wastewater ranged between 0.003 mg/l and 150 mg/l for the 17 factories as shown in Fig. 8. All average values of total nitrogen of the wastewater meet the maximum limit set by KEPA for irrigation water purposes except for those values of total nitrogen (above 65 mg/l) for one factory (Kuwait Lube Oil Company) and this parameter should be treated. In this

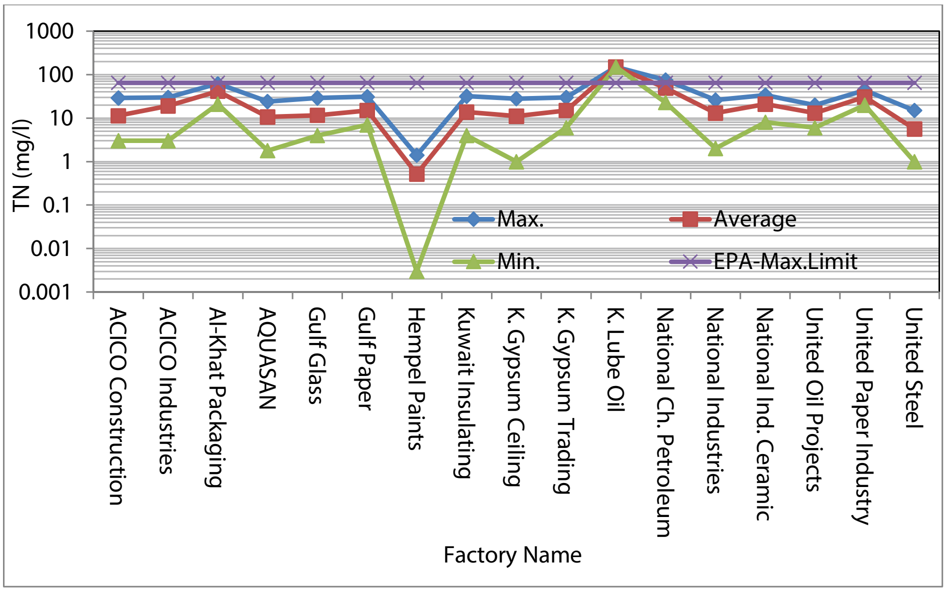

Fig. 8. Changes in total nitrogen values of wastewater for Shuaiba factories.

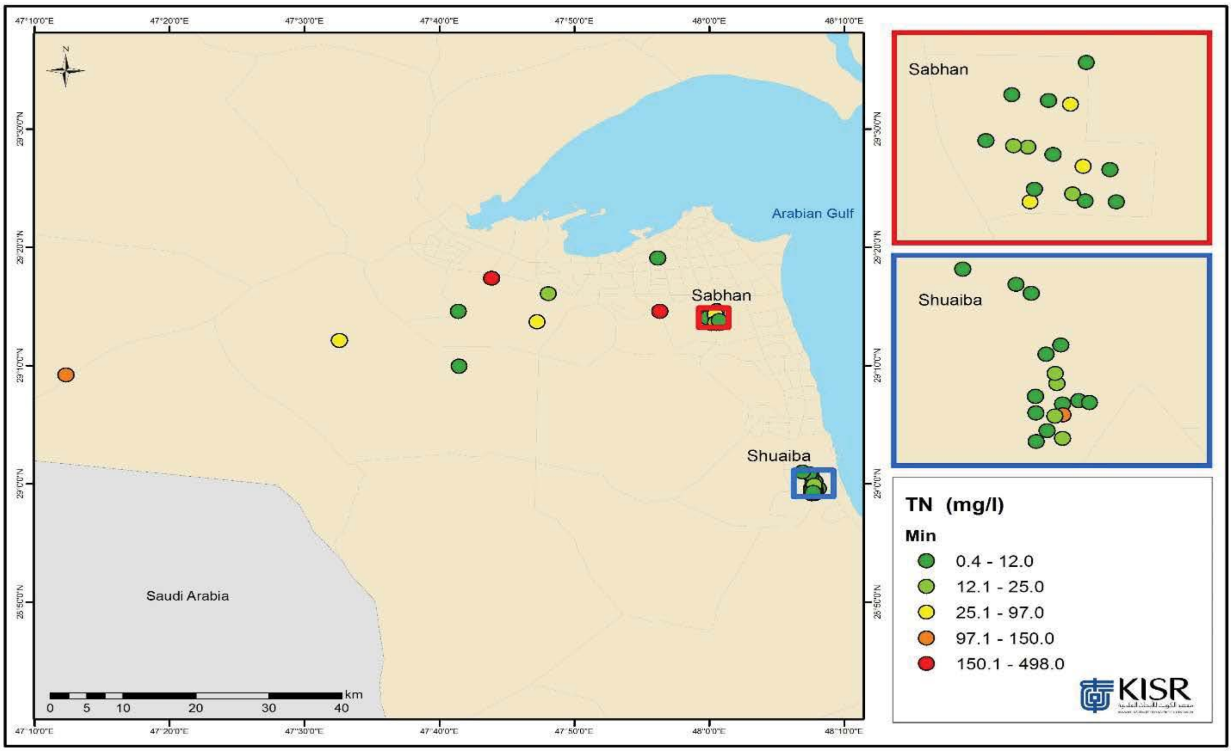

Fig. 9. Distribution map of minimum values of total nitrogen (mg/l) in wastewater for various industries in Kuwait.

Figure, Hempel Paints factory indicated low nitrogen concentrations in the wastewater due to the hydrocarbon source of the product. Distribution GIS maps were generated for total nitrogen based on the data of the GIS database using ArcGIS software as shown in in Figs. 9–11. Shuaiba area results were shown in the bottom blue square in Figs. 9–11.

A total of four sites (Gulf Glass Company, Kuwait Insulating Material Manufacturing Company, National Industries for Ceramic Company, and United Steel Industries Company) out of seventeen factories used on-site treatment systems. The water treatment system varied between dissolved air floatation (DAF), wash water system, softener, and water filtration units.

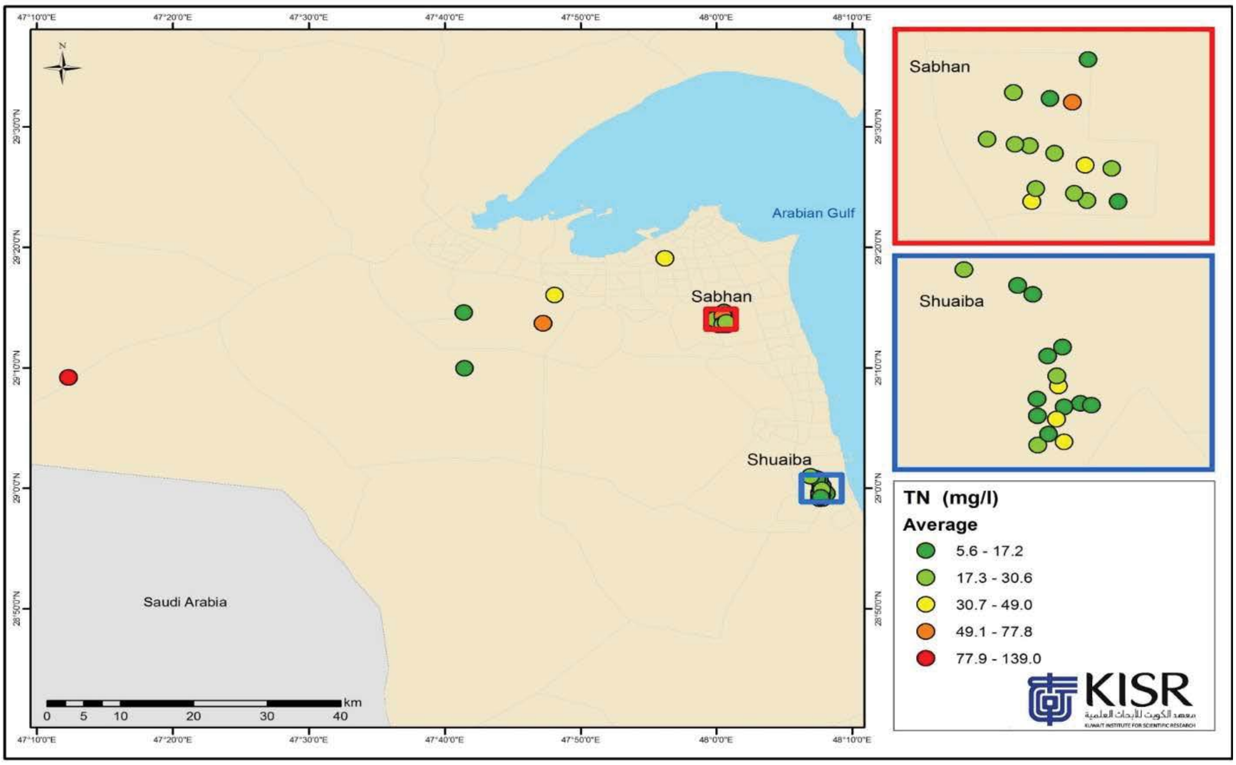

Fig. 10. Distribution map of average values of total nitrogen (mg/l) in wastewater for various industries in Kuwait.

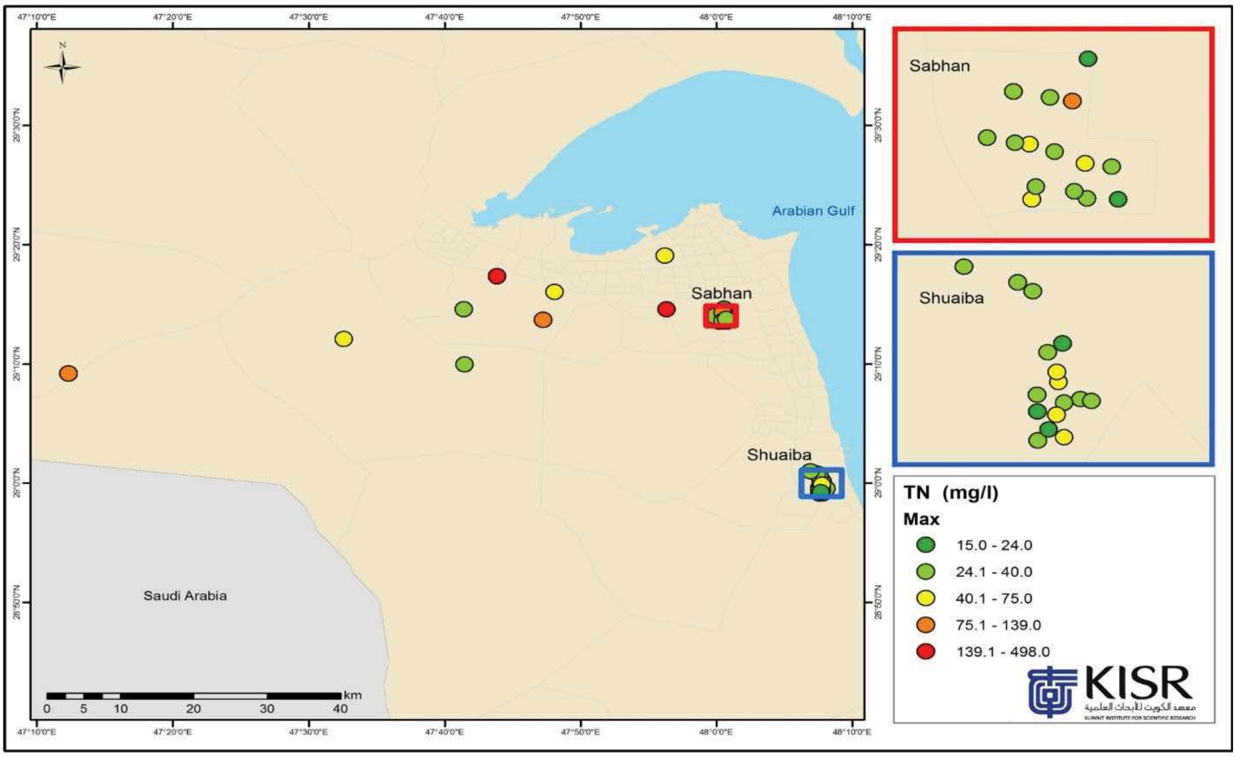

Fig. 11. Distribution map of maximum values of total nitrogen (mg/l) in wastewater for various industries in Kuwait.

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

5. Conclusions

A field study was carried out to collect data on the quality and quantity of wastewater from 17 petroleum factories in the Shuaiba industrial area, and develop a database for the target industries using the ArcGIS technique. Wastewater samples were collected and analysed for chemical parameters. The laboratory results of total nitrogen indicated that their concentrations in the raw wastewater met KEPA irrigation water standards except for those values of total nitrogen (above 65 mg/l) for one factory (Kuwait Lube Oil Company). 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, the following recommendations are forwarded:

- The industrial wastewater database should be updated continuously by the Public Authority Industry (PAI) including all factories.
- GIS is a suitable platform for industrial wastewater management.
- Onsite treatment systems such as pH buffer tanks, sand and carbon filtration, and disinfection units should be installed to treat the industrial wastewater for a group of industries of similar sources to ensure that the quality of industrial wastewater meets the irrigation water standards set by KEPA.

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.

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Balaban Desalination Publications

The 15th Gulf Water Conference

(2024) 286–294
doi: 10.5004.dsal.2024.700062

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Towards a novel wastewater treatment process: a submerged membrane elector-bioreactor (SMEBR)-simultaneous biodegradation, electrocoagulation, and membrane iltration

Khalid Bani-Melhem[1,*], Maria Elektorowicz[2]

[1]*Water Technology Unit (WTU), Center for Advanced Materials (CAM), Qatar University, P.O. Box 2713, Doha, Qatar, email: kmelhem@qu.edu.qa,*

[2]*Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Quebec, Canada H3G 1M8*

A B S T R A C T

The limited freshwater resources make the need for wastewater treatment and reuse a mandatory option in many countries around the world specifically in arid and semi-arid regions like the Arab Gulf area due to severe water scarcity. Therefore, focusing on advanced wastewater treatment methods has become a hot issue in recent years. Membrane processes belong to this group and attract a high degree of attention from researchers in different academic institutions. In the last few decades, membrane bioreactor (MBR) technology, specifically the submerged membrane bioreactor (SMBR) which integrates membrane filtration with an activated sludge process (ASP) has exhibited promise as a very attractive method for various kinds of wastewater treatment. The SMBR has many advantages in comparison with ASP such as superior effluent quality, higher mixed liquor suspended solids (MLSS) and organic pollutant loading, independent control of hydraulic retention time (HRT), and sludge retention time (SRT). However, the phenomenon of membrane fouling is still considered one of the main obstacles to SMBR technology. Many methods have been developed and investigated to overcome this serious problem. Among the different proposed approaches, using the electrochemical methods by applying a direct current (DC) field on the activated sludge has been shown as a promising and novel approach. One of the early developed electrochemical methods with SMBR is called Submerged Membrane Electro-Bioreactor (SMEBR). The SMEBR integrates three processes in one reactor unit: biological treatment, membrane filtration, and electrocoagulation. The method was developed at Concordia University, Montreal-Canada in 2008 and later registered as a patent in the USA in 2010. This paper presents a comprehensive review of the conducted studies on SMEBR and its application in wastewater treatment and the potential of reducing the membrane fouling phenomenon. The paper summarizes the advantages of SMEBR in comparison with other treatment technologies and highlights the last findings of SMEBR.

Keywords: Submerged; Membrane fouling; Electro-bioreactor; Activated sludge; Wastewater

* Corresponding author.

1. Introduction

Human activities (domestic, industrial, and agricultural sectors) produce millions of tons of wastewater every year around the world. On the other hand, the uncontrolled increase in world population poses a huge pressure on freshwater resources. Consequently, many people around the world, especially in developing countries, lack access to fresh water. Not only the domestic sector suffer from the limited water supply, but also agricultural and industrial activities are heavily affected, as access to enough water resources for all year becomes a big challenge, especially in regions characterized as arid or semi-arid areas like the Middle East and North Africa (MENA), Asia, and Latin America (Ezugbe et al., 2020). In response to this situation, the decision-makers in these countries should recognize the treated wastewater as a valuable non-conventional water resource in the water budget. However, to be safe for reuse in human activities, wastewater should be treated effectively.

During the past few decades, several efforts have been made to develop various wastewater treatment technologies which include physical (conventional filtration), chemical (coagulation-flocculation), and biological processes (Activated sludge process). One of the wastewater treatment technologies that have received great attention over this period is membrane technology (MT). During the past few years, membrane separation technologies have grown very fast as one of the most effective and promising methods in water purification (Bani-Melhem et al., 2023). In the membrane process, the feed stream is divided into two streams by a membrane module: a retentate (or concentrate) and a permeate fraction (Fig. 1). Membrane technologies (MT) have a long history that began in 1748, however the golden age (1960–1980) of this technology began in 1960 when Loeb and Sourirajan developed the first asymmetrically integrated skinned cellulose acetate RO membrane for seawater desalination. The full description of this event is reported by Mastsuura (2001). The first use of membrane technology was initially limited to tertiary treatment and polishing (Cieck, 2003). Insufficient knowledge of membrane applications and the high capital and operating costs were considered negative factors and limited the spread of membrane technologies worldwide during the early stages (Cieck, 2003). However, in the last couple of decades, the MT witnessed a scientific revelation in terms of research and development which makes the MT gain many benefits in comparison with other treatment processes. Specifically, its advantages appear in the production of water of invariable quality, the reduction in the equipment size, low capital cost, and energy requirement and compactness of the installation, and the possibility to fully automate the process (Talukder et al., 2022; Othman et al., 2022). Furthermore, the elimination of chemical usage makes MT an environmentally friendly process and easily accessible to many users (Ezugbe et al., 2020).

Nowadays, Various types of membrane separation processes have been developed for specific industrial applications. Membranes can be classified into four main groups based on the driving forces across the membrane (Fig. 2). The first group is a pressure-driven membrane process which includes microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) (Verma et al., 2021). The second group, based on concentration differences across the membranes, includes dialysis (Chen et al., 2022) and pervaporation (Li et al., 2023). The third group, which contains electro-dialysis membranes, is based on an electrical potential (Sophie, 2023). The fourth group includes gas permeation (Valappil, 2021) and membrane distillation (MD) (Yan et al., 2021), in which partial pressure is the driving force across the membrane. Membrane technologies could also be classified based on membrane types or based on membrane configurations and modules (Bani-Melhem, 2008). The applications of membrane technologies have covered many

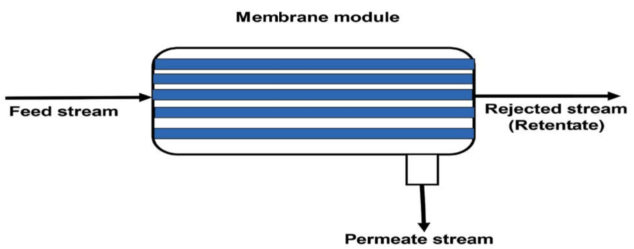

Fig. 1. Concept of membrane technology concept.

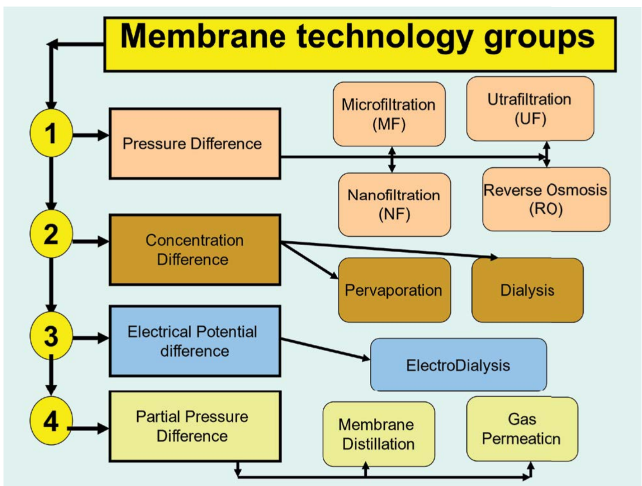

Fig. 2. Classification of membrane technology based on driving forces across the membrane (adapted from Bani-Melhem, 2008).

fields such as water purification (Bottino et al., 2009), wastewater treatment (Ezugbe and Rathila, 2020), endocrine-disrupting compounds and pharmaceutical products (Abdullah et al., 2023), and virus removal (Zhu et al., 2021).

In the last few decades, membrane bioreactor (MBR) technology has exhibited promise as a very attractive method for various kinds of wastewater treatment. As in any developed membrane technology, the phenomenon of membrane fouling is still considered one of the main obstacles to SMBR technology. Many methods have been developed and investigated to overcome this serious problem. One of the novel methods of controlling membrane fouling in SMBR is the applying electrochemical methods in which a direct current (DC) field is applied to the activated sludge. One of the early developed electrochemical methods with SMBR is called Submerged Membrane Electro-Bioreactor (SMEBR). In the SMEBR process, three processes are integrated into one reactor unit: biological treatment, membrane filtration, and electrocoagulation. The method was developed at Concordia University, Montreal-Canada in 2008 (Bani-Melhem, 2008) and later registered as a patent in the USA in 2010 (US Patent, 2010). The objective of this paper is to deliver a comprehensive discussion about the basic design of SMEBR, its application in wastewater treatment, and the potential to reduce the membrane fouling phenomenon. The paper also summarizes the advantages of SMEBR in comparison with other treatment technologies and highlights the limitations of implementing SMEBR technology.

2. Membrane bioreactor technology

One of the potential methods of MT is the membrane bioreactor (MBR) technology that was invented for the first time by Smith et. al (1969). In MBR, an ultrafiltration (UF) membrane to separate the liquid phase from the solid phase in the bioreactor replaced the secondary clarifier of the activated sludge process (ASP) (Fig. 3A). From a technical point of view, the MBR process is a modified version of the conventional ASP. During the early years of developing MBR, the membrane filtration unit was placed outside the bioreactor (external configuration (Fig. 3B), but a breakthrough happened in 1989 when Yamamato proposed to immerse the membrane unit inside the bioreactor. The new configuration was called the submerged membrane bioreactor (SMBR) (Fig. 3C) (Yamamato, 1989). The choice between side stream and submerged configurations depends on many factors such as the

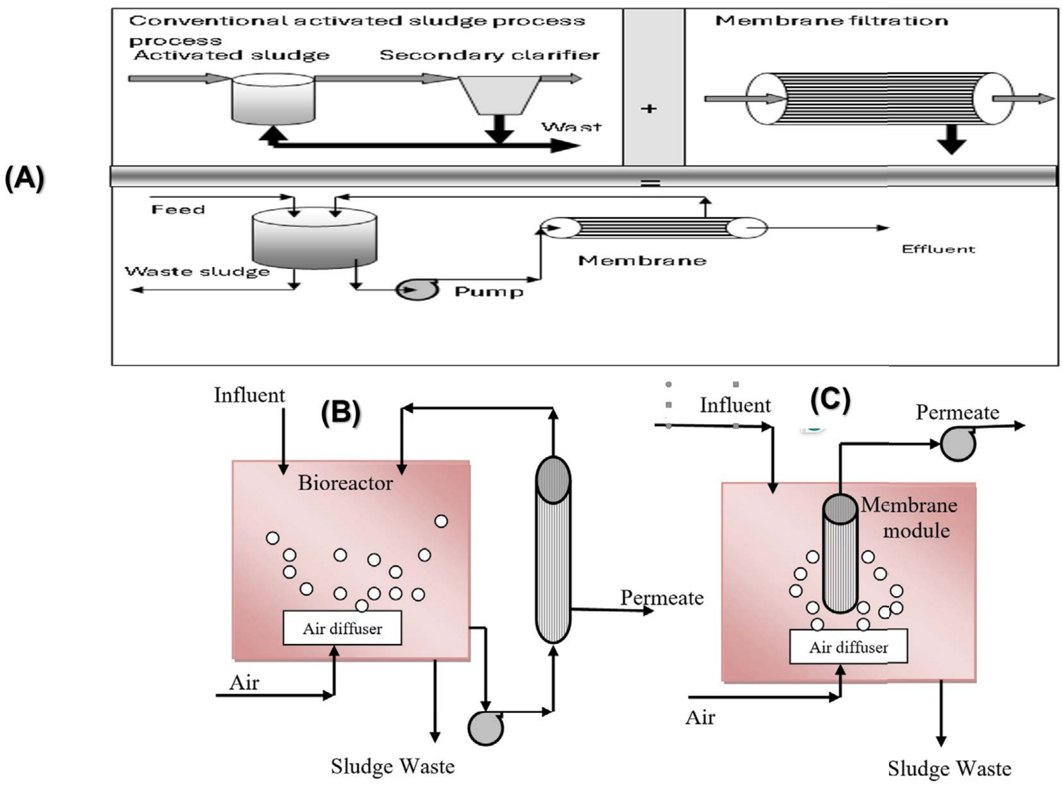

Fig. 3. (A) The first concept of MBR technology, (B) External MBR system, and (C) SMBR (adapted from Bani-Melhem, 2018).

specific wastewater treatment needs, available space, and operational considerations, with each configuration offering unique advantages and challenges. The external design allows for easier access to the membranes for maintenance but may pose challenges in terms of energy consumption. Conversely, the submerged configuration integrates the membranes directly within the bioreactor tank, promoting a more compact footprint and efficient use of space.

Nowadays, SMBR technology presents a space-saving alternative in wastewater treatment compared to traditional activated sludge systems because of the elimination of the need for large settling tanks. The compact design of SMBR not only reduces the physical footprint of the treatment plant but also enhances treatment efficiency by maintaining a higher concentration of activated sludge (higher mixed liquor suspended solids (MLSS) and organic pollutant loading) in a confined space. Furthermore, the SMBR produces superior effluent quality. The use of submerged membranes allows for higher sludge retention times (SRT), independent control of hydraulic retention time (HRT), and sludge retention time (SRT), and improved solids separation, making them a practical and space-efficient solution for modern wastewater treatment facilities, especially in locations where land availability is a limiting factor. Table 1 summarizes a comparison between external MBR and SMBR in terms of energy consumption and other parameters. While SMBR is generally considered more energy-efficient due to reduced pumping requirements, the challenge lies in managing and preventing membrane fouling (Sano et al., 2022), which necessitates effective cleaning strategies.

Many methods have been developed and investigated to overcome this serious problem. The Submerged Membrane Electro-Bioreactor (SMEBR) has proved a promising technology in reducing membrane fouling in SMBR applications. The idea of SMEBR is based on the integration of the electrocoagulation (EC) process (Al-Qodah et al., 2018; Al-Qodah et al., 2020) with SMBR. The following section highlights in more detail the SMEBR technology.

3. The SMEBR system

3.1. Description of the SMEBR system

The original design of the SMEBR system appears to lie at the intersection of three more fundamental technologies: biodegradation, electrochemistry (in majority represented by the electrocoagulation (EC) phenomenon), and membrane filtration. One possible conceptual framework for the proposed design of the SMEBR is shown in Fig. 4A. Each defined area brings a certain perspective to the SMEBR system, as represented by each lobe of this diagram.

Each of these processes was studied separately. Each intersection between two lobes shows the possible interaction of two processes during wastewater treatment. For example, when the lobe of the biological process intersects with the lobe of membrane filtration, a membrane bioreactor technology (MBR) is established. The intersection of the three lobes forms a central area that characterizes the behavior of the SMEBR system. Consequently, the distinguishing point between the proposed method in this paper and the other study in the literature is the integration of three processes, that is to say, biological, electrokinetic, and filtration into one hybrid unit as an advanced wastewater treatment method.

The core design of the SMEBR is the integration of EC with the SMBR system. Several studies reported the effectiveness of the application of EC on different kinds of wastewater (Al-Qodah et al., 2018; Al-Qodah et al., 2020).

The basic design of SMEBR was described in detail by Bani-Melhem (2008) and its performance for fouling reduction was proven by Bani-Melhem and Elektorowicz (2010) and for producing super water quality as well (Bani-Melhem and Elektorowicz 2011). Fig. 4B shows the main elements of designing the SMEBR system. From a technical point of view, SMEBR technology was designed based on applying a DC field between immersed circular electrodes around an immersed membrane filtration module. Two zones can be formed in SMEBR systems as shown from the top view of the designed SMEBR (Fig. 4C): Zone I between

Table 1
Comparison between MBR configurations

Item	External MBR	Submerged MBR (SMBR)
Shape	Outside the bioreactor	Inside the bioreactor
Cost	High	Low
Energy consumption	The energy demand is high	The energy demand is low (can be up to two orders of magnitude than external MBR
Space	Need more space	Need less space
Flux	Operate at high flux	Operate at low flux

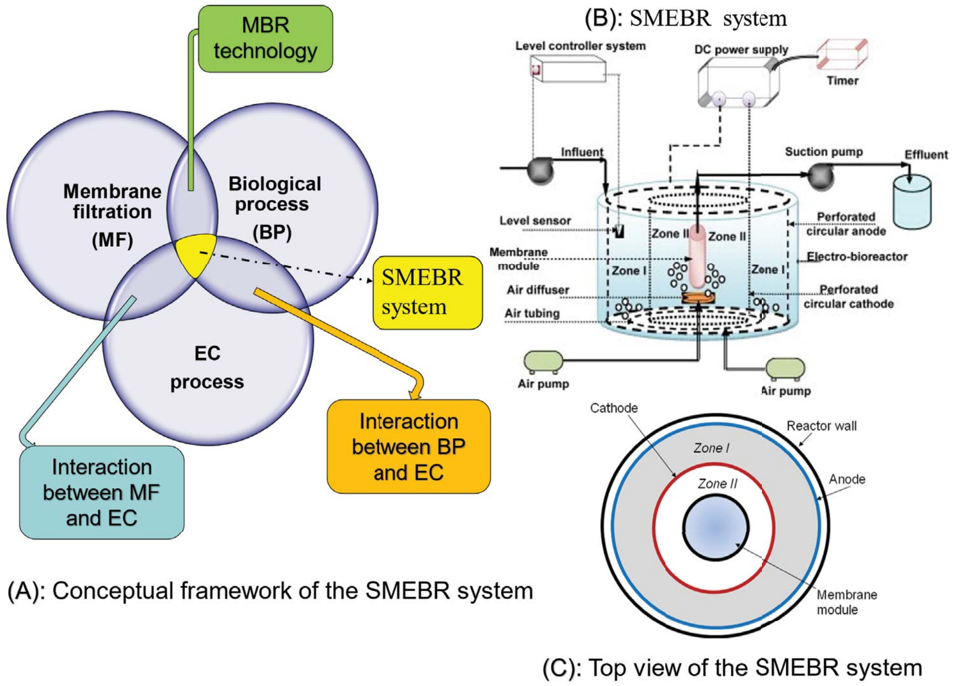

Fig. 4. (A) Basic idea of the SMEBR system, (B) Main elements of SMEBR and (C) Top view. (Bani-Melhem and Elektorowicz 2011).

the wall of the bioreactor and the cathode, and Zone II between the cathode and the membrane module. The significant benefits of designing the SMEBR system are (i) a smaller footprint; (ii) no chemicals are required for coagulation; (iii) reducing the operating costs by reducing the requirements of aeration in conventional SMBR systems; and (iv) improving sludge dewatering conditions (Bani-Melhem, 2008).

3.2. Electrodes configuration

Designing the electrodes in the SMEBR system is important for the uniform distribution of the DC field strength on the mixed liquor solution inside the electro-bioreactor. During the designing stage of the SMEBR system, the design of electrodes was governed by the following constraints (BaniMelhem, 2008):

- The electrodes should be arranged inside the bioreactor in a geometry that must not affect the current density between the electrodes.
- The electrical field cannot affect the longevity of membrane material, for example through advanced oxidation of the polymeric materials.
- Electrodes should be designed so as not to decrease the efficiency of the electrical current between the electrodes.
- The DC field should be identical in all directions in the bioreactor to get homogeneous flocs formation in the treated solution, which means that the electrodes should be designed in a way such that the ML solution should be in contact with the electrodes by the same order of magnitude as the electrical current distribution.
- Both electrodes assemblies in the electro-bioreactor should be designed in a way such that they would not interfere with the feed and the flow toward the membrane module.
- The electrode assembly is the heart of the present treatment invention; therefore, the appropriate selection of its materials is very important.
- The SMEBR design and configuration should take into consideration the requirements of the different simultaneous processes taking place inside the electro-bioreactor such as biodegradation, electrocoagulation, and sedimentation. During these processes, the SMEBR is governed by the following fluid motions (Fig. 5).
    - Supply of wastewater from outside and across to the anode.
    - Air flow from the bottom to the top.
    - Electro-formation of flocs and their settling.
    - Treated water flows through the cathode and toward the membrane module.

Solutions to solve the above constraints mean the successful design of the SMEBR system. To operate the SMEBR in a better way and to meet the above requirements, the SMEBR system should be designed according to the following criteria:

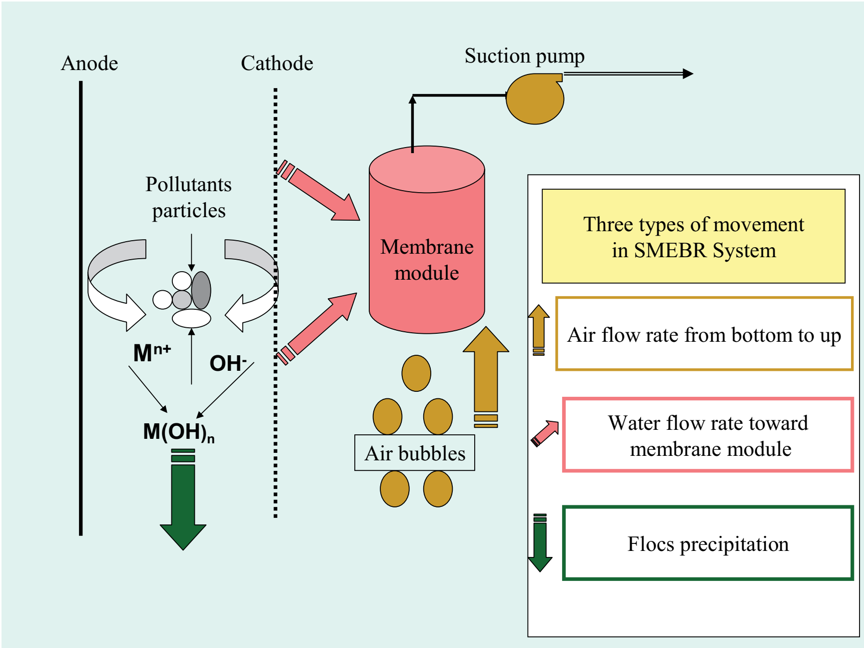

Fig. 5. Major types of fluid motion occurring in the SMEBR system (Bani-Melhem, 2011).

- The membrane unit must be placed in the center of the reactor.
- The electrodes must be placed around the membrane module at an appreciable distance from the membrane.
- An accurate distance between the electrodes should be optimized to minimize the potential effect of an acidic (oxidation) zone on the microbial community.
- Perforated electrodes should be used in the design but not interfere with the feed and the flow toward the membrane module.

As shown in Fig. 3, the proposed design of the SMEBR system divides the hybrid reactor into two zones to achieve the above-mentioned constraints. Generally, in Zone I, three processes take place: biodegradation, electrocoagulation, and electro-sedimentation, while Zone II has two processes: further biodegradation and membrane filtration.

3.3. Electrical parameter constraints

In addition to the design constraints related to the electrode system, as mentioned in the above section, the SMEBR system is governed by several electrical parameters during the treatment process. The selected DC field and the operating mode to supply this DC field into the ML solution are significant constraints in the SMEBR operation. It is very important to identify the best electrolysis conditions in terms of the appropriate DC density. Furthermore, the selected DC field should be applied intermittently mode to the ML solution in the SMEBR system so as not to impede biological treatment (Bani-Melhem, 2008). Moreover, the distance between the electrodes should be designed to prevent the overlap between the acid and base conditions in Zone I that results from the electrochemistry occurring on the anode and the cathode. Also, an optimal distance should be selected between the cathode and the membrane module in Zone II to prevent any possibility of membrane surface damage.

3.4. Controlling operational parameters

The successful design of the SMEBR system should be based on assessing accurate operational parameters that would be able to simultaneously control all the preferential processes: biodegradation, electro-coagulation, sedimentation, and filtration within the system. Biodegradation processes are affected by the surrounding environmental conditions (temperature, pH, O_2 concentration) in the bioreactor. Applying a DC electrical field onto a mixed liquor solution will affect all these conditions in different ways (e.g., temperature may rise, pH would decrease close to the anode, and increase close to the cathode). The recommended range for pH for microorganisms is within the range of 6–9 (Bani-Melhem and Smith, 2012). Subsequently, an interrupted supply of electrical field is needed to preserve the viability of microorganisms. However, at the same time, a DC (at an accurate voltage gradient) is required for an effective electro-coagulation process to create flocs in the bioreactor so the small particles can aggregate and move away from the membrane module.

On the other hand, the supplied oxygen might also affect the behavior of the microorganisms in the bioreactor; however, an excess of air may break down the flocs' formation. Therefore, to achieve the overall objectives of the designed configuration, five parameters should be controlled and optimized during the SMEBR operation, those are DC field, exposure time to DC, air supply, hydraulic retention time (HRT), and sludge retention time (SRT).

3.5. Applications of the SMEBR

Since its invention for the first time in 2010, The SMEBR has shown great potential for reducing membrane fouling by many researchers. Furthermore, the SMEBR exhibits significant pollutant removals. Table 2 summarizes some results from the literature about the performances of the SMEBR for fouling reduction and pollutant removal.

3.6. Advantages of the SMEBR

In comparison with traditional wastewater treatment methods, the SMEBR system has many significant benefits such as (i) a smaller footprint; (ii) no chemicals are required for coagulation; (iii) reducing the operating costs by reducing the requirements of aeration in conventional SMBR systems; and (iv) improving sludge dewatering conditions. The designed SMEBR system may find a direct application for various types of wastewater, including sewage, without extensive pretreatment. Such a solution is required by several small municipalities, mining areas, agriculture facilities, military bases, and different regions. Finally, such a compact hybrid system can easily be adapted to a mobile unit, and it can be driven by solar energy.

3.7. Some limitations of the SMEBR

While all the designed parameters are important in SMEBR, the applied DC field, and DC exposure time

Table 2
Some results from the literature about the performances of the SMEBR

Applications	Type of electrodes	Operating conditions	Fouling reduction (%)	Pollutant removals/ Results achieved	References
Municipal Wastewater (Synthetic)	Ande: Fe Cathode: Fe	Dc = 1 V/cm Mode of DC: 15 min ON/45 min OFF)	16.3%	COD: >96% PO4-P: >98%	Bani-Melhem and Elektorowicz, (2011).
Municipal Wastewater (Synthetic)	Ande: Al Cathode: Fe	Dc = 1 V/cm Mode of DC: 15 min ON/45 min OFF)	52%	PO4-P: >98%	Bani-Melhem et al., 2009
Municipal Wastewater (Synthetic)	Ande: Al Cathode: Fe	NA	Fouling decreased significantly	COD: 92%% PO4-P: 99% NH3-N: 99%	Elektorowicz et al., 2011.
Municipal Wastewater (Synthetic)	Ande: SS (mesh) Cathode: Cu (wire)	0.036 V/cm, 0.073 V/cm	20–25%	20 times reduction of filtration resistance, reduced sludge EPS	Liu et al., 2012
Landfill leachates	Ande: Al (sheet) Cathode: Al (sheet)	HRT = 48 h SRT = 90 d	Fouling decreased significantly	COD: 98.5%% PO_4^{3-}–P: 99% NH3-N: 99% UV254: 96% Heavy metals: 95% Humic acid: 96%	Farsani et al., 2022.
Municipal Wastewater (Synthetic), pharmaceuticals	Ande: AL (mesh) Cathode: SS (mesh)	DC = 0.3, 0.5 and 1.15 mA/cm^2	24, 44 and 45%	COD: 100% DOC: 100%	Borea et al., 2019
Reverse osmosis pre-treatment	Ande: Fe (perforated) Cathode: Fe (Perforated)	DC = 5, 10, 15, 20, 25, 30 mA/cm^2	Fouling decreased significantly	SVI decreased, Increased effluent quality	Hosseinzadeh et al., 2015

play a significant role in a successful SMEBR design. A low DC field and low DC exposure time would not create sufficient conditions for better coagulation, but similarly, a high DC field and higher exposure time might produce a negative impact represented by a decrease in the growth of microorganisms. It seems there is an optimum range of DC exposure time that could be studied in the future.

3.8. Recommendations for future research

The SMEBR system is a completely new design for wastewater treatment combining three fundamental processes (biological, membrane filtration, and electrokinetic) in one hybrid reactor. Although the system proved effective efficiency in terms of pollutant removal and fouling reduction, there is still a wide range of investigation that needs to be explored. Although the system showed good performance on a laboratory scale, a pilot scale investigation would be required to expose the system to a variable quality of wastewater influent. Because cost analysis is a major factor in succeeding in any newly developed method, the feasibility of the newly designed system as a wastewater treatment method needs detailed analysis in terms of cost analysis. The impact of various operational and design parameters, such as sludge retention time (SRT), hydraulic retention time (HRT), and transmembrane pressure (TMP) need further investigation based on pilot scale operation. One of the important design parameters is the applied DC field, which might be energy-consuming therefore investigating the operation of SMEBR based on renewable energy, such as solar energy, would be attractive for future research, specifically in the GCC countries where solar energy can be recovered during the whole year. Electrodes' materials are important parameters in the designing of the SMEBR system and further research should be highlighted on the selection of the best materials required to run the system. The optimum distance between the boundaries of the two zones in the electro-bioreactor would give even better results in terms of decreasing the fouling rate within the SMEBR system and is addressed for future research.

4. Conclusions

In this paper, the submerged membrane electro-bioreactor (SMEBR) system was described in detail as a novel wastewater treatment method to reduce membrane fouling and enhance effluent quality. It should be emphasized that the SMEBR system is not just an addition of the electrocoagulation (EC) to a submerged membrane bioreactor (SMBR). It is a completely new design for wastewater treatment combining three fundamental processes (biological, membrane filtration, and electrokinetic) in one hybrid reactor. Although all previous studies related to the SMEBR system confirmed the efficacy of the SMEBR system in reducing membrane fouling and producing effluent quality, there are still more aspects that need to be studied to make the SMEBR system more competitive with other treatment technologies. In conclusion, the feasibility of the designed SMEBR system for wastewater treatment needs further research to be verified and the operating conditions need to be optimized for large-scale applications.

Acknowledgement

Authors acknowledge the Canadian Natural Sciences and Engineering Research Council (NSERC) Strategic Grant Program for its financial support for SMEBR project.

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Balaban Desalination Publications

The 15th Gulf Water Conference

(2025) 295–307
doi: 10.5004.dsal.2025.700041

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Farmers' attitude regarding the use of treated wastewater in agricultural irrigation, the case of Saudi Arabia

Mohammed A. Alomair[1], Ammar M. Ebrahim[2]*, Randah M.Alqurashi[2], Salah M. Sidahmed[1], Mohamed M. El-Kafrawy[1–3]*, Fathi A. Alnajime[1] , Siddig H. Hamad[2], Rady Tawfik[2], Khalid G.Turk[2], Abdulrahman S. Alablan[1], Emad Al-Karablieh[4]

[1]*Saudi Irrigation Organization (SIO), P.O. Box 279 Al-Hassa, 31982, Saudi Arabia*
email: m.elkafrawy@sio.gov.sa (M.M. El-Kafrawy)
[2]*King Fasial University, , P.O Box 400, Al-Ahsa 31982, Saudi Arabia*
email: aedrees@kfu.edu.sa (A. Ebrahim)
[3]*Soils, Water and Environment Res. Inst. ARC, Giza, Egypt*
[4]*The University of Jordan, Amman, Jordan*

ABSTRACT

Reuse of treated wastewater could provide a key solution to address sustainable water resources management in agriculture. However, the success of this practice depends on farmers' acceptance and involvement, which require careful assessment and evaluation. The purpose of this paper is to investigate the farmers' perception about the treated wastewater reuse from economic benefit, socially acceptable, environmentally dimension and health risks. A sample consist of 391 farmers in five regions in KSA were interviewed using structured questionnaire through a systematic random sampling method to explore how they perceive the quality of treated wastewater. The sample size and distribution were determined according to the number of agricultural holdings, cultivated area and source of irrigation water. Descriptive statistics including cross tabulation is used as useful tool for evaluating the significance of anomalies between regions. The percentage of farms using treated wastewater was in average 65% in the total sample, however about 72% of farmers in Al-Ahssa and Qatif are using treated wastewater. Water scarcity and the non-availability of alternative water resource was among the main reasons for accepting the use of treated wastewater. About 78% of farmer are satisfied of using treated wastewater for irrigation. The majority of farmers expressed their desire to use treated wastewater as a complementary source 43% and 39% as alternative source. The highest positive impact of the use of treated wastewater in irrigation from the farmers' perspective was the impact on productivity, reduction of the cost of fertilizers and saving the cost of water groundwater abstraction. The highest perception of negative impact was pest prevalence on the farm, fear from consumer acceptance, health related aspects, soil

Corresponding author

ISBN 0-86689-078-5

contamination and not suitable for personal use. Only 57% of farmers indicate that they are receiving extension service on the use of treated wastewater. In conclusion, public awareness, famer's capacity building and agricultural extensions program must be taken to change negative perceptions of farmers. Farmers are more likely to accept the use of treated water when there is awareness of water scarcity, ensure water quality and economic benefits exceeds costs.

Keywords: Socioeconomic factors; Farmer's perceptions; Reuse of treated wastewater

1. Introduction

Reusing treated wastewater is crucial for managing water resources sustainably, particularly in water-stressed nations in arid regions of the world that rely on groundwater and desalination to meet their water needs (Asaad and Suleiman, 2023). The Kingdom of Saudi Arabia faces a significant challenge due to the scarcity of sustainable water resources. Within this context, the utilization of treated wastewater emerges as a crucial strategy to alleviate this pressing issue (Badr et al., 2023). The repurposing of treated wastewater stands as a promising alternative, serving to alleviate pressure on finite freshwater reserves, particularly in agricultural applications. This practice not only tackles water scarcity but also has the potential to fundamentally transform the Kingdom's approach to resource management, fostering sustainability and bolstering resilience in light of escalating water demands. Recognizing the importance of redirecting treated wastewater is fundamental in addressing Saudi Arabia's water scarcity challenges and charting a course towards a more sustainable and resource-efficient trajectory.

A heavy reliance on groundwater has precipitated an alarming depletion of this finite resource, surpassing its natural replenishment capacity (Baig et al., 2020). The project endeavors to align with the Saudi Irrigation Organization strategy, aiming to bolster the reuse of treated wastewater in irrigation practices and extend its application across all regions within the Kingdom. Its objectives encompass not only fostering awareness among farmers but also fostering their acceptance of using this water source. Additionally, the project aims to furnish developmental recommendations to fortify the institution, enabling it to activate operational strategies that surmount obstacles and fortify its capacity to realize its outlined objectives.

Treated wastewater (TWW) has been consistently utilized in the projects overseen by the Saudi Irrigation Organization across Al-Ahssa, Riyadh, and Qatif for an extended duration. Notably, in the Riyadh project, treated wastewater stands as the sole irrigation source, while in the Al-Ahssa project, it presently serves as the primary irrigation source. In Saudi Arabia, approximately 84% of annual freshwater consumption is attributed to irrigation, significantly straining water resources in this arid and semiarid region (MoEWA, 2018). The country predominantly exists within regions devoid of perennial rivers, lakes, or continuous flowing streams, experiencing high evaporation rates and an average yearly precipitation of less than 100 mm (MoEWA, 2022). With over 65% of cultivated land reliant on irrigation, Saudi Arabia heavily depends on non-renewable groundwater, constituting roughly 90% of agricultural water usage (MoEWA, 2018)

Regrettably, a lack of comprehensive water regulations and policies, coupled with inadequate monitoring and inefficient irrigation practices over the past forty years, has led to the unsustainable exploitation of non-renewable groundwater resources(Baig et al., 2020). In response to these pressing water scarcity issues and the imperative to preserve groundwater reservoirs, authorities have actively pursued alternative water sources to satisfy the agricultural sector's demands (Alotaibi et al., 2023).

Treated wastewater has garnered significant attention in Saudi Arabia as a potential solution to bridge the expanding gap between water demand and supply (Ouda, 2014). Despite these substantial initiatives aimed at advancing the development and utilization of treated wastewater in agricultural irrigation, its widespread acceptance remains limited within the country (MoEWA, 2022). The production of treated wastewater in Saudi Arabia in 2022 about 1.95 billion m^3, whereas the utilized amount 434 million m^3 with an average reuse rate of approximately 22% during this period (MoEWA, 2022). The surplus treated wastewater is commonly discharged into various environments, including the Arabian Gulf, Red Sea, sand dunes, and wadis (Chowdhury and Al-Zahrani, 2013). In 2022, approximately 12% of treated wastewater found application in agricultural reuse, contributing to about 4% of the total agricultural water consumption(Chowdhury and Al-Zahrani, 2013).

Employing treated water for agricultural irrigation stands as a potentially effective remedy for mitigating water scarcity concerns. However, its widespread adoption remains elusive due to several formidable obstacles, foremost among them being the prospective environmental and human health hazards associated with improper reuse (Badr et al., 2023). These hazards stem from residual concentrations of heavy elements, micro-organic pollutants, or contaminants characterized by heightened biological activity (e.g., pharmaceutical remnants). Moreover, elevated salinity levels prevalent in treated water pose a potential constraint on crop productivity over the medium to long term (Bilal et al., 2020; Oubelkacem et al., 2020). Additionally, the dearth of societal acceptance toward utilizing treated water for crop irrigation emerges as a pivotal impediment hindering the expanded utilization of this water resource in agricultural domains(Alzahrani et al., 2023). As Saudi Arabia endeavors to augment the utilization of treated wastewater in agricultural pursuits, an in-depth examination of farmers' acceptance becomes imperative. Thus, our focus lies on investigating farmers' openness to incorporating treated wastewater specifically within five historically reliant regions in Saudi Arabia for irrigation purposes. Several studies indicate that farmers will adopt treated wastewater if they perceive it as an economically beneficial, socially acceptable, environmentally sound, and have little or no health risks (Abu Madi et al., 2003; Al-Karablieh Emad et al., 2019; Choukr-Allah, 2010; Qadir et al., 2010). (Al-Karablieh et al., 2024) Investigates the impact of irrigating strawberry plants with treated wastewater (TWW) on soil properties, plant growth, heavy metal accumulation, and microbial contamination. Heavy metal levels in strawberries remain within safe limits, microbial contamination rises significantly with TWW irrigation, posing health risks. This finding emphasizing the importance of addressing public concerns about microbial safety despite the potential benefits of wastewater reuse in agriculture.

In a study conducted by(Badr et al., 2023) to evaluates the quality of irrigation water, focusing on treated wastewater in Al-Ahsa Oasis, Saudi Arabia. Using irrigation water quality indices, it assesses its suitability for agricultural irrigation. Results indicate that treated wastewater mixed with groundwater is acceptable for irrigation, but spatial variations exist. While groundwater mixed with agricultural drainage shows higher levels of certain contaminants, treated wastewater demonstrates effective treatment plant performance. However, a significant portion of samples face severe irrigation restrictions, highlighting challenges in water quality. Regular monitoring of treated water quality and treatment plant efficiency is crucial for ensuring the sustainability of wastewater reuse in agricultural irrigation, particularly for addressing farmers' attitudes toward its usage in Saudi Arabia. A study conducted by (Alzahrani et al., 2023) to examines public acceptance of reusing tertiary treated wastewater for agriculture in Saudi Arabia's Al-Ahsa Governorate. Findings from 344 participants show 77% support for this practice, driven by trust in authorities and perceived water resource augmentation. Concerns about health risks and psychological factors influence opposition. Support is stronger for non-direct uses like park irrigation compared to vegetable irrigation. The study highlights the need for public awareness campaigns to promote the safety of treated wastewater reuse in agriculture.

This study aims to bridge the existing void by furnishing policymakers with comprehensive, contemporary insights into the extent of farmers' acceptance regarding the reuse of treated wastewater. The research delves deeply into respondents' informational sources, their comprehension of water and wastewater dynamics, and various demographic attributes to elucidate their attitudes toward treated wastewater reuse.

2. Materials and methods

The questionnaire is designed to collect the study data from five regions: Al-Ahssa, Qatif, Riyadh, Taif and Medina, so that it contains three sections that achieve the objectives of the study: Section I: Social and economic characteristics of farmers, Section II: Farm data and irrigation method, Section III: Treated wastewater reuse options. The farmer's opinion on the impact of its use in irrigation and the reasons that make him accept its use or refrain from use, leading to the completion of the section on assessing farmers' opinions on the use of treated wastewater in irrigation

The design of a questionnaire form that meets the purpose of the study, and the collection of a stratified random sample consisting of (391) single distributed over the study areas, and this part comes to complement the previous stages in terms of data processing, statistical analysis, drawing conclusions and studying economic variables related to the subject of the study. In conducting the study, potential biases in data collection were addressed through several strategies. These included stratified random sampling to ensure representation from diverse regions, a mix of closed-ended and open-ended questions to mitigate response bias, and efforts to minimize self-selection and interviewer biases through targeted recruitment and standardized procedures. Additionally, cultural sensitivity in questionnaire design and pilot testing aimed to mitigate cultural biases among respondents. These measures collectively aimed to enhance the validity and reliability of the study findings.

2.1. Statistical analysis

Statistical analyses were performed using Stata12® version. Simple descriptive analyses, including frequencies, percentages, means, and standard deviation (SD) were computed for demographic and socio-economic characteristics and the other variables of interest such as farmers' attitudes and awareness about treated wastewater. Limited dependent variable regression was carried out for farmers' perceptions. The Chi-square test was carried out to determine the significance level of association and the relationship between the categorical independent variables of demographic and socio-economic factors and the outcome variable of acceptance of treated wastewater reuse in agriculture.

2.2. Probit analysis

Several well-known multivariate statistical methods, such as multiple regression analysis, discriminant analysis, and logistic regression modeling, can be employed to forecast binary dependent variables. However, utilizing multiple regression and discriminant analysis can present challenges, particularly when the dependent variable comprises only two values. Employing multiple regressions breaches an assumption vital for hypothesis testing. Assuming a normal error distribution becomes unreasonable when the dependent variable consists of only two values. Additionally, predicted values lack constraints to ensure they fall within the zero-to-one range necessary to be considered probabilities. Moreover, employing discriminant analysis necessitates multivariate normality of independent variables and equivalent variance-covariance matrices within the binary dependent variable for optimal functionality (Dragonetti et al., 2020)

The exploration of factors influencing the acceptance of utilizing TWW will involve employing limited dependent variable regression. The willingness to accept TWW is regarded as a binary variable, denoted by either acceptance or rejection of treated wastewater in agronomic practices. In this context, defining Y_i as a series of dependent binary random variables, taking on values of either 1 or 0, X_i represents a K-vector of identifiable explanatory variables, β_0 signifies a K-vector of undisclosed parameters, and F stands for a specific known function. Among the functional forms commonly utilized in these scenarios are the linear probability, probit, and logit models (Stern, 1989). The linear probability model has a defect in that F of this model is not a properly distributed function, as it is not constrained to lie between 0 and 1. However, the probit model, like many other models using the normal distribution, may be justified by appealing to a central limit theorem. Stern (1989) concluded the difficulty to distinguish between them statistically unless one has an extremely large number of observations. The choice between them is largely one of convenience and program availability and researchers preferences (Al-Karablieh, 2010; Dey and Astin, 1993; Perry et al., 1986; Stern, 1989). The logit model, however, is more common (Shideed, 2005). For this purpose, two models were analyzed using the limited dependent variable regressions. Consider the following regression model as described by (Maddala and Lahiri, 1992) in Eq. (1):

$$Y_i^* = \beta_0 + \Sigma_{j=1}^{k} \beta_j x_{ij} + u_i \qquad (1)$$

where Y_i^* is not observed. It is commonly called a "latent" variable, x's are the socio-economic factors, u_i is the error term. However, the latent variable can only be observed as a dichotomous variable as Y_i is defined by Eq. (2):

$$Y_i = \begin{Bmatrix} 1 \text{ if } Y^* > 0 \\ 0 \text{ otherwise} \end{Bmatrix} \qquad (2)$$

where Y_i is a variable measuring the acceptance/non-acceptance of re-using TWW. If the cumulative distribution of u_i is logistic, we have what is known as logit model as shown in Eq. (3):

$$\log \frac{P_i}{1-P_i} = \beta_0 + \sum_{j=1}^{k} \beta_j x_{ij} \qquad (3)$$

where P_i is the probability of adoption. The left-hand side of this equation is called the log-odds ratio, thus the log-odds ratio is a linear function of the explanatory variables. If the coefficient of a particular variable is positive, it means that higher values of that variable result in a higher probability of acceptance or WTA, while a lower value of a particular variable implies a lower probability of WTA (Sarap and Vashist, 1994).

As indicated by Maddala and Lahiri (1992), there is a problem with the use of the conventional R^2 measure when the explained variable has only two values. They suggest the proportion of correct predictions as a measure for the goodness of fit. However, the logistic model does not require the assumption of multivariate normality and equal covariance matrices. Furthermore, the probability estimates are insured to fall within zero to one. In addition, it is asymptotically efficient and consistent (Rosenberg et al., 1991). The following variables were taken in the analysis as independent variables are displayed in Table 1 for socioeconomic variables and indicators of farmers' perceptions about the using of treated wastewater for irrigation. Table 1 outlines the definitions and measurement units for socioeconomic variables and perception indicators used in the study. It clarifies the meaning and scale for each variable, such as age in years, educational level in years of education, household size, and income levels categorized in Saudi Riyals. Moreover, it details various perceptions related to the use of TWW in agriculture, including satisfaction, willingness to use TWW as an alternative or complementary source, and its perceived impacts on productivity, soil, fruit quality, costs, water usage, among others. Table 1 provides a comprehensive understanding of how these variables were defined and assessed in the questionnaire, aiding in the interpretation of the study's findings and correlations between different factors and attitudes toward TWW usage in farming practices.

Table 1
Definition of socioeconomic variables and perception indicators

Location	Explanation of variables	Unit or measures
Age	Farmers' age	Years
Education	Educational level	Years of education
Family size	Household size	Members
Work status	Status of work	0 = not work, 1 = retied, 2 = working
Income level	Income level measured in SR	0 = <3000, 1 = 3000–5000, 3 = 5000–7000, 4 = 7000–10000, 5 = 10000–15000, 6 = >15000
Agr. experience	Agricultural experience	Years
Holding size	The holding size	Dunam
Irrigated area	The irrigated areas	Dunam
Land ownership	Land ownership	1 = owner, 0 = otherwise
Use groundwater	Using groundwater for irrigation	1 = yes, 0 = otherwise
Sufficient water	Receiving sufficient water	1 = yes, 0 = otherwise
Water store	Storing water in farm	1 = yes, 0 = otherwise
Store damage	Changing water quality due to water store	1 = yes, 0 = otherwise
Permanent lab	No of permanent laborers in farm	No of workers
Occasional lab	No of occasional laborers in farm	No of workers
WWT satisfaction	Are you content with using treated wastewater for irrigation?	1 = yes, 0 = otherwise
WTU TWW	Do you have a desire to use treated wastewater for irrigation	1 = yes, 0 = otherwise
TWW alternative	Do you have a desire to use TWW for irrigation as an alternative source	1 = yes, 0 = otherwise
TWW new source	Do you have a desire to use TWW for irrigation as a new source	1 = yes, 0 = otherwise
TWW com source	Do you have a desire to use TWW for irrigation as a complementary source	1 = yes, 0 = otherwise
Productivity impact	Using TWW have an impact on crop productivity	1 = positive, 0 = no impact, –1 negative
Soil impact	Using TWW have an impact on soil	1 = positive, 0 = no impact, –1 negative
Fruit impact	Using TWW have an impact on fruit quality	1 = positive, 0 = no impact, –1 negative
Return impact	Using TWW have an impact on total farm returns	1 = positive, 0 = no impact, –1 negative
Costs impact	Using TWW have an impact on water costs	1 = positive, 0 = no impact, –1 negative
Water impact	Using TWW have an impact on water consumption level	1 = positive, 0 = no impact, –1 negative
Fertilizers	Using TWW have an impact on fertilizers use	1 = positive, 0 = no impact, –1 negative
Pest impact	Using TWW have an impact on pest incidence	1 = positive, 0 = no impact, –1 negative
Health impact	Using TWW have an impact on human health	1 = positive, 0 = no impact, –1 negative
Consumer	Using TWW have an impact on final consumers	1 = positive, 0 = no impact, –1 negative
Extension services	Receiving extension services	1 = yes; 0 = otherwise
Public ext	Receiving public extension services	1 = yes; 0 = otherwise
No alternative	Using TWW due to no alternative available	1 = yes; 0 = otherwise
GW salinity	Using TWW due groundwater salinity	1 = yes; 0 = otherwise
Water scarcity	Using TWW due to water scarcity;	1 = yes; 0 = otherwise

Source: questionnaire

3. Results and discussion

Across the entire sample, the mean age was 57 years, with the predominant demographic being farmers aged 50 years and above, constituting 73% of the total. Within the specific study regions, the mean ages were as follows: Al-Ahssa (60 years), Al-Qatif (59 years), Riyadh (58 years), Al-Taif (47 years) and Al-Madina (58 years), Approximately, 37% of the farmer sample possessed a bachelor's or postgraduate degree across all study areas. However, the distribution of this percentage varied significantly within the distinct study regions: Al-Ahssa 8%; Al-Qatif 11%, Riyadh 72%, Al-Taif 50% and Al-Madina 48% or higher (73%). The educational level of the study sample, where the highest percentage of high educational level were found in Riyadh with 15 years of educations, the lowest was in Alhssa with a primary schools. was those who had a secondary school education 35.2%, followed by the percentage of 26.4% of university graduates and more, then 16.8% of primary as shown in Table 2.

The average family size is 7.2 person; Madina has the lowest household size. The average year of experience in farming is 29 years. This might due to the sample bias

Table 2
Descriptive statistics of socioeconomic factors and farmers' attitudes toward using TWW

Location	Al-Ahssa	Riyadh	Taif	Qatif	Madina	Mean
Age	60.13	58.06	47.40	59.37	58.24	57.34
Education	7.02	15.55	13.90	8.87	12.64	11.31
Family size	7.92	7.80	6.53	8.37	3.70	7.20
Work status	0.79	1.68	1.60	1.33	1.06	1.25
Income level	2.46	5.45	4.10	3.85	3.70	3.84
Agr. experience	37	24.8	19.7	37.0	25.4	29.73
Holding size	5.5	119.5	26.4	9.6	53.0	46.4
Irrigated area	4.23	52.17	20.12	8.31	40.89	24.87
Land ownership	0.66	0.97	0.72	0.33	0.88	0.74
Use groundwater	0.22	0.17	0.84	0.30	0.40	0.33
Sufficient water	0.84	0.38	0.29	0.93	0.76	0.63
Water store	0.34	0.84	0.50	0.13	0.18	0.46
Store damage	0.41	0.79	0.36	0.89	0.84	0.62
Permanent lab	1.23	6.74	3.19	2.22	2.78	3.34
Occasional lab	3.65	8.00	4.09	1.59	2.00	4.45
WWT satisfaction	1.50	1.21	0.41	0.39	1.10	1.08
WTU TWW	1.00	0.99	0.47	1.00	1.00	0.92
TWW alternative	0.53	0.50	0.17	0.13	0.28	0.39
TWW new source	0.17	0.08	0.09	0.07	0.02	0.10
TWW com source	0.30	0.40	0.21	0.80	0.70	0.42
Productivity impact	0.50	0.94	–0.22	–0.70	0.84	0.42
Soil impact	0.62	0.36	–0.34	–0.70	0.78	0.27
Fruit impact	0.41	0.58	–0.40	–0.70	0.70	0.24
Return impact	0.54	0.57	–0.02	–0.61	0.54	0.33
Costs impact	0.54	0.77	–0.17	–0.76	0.56	0.35
Water impact	0.51	0.65	–0.12	–0.15	0.72	0.40
Fertilizers	0.62	0.76	–0.33	–0.39	0.72	0.41
Pest impact	0.36	0.06	–0.55	–0.74	–0.28	–0.07
Health impact	0.17	0.09	–0.22	–0.59	0.16	0.00
Consumer	0.35	0.14	–0.52	–0.46	0.08	0.04
Extension services	0.54	0.94	0.22	0.61	0.22	0.57
Public ext	0.38	0.61	0.38	0.61	0.12	0.43
No alternative	0.28	0.11	0.12	0.63	0	0.22
GW salinity	0.02	0	0.02	0	0.34	0.05
Water scarcity	0.03	0.21	0.26	0.02	0.02	0.11

of selecting older ages of farmers. The average holding size is about 46 dunums, whereas the average irrigated areas is 24 dunums. About 74% of the interviewed farmers are landlord. Only in Taif the land owner are 33% of the sample as shown in Table 2.

Among the study participants, 57% of farmers acknowledged receiving agricultural services, advice, and guidance on the utilization of treated wastewater in irrigation. According to the farmers, the primary reason for accepting the use of treated wastewater in irrigation was either the absence of alternative sources or the accessibility of this specific source for use as shown in Table 2.

Fig. 1 illustrates the varying distributions of farmers' monthly income levels across different regions, highlighting disparities in income distribution among the surveyed areas. In Riyadh, a significant 72% of farmers earn above 15000 SR. In Al-Ahssa, it's 15%, followed by Qatif (15%), Madina (8%), and Taif (16%). Overall, 30% of farmers fall into this highest income bracket. With less 3000 SR < 3000 SR: in Al-Ahssa, this income level constitutes 37% of farmers' income, while in Riyadh, it's 2%. Taif and Qatif have 3% and 7%, respectively, while Madina stands at 20%. Overall, this income bracket represents 17% of the total sample.

The results shows that 65% of the farmers in the sample are already using treated wastewater for irrigation, about 78% in Al-Hassa, whereas only 7% of farmers in Taif are using TWW as shown in Fig. 2. Aside from conducting the assessment of farmers' perspectives on utilizing treated wastewater in irrigation, the study also inquired about their level of satisfaction regarding its use. The findings reveal a prevailing sense of contentment, with just 22% expressing dissatisfaction. Fig. 2 presents data on the utilization of treated wastewater for irrigation purposes across different regions: Al-Ahssa, Riyadh, Taif, Qatif, and Madina. Among the surveyed regions, the highest usage of treated wastewater for irrigation is observed in Al-Ahssa with 101 instances, followed by Riyadh (87), Qatif (32), Madina (30), and Taif (4). In total, 254 instances were reported, constituting 65% of the overall responses.

Most farmers within the study sample expressed a preference for utilizing treated wastewater either as a complementary sources (42%) or as their primary alternative sources (39%). According to the farmers' perspective, the most significant positive impacts of using treated wastewater in irrigation were observed in the following aspects, respectively: increased productivity, reduced fertilizer usage, cost reduction, and augmented water availability. Only about 8% of farmers are denying to use treated wastewater for irrigations. About 53% for farmers in Taif are refusing the use of TWW, and about 80% of farmers in Qatif prefers to use TWW as complementary source to the existing water source in the farm as shown in Fig. 3, which offers insights into the utilization of treated wastewater for irrigation purposes across different regions, indicating varying levels of acceptance and implementation of this practice among the surveyed areas.

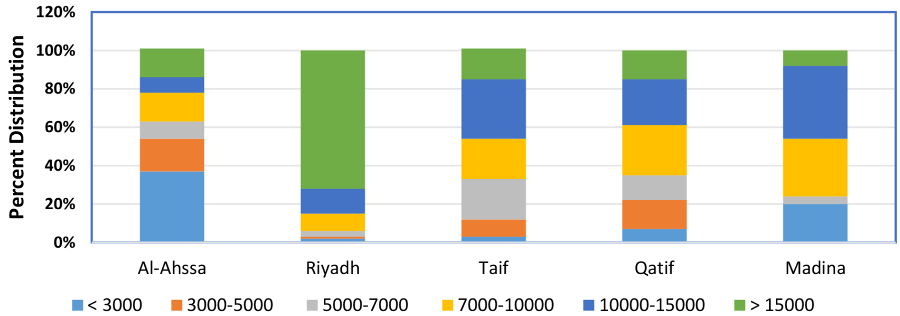

Fig. 1. Distribution of monthly income level by region in Saudi riyals.

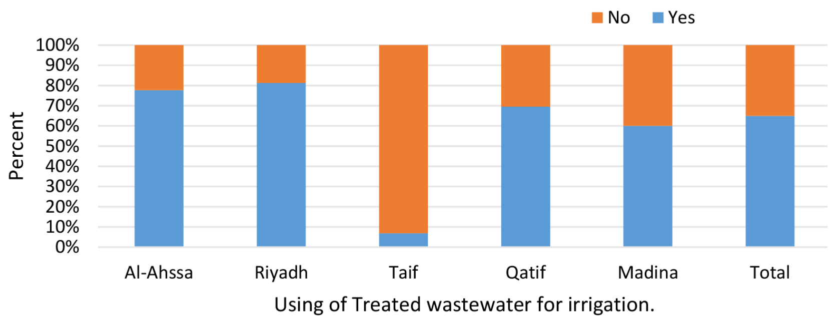

Fig. 2. Using of treated wastewater for irrigation.

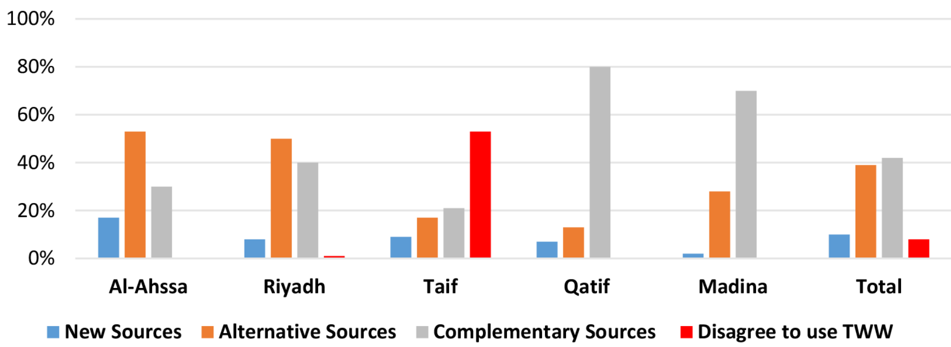

Fig. 3. Farmers' willingness to use treated water for irrigation.

The furrow irrigation system is practiced by 53% of the farmers in the sample, whereas drip irrigation is about 25% and pressurized system about 20%. About 72% of Qatif farmers are using furrow irrigation, drip irrigation are common in Riyadh and Taif with 37% as shown in Fig. 4.

Fig. 5 offers a comprehensive view of how farmers in KSA perceive the effects of utilizing treated wastewater across different facets of agricultural practices, displaying a varied range of opinions from positive to negative impacts across various categories. Farmers perceived the most significant adverse effects of employing treated wastewater in irrigation to be on two key factors: the proliferation of pests on the farm and the afraid of consumer acceptance of product produced of TWW. About 23% of respondents have a perception that the use of TWW will negatively affect the crop yield and farm productivity. About 61% of respondent indicate that the

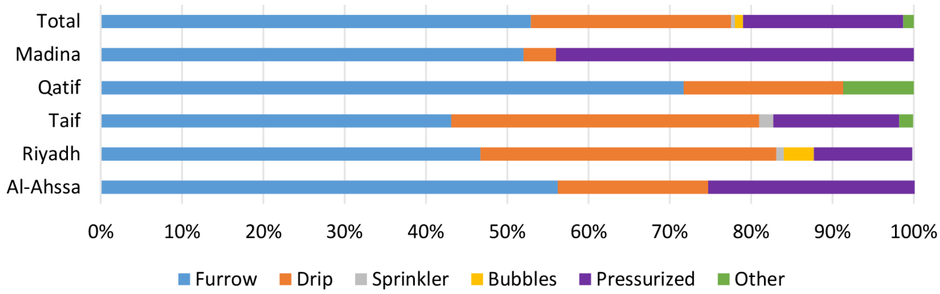

Fig. 4. Irrigation system applied by farmers in the sample

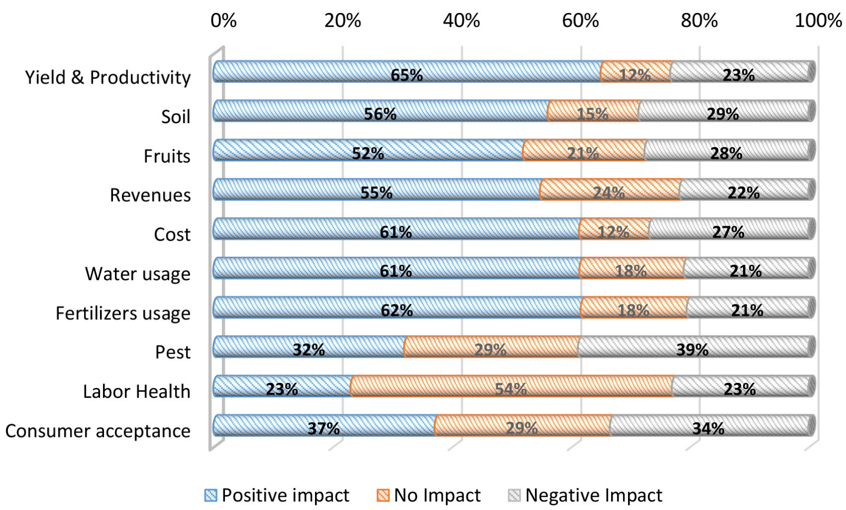

Fig. 5. Farmers' perception about the impact of using TWW.

using of TWW had a positive impact on cost reduction, increasing of water usage and saving fertilizers cost. About 56% of farmers see a positive impact on soil due to treated wastewater usage. 15% perceive no impact, while 29% believe it has a negative impact on soil. 52% of farmers perceive a positive impact on fruits quality from using treated wastewater. 20% see no impact, while 28% perceive a negative impact.

Among the study participants, 57% of farmers acknowledged receiving agricultural services, advice, and guidance on the utilization of treated wastewater in irrigation. According to the farmers, the primary reason for accepting the use of treated wastewater in irrigation was either the absence of alternative sources or the accessibility of this specific source for use.

Table 3 outlines the socioeconomic factors influencing the acceptance of using treated wastewater (TWW). The table seems to present coefficients, standard errors, z-scores, p-values, and other statistical values associated with various factors affecting the acceptance of TWW usage. The probit stepwise regression analysis was used to determine the significant independent variables affecting the farmers' acceptance to use TWW. The coefficient column presents the coefficients associated with each factor. For instance, satisfaction of using TWW has a coefficient of 1.39, indicating its positive impact on the acceptance of TWW. The dy/dx and ey/ex values indicate the marginal effects and the elasticity of one variable with respect to dependent variable willingness to use TWW, displaying how much one variable changes concerning a change in another variable. The statistical information at the bottom is displayed to summarize the model's goodness-of-fit and accuracy in predicting the acceptance of using treated wastewater based on the specified socioeconomic factors. The log likelihood, pseudo R^2, LR chi-square test, count R^2, and percent of cases correctly classified provide insights into the model's performance and accuracy in predicting acceptance based on these socioeconomic factors.

The education level with a coefficient of –0.100, higher levels of education appear to slightly decrease the willingness to use TWW. Whereas the farmers who receive public extension services with a coefficient of –1.132 suggests that this factor has a negative impact. Public extensions might be associated with a decreased willingness to use TWW. However, farmers who receive extension services in general indicating a positive influence. Extension services seem to positively impact the willingness to use treated wastewater. The lack of alternative water sources with a coefficient of 0.99 implies that a lack of alternative sources significantly increases the willingness to use treated wastewater. Farmer who are using groundwater as a source of irrigation has a strong negative impact with a coefficient of –2.018, suggesting that reliance on groundwater significantly decreases the willingness to use TWW. Fertilizers saving with a coefficient of 0.589 indicates a positive relationship, implying that the ability to save on fertilizers might increase the willingness to use treated wastewater.

Table 4 shows the results of the analysis of factors affecting the acceptance of farmers to use TWW as an alternative source of irrigation water. The results suggests that certain socioeconomic factors significantly influence the acceptance of using treated wastewater as an alternative source for irrigation, as indicated by their coefficients, significance levels (*p*-values), and effects on the likelihood of acceptance.

The variables listed (Extension serv., Fruit impact, Health impact, Costs impact, Work kind, Occasional lab, Store damage, Holding size, Satisfaction, Land ownership, Groundwater) are the independent variables being analyzed for their impact on the acceptance of using treated wastewater for irrigation. The positive coefficients (e.g., Extension serv., Fruit impact, Health

Table 3
Socioeconomic factors affecting the acceptance of using TWW

Willingness to use TWW	Coefficient	Std. error	*z*-core	$P>\|z\|$	*dy*/*dx*	*ey*/*ex*
Satisfaction of TWW	1.391	0.352	3.95	0.000	0.083	0.028
Education level	–0.100	0.038	–2.63	0.009	–0.006	–0.202
Public extensions	–1.132	0.438	–2.58	0.010	–0.067	–0.061
Extension services	0.960	0.458	2.1	0.036	0.057	0.022
Work kind	0.539	0.225	2.4	0.016	0.032	0.104
Lack of alternative source	0.999	0.531	1.88	0.060	0.059	0.010
Using groundwater	–2.018	0.618	–3.26	0.001	–0.120	–0.292
Fertilizers saving	0.589	0.187	3.15	0.002	0.035	0.030
Constant	2.096	0.769	2.73	0.006		

log likelihood = –42.09, pseudo R^2 = 0.618, LR chi^2 (8) = 136, prob > chi^2 = 0.00, count R^2 = 0.948, percent of cases correctly classified = 94.82%

Table 4
Socioeconomic factors affecting the acceptance of using TWW as alternative sources

TWW alternative	Coefficients	Std. error	*z*-core	*P* >|*z*|	*dy*/*dx*	*ey*/*ex*
Extension serv.	0.416	0.156	2.66	0.008	0.122	0.213
Fruit impact	0.298	0.125	2.39	0.017	0.087	0.313
Health impact	0.426	0.128	3.33	0.001	0.124	0.364
Costs impact	–0.220	0.114	–1.93	0.054	–0.064	–0.291
Work kind	–0.162	0.082	–1.98	0.047	–0.047	–0.227
Occasional lab	–0.043	0.014	–3	0.003	–0.012	–0.234
Store damage	–0.492	0.158	–3.12	0.002	–0.144	–0.360
Holding size	0.001	0.001	1.87	0.061	0.000	0.042
Satisfaction	0.374	0.126	2.96	0.003	0.109	0.340
Land ownership	0.382	0.185	2.06	0.039	0.111	0.290
Groundwater	–0.379	0.182	–2.08	0.038	–0.111	–0.194
Constant	–1.053	0.289	–3.64	0		

log likelihood = –198, pseudo R^2 = 0.229, LR chi^2 (8) = 118, prob> chi^2 = 0.00, count R^2 = 0.741, percent of cases correctly classified = 74.0%

impact, etc.) suggest a positive relationship between the respective variable and the likelihood of using TWW for irrigation. For instance, higher values of these variables tend to increase the likelihood of accepting TWW usage as an alternative source. The negative coefficients (e.g., Costs impact, Work kind, Occasional lab, etc.) indicate a negative relationship with the likelihood of using TWW. Higher values of these variables might decrease the likelihood of accepting TWW usage. The statistical measures provided at the end of the table (log likelihood, pseudo R^2, LR chi^2, prob> chi^2, count R^2, percent of cases correctly classified) offer insights into the goodness of fit and predictive power of the model. For instance, the pseudo R^2 indicates the proportion of variation explained by the model, while the percentage of cases correctly classified represents the accuracy of the model's predictions.

Table 5 represents another probit regression analysis assessing the influence of various socioeconomic factors on the acceptance of using treated wastewater (TWW) as a new source, likely for irrigation purposes as well. TWW new source indicates the acceptance or use of treated wastewater as a new source, possibly for irrigation. The variables listed (Return impact, Store damage, Extension serv., Costs impact, Fertilizers, Satisfaction, Health impact, Holding size, Pest impact) are the independent variables analyzed for their impact on the acceptance of using treated wastewater as a new source.

Positive coefficients (e.g., Return impact, Extension serv., Costs impact, Pest impact) suggest a positive rela-

Table 5
Socioeconomic factors affecting the acceptance of using TWW as a new source

TWW new source	Coefficients	Std. error	*z*-score	*P* >|*z*|	*dy*/*dx*	*ey*/*ex*
Return impact	0.456	0.195	2.34	0.019	0.066	1.229
Store damage	–0.346	0.203	–1.71	0.088	–0.050	–0.516
Extension serv.	0.418	0.218	1.92	0.055	0.060	0.509
Costs impact	0.534	0.190	2.8	0.005	0.077	1.439
Fertilizers	–0.408	0.182	–2.24	0.025	–0.059	–1.281
Satisfaction	–0.400	0.177	–2.26	0.024	–0.058	–0.961
Health impact	–0.407	0.186	–2.19	0.028	–0.059	–0.900
Holding size	–0.008	0.004	–2.11	0.035	–0.001	–2.388
Pest impact	0.349	0.163	2.14	0.033	0.050	0.667
Constant	–1.614	0.300	–5.39	0		

log likelihood = –101, pseudo R^2 = 0196, LR chi^2 (9) = 49.6, prob> chi^2 = 0.00, count R^2 = 0.899, percent of cases correctly classified = 89.9%

tionship between the respective variable and the likelihood of accepting TWW usage as a new source. Higher values of these variables may increase the likelihood of acceptance. Negative coefficients (e.g., Store damage, Fertilizers, Satisfaction, Health impact, Holding Size): Indicate a negative relationship with the likelihood of using TWW as a new source. Higher values of these variables might decrease the likelihood of acceptance. The statistical measures provided (log likelihood, pseudo R^2, LR chi^2, prob> chi^2, count R^2, percent of cases correctly classified) evaluate the model's goodness of fit and predictive ability. The pseudo R^2 indicates the proportion of variation explained by the model, while the percentage of cases correctly classified represents the accuracy of the model's predictions. This analysis suggests that various socioeconomic factors significantly influence the acceptance of using treated wastewater as a new source, based on their coefficients, significance levels (*p*-values), and effects on the likelihood of acceptance.

Table 6 illustrates the results of another probit regression analysis examining the influence of various socioeconomic factors on the acceptance of using treated wastewater (TWW) as a complementary source, likely for irrigation alongside other water sources. The dependent variable represents the acceptance or use of treated wastewater as a complementary source, likely for irrigation.

The variables listed (Store damage, Extension serv., Fruit impact, Occasional lab, Work kind, Health impact, Agr. experience, Pest impact, Water impact, Water store, Fertilizers, Return impact) are the selected independent variables analyzed using stepwise regression analysis for their impact on the acceptance of using treated wastewater as a complementary source. Positive coefficients (e.g., Store damage, Occasional lab, Work kind, Agr. experience, Water impact, Fertilizers) suggest a positive relationship between the respective variable and the likelihood of accepting TWW usage as a complementary source. Higher values of these variables may increase the likelihood of acceptance. Negative coefficients (e.g., Extension serv., Fruit impact, Health impact, Water store, Pest impact, Return impact) indicate a negative relationship with the likelihood of using TWW as a complementary source. Higher values of these variables might decrease the likelihood of acceptance. The statistical measures provided (log likelihood, pseudo R^2, LR chi^2, prob> chi^2, count R^2, percent of cases correctly classified) evaluate the model's goodness of fit and predictive ability. The pseudo R^2 indicates the proportion of variation explained by the model, while the percentage of cases correctly classified represents the accuracy of the model's predictions. This analysis suggests that various socioeconomic factors significantly influence the acceptance of using treated wastewater as a complementary source, based on their coefficients, significance levels (*p*-values), and effects on the likelihood of acceptance.

The study's findings highlight the significant potential of utilizing treated wastewater for irrigation in Saudi Arabia, offering opportunities to enhance water use efficiency, address water scarcity challenges, and improve agricultural productivity sustainably. Practical implications include the need for supportive policies, infrastructure development, public awareness campaigns, and continued research to promote safe and efficient wastewater reuse in agriculture while safeguarding human health and the environment. Practical implica-

Table 6
Factors affecting the acceptance of using TWW as a complementary source

TWW com source	Coefficient	Std. error	*z*-score	$P > \lvert z \rvert$	*dy*/*dx*	*ey*/*ex*
Store damage	0.667	0.152	4.41	0	0.209552	0.32822
Extension serv.	–0.279	0.153	–1.83	0.068	–0.088	–0.174
Fruit impact	–0.282	0.121	–2.32	0.02	–0.088	–0.399
Occasional lab	0.029	0.012	2.51	0.012	0.009	0.115
Work kind	0.162	0.079	2.04	0.041	0.051	0.164
Health impact	–0.240	0.126	–1.9	0.058	–0.075	–0.270
Agr. experience	0.011	0.005	2.46	0.014	0.004	0.316
Pest impact	–0.239	0.101	–2.36	0.018	–0.075	–0.259
Water impact	0.361	0.114	3.16	0.002	0.113	0.485
Water store	–0.324	0.155	–2.09	0.037	–0.102	–0.169
Fertilizers	0.327	0.115	2.84	0.005	0.103	0.459
Return impact	–0.292	0.120	–2.44	0.015	–0.092	–0.441
Constant	–0.739	0.259	–2.85	0.004		

log likelihood = –212.9, pseudo R^2 = 0196, LR chi^2 (12) = 100.4, prob > chi^2 = 0.00, count R^2 = 0.731, percent of cases correctly classified= 73.06%

tions advocate for capacity building, farmer education, tailored regional approaches, and robust monitoring mechanisms. Addressing regional variations in attitudes necessitates customized interventions aligned with local socioeconomic dynamics. Such multifaceted strategies aim to ensure safe and effective wastewater reuse practices, promoting sustainable water management and agricultural resilience in the region. Regional variations in attitudes towards wastewater reuse in agriculture are evident in the study's findings, influenced by factors such as education level, income, and access to alternative water sources. Policy-makers must account for these differences when crafting policies and programs to encourage wastewater reuse. Customizing interventions to meet the unique needs and challenges of each region is crucial for their success. Collaborating with local stakeholders, including farmers, community leaders, and agricultural organizations, is essential for gaining insights into regional dynamics and developing tailored strategies for promoting wastewater reuse effectively.

4. Conclusions

Farmers' awareness, acceptability, and support are directly related to the success of the wastewater reuse initiatives. In this work, 92% of the participants support the reuse of treated wastewater in agriculture and 65% of respondents are already using TWW. The perceptions about the impacts of treated wastewater usage on various agricultural facets, such as yield, soil, fruits, revenues, costs, and water usage, are diverse. While a majority of farmers perceive positive impacts on certain aspects like cost reduction, water usage, and fertilizers, there are concerns about negative impacts on pests, soil quality, and consumer acceptance.

Farmers necessitate comprehensive education regarding the health hazards linked to wastewater application and the implementation of suitable management protocols. Additionally, efforts should focus on persuading farmers about the allure of treated wastewater as a viable resource, highlighting its potential for cost savings through diminished reliance on fertilizers.

Recommendations for policy-makers and practitioners include developing stringent regulations, investing in treatment infrastructure, providing education on safe usage, fostering research collaborations, implementing robust monitoring systems, engaging with the public, and offering financial incentives to maximize the benefits of treated wastewater reuse in agriculture, thus ensuring water security, agricultural sustainability, and economic development in Saudi Arabia.

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The 15th Gulf Water Conference

(2025) 308–314
doi: 10.5004.dsal.2025.700024

WSTA 15th Gulf Water Conference
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Ecofriendly and low-cost adsorbent for efficient removal of lead and nickel from aqueous solution

Amal S. Al Rahbi*, Nalini Uthman, Wafa A. Al Rawahi, Amani Al Nabhani, Khulod Al Maqbali, Maryam Al Hattali, Zahra Al Zuhimi

Department of Applied Sciences, University of Technology and Applied Sciences, Muscat, Oman.
* *amal.alrahbi@utas.edu.om*

ABSTRACT

This study aims to investigate the removal of heavy metal from industrial waste water using a low-cost bio-adsorbent. Banana peels was treated chemically with phosphoric acid and methanol. The ability of treated banana peel to remove lead and nickel from wastewater was investigated. Adsorption experiments were performed to optimize the effect of process conditions such as adsorbent dose, pH and contact time on heavy metals removal. Banana peels treated with phosphoric acid was found to have a higher removal efficiency compared to the one treated with methanol. The maximum removal efficiency of lead and nickel was found to be 78 and 43% with the banana peels treated with phosphoric acid at pH 6 and with using 2 g of treated peels. The lead removal efficiency was found to increase from 27 to 95 % with the increase of adsorbent dosage from 0.5 to 4 g, respectively. The adsorption processes for lead and nickel were well described by Langmuir and Freundlich isotherm model, respectively. The experimental results suggest that the fabricated bio adsorbent is an alternate low-cost adsorbent for waste water treatment.

Keywords: Banana peels; Bio-adsorbent; Water pollution; Lead; Nickel

1. Introduction

With the expansion of human activity and chemical industries, such as electroplating, batteries, pesticides, mining, rayon, tanning, fluidized bed bioreactors, textile, metal smelting, petrochemical, paper, and electrolysis applications, the amount of heavy metals in wastewater has been rising. Wastewater tainted with heavy metals seeps into the environment, endangering both the ecology and human health. Because heavy metals are not biodegradable and may cause cancer, their presence in water at excessive concentrations may have a detrimental effect on the health of living things (Qasem et al., 2021). Lead (Pb), zinc (Zn), mercury (Hg), nickel (Ni), cadmium (Cd), copper (Cu), chromium (Cr), and arsenic (As) are the most commonly occurring heavy metals. To effectively remove heavy metals from wastewater, the use of chemically modified banana peels has gained attention due to their potential as an adsorbent. Banana peels have been found to contain pectin, which can be chemically modified to enhance its adsorption properties (Khamsucharit et al., 2017). Additionally, the surface of banana peels can be activated to improve the adsorption of heavy metals (Mohd et al., 2020). The high content

*Corresponding author

of antioxidants in banana peels also contributes to their potential as an effective adsorbent material (Kanazawa et al., 2000). Furthermore, the use of banana peels as biosorbents for wastewater purification purposes has been explored, with promising results in reducing the need for additional chemicals, thus minimizing environmental impact (Fosso-Kankeu et al., 2019).

In the broader context of heavy metal removal, the adsorption of heavy metals from water using various materials, including nanomaterials, has been extensively studied (Kromah et al., 2021; Asriza et al., 2022). Studies have shown that mineral adsorbents and synthetic materials exhibit strong capabilities for removing heavy metal ions from water (Song et al., 2014; Chen et al., 2017). Furthermore, the adsorption of heavy metals by biochar has been highlighted as an effective and renewable method for controlling heavy metal pollution (Yang et al., 2021). The effectiveness of banana peels as an adsorbent for heavy metals is supported by research on the adsorption of heavy metals by other natural materials such as sawdust (Lim et al., 2008). Additionally, the adsorption properties of loess calcareous nodules to heavy metal ions in aqueous solutions have been investigated, emphasizing the importance of the adsorbent's performance in the adsorption process (Qi et al., 2021). In the context of wastewater treatment, the integration of cleaner production and wastewater treatment using biogas production has been explored, demonstrating the potential for sustainable approaches to waste management (Rahayu et al., 2018). Furthermore, the potential of banana peels as an adsorbent aligns with the need for effective wastewater treatment, especially in industries such as textile manufacturing, where wastewater quality parameters are a significant concern (Rabbi et al., 2018).

The use of banana peels as an adsorbent for the removal of heavy metals from industrial wastewater has gained attention in recent literature. Several studies have demonstrated the potential of banana peels for this purpose. For instance, Deshmukh et al. (2017) investigated the use of dried banana peels as an adsorbent for the removal of cadmium ions from aqueous solutions, highlighting the presence of functional groups on the walls of agricultural waste that facilitate the adsorption process. Similarly, Mirzaienia et al. (2016) discussed various methods for the removal of nickel and lead from industrial wastewater, including the use of banana peels as biosorbents. Furthermore, Afolabi et al. (2021) specifically focused on the biosorption of copper and lead ions onto banana peels in single and binary systems, demonstrating the effectiveness of natural banana peels in removing these heavy metals from aqueous solutions. Moreover, the modification of banana peels has been explored to enhance their adsorption capacity for heavy metals. Adhikari et al. (2023) discussed the chemical modification of banana peels for the adsorptive removal of chromium (VI) from aqueous solutions, indicating the potential for using modified banana peels to remove various heavy metals from water. Additionally, Olaoye et al. (2018) highlighted the efficacy of banana peel activated carbon in the removal of cyanide and selected metals from wastewater, further emphasizing the potential of modified banana peels as an adsorbent for heavy metal removal. Furthermore, the use of banana peels in electro kinetic remediation for the removal of nickel from contaminated soil has been investigated, demonstrating the versatility of banana peels in different remediation techniques. Additionally, the potential of banana peels as biosorbents for the removal of organic contaminants and dyes from wastewater has been explored in the literature, indicating the broad applicability of banana peels in water treatment processes.

The literature review indicates that chemically modified banana peels have shown promise in the removal of heavy metals, including nickel and lead, from industrial wastewater. The adsorption capacity of banana peels, along with their potential for modification to enhance their effectiveness, makes them a viable and sustainable option for water treatment processes. The objective of this study was thus to use the chemically modified banana peels as an adsorbent for the removal of heavy metals from wastewater that aligns with broader efforts to develop sustainable and effective methods for wastewater treatment. The potential of banana peels as an adsorbent is supported by their chemical composition, surface activation, and antioxidant properties, making them a promising and environmentally friendly option for heavy metal removal from wastewater.

Herein, this study aimed to examine the effectiveness of banana peels as a low-cost and environmentally benign waste for nickel and lead removal from aqueous solution. The influence of operating variables such as pH, contact time, adsorbent dosage and initial heavy metal concentration on metals adsorption were investigated.

2. Materials and method

2.1. Materials

Concentrated nitric acid, methanol, phosphoric acid, nickel (II) nitrate and lead (II) nitrate were obtained from Sigma Aldrich and used without further purification. To prepare the stock standard solutions, the required amounts of lead (II) and nickel (II) nitrate were dissolved in deionized water and mildly acidified with nitric acid. Banana peels were used as biosorbent for the removal of lead and nickel. Banana peels were collected from a restaurant located at University of Technology and applied sciences, and used as the biomass material for the adsorption experiments. Banana peel consists of protein (0.9%), lipid (1.7%), carbohydrate (59%) and fiber (31%).

They were washed several times with distilled water to remove impurities and other unwanted materials, then the peels were sun-dried for 20 h. Then, peels were cut into small pieces (0.5–1 cm) and subsequently dried in oven at 110°C for 48 h.

2.2. Biomass modification

The obtained peels were chemically treated with methanol and phosphoric acid. Methanol was used to modify the carboxylic groups on the surface of the banana peels and phosphoric acid was used because it has a high impact in the physiochemical properties such as the amount of surface acidic functional groups that has an influence in the adsorption mechanism (Jeong et al., 2018).

20 g of dry banana peels were mixed with 50 ml of 99.9% methanol to which 16 ml of (0.1 M) HCl has been added. The mixture was stirred and heated at 60°C for 48 h. Finally, the peels were then washed several times with cold distilled water. The prepared adsorbent was labeled as PAM (Memon et al., 2008).

In addition, the peels were chemically treated with phosphoric acid. About 30 g of banana peels were soaked in a 250 ml phosphoric acid H_3PO_4 (30% w/w) and stirred at 400 rpm for 2 h. The mixture was then heated at 230°C for 2 h. Then, the sample was filtered and washed many times with distilled water until a neutral pH was obtained (Zhou et al., 2017). The prepared adsorbent was labeled as PAP.

2.3. Biosorbent batch experiments

Stock solutions of lead (40 ppm) and nickel (20 ppm) were prepared from the (1000 ppm) reference solutions suitable for flame atomic absorption spectrometry. Standard solutions of the desired concentrations (1–40 ppm) were prepared by successive dilutions of the prepared stock solution using 1% HNO_3. The adsorption experiments were conducted in 25 ml flasks containing 50 ml of adsorbate solutions with a concentration of 40 ppm of lead concentration and 20 ppm of nickel with a certain amount of adsorbent of 0.5–4 g at an ambient temperature. The influence of contact time on adsorption of lead and nickel was examined using a 2 g dosage of the treated peels mixed with 50 ml of (40 ppm) lead or (20 ppm) nickel for certain period of time (5, 15, 30, 60, 120, and 200 min). The effect of adsorbent dosage on the adsorption of lead and nickel was examined using different adsorbents masses in the range of 0.5–4 g and the pH was adjusted to 6.

The effect of pH for lead and nickel adsorption was examined using 2 g of adsorbents and pH was adjusted in the range of 2–7 by adding a buffer solution. The adsorbents were mixed with 50 ml of adsorbate solution and placed in a shaker with constant shaking at 300 rpm for 90 min. Atomic absorption spectrophotometer (AAS) was used to determine the residual concentration of metals.

The metal removal (%R) and adsorption capacity (mg/g) were calculated as follows:

$$\text{Removal (\%)} = \frac{C_i - C_e}{C_e} \times 100 \tag{1}$$

$$q_e = \frac{\left(C_i - C_e\right)V}{m} \tag{2}$$

where C_i is the initial concentration of dye solution (ppm) and C_e is the concentration of dye solution after adsorption, q_e is the adsorption capacity at specific time (mg/g), m is the mass of sample (g) and V is the volume of water (L).

3. Results

3.1. FT-IR spectroscopy of the prepared adsorbents

FTIR analysis was done to gain further insight about the potential functional groups present in the primary adsorbent structure and the treated one. FTIR spectra of banana peels, banana peels treated by methanol and banana peels treated with phosphoric acid are shown in Fig. 1. The presented FTIR spectra shows similar IR bands. A broad band around 3290 cm^{-1} corresponded to the hydroxyl group was detected with the three samples. Bands corresponding to the alkyl chains at 2918 cm^{-1}, C–H and C=O stretching of carboxylic acid or ester at 2850 cm^{-1}, COO− anion stretching at 1734 cm^{-1}, C=O groups at 1604 cm^{-1}, were also detected. These results confirm the presence of significant amounts of acidic oxygen-containing functional groups such as carboxyl and hydroxyl which may has a significant role in enhancing metals removal. The spectra of treated peels showed a notable reduction in the intensity of the OH, C–H, and –COOH peaks at 3306, 2918, and 1604 cm^{-1}, respectively. These results agreed with the results obtained by (Memon et al., 2008).

3.2. Adsorption parametric study

3.2.1. Influence of pH

Protons can be adsorbed or released during the biosorption process, hence the pH has an impact on both the overall charge of the biosorbent and the solubility of metal ions (Romera et al., 2007). The influence of pH on lead and nickel adsorption was studied using the treated banana peels and the pH was varied from 2 to 7. As it is depicted in Fig. 2, the maximum metals removal was obtained at pH 6. The metals removal was found to increase with the increase of pH from 2 to 6, after which

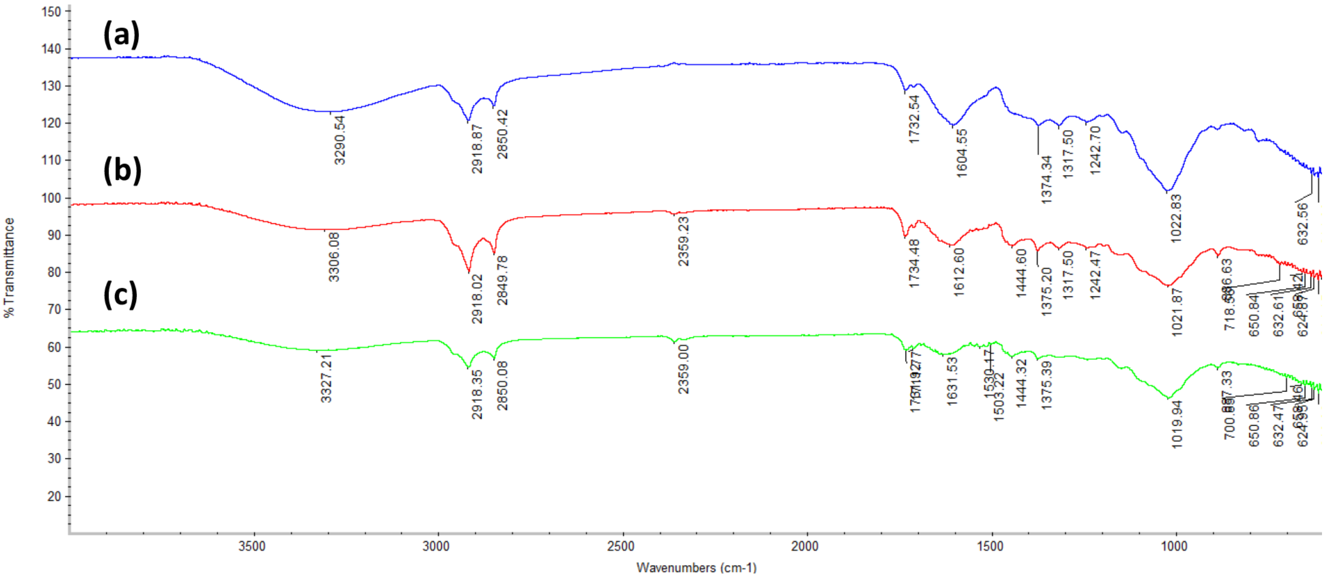


Fig. 1. FTIR spectra of (a) the original banana peel, (b) PAM and (c) PAP.

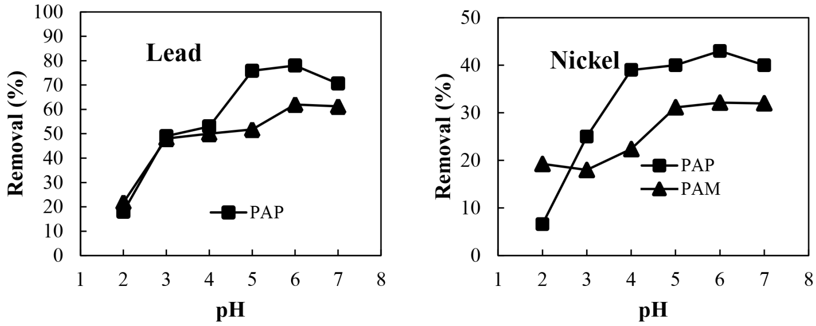


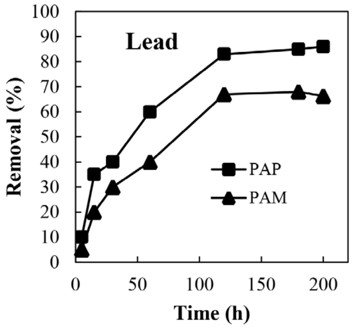
Fig. 2. Influence of pH on metals removal.

adsorption decreased as the pH of solution increased. Above pH 6 metal precipitation is favored (Davis et al., 2003). The maximum lead removal of 78% was obtained by the sample treated with phosphoric acid (PAP) compared to 62% by PAM. The removal effectiveness of the chemically treated adsorbent for nickel removal was found to be lower than that for lead as only 43% was obtained by PAP at the same pH. The results showed that the optimum pH for metals removal was 6. The adsorption increases in the acidic medium due to presence of carboxylic groups, which has a high ability for metals adsorption. Adsorption sites do not activate at higher pH values, however at lower pH values, H^+ and metal cations compete for the available adsorption sites.

3.2.2. *Influence of contact time*

It is crucial to study the influence of contact time of metals removal to determine the potential for rapid binding, kinetics, and the process of removing metal ions by biosorbents, as well as the optimal time for complete removal of the intended adsorbate ion. The results of lead and nickel removal using the chemically treated banana peels at different contact times are presented in Fig. 3. Metals removal was found to increase with the increase of contact time from 5 to 200 min. The maximum uptake of lead was observed with the sample treated with phosphoric acid which was about 34.5% at 200 min. However, the sample treated with methanol had a maximum removal of 24% at 200 min. Phosphoric acid has been proven to be an effective activating agent to enhance the properties of carbon-based products (El-mouwahidi et al., 2017). The main factor influencing the as-prepared adsorbents ability to remove lead was their ability to dehydrate the polysaccharides and generate a significant number of acidic surface functional groups (Thuan et al., 2017).

The results for nickel removal using the chemically treated banana peels at different contact times are presented in Fig. 2b. The maximum nickel removal of 11%



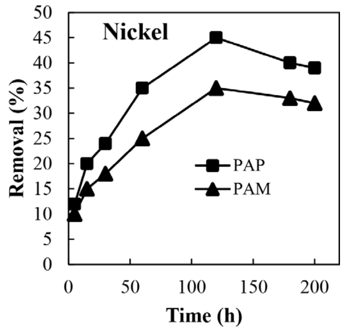


Fig. 3. Influence of time on metals removal.

was observed with the sample treated with phosphoric acid at 200 min. In the study conducted by Gogoi at el,. (2015) the effect of contact time on adsorption of nickel by using sawdust treated with citric acid was examined, and a maximum removal of 35% was observed at 60 min.

A neem (*Azadirachta indica*) sawdust biosorbent treated with hydrochloric acid was used by Rao et al. (2017) to remove and Ni ions from wastewater. The maximum nickel removal was achieved after 180 min.

3.2.3. Influence of adsorbent dosage

Fig. 4 illustrates the remarkable relation between adsorbent dosage and metals removal at an initial concentration of 40 ppm. The effect of sorbent dosage on lead and nickel adsorption was studied using the treated banana peels as adsorbent, the dosage was varied from 0.5 to 4 g. For both samples the optimum dosage was found to be 3 g. The lead removal was found to reach 82 and 78% by PAP and PAM, respectively with the use of 3 g of peels. The same trend was observed with nickel removal. The results of the effect of adsorbent dosage on nickel uptake by the prepared samples are presented in Fig. 4. Nickel removal was found to increase with the increase of dosage. The maximum nickel removal was found to be 50 and 43% by PAP and PAM, respectively. This result agrees with those reported by Singh et al. (2020).

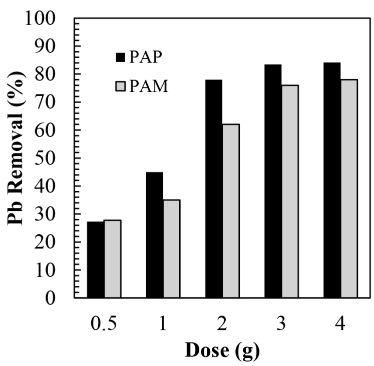
3.2.4. Influence of initial concentration

Various concentrations (10–40 ppm) were chosen to examine the variation of removal efficiency with initial concentration. The study was carried out under the conditions of room temperature, contact time (30 min), sample dosage (2 g), and constant pH 6. As the results presented in Fig. 5 shows that the removal efficiency increased with the increase of metal ions concertation from 10 to 40 ppm. The sample treated with phosphoric acid has the maximum metals removal. For example, the removal increased from 68 to 78% for lead and from 26 to 46% for nickel. The increase in specific area of the adsorbent and the higher chance of contact between the adsorbent particles and metal ions may be the cause of the observed increase in the metal's removal (Dargahi et al., 2016).

The Langmuir [Eq. (3)] and Freundlich [Eq. (4)] adsorption isotherm models were used to analyze data in order to determine which model was most appropriate for the adsorption of nickel and lead ions and the results are presented in Fig. 6.

Langmuir adsoprtion isotherm

$$\frac{C_e}{Q_e} = \frac{1}{K_L q_m} + \frac{C_e}{q_m} \quad (3)$$



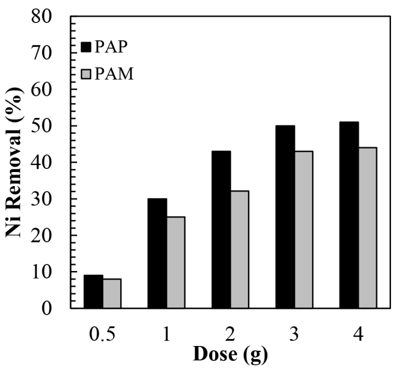


Fig. 4. Influence of adsorbent dose on metals removal.

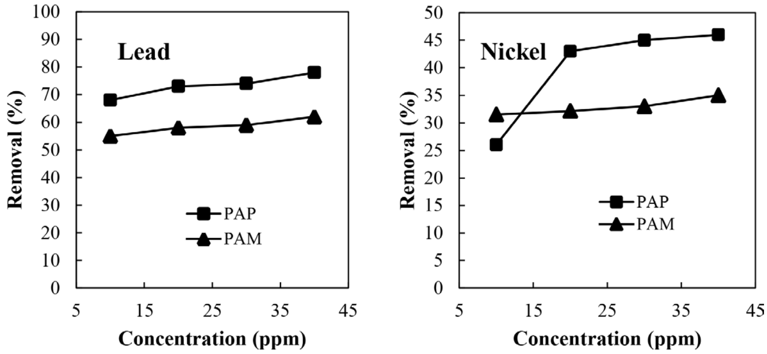


Fig. 5. Influence of initial metal concentration of removal.

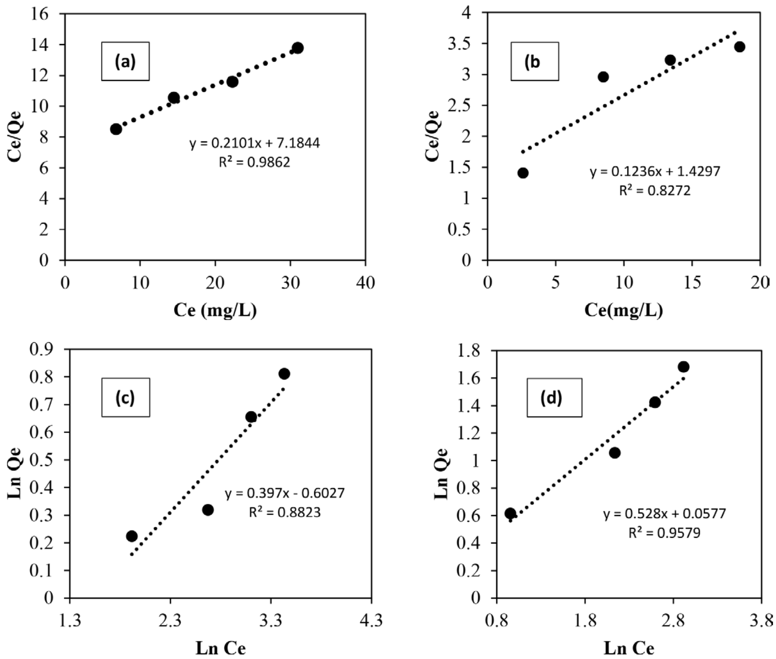


Fig. 6. (a) Langmuir isotherm on the adsorption of lead ion (b) Langmuir isotherm on the adsorption of nickel ion (c) Freundlich isotherm on the adsorption of lead ion (d) Freundlich isotherm on the adsorption of nickel ion.

Freundlich adsorption isotherm:

$$\ln Q_e = \ln K_F + \frac{1}{n}\ln C_e \qquad (4)$$

The lead ion adsorption process onto the surface of prepared adsorpent showed a stronger correlation with the Langmuir adsorption isotherm with R^2 value = 0.9862. This indicates that the lead ion's highest surface coverage on the used adsorbent occurred in a monomolecular layer on the adsorbent surface.

However, the data fitting results for the Langmuir and Freundlich isotherm adsorption model for the nickel ion indicated that the Freundlich isotherm best explained the nickel ion adsorption. The R^2 value from the Freundlich isotherm was found to be 0.9579. Surfaces that are extremely heterogeneous are typically described by Freundlich equation.

Conclusion

Banana peels were chemically treated methanol and phosphoric acid. Adsorption technique was used to examine the effectiveness of the synthesized adsorbents for the removal of nickel and lead from aqueous solutions. The adsorption capacity of the prepared adsorbent was found to influenced by pH, contact time, adsorbent dosage and initial metal concertation. Banana peels treated with phosphoric acid exhibited a higher lead removal (84%) as compared to nickel using the initial concentration of 40 ppm, dosage of 4 g and pH of 6.

The adsorption data were evaluated with the Langmuir and Freundlich isotherms and the adsorption process followed the Langmuir isotherm model for lead, and Freundlich isotherm model for nickel. The adsorption process of lead occurred on a monomolecular layer on the adsorbent surface, while the adsorption of nickel ion found to be a chemical process. Banana peels treated with phosphoric acid is suitable for use as an adsorbent for Pb(II) in industrial wastewater because of its high adsorption efficiency.

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Balaban Desalination Publications

مؤتمر الخليج الخامس عشر للمياه
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(2024) 315–323
doi: 10.5004.dsal.2024.700068

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Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Comparative wastewater quality indicators and multivariate analysis of Riyadh sewage treatment plants and its impact on irrigation of Riyadh district

Ahmed M. Elfeky[1,*], Ahmed A. El-Shafei[1,2], Faisal M. Alfaisal[3]

[1]*Agricultural Engineering Department, College of Food and Agriculture Sciences, King Saud University, Riyadh 11451, Saudi Arabia, email: aelfeky@ksu.edu.sa*

[2]*Agricultural and Biosystems Engineering Department, Faculty of Agriculture, Alexandria University, Alexandria 21545, Egypt*

[3]*Department of Civil Engineering, College of Engineering, King Saud University, P.O. Box 800, Riyadh, 11421, Saudi Arabia*

ABSTRACT

The ability of the communities to continue to live normally is doubtful if sufficient water is not allocated to agricultural irrigation. As a result, we try to analyze a non-conventional source of non-potable water for irrigation. The investigation assessed wastewater treatment plants in Riyadh, Saudi Arabia, particularly emphasizing tertiary-treated wastewater used for irrigation and groundwater replenishment. The present investigation aimed to evaluate the physicochemical parameters of Riyadh wastewater treatment plants (WWTPs) for being used in irrigation. In this study, 12 physicochemical and 1 microbial parameter were collected during 2013–2016. The treated wastewater (TWW) quality parameters were: chemical oxygen demand (COD), dissolved oxygen (DO), Cl^-, Na^+, Ca^{++} Mg^{++}, ammonia (NH_4), nitrate (NO_3), total dissolved solids (TDS), EC, pH, and *Escherichia coli* (*E. coli*). The Canadian Wastewater Quality Index (CWQI), and Comprehensive Water Pollution (CPI) were utilized for the assessment of wastewater quality for irrigation purposes. Additionally, principal component analysis (PCA) was used to determine the dependable parameters. The CWQI outcomes ranged from 73.75% to 95.26%. The variations during four years were acceptable and of sufficient quality for irrigation. The CPI results ranged from 0.16 to 1.61. However, it was found that the average CPI was 0.6, showing that there had been some light pollution throughout the entire time interval. The principle component analysis revealed that the first main component, representing 19% of the dataset, is crucial for understanding effluent characteristics. Other components include COD, NH_4, *E. coli*, NO_3, and Na, providing a dominant pattern. These factors provide a dominant pattern for understanding wastewater characteristics. The effluent from the Riyadh wastewater treatment plant is suitable for irrigation over the year. A substantial correlation between nitrite, turbidity, and CWQI was found using a stepwise regression model.

Keywords: Principle component analysis; Canadian wastewater quality index; Comprehensive water pollution; Treated wastewater reuse

* Corresponding author.

1. Introduction

The Gulf Cooperation Council (GCC) countries produced 2853 million m^3/year ($Mm^3\ y^{-1}$) of wastewater in 2015, with Saudi Arabia contributing 54% (1546 $Mm^3\ y^{-1}$) and Saudi Arabia treating 69% (1063 $Mm^3\ y^{-1}$) (Aleisa and Al-Zubari, 2017). The TWW use in agriculture equals 400 million m^3 (Mm^3), which represents 37.6% of TWW in Saudi Arabia. Additionally, the amount of TWW in Riyadh is 556 Mm^3 in 2021, however, only 41.9 Mm^3, or 7.5%, of that, is used for agriculture (MEWA, 2021). According to the 2030 Saudi Vision, Saudi Arabia intends by 2025 to entirely use TWW to reach 100% utilization of TWW, which would be considered a vital water source (Ouda, 2016). TWW is available all year and contains nutrients required for agricultural growth (Mancuso et al., 2022). So, it can be used as a source throughout the year. The total annual capacity of the 133 WWTPs in Saudi Arabia is 1.87 billion m^3. In the future, TWW will be depended on as an unconventional water resource, especially after the green Riyadh project (RCRC, 2021). The greatest option for wastewater use is groundwater recharge, followed by environmental utilization.

Water quality indices (WQI) simplify the representation of water quality by reducing the amount of data points by employing physicochemical and bacteriological parameters (Poonam et al., 2013). The Canadian Wastewater Quality Index (CWWQI) is a tool developed by the Canadian Council of Ministers of the Environment (CCME) (Saffran et al., 2001), to facilitate the monitoring of complex and technical data on water quality (Hurley et al. 2012). The index aids water managers in giving a clear and consistent explanation of overall water quality (Khan et al., 2004; Glozier et al., 2006). The CWWQI has been explored extensively for drinking water, groundwater, and surface water, despite its limited use for wastewater.

Multivariate statistical methods, such as factor/principal component analysis (FA or PCA) and cluster analysis (CA), can be used to discover relationships across disparate datasets (Wang et al., 2017). PCA is a statistical method that uses an orthogonal transformation to convert correlated data into linearly uncorrelated principal components. By reducing vast chemical datasets to a few components and discovering previously undiscovered relationships, this technique helps to a better understanding of water quality (Khound and Bhattacharyya, 2017). PCA improves process quality and performance by detecting and diagnosing defects and dealing with changing operating situations by iteratively updating the covariance structure (Bayo and López-Castellanos, 2016). These methods are extremely successful in environmental research and are crucial in enhancing the quality of water quality data. The integration between WQI and statistical techniques (PCA) in KSA improves understanding of the variation in water quality parameters. The purpose of the study is to examine the temporal variations in the features of TWW quality as well as the key factors affecting TWW quality, to ascertain if TWW is suitable for irrigation, and to comprehend the statistical relationship between parameters. As well as we try to explain how the factors related to wastewater quality affect the CWQI and show how to reduce the redundant variables by using PCA in conjunction with statistical techniques.

2. Materials and methods

Riyadh is the capital of Saudi Arabia. It has a population of 7.5 million (25 % of total population) (GASTAT, 2018).

2.1. Description of Riyadh wastewater treatment plants

Riyadh is divided into four populated areas: East Riyadh, North Riyadh, Manfouha, and Heet as described in details shown in Table 1.

The research included an evaluation of wastewater treatment plants in Riyadh Province, Saudi Arabia, composed of tertiary-treated wastewater from the city and used for irrigation and groundwater recharge.

2.2. TWW quality parameters

The historical TWW parameters data were collected for four years from WWTPs, which are located in the Riyadh province (Table 1). The TWW quality parameters included thirteen parameters: chemical oxygen demand (COD) (mg L^{-1}), dissolved oxygen (DO) (mg L^{-1}), Cl^- (mg L^{-1}), Na^+ (meq L^{-1}), Ca^{++} (meq L^{-1}), Mg^{++} (meq L^{-1}), NH_4^+–N (mg L^{-1}), NO_3^-–N (mg L^{-1}), total dissolved solids (TDS) (mg L^{-1}), EC (dS.m^{-1}), pH, turbidity and *Escherichia coli* (*E.coli*) (Cell/100 ml). All sampling and analytical techniques were carried out following the American Public Health Association (Greenberg et al.,1992). According to (American Public Health Association, 1998), the measured parameters include biochemical oxygen demand (BOD), total suspended solids (TSS), nitrogen (N), dissolved oxygen (DO), and pH. According to Saleem et al. (2000), the conventional standard plate count method (MPN) per 100 mL was used for the microbiological analysis. SAR was calculated using the link between soluble calcium, soluble magnesium, and soluble sodium divalent cations. A calcimeter was used to measure the calcium carbonate content, and the turbidity method was used to measure the sulfate (SO_4) concentration (Swift and Sparks, 1996). Unlike the utilization of sulfuric acid

(H_2SO_4) for assessing HCO_3 concentration, the measurement of chloride (Cl^-) concentration involved the use of silver nitrate ($AgNO_3$) as per Maiti (2004). The soluble Ca^{++} and Mg^{++} concentrations were determined using the versenate titration method (EDTA) according to Maiti (2004), while soluble Na^+ and K^+ concentrations were measured using a flame photometer. NH_4 was measured with a Keldahel and calibrated with H_2SO_4 (Kroon, 1993). According to Swift and Sparks (1996), turbidity was measured using a spectrometer in a nephelometric turbidity unit (NTU). According to Hussein and Magram, (2012), the total dissolved solids (TDS) were quantified using the gravimetric method. The EC was measured via an EC meter.

2.3. Evaluation of the suitability of water for irrigation purposes

2.3.1. Calculating the Canadian Water Quality Index (CWQI)

CWQI was calculated as follows (De Rosemond et al., 2009; Hurley et al., 2012):

$$\mathrm{CWQI} = 100 - \frac{\sqrt{F_1 + F_2 + F_3}}{1.732} \quad (1)$$

where F_1 is the percentage of measured parameters that do not meet the limit at least once in the period. It is calculated as follows:

$$F_1 = \frac{\text{number of failed parameters}}{\text{total number of parameters}} \quad (2)$$

F_2 is the percentage of individual tests that do not meet limitation which is calculated as:

$$F_2 = \frac{\text{number of failed tests}}{\text{total number of tests}} \quad (3)$$

F_3 is the failed test values that do not comply with their purposes which are calculated as follows:

$$F_3 = \frac{\text{nes}}{0.01\,\text{nes} + 0.01} \quad (4)$$

where nes is the collective number of times that tests are higher than compliance divided by the total number of tests. It is calculated as follows:

$$\text{nes} = \frac{\sum_{i=1}^{n} \text{Extrusion}_i}{\text{number of tests}} \quad (5)$$

where Excursion is the number of times that the individual test is higher than a limitation. It is calculated as:

$$\text{Extrusion} = \frac{\text{failed test value}}{\text{limitation}} - 1 \quad (6)$$

These factors can be calculated from the following equations This calculation method was illustrated in detail (Obiad and Al-Sultan, 2020). The wastewater

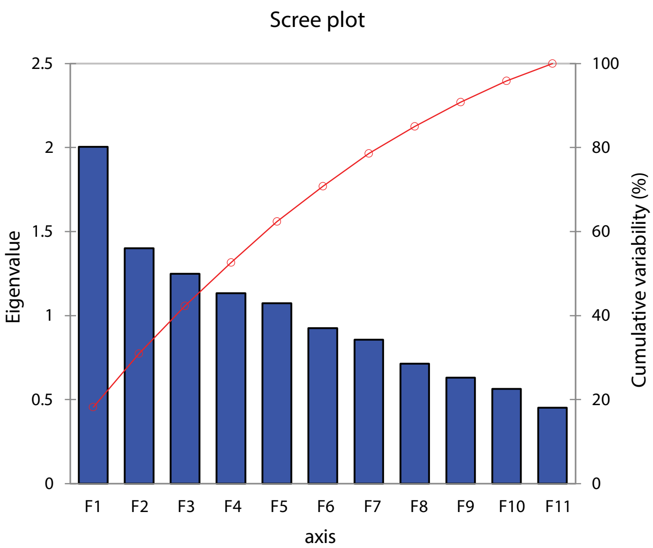

Fig. 1. Scree plot of the 11 components resulting from the PCA of TWW parameters.

Table 1
Major wastewater plants in Riyadh province (Alkhudhiri et al. 2019)

Wastewater plant	Design capacity (m^3/d)	Technology	Treatment type	Purpose
Manfouha	North 200000 South 200000 East 200000	Trickling filter-activated sludge	Tertiary	Agriculture irrigation
Heet-Alkharj	Phase I 100000 Phase II 100000 Phase III 200000	activated sludge	Tertiary	Groundwater recharge
Alhayer	Phase I 400000	activated sludge	Tertiary	Irrigation and groundwater recharge
Refinery	20000	Clarification& filtration	Tertiary	Agriculture irrigation

quality was then ranked in different categories as described in Table 2 (Khan et al., 2004).

2.3.2. Comprehensive Pollution Index (CPI)

CPI is calculated by using a measured concentration of parameters compared with the permissible limit in irrigation wastewater quality prescribed by Saudi standards (Al-Jasser, 2011) as follows (Matta et al., 2020):

$$\text{Pi} = \frac{\text{Measured concentration of individual parameter}}{\text{Standard permissible concentration of parameter}} \quad (7)$$

$$\text{CPI} = \frac{1}{n}\sum_{n}^{1}\text{Pi} \quad (8)$$

where Pi is the index of a single parameter of water quality measured, and n is a number of the parameters. CPI ranges are defined between 0 to 2. The classifications for TWW quality are clean (values 0–0.2), sub-clean (values 0.21–0.4), slightly polluted (values 0.41–1.0), moderately polluted (values 1.01–2.0), and severely polluted (values 2.01).

2.4. Multivariate statistical analysis approach

Principle component analysis (PCA) as a multivariate statistical technique was utilized to comprehend the temporal change in water quality metrics. By using this tool, the amount of input variables required to develop straightforward and trustworthy prediction models that correlate target variables may be reduced. The strategy of PCA was followed using XLSTAT software (Awolusi et al., 2018). The strategy involved data normalization, which standardized data by removing the mean and dividing by the standard deviation. This ensures equal contribution of each variable to the research. A covariance matrix represents the relationships between variables. Eigenvectors and eigenvalues were determined, and primary components were identified. The method also enhances representation quality by lowering dataset dimensionality. The statistical analysis was conducted using the XLSTAT application (Version 2018; Excel Add-ins soft SARL, New York, NY, USA). The thirteen quality factors produced 1430 samples during a four-year period.

3. Results and discussions

3.1. TWW parameters of Riyadh TWWPs

The data shows that 18.75% of COD data, 29.17% of NO_3, and 39.58% of NH_4 values were over the maximum permitted level for restricted irrigation. Additionally, 56.25% of turbidity and 4.167% of *E. coli* data exceeded the maximum permitted level. However, 95.83% of *E. coli* and 43.75% of turbidity data were below the limit. The dissolved oxygen, SAR, Na, Ca + Mg, TDS, EC, and pH samples were all below the maximum permitted limit as shown in Table 3.

3.2. TWW Comprehensive Pollution Index (CPI)

As shown in Table 3, the CPI results were found to vary in the range of 0.06–2.8 for free chlorine with an average of 0.44 (slightly polluted), whereas for SAR the CPI results varied from 0.24–0.27 with an average of 0.42 (slightly polluted), however in the Na from 0.26–0.98 with an average 0.48 (slightly polluted). The CPI results were found to vary in the range of 0.27–0.75 with an average of 0.45 (slightly polluted) for *E. coli*, whereas COD varied in the range of 0.01–4.01 with an average of 0.93 (slightly polluted). The CPI results of NO_3–N varied from 0.01–2.67 with an average of 0.89 (slightly polluted). The CPI results of NH_4–N varied from 0.44–4.02 with an average of 0.51 (slightly polluted). The CPI results of TDS and EC varied from 0.58–3.33, and 0.79–0.9, respectively with averages of 0.73, and 0.87, respectively. The water quality of TWW in Riyadh TWWPs was slightly polluted, however, there are no significant public health risks linked to the reuse of these treated wastewater, particularly for irrigated crops throughout the entire period. The study found that 43.75% of turbidity data exceeded the maximum permitted level for RI. This might be because of inadequate influent treatment or elevated turbidity, which

Table 2
Wastewater quality category based on CWWQI

Quality range	WWQI	Water category
Excellent	95–100	Very close to natural or pristine levels
Good	80–94	Rarely depart from natural or desirable levels
Fair	65–79	Sometimes depart from natural or desirable levels
Marginal	45–64	Often depart from natural or desirable levels
Poor	0–44	Quality is almost always threatened or impaired

lowers chlorine effectiveness in water with high COD and turbidity. A similar result of Al-Hammad et al. (2014) mentioned that 66% of samples exhibited turbidity levels between 6.0 and 8.2 NTU, above the 5.0 NTU limit. While the turbidity measurements of 33% of the samples fell within the recommended limit. However, Al-A'ama and Nakhla (1995); and Al-Turki (2010) recorded lower findings, with mean values of 1.6 and 2.3 NTU, respectively, from studies of municipal WWTP in the KSA (Jubail and Buraidah). Although WWTP lessens the number of harmful microorganisms, they do not get rid of them entirely. Although desalination of TWW is a costly option, it is usually not necessary for use in agriculture. Many crops that are watered with wastewater that has been treated present different health risks; some of these crops may even include pathogenic microorganisms that are not thought to be detrimental to humans. These include industrial crops like cotton or fodder, fruits that are dried for at least 60 days after irrigation, watermelons produced for edible grains or seeds, and crops that are inaccessible to humans. There might not be any health dangers associated with these crops (Shakir et al., 2017).

3.3. TWW Canadian Wastewater Quality Index (CWQI)

The CWQI outcomes of TWW of Riyadh TWWPs over a four-year period ranged from 73.75% to 95.26% as shown in Table 4. The worst months were February, June, and December of 2015, and June 2016, which represented 8.3% of samples and fell into the fair category. The remaining 44 residual months had a good category and rarely deviated from natural or desirable levels. The study found that the reuse of treated wastewater could not pose harm to public health, especially for users and irrigated crops. These findings contradict the research in the Al-Mafraq wastewater treatment plant in Jordan, which had water quality that fell into the marginal and fair categories (Gharaibeh, M. A., & Shara'a, 2016). However, our finding agreed with Obiad and Al-Sultan (2020), who proved that the CWQI of the TWW was 80.19, indicating good quality. They recommended that TWW was not suitable for food crops because of its soluble organic content, but it was ideal for irrigating a wide range of other crops, such as ornamental plants and grasses.

3.4. Principle component analysis

Principle component analysis (PCA) was utilized in the investigation to comprehend how different water quality metrics interacted. For each of the thirteen characteristics, which included 1430 samples, standardized variables were employed. Kaiser's criteria were used to identify significant eigenvalues (Chong and Jun, 2005). There were found to be five main factors, with the most significant ones being represented by the largest eigenvalues.

3.5. The eigen values of PCA and screen plot

The variability in TWW quality across the study period is shown by the eigenvalues of five components in Table 5, which accounts for 62.3% of the variability

Table 3
The classification of TWW parameters samples from Riyadh TWWPs, over four years, based on the standard limit for restricted irrigation

Parameters	Restricted irrigation standards	Over the limit (%)	Below the limit (%)	Comprehensive Pollution Index (CPI) (Mean +STDEV)	CPI (Max)	CPI (Min)
Free chlorine (mg L^{-1})	0.5	8.33	91.67	0.44 ± 0.09	2.08	0.06
Dissolved oxygen (DO) (mg L^{-1})	–	0.00	100.00	–		
SAR	11.3	0.00	100.00	0.42 ± 0.08	0.72	0.24
Na (mg L^{-1})	40	0.00	100.00	0.48 ± 0.11	0.98	0.22
Ca+ Mg (mg L^{-1})	50	0.00	100.00	–	0.42	0.26
E. coli (100 cell mm^{-1})	1000	4.17	95.83	0.45 ± 0.12	0.75	0.00
COD (mg L^{-1})	80	18.75	81.25	0.93 ± 0.77	4.1	0.27
NO_3 (mg L^{-1})	10	29.17	70.83	0.89 ± 0.52	2.67	0.01
NH_4 (mg L^{-1})	5	39.58	60.42	1.39 ± 0.75	4.02	0.01
Turbidity (NTU)	5.8	56.25	43.75	0.51 ± 0.03	0.57	0.44
TDS (mg L^{-1})	2500	0.00	100.00	0.73 ± 0.39	3.33	0.45
EC (mg L^{-1})	3	0.00	100.00	0.73 ± 0.93	3.33	0.58
pH	6–8.4	0.00	100.00	0.87 ± 0.02	0.9	0.79

Table 4
The variations in CWQI for TWW of Riyadh TWWPs over a four-year period

Months	Jan-13	Feb-13	Mar-13	Apr-13	May-13	Jun-13	Jul-13	Aug-13	Sep-13	Oct-13	Nov-13	Dec-13
CWQI	74.23	81.64	88.93	81.60	84.58	84.86	82.43	88.94	88.31	79.86	86.86	90.89
Classification	fair	good	good	good	good	good	good	good	good	fair	good	good
Months	Jan-14	Feb-14	Mar-14	Apr-14	May-14	Jun-14	Jul-14	Aug-14	Sep-14	Oct-14	Nov-14	Dec-14
CWQI	82.28	85.36	82.34	90.07	85.26	85.38	82.07	90.10	84.68	79.75	85.53	85.26
Classification	good	good	good	good	good	good	good	excellent	good	fair	good	good
Months	Jan-15	Feb-15	Mar-15	Apr-15	May-15	Jun-15	Jul-15	Aug-15	Sep-15	Oct-15	Nov-15	Dec-15
CWQI	84.75	78.85	80.28	81.32	79.65	77.01	79.91	83.88	87.11	85.93	90.44	73.57
Classification	good	fair	good	good	good	fair	fair	good	good	good	good	fair
Months	Jan-16	Feb-16	Mar-16	Apr-16	May-16	Jun-16	Jul-16	Aug-16	Sep-16	Oct-16	Nov-16	Dec-16
CWQI	79.96	80.89	83.14	83.35	94.19	78.10	90.88	89.87	90.35	95.26	83.98	83.71
Classification	fair	good	good	good	excellent	fair	good	good	good	excellent	good	good

in the data set. As a consequence, the number of variables in the data set was reduced from 13 to 5 components. The most significant variable in the dataset is the first primary component (PC1), which makes up 18.2% of the overall information. This element offers a prevailing pattern for comprehending the TWW's characteristics.

Principal components were placed in order of variance coverage in a scree plot shown in Fig. 1, which is a diagnostic tool for evaluating the performance of PCA on data. A scree plot is a graphical representation of the variation captured by each PC in PCA analysis, displaying the eigenvalues of each component in the y-axis and their proportion of variance explained. The five principal components can be used for further analysis such as regression analysis.

The squared cosines of a PCA, which measured the correlation between variables and principal components, were between 0 and 1. However, these values were close to 1, indicating a high correlation where the components with higher loadings better describe the data (Bayo and López-Castellanos, 2016).

According to the findings of the principle component analysis, the first primary component (PC1) in the dataset, which accounts for 18.2% of the total information, was the most important component. This component can provide a dominant pattern of the dataset to aid in understanding the TWW's qualities. It reflected the parameters loading of Ca + Mg, EC, $NO_{3,}$ and turbidity. The second component, which accounts for 12.7% of the data variation, was including NH_4, COD, and DO.

3.6. Regression analysis

The study discovered a strong relationship between turbidity, nitrite, and CWQI. To predict CWQI, a stepwise regression model was utilized, with Model 5 having the fewest variables. The model was significant according to the ANOVA test, which had a maximal F value of 20.5 and a p-value of <0.0001. Because of its greater coefficient of determination (0.708), Model 1 was the best. To quantitatively evaluate each model's quality, the coefficient of determination (R^2), and mean squared error (MSE) were employed as shown in Table 6.

The characteristics that have substantially contributed to CWQI were found using stepwise regression analysis. The findings indicate that a substantial contribution to CWQI has been made by 7 out of 13 parameters. Turbidity accounts for 33.5% of the variability of total parameters in model 1, whereas the other parameters are nitrite, pH, ammonia, *E. Coli*, sodium, and free chlorine at 14.2%, 5.3%, 9.3%, 3.4%, and 2.1%, respectively. In Model 2, turbidity also contributes to

Table 5
The eigenvalue of the six components

	F_1	F_2	F_3	F_4	F_5
Eigenvalue	2.004	1.402	1.248	1.133	1.074
Variability (%)	18.215	12.741	11.348	10.302	9.761
Cumulative (%)	18.215	30.956	42.304	52.606	62.367

Table 6
Model summary for the CWQI

Model	R	R^2	MSE	Adjusted R^2	Sum of square	df	Mean of square	F	P -value
1	0.842	0.708	7.786	0.657	756.146	7	108.021	13.874	<0.0001
2	0.789	0.623	9.354	0.588	665.356	4	166.339	17.783	<0.0001
3	0.756	0.571	10.652	0.531	609.553	4	152.388	14.306	<0.0001
4	0.721	0.519	11.665	0.486	554.313	3	184.771	15.840	<0.0001
5	0.690	0.477	12.414	0.453	508.931	2	254.466	20.498	<0.0001

Table 7
The CWQI equations for the selected TWW quality parameters

Model 1	[1]CWQI = 173.93–3.99free chlorine–0.46Na–2.47–03E. COLI–0.26NO_3–0.59NH_4–0.37turbidity–10.232pH
Model 2	[2]CWQI = 150.18–0.23NO_3–0.61NH_4–0.47turbidity–7.81pH
Model 3	[3]CWQI = 97.14–0.37CaMg–0.25NO_3–0.423NH_4–0.53turbidity
Model 4	[4]CWQI = 95.04–0.36CaMg–0.23NO_3–0.54turbidity
Model 5	[5]CWQI = 91.1–0.24NO_3–0.57turbidity

Predicators
[1]free chlorine / Na / E. COLI / NO_3 / NH_4 / turbidity / pH
[2]NO_3 / NH_4 / turbidity / pH
[3]Ca Mg / NO_3 / NH_4 / turbidity
[4]Ca Mg / NO_3 / turbidity
[5]NO_3 / turbidity

interpreting 33.5% of all parameters, whereas nitrite, pH, and ammonia have 14.2%, 5.35%, and 9.3% of all parameters. In addition, the same contribution is in turbidity and nitrite. However, the percentage of contribution ammonia decreased from 9.3% in Model 2 to 4.4% in Model 3, and calcium and magnesium participated in interpreting 4.47% of the data. Turbidity contributes the same maximum percentage (33.5%) in interpreting all parameters in model 4, whereas nitrite and ammonia have a percentage contribution of 14.2%, 4.3% of all parameters. However, model 5 includes just turbidity and nitrite parameters of the same contribution in model 4.

The most crucial characteristics for predicted CWQI have been used stepwise and standardized multiple linear regression analysis. The five produced equations for the selected TWW quality parameters in the preceding sections were analysed to determine the quality and prediction of CWQI as shown in Table 7.

4. Conclusion

The design of effective treatment infrastructure, which annually processes billions of liters of sanitary and stormwater flow, depends on knowing the components of wastewater. The findings demonstrated that the TDS, EC, pH, free chlorine, SAR, Na, Do, and Ca + Mg parameters did not exceed the maximum levels allowed for restricted irrigation. The percentage of samples that exceeded the maximum allowed levels of turbidity, NH_4, NO_3, COD, and *E. coli* parameters, were 56.25%, 39.85%, 29.17%, 18.75%, 4.17%. The CWQI and CPI facilitate environmental evaluation, especially in nations with limited resources, by lowering the standards for water quality and offering data to support resource management decisions. However, the selection of indicators calls for expert opinion. The average CPI values ranged from 0.16 to 1.61, indicating modest pollution throughout the study. The CWQI outcomes ranged between 73.75% to 95.26%, indicating that the reuse of treated wastewater could not harm public health, especially for irrigated crops. The principal component analysis of a wastewater dataset reveals that the first major component, accounting for 18.2% of the total, is the most important, displaying parameter loading for TWW features of EC, Ca + Mg, turbidity, and NO_3. The second component exists NH_4, COD, and DO. The study found a strong correlation between turbidity, nitrite, and CWQI. A stepwise regression model was used to predict CWQI, with Model 5 having the fewest variables. Model 1 was the best.

TWW is suitable for restricted irrigation, which is beneficial for dry and semi-arid regions, providing essential nutrients for plant and soil health. Sustainable irrigated agriculture reduces overexploitation, improves water quality, conserves ecosystems, and boosts resource recovery. It also contributes to climate change mitigation by reducing energy consumption. The results may also benefit farming methods that preserve soil health and water sustainability. For instance, steps can be taken to improve fertilizer consumption or put soil conservation policies into place if certain agricultural practices cause soil pollution. In order to support sustainable agricultural production, this can assist farmers and other stakeholders in putting solutions into practice that reduce water pollution and increase nutrient uptake. Policymakers may utilize the study's conclusions to direct funding toward the implementation of pollution control legislation and program monitoring, according to the report. Additionally, in order to lessen water pollution and support sustainable production, it suggests agricultural practices include conserving soil and increasing the use of fertilizer. The outcomes of this study have the potential to improve the environment and welfare of the community by establishing evidence-based regulations for wastewater management and agriculture in Riyadh. The findings can guide the development of evidence-based policies and recommendations for Riyadh's agricultural and wastewater management, aiding in monitoring plans and setting water quality goals. Understanding current trends and potential future changes can also aid in long-term planning initiatives like infrastructure development and land-use planning.

Acknowledgments

Authors would acknowledge the support from Researchers Supporting Project number (RSP2024R297), King Saud University, Riyadh, Saudi Arabia.

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The 15th Gulf Water Conference

(2025) 324–331
doi: 10.5004.dsal.2025.700023

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Green synthesis of zinc oxide nanoparticles for wastewater treatment

Amal S. Al Rahbi*, Sharifa Al Awaid, Huda Al Amri, Rehab Al Syiabi, Hafsa Al Dowiki

Department of Applied Sciences, College of Applied Sciences and Pharmacy, University of Technology and Applied Sciences, Muscat, Oman
**amal.alrahbi@utas.edu.om*

ABSTRACT

This study focuses on the use of a green synthetic strategy to synthesize zinc oxide nanoparticles using *Albizia lebbeck pods* extract. The synthesized nanoparticles were characterized using ultraviolet-visible spectroscopy, Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and scanning electron microscopy (SEM). The influence of nanoparticles preparation method was examined. XRD patterns confirmed the formation of hexagonal wurtzite structure and SEM results showed high agglomeration with irregular shape. The catalytic degradation of methyl orange and methylene blue dyes using the synthesized nanoparticles was examined. Results indicate that the removal efficiency of 87 and 82% was obtained for methyl orange and methyl blue within 60 min using nanoparticles dosage (0.02 g) and initial dye concentration (40 ppm). The experimental data were suitably fitted by Langmuir isotherm indicating a monolayer nature of the adsorption process. The obtained results demonstrate that the synthesized zinc oxide nanoparticles could be effectively utilized as adsorbents for the removal of methylene blue and methyl orange from aqueous solutions.

Keywords: Green synthesis; ZnO; Wastewater; Contaminants

1. Introduction

Worldwide, scientists are very interested in water purification. The most frequent effluents that are discharged directly into water resources are dyes, including malachite green, remazole-red (RR), methyl orange, crystal violet, and methylene blue (MB). The presence of dyes in aquatic environments adversely alters their aesthetic qualities (Eghbali et al., 2019). Therefore, it is essential to remove dyes from waste water. Organic dyes have been eliminated from industrial emissions using a variety of technologies, including biological, adsorption, membrane, ozonation, coagulation–flocculation, and advanced oxidation processes (Sharma et al., 2011). Adsorption is one of the most commonly used methods for eliminating dyes from colored aqueous solutions. The outstanding mechanical properties and good sorption ability of nanoparticles arising from specific mixed oxides have led to their increasing use as nano-sorbents in water-treatment systems. Zinc oxide (ZnO) nanoparticles (NPs) have emerged as a promising adsorbent for dye removal from wastewater due to their unique properties. Their high surface area, tunable surface chemistry, and diverse adsorption mechanisms allow them to effectively capture and bind a wide range

*Corresponding author

ISBN 0-86689-078-5

of dyes. ZnO nanoparticles have been studied for their potential in removing methyl blue and methyl orange dyes from wastewater. Several studies have investigated the synthesis, characterization, and photocatalytic activity of ZnO nanoparticles against these dyes.

Zinc oxide nanoparticles (ZnO NPs) are synthesized using various methods, including spray pyrolysis, hydrothermal processing, sol-gel, vapor condensation and thermal hydrolysis. However, a novel synthesis technique known as the "biosynthesis" has been introduced. In this technique, natural plant extracts are rich in compounds such as flavonoids, which are released in the form of phytochemicals. These compounds have the ability to chelate nanoparticles and decrease metal ions, acting as both stabilizing and capping agents and reducing agents (Rekha et al., 2010). Many plant extracts were suggested by researchers as potential ingredients in the green synthesis of ZnO NPs. These included the leaf extracts from *Hibiscus rosasinensi* (Divya et al., 2013*),* *Aloe Barbadensis Miller (Aloe Vera)* (Sangeetha et al., 2011), *Carrot grass* (Rajiv et al., 2013), *Calotropis procera* (Vidya et al., 2013) and *Cassia auriculata* (Ramesh et al., 2014).

Zinc oxide nanoparticles (ZnO NPs) have been widely studied for their potential applications in various fields, including environmental remediation. The removal of dyes from wastewater is a significant challenge in many industries, and the use of ZnO NPs offers a promising solution. Previous studies have shown that ZnO NPs have excellent photocatalytic properties and can effectively degrade organic pollutants. Green synthesis of zinc oxide nanoparticles (ZnO NPs) has shown promising results in the removal of dyes from wastewater. Several studies have highlighted the effectiveness of ZnO NPs in eliminating various dyes, such as Ismate violet and Crystal Violet, methyl blue and methyl orange from aqueous solutions (Sachin et al., 2023; Mansour et al., 2022; Yang et al., 2023).

Green synthesis routes utilizing natural resources like rosin, and lychee peel have been employed to produce ZnO NPs for efficient methyl blue removal (Nhu et al., 2022; Sachin et al., 2023). In the study carried out by (Umar et al., 2019), the green synthesis of stable ZnO nanoparticles using Albizia lebbeck stem bark was reported. The research evaluates the antimicrobial, antioxidant, and cytotoxic activities of these nanoparticles on human breast cancer cell lines, showcasing their potential in various applications. Here, we present an environmentally friendly approach for synthesizing zinc oxide nanoparticles (ZnO NPs) using plant extracts from *Albizia Lebbeck Pods* as a reducing agent and zinc nitrate as a precursor for the removal of methyl blue and methyl orange from waste water. The influence of nanoparticles dosage, initial dye concertation and contact time on the removal of dyes were examined.

2. Materials and method

2.1. Preparation of ZnO NPs

Fresh *Albizia Lebbeck Pod* (ALP) was collected from Muscat, Oman. The collected plants were washed with distilled water three times to remove the dust and then grounded. Then, 3 g of ALP coarse powder was mixed with 100 ml of distilled water. After that, the mixtures were heated at 60°C with stirring for 1 h. Then, the extract solution was allowed to cool, filtered under suction and the filtrate was stored at 4°C for further use (Mansoob et al., 2019). Then, 30 ml of each extracted solutions were taken and heated up to 60°C with stirring. Then, 3 g of Zn $(NO_3)_2.6H_2O$ was added and the solutions were stirred for 3 h. The solution was kept in stirrer for 3 h until the yellow paste has formed which confirm the synthesis of ZnO nanoparticles. Then, the paste was calcined in a muffle furnace for 2 h at 300°C. After calcination, the yellow paste has turned to yellowish-white powder. Fig. 1 shows the preparation procedure of ZnO NPs (Khan et al., 2019).

Characterizing green-synthesized ZnO NPs has involved the use of a number of analytical methods. A UV-Vis spectrophotometer was used to measure the optical characteristics of the produced nanoparticles in the 200–700 nm wavelength range. Fourier transform infrared (FTIR) spectra were obtained in the 4000–500 cm^{-1} range using an FT-IR spectrophotometer (Shimadzu). X-ray diffraction (XRD) was used to assess the phase crystallinity and crystallite size using Cu-Kα radiations (λ = 0.15406 nm) in the 2θ range from 20° to 80°. The produced nanoparticles' surface morphology was assessed using scanning electron microscopy (SEM, JSM-7600F-JEOL).

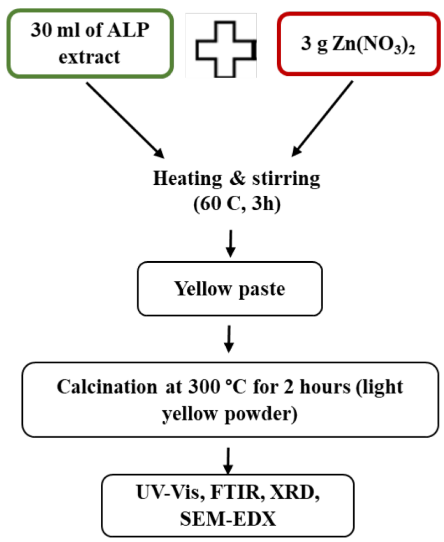

Fig. 1. Schematic model of synthesis of ZnO NPs from the leaf extracts of *Albizia lebbeck* pods.

2.2. Catalytic degradation of dyes

A stock solution of dyes was obtained by dissolving a predetermined weight of dyes in in distilled water. Dilutions of the stock solution were used to create the appropriate concentrations for the adsorption experiments. Following UV-Vis spectroscopy measurements, a curve was utilized to determine the concentration of each experiment which was used to transform absorbance data into concentrations.

The influence of contact time on dye removal was examined using 10 ml of 40 ppm of the prepared dyes and mixed with 0.02 g of the synthesized nanoparticles. The removal was measured every 30 min by using UV-spectrophotometer. The influence of dosage (0.02-0.1g) was investigated using 10 ml of 10 ppm standard solution of dyes for 30 min. The influence of dye concentration varying from 10 to 40 ppm was studied also using 0.02 g of the prepared nanoparticles at 30 min. Langmuir, Freundlich, Temkin isotherm models were employed to study the adsorption process.

The removal efficiency and adsorption capacity were calculated using the following equations:

$$\text{Removal (\%)} = \frac{C_i - C_e}{C_e} \times 100 \quad (1)$$

$$q_e = \frac{\left(C_i - C_e\right)V}{m} \quad (2)$$

where C_i is the initial concentration of dye solution (ppm) and C_e is the concentration of dye solution after adsorption by ZnO NPs (ppm), q_e is the adsorption capacity at specific time (mg/g), m is the mass of sample (g) and V is the volume of water (L).

3. Results and discussion

3.1. Characterization

UV–Vis spectroscopy was used to confirm the formation of ZnO NPs. The synthesized ZnO NPs was analyzed by UV-spectroscopy at the wavelength range of 200–800 nm. Fig. 2a shows the absorption spectra of the synthesized ZnO NPs. As presented in Fig. 2a, a narrow absorption band was observed at 370 nm which proved the presence of ZnO nanoparticles. This result agreed with the results obtained by Zare et al., (2017).

Metal oxides generally shows absorption bands in the fingerprint region. The synthesized ZnO NPs FTIR spectrum showed vibration peaks at 815 and 536 cm^{-1} (Fig. 2b). The adsorption at 536 cm^{-1} corresponds to the corresponds to the stretching vibrations of the Zn–O bonds. The observed peak at 815 cm^{-1} is due to the generation of tetrahedral coordination of Zn. The peaks observed at 1378 and 1324 cm^{-1} corresponds to C=O asymmetric and C=O stretching vibration, respectively.

The size and crystalline nature of ZnO NPs was determined by XRD analysis. XRD results showed in Fig. 2c confirmed the structure of the synthesized ZnO nanoparticles. The XRD pattern provided peaks 2θ from 0° to 70° at which the highest relative intensity of species of ZnO NPs was founded at 32.04, 34.62, 36.42, 47.79, 56.80, 63.2 and 68.07. Based on the International Center of Diffraction Data card (JCPDS-36–1451), these planes can be indexed to the hexagonal wurtzite structure. The peaks located at 32.04, 34.62, 36.42 corresponds to (100), (002), (101) plans of ZnO respectively (Vijayaprasath et al., 2016). The excellent crystallinity of the ZnO nanoparticles is indicated by the strong diffraction peaks. The obtained XRD result of ZnO nanoparticles is in good agreement with the reported one in literature (Siripireddy et al., 2017, Ramesh et al., 2015). SEM analysis (Fig. 2d) shows the random distribution of irregular spherical and rod shaped with some agglomeration. EDS analysis confirms the presence ZnO nanoparticles. The elemental analysis yielded ~ 52% of zinc and ~24% of oxygen.

3.2. Catalytic degradation of synthetic dyes

The influence of ZnO NPS synthesis temperatures was investigated at 60 and 90°C. The synthesized NPs were examined for MB and MO removal. Fig. 3 shows the influence of nanoparticles synthesis temperature on MB and MO adsorption. It was noted that as the nanoparticle synthesis temperature was increased, the removal of MB was decreasing and this is could be due to the agglomeration of nanoparticles at a high synthesis temperature. However, the difference was not that much high with MO. Therefore, a synthesis temperature of 60°C was chosen for the parametric study.

The results of MO and MB removal using the synthesized ZnO NPs are shown in Fig. 4. The removal of MO on the synthesized nanoparticles was less compared to that of MB. The greater the reaction time, the higher the removal of both dyes. To get the required time needed to attain the equilibrium for the adsorption of MB and MO onto the synthesized nanoparticles, 0.02 g of the ZnO NPs was mixed with each solution of 40 ppm of each dye. The % removal of MB after 1 h was 64% and reached 78% after 7 h; whereas in the case of MO, the % removal was 84 % after 1 h and increased to 95% after 7 h. As the removal process starts, numerous unoccupied binding sites exist on the adsorbent surface. These readily attract and bind dye molecules, leading to a rapid initial increase in removal efficiency. In addition, dye molecules need time to diffuse through the solution and reach the adsorbent surface. With longer reaction times, more molecules have the opportunity to encoun-

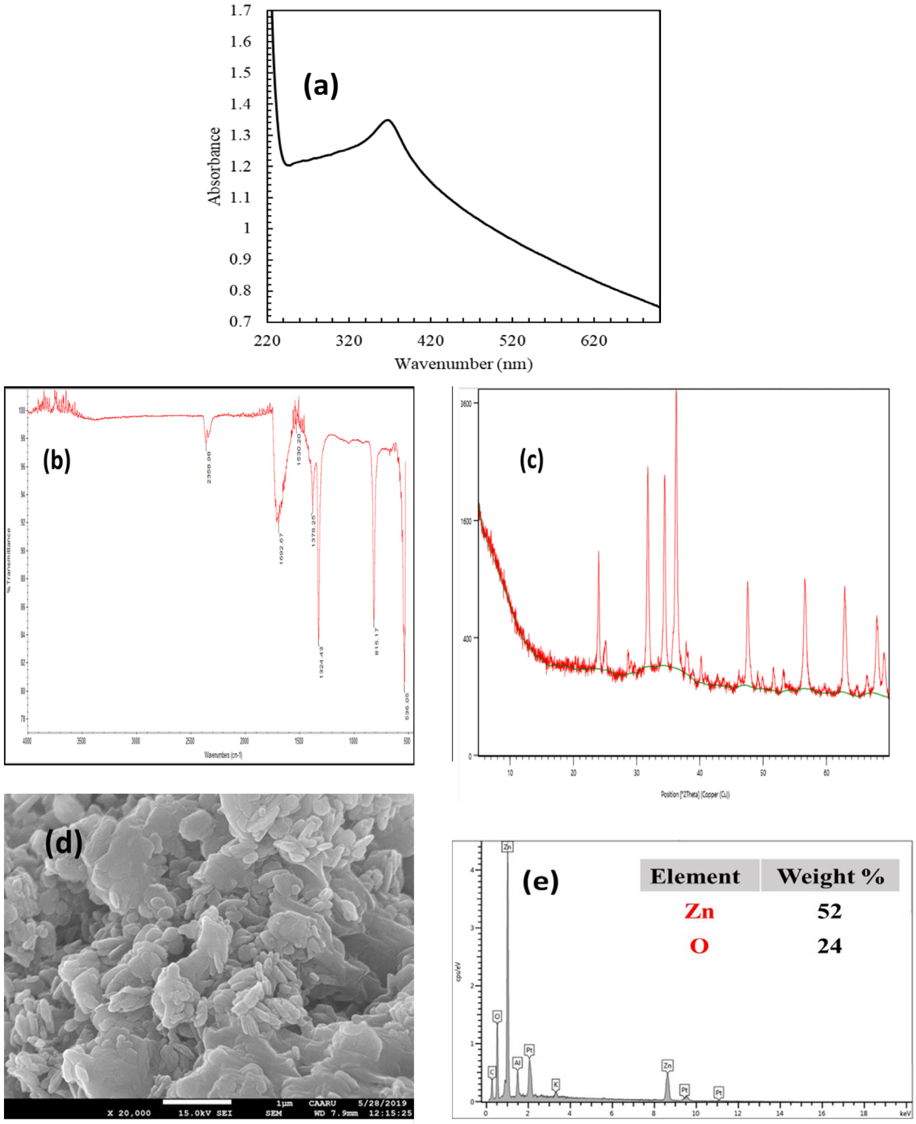

Fig. 2. Characterization of the synthesized ZnO NPS (a) UV-Vis, (b) FTIR, (c) XRD, (d) SEM and (e) EDS.

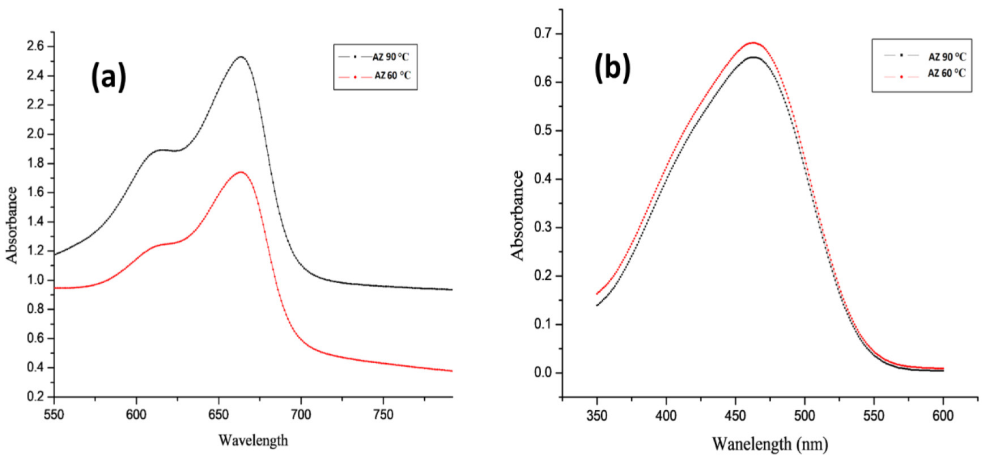

Fig. 3. UV spectra for the degradation of MB (a) and MO (b) at different synthesis temperatures.

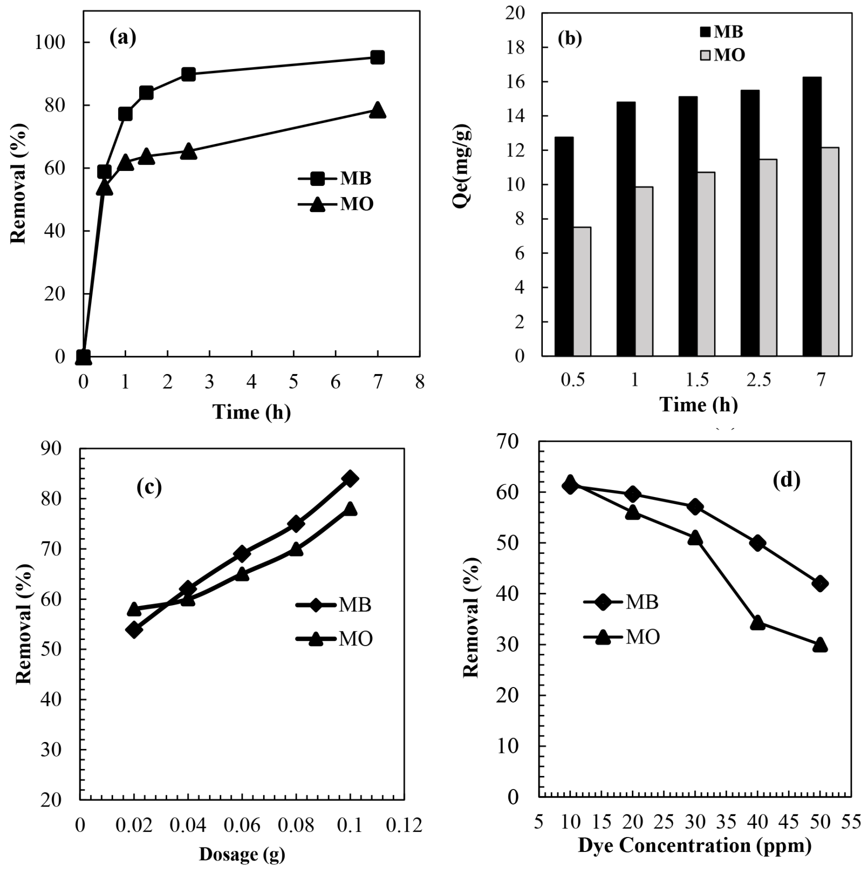

Fig. 4. Catalytic degradation of (a) MB and MO and (b) adsorption capacity vs. time using (c) influence of nanoparticles dosage and (d) influence of initial dye concentration on removal efficiency.

ter and bind to the available sites, contributing to continued removal. In some cases, once initial single-layer adsorption fills the readily accessible sites, subsequent dye molecules can form additional layers on top. This multilayer accumulation contributes to higher overall removal over time, although the rate generally becomes slower compared to the initial single-layer phase. Figure 4.b shows the adsorption capacity obtained for both dyes. The maximum adsorption capacity was found to be 15.8 and 12 mg/g for MO and MB, respectively.

Another important parameter that affects the adsorption process is adsorbent dosage. The influence of adsorbent dosage was examined at 30 min reaction time. The effect of nanoparticles dosage of on dyes removal is presented in Fig. 4c. The removal was found to increase with the increase of nanoparticles dose. The maximum MB and MO removal efficiency of 84% and 78, respectively was obtained with using 0.1 g ZnO NPs. More surface area with binding sites is provided with the increase of dose leading to a higher removal efficiency.

Fig. 4d shows the influence of primary dye concentration on removal efficiency. The removal efficiency was found to decrease with the increase of dye concentration. With the increase of dye concentration from 10 to 50 ppm, MB removal was found to decrease slightly compared to MO. These results suggest that the dye molecules are rapidly adsorbed at lower concentrations due to an adequate number of unoccupied active sites being present. Similar results have been obtained by Panda et al., (2024). Anionic and cationic dyes have different properties may cause a variation in adsorption behavior. The uptake of ZnO NPs for 50 ppm of MB and MO concentration reached to 40 and 32%, respectively. The saturation of adsorption sites on the adsorbent's surface could be the cause of these results.

The process of adsorption can be better understood through adsorption isotherms. In this study, three models for equilibrium adsorption isotherms were applied, and correlation coefficients (R^2) were used to determine which model fit the data best as presented in Fig. 5. The results are listed in Table 1, which shows the correlation coefficients and isotherm parameters. The adsorption data was found to align with the Langmuir isotherm model, as indicated by the high R^2 values of

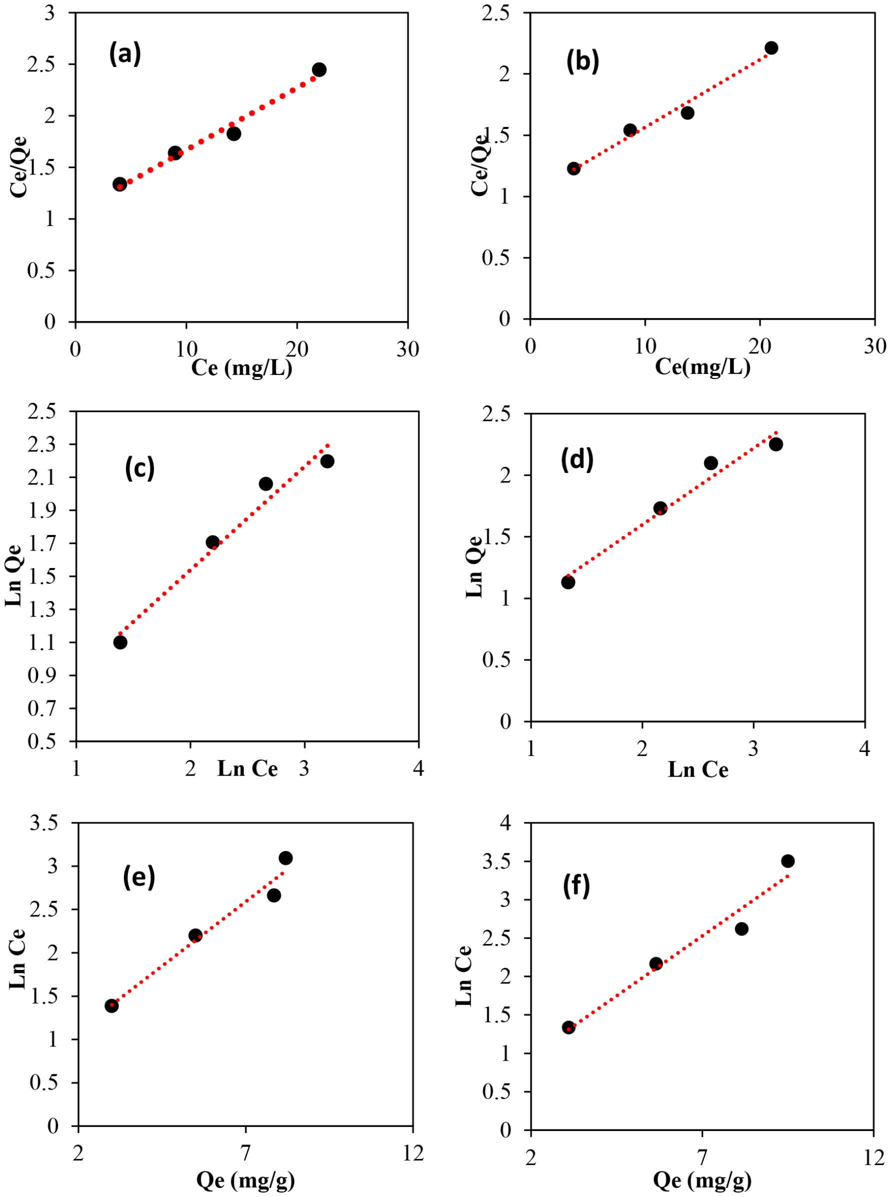

Fig. 5. Langmuir isotherm for (a) MB and (b) MO, Freundlich isotherm for (c) MB and (d) MO, Temkin isotherm for (e) MB and (f) MO.

Table 1
Adsorption isotherms parameters

Samples	Dye	Langmuir isotherm model			Freundlich isotherm model			Temkin isotherm model		
		q_{max} (mg/g)	K_L	R^2	K_F	n	R^2	K_T	B_t	R^2
ALP	MB	12	0.056	0.9779	1.329	1.594	0.965	5.548	0.297	0.965
	MO	9.5	0.052	0.9771	1.426	1.608	0.965	3.012	0.312	0.955

0.97 for MB and MO. The Langmuir isotherm suggests that adsorption occurs in a monolayer formation, where the adsorbent's adsorption sites are structurally uniform, possess equivalent energy levels, and are identical. There is no interaction between molecules adsorbed on neighboring sites, resulting in minimal intermolecular repulsion (Panda et al., 2024).

4. Conclusion

This research described a green approach for the formation of ZnO NPs using albizia lebbeck pods as a reducing and capping agent. Structural and optical studies conducted using UV, FTIR, XRD, and SEM analysis confirmed the formation of efficient ZnO NPs. The Albizia lebbeck pods possess some phytochemicals which not only performs in the reduction of the particle sizes but also provide sufficient stabilization. The initial concentration of the dye solution, preparation conditions, and the contact duration for both cationic and anionic dyes were evaluated as parameters that affected the adsorption capacity of the synthesized nanoparticles. The produced ZnO NPs exhibited significant dyes removal. The MB and MO degradation efficiency of the synthesized nanoparticles reached 84 and 78%, respectively. The Linear Langmuir Isotherm model provides the most accurate representation of the dye binding process. The green synthesis of zinc oxide nanoparticles presents a sustainable and effective approach for dye removal from wastewater, showcasing its potential as an environmentally friendly solution for water purification processes.

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The 15th Gulf Water Conference

مؤتمر الخليج الخامس عشر للمياه

(2025) 332–343
doi: 10.5004.dsal.2025.700034

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

Business model for small-scale decentralized wastewater treatment and sludge management in Jordan

Mohammad A. Tabieh[1]*, Emad K. Al-Karablieh[1], Tala H Qtaishat[1], Nael H. Thaher[1], Amer Z. Salman[1], Mohammad I. Majdalawi[1], Madi. T. Al-Jaghbir[2], Nehaya. K.Al-Karablieh[3], Ahmad I. Jamrah[4]

[1] *Department of Agricultural Economics and Agribusiness Management. School of Agriculture, The University of Jordan, Amman, Jordan email: m.tabieh@ju.edu.jo*
[2] *Department of Family and Community Medicine. School of Medicine, The University of Jordan, Amman, Jordan*
[3] *Department of Plant Protection. School of Agriculture, The University of Jordan, Amman, Jordan*
[4] *Department of Civil Engineering, The University of Jordan, Amman, Jordan*

ABSTRACT

Wastewater treatment is often driven by government mandate. The dissemination of decentralized wastewater management as complementation to large-scale centralized wastewater treatment plants in areas that cannot be connected due technical engineering issues or cost-efficiently can play a decisive role to achieve the SDG6. This paper describes the necessary conditions for successful business model and identifies the most important barrier to implement decentralized wastewater and sludge management system in Jordan. The absence of sustainable business models for decentralized system represents probably the major institutional barrier to this improvement. Wastewater systems in small towns and villages are usually too small and fragmented to raise the revenues and gather the capacities needed to operate and maintain them. Decentralized management can be economically and technically efficient, and conductive to sustainable urban development in the application area according to site specifics. Private sector can be enhanced to create outsources to these services and to alleviate the pressure of the public budget. The market of decentralized system has to be regulated by public control to ensure that quality and due diligence are maintained. Effective and enforced legislation and standards for construction, operation, and reuse are required. Revising by-laws and regulations are needed to include private capital expenditures and O&M for services providers. Expanding the role of the private sector that involves the divestiture of assets from the public to the private sector (such as design-build-operate), and a variety of public-private partnerships such as service contracting. Privatization also cannot be implemented unless certain policy barriers are overcome. These include policies related to operation, revenue collection, grants, taxation, and procurement, as well as trading regulatory. The challenges and barrier to business in decentralized wastewater management are: uundefined institutional responsibility; unclear and fixed responsibility for O&M; lack of regulator and

*Corresponding author

ISBN 0-86689-078-5

certification bodies, lack of education, training and capacity building of the administrative and operational staff; unclear tariff system, insufficient private sector involvement (design, construction, O&M); weak competitive market for O&M; lack of cost recovery mechanism and revenues collections, subsidy policy and low collection rate; and lack of implemented and innovative strategies. The decentralized model needs to be established based not only on the demand of services, but also on the vulnerability of surface and groundwater contamination, health issues and environmental pollutions. Full operational cost recovery can be attained from business operation, if the revenue generated can exceed the operational cost in addition to profit margin for the private sector.

Keywords: Decentralized wastewater treatment system; Business model; Barriers and challenges

1. Introduction

Decentralized wastewater treatment plants (DWWTPs) offer an opportunity to introduce waste water (WW) treatment and generate treated effluents to be used for irrigation water and others uses, in places that are not connected to centralized treatment plants and that cannot be connected cost-efficiently. The advantages of decentralized technologies include their capability to provide WW treatment infrastructure in remote and hilly rural communities and their flexible adaptation to fast-growing semi-urban settlements. DWWM can service locations that cannot be serviced by centralized systems due to technical and financial limitations [1,2].

Decentralized wastewater treatment encompasses various methods for handling, treating, and reusing wastewater from individual homes, industries, clusters of buildings, and whole communities. Site-specific assessments determine the most suitable treatment system for each location. These systems, forming permanent infrastructure, can operate independently or integrate with centralized sewage treatment (semi-centralized). Ranging from simple soil dispersal (like septic systems) to complex mechanized units, they treat waste from multiple sources, discharging to soil or surface waters. Typically situated near where wastewater is produced, these systems serve areas within 3–5 km without access to a centralized sewer system [3].

Wastewater treatment enterprises produce outcomes that are beneficial not only to the consumer, but also to the society. Wastewater treatment reduces the amount of waste released into the environment, and has an impact on health risks associated with environmental pollution. It also reduces the freshwater loss induced through water pollution and reduces the amount of money spent by a country on environmental rehabilitation projects required to battle pollution. Household WW systems can help in recycling treated wastewater for reuse [4].

Implementing private operations aligns with Jordanian government policies on public-private partnerships (PPPs) and utility management [5]. Despite commercializing water services, the government acknowledges social responsibilities. Tariff determination by Ministry of Water and Irrigation (MWI) includes a lifeline component, ensuring a fixed charge for limited consumption. However, the set price limit per cubic meter is significantly lower than the production cost [2,6,7].

The current state of research reveals several critical gaps in our understanding of sustainable DWWM frameworks. Firstly, there exists a notable deficiency in comprehensively grasping the multifaceted framework conditions integral to DWWM's sustainability. Additionally, the assessment of institutional and legal setups, along with their associated roles, responsibilities, and coordination mechanisms within DWWM, remains insufficient. Furthermore, the identification of specific areas necessitating improvement within these frameworks to enhance DWWM feasibility is limited. Moreover, the exploration of potential business models for DWWM is notably lacking, with inadequate consideration given to various crucial dimensions such as economic viability, environmental sustainability, technical feasibility, legal compliance, managerial effectiveness, regulatory requirements, and societal acceptance. Addressing these research gaps is crucial for advancing our understanding and implementation of sustainable DWWM practices.

The objectives of this study is to assess the current status of existing framework conditions for sustainable DWWM, including institutional and legal setup, roles and responsibilities and coordination mechanisms; to develop brief recommendations for policy makers on how to improve the institutional and legal setup, roles and responsibilities and coordination mechanisms for improving the feasibility of DWWM; and to discuss potential scenarios for business model for DWWM, considering economic, environmental, technical, legal, managerial, regulatory and social aspects.

By addressing these research gaps and specific objectives, the study aims to provide valuable contributions to the field of decentralized wastewater management, informing policy formulation, strategic interventions, and practical implementations for enhancing sustainability and resilience in water resource management systems.

2. Review of literature

The basic idea behind the use of centralized water treatment is that WW is transported out of the city and far away from residential sites as quickly as possible in order to reduce public health risks. To a great extent, this centralized sewage treatment approach can solve the problems of sanitation very efficiently [8]. The centralized approaches are often plagued by high capital investment cost, improper operation, and an over reliance on treatment technologies that are unaffordable in rural areas with low population densities and dispersed or scattered households. In a few EU countries (Germany and The Netherlands) demonstrative decentralized systems serving up to 1,000 people have been implemented in urban areas [9].

The extension of centralized sewerage networks cannot keep up with city growth, and alternative sanitation systems are needed for citywide inclusive sanitation. The European Committee for Standardization defines small WWTPs as systems that serve less than 50 PE. The European Commission as reported by [10] defined decentralized WW treatment technologies as serving less than 5,000 PE, whereas [1] defined this threshold at WW flows of 1,000 m^3/d or 10,000 PE respectively. According to [1] DWWTPs provide treatment for WW flows with close COD/BOD ratios from 1 to 1,000 m^3/d. In Jordan, the term 'DWWM systems' is used for WTPs with a capacity below 5000 PE at or near the point of WW generation that may include different plant sizes and treatment technologies, such as onsite treatment plants for individual homes, plants serving small to middle-sized clusters of homes or even entire communities. The debate about the less than 5,000 PE refer to the size of the total community population or the size of the potential connected population or the size of the treatment plant. For example, if a community of 9,000 is connected to two WWTP of 4,500 PE each due to topographical factors, then it can be considered as two decentralized WWTPs.

Business models are defined by two categories "who do what" and "who pays for what". However, business models for DWWM consider several options to bundle services together and organize them at different scales ("what"), and to define user groups who will contribute to the revenues of the WW services ("who"). The first part "who do what "concerned how to run the project, legal and administrative issues, ownership, choice of treatment technology, revenues collection. The second parts "who pays for what" the attention is to define the user groups who will contribute to the revenues of the WW services, degree of aggregation, and clustering service provision.

Under a privatization arrangement of WW business, the private firm has potentially profitable opportunity of owning and operating a water system while the local government has the opportunity of having cost-effective delivery of an essential service. Privately owned utilities are expected to perform more efficiently and effectively than publicly owned utilities. The most frequently cited advantages of private involvement are construction and operational savings, improved regulatory compliance and risk management, reduced politics and bureaucracy, improved procurement and scheduling practices, access to expert personnel, tax benefits and cash flow to the local government, debt capacity benefits, and access to private capital [11].

The results of the study by Sansom et al. [12] show that a wide variety of activities and business processes are being outsourced in the water and sanitation sector in a wide range of countries. Even in countries where there is strong political resistance to more complex private sector participations (PSPs), contracting out is seen as relatively acceptable. Overall, previous studies demonstrate that Micro-PSP generally delivers better quality services at a lower cost, with competition for the market being a vital driver to reduce costs [13].

3. Methodology

The initial phase of this study involved developing a business model for a decentralized wastewater treatment system with an in-depth analysis of existing document policies and a comprehensive review of relevant literature including academic papers, industry reports, and case studies related to wastewater management, environmental regulations, regional and national policies to understand the regulatory landscape governing wastewater treatment and to gather insights into successful models, technological advancements, operational frameworks, and financial structures associated with decentralized systems [14–17].

The village of Rasoon in Ajloun Governorate has been selected as an exemplary location, following earlier investigations conducted by the SMART project in agreement with the MWI. Valuable data for detailed investigations in this area, such as land use, soil texture, topography, slope, depth to groundwater, water consumption, and population, served as the criteria for selecting this case study. Given its rural setting and recognition as a hotspot area featuring vulnerable groundwater resources, Rasoon serves as an exemplary showcase for a decentralized solution under typical rural Jordanian conditions. The study area is considered one of the most important well fields, partially providing drinking water to three governorates.

Key informant stakeholders were invited to participate in a focus group discussion to generate rich qualitative data regarding the extent to which project objectives are being achieved. These stakeholders included finance and planning bodies, sector ministries, sub-national bodies, non-governmental actors (including civil society organizations), and private sector firms with experience in the construction of DWWTP. During field visits to selected sites, interviews were conducted with local government officials, mayors, and private vendors involved in providing services to the targeted community.

Following this, stakeholder engagement emerges as a pivotal step, involving the collaboration and opinion gathering from affiliated ministries and private sector entities that actively participated in constructing small-scale decentralized wastewater treatment systems (DWWM). Focus group discussions are employed to capture the firsthand experiences, challenges faced, successes achieved, and perspectives of relevant stakeholders. Participants, including private operators, public officials, academia, and NGOs, examined challenges in legislation, financing, construction, capacity development, operation, and maintenance for establishing sustainable DWWM. Working groups analyzed challenges and proposed solutions.

This study considers factors such as technological efficacy, affordability, scalability, adaptability to local conditions, and sustainability. Alongside, a thorough financial modeling exercise is conducted, encompassing cost estimations for infrastructure setup, technology procurement, operational expenses, and maintenance. Furthermore, revenue streams are identified, exploring potential sources such as user fees, government subsidies, grants, or partnerships with private entities to ensure financial sustainability. The business model integrates the findings from stakeholder engagements, technology assessments, and financial projections. It delineates the value proposition of the DWWM system, outlines revenue generation models, and emphasizes potential partnerships with affiliated ministries and the private sector.

4. Results and discussion

4.1. Population context and demand for DWWM

Rising population levels exert greater demand on land, water, and food resources, impacting both their quantity and quality. Scarce water areas experience intensified pressure on sanitation systems, leading to water quality deterioration, resource depletion, and environmental harm [18, 19]. The sewer system coverage based on the water and sewer subscription data reach to 66% in 2018 [20]. The capital financing of WW collection and treatment comes from the government treasury as well as international grants and loans. Additionally, 55% of the total cost of WW collection and treatment services are covered by individual households' water bill. The government charges only the houses connected to the water supply networks. Those who depend completely on buying water from tankers are not required to pay for WW collection and treatment [21].

The coverage of sanitation services is lower than the water coverage, while the WW treatment quality needs significant improvements as some WWTPs are either overloaded or are employing inefficient technologies. The WW generated is treated in 33 WWTPs amounted to 170 mcm in 2022 and is being reused primarily for irrigation purposes in the Jordan Valley. About 90% of treated WW are used in agriculture, nearly 80% are used in JV blended with fresh surface water and 20% are directly used near WWTPs. The treated WW represents about 1% of the water budget in 2022[22]. Whereas, the proportion with safe sanitation exceeds 88%, with one third of the population using septic tanks and cesspits.

The result of the year 2022 shows that about 66% of generated WW is reaching and safely treated in WWTPs. However, many of the centralized WWTPs produce effluents that do not match with the JS893/2006 and consistently failed to meet Jordanian standards for discharge into streams, and required immediate rehabilitation [7,23,24]. In areas where there is no public WW system, residents use private or individual WW disposal systems. Due to financial constraints, these private systems depend mainly on the simple manner of cesspools, rather than using the more satisfactory method of septic tanks. A cesspool is not recommended as a substitute for a septic tank, which require regular empting, since the raw sewage discharged into the cesspool tends to seal the openings in the lining and the surrounding porous formation, thereby reducing the leaching area and often causing the cesspool to overflow. Such conditions are dangerous because the pollution enters the soil at a depth below the upper layers of the soil where are found the aerobic nitrifying bacteria which carry on the work of purification of waste organic matter.

4.2. Institutional and regulatory framework for DWWM

The new released National Water Strategy 2023–2040 [7] addresses the need to expand the sanitation services to cover the upcoming forecasted service demand and to rehabilitate the existing infrastructure of WW collection networks and irrigation water networks. The policy document indicates that decentralized systems also will be used where appropriate. The management of both centralized and decentralized systems will be enhanced. The sanitation strategy will take health, hygiene and environmental imperatives into consideration while implementing the larger task of waste and WW treatment in urban centers and small towns. Furthermore, the policy is intended to expand WW treatment capacity to cover 835 small communities with <5,000 PE of Jordan. The policy document indicates that for localities with fewer than 5,000 inhabitants, construction of WW collection and treatment systems is not proposed unless the localities are in close proximity to existing treatment and collection facilities or face exceptional circumstances based on sanitation and health considerations. About 28% of the national population falls in this category.

The DWWM policy offers an opportunity to introduce WW treatment and generate irrigation water in places that are not connected to centralized WWTPs. The advantages of decentralized technologies include their capability to provide WW treatment infrastructure in remote and hilly rural communities and their flexible adaptation to fast-growing semi-urban settlements [2,25]. This policy stresses the need to expand WW management by implementing the practice of recycling and reusing water beyond the existing conventional WW service system and reuse become imperative for the viability of water budget. For reuse of treated effluent originating from a WWTP with a capacity of up to 5,000 PE, reuse shall be performed following the quality parameters for treated effluent as suggested in the DWWM policy "Regulatory specifications and programs for treated domestic WW from treatment plants with a capacity of up to 5,000 population equivalents". Furthermore, a group of several different neighboring WWTPs with a design capacity of up to 5,000 PE each is considered a DWWM cluster.

4.3. Current challenges to business model in DWWM

In addition to their financial appeal, successful private sector ventures depend on clear and stable institutional, regulatory, and market conditions. Overcoming various obstacles discussed in anecdotal interviews and experiences within the country is crucial. The following list summarizes these concerns [26].

- Institutional roles regarding DWWM (less than 5,000 PE), particularly concerning Water authority of Jordan (WAJ) have a lack clarity.
- Ownership and maintenance responsibilities are undefined (referencing private operations).
- The regulatory framework is inadequate and lacks clarity.
- There's a lack of certification for O&M systems (capacity building, education and training).
- Insufficient involvement of the private sector (in design, construction, and O&M).
- Limited interest from the private sector due to uncertainty about tariffs ensuring full cost recovery and reasonable profits.
- Revenues from selling treated effluent (fresh water substitution) are believed to not cover costs, especially as the water tariff is very low (subsidized).

Apart from the outlined institutional challenges, effective private sector engagement in developing sustainable water supply and sanitation services hinges on several factors[27] such as:

- Ensuring long-term financial viability requires a level of regulatory and financial stability concerning tariffs and commitments for subsidy support, instilling confidence in investors. Any perception of uncertainty in honoring these assurances could limit investor interest, leading them to focus solely on operational aspects and avoid investments in infrastructure maintenance and expansion.
- Consumer buy-in, demonstrated by their willingness to pay charges and actively support these initiatives, especially acknowledging the social benefits of a well-functioning wastewater system.
- Commitment from other stakeholders, such as the agricultural sector or agencies involved in carbon credit systems, to provide extended assurances regarding revenue streams.
- Collaborative support from additional institutions, like environmental protection agencies, ensuring operators work in tandem to achieve broader societal benefits.
- Meeting essential investor expectations, such as ensuring positive cash flow, secure returns on capital, and guaranteed margins, among other benchmarks.

4.4. Ownership of DWWM systems

Currently in Jordan WWTPs are solely owned by the public sector and managed in various ways, either directly by WAJ, water utilities, or via contractual arrangements. The MWI oversees water strategies, policy formulation, and water resource planning. Under MWI, a Performance Management Unit (PMU) monitors corporatized utilities, develops PPPs, and advocates private sector involvement in water services. The water sector management is highly centralized with pervasive political influence, limiting the autonomy of supposedly "independent" water companies. Regulatory functions primarily involve monitoring company performance through indicators. Despite principles favoring separation of policy, regulation, and commercialization, WAJ assumes multiple roles as operator, supervisor, and regulator, often overseeing PPP projects via contractual regulations and conducting audits.

While DWWM integration remains incomplete in Jordan's wastewater sector, several privately owned WWTPs exist, indicating a need for small-scale solutions in suburban and rural areas. O&M for DWWM systems, serving less than 5,000 people, involve agreements between MWI/WAJ, water utilities, and private sector entities, regulated by public authorities and a certification scheme for O&M education and training[28].

Ownership models in Jordan's DWWM could be range from state enterprises and municipal bodies to commercial companies and private operators. Municipalities hold responsibility for sanitation services, including sewer systems and wastewater treatment, while WAJ oversees urban WW services, water projects, and resource planning. Although WAJ operates as an autonomous body, it faces constraints due to civil service regulations and government oversight by audit bureaus[29]. Advantages and disadvantages are associated with each ownership form are shown in (Table 1). The evidence on efficiency differences and other differences between utilities with alternative ownership forms is mixed [11]. Some studies indicate that the private sector can provide services more efficiently; others are not so conclusive[13]. Both sectors seem to suffer from a degree of inefficiency. Local officials prefer to retain ownership of utility assets and use partnerships for operational services.

The municipality or community ownership of DWWTP is an attractive solution to Jordan, largely because land acquisition is a major barrier. The municipality can choose the appropriate location of the DWWTP and allocate the land ownership to municipality, even if the land is privately owned because it is the public interest as set out in the land expropriation law for public benefits.

4.5. The business model concept

Business model can be generally describing the core aspects of a business, commodity or providing service, which are provided, the following items needed to be identified and thoroughly described:

- The purpose (e.g. sanitation coverage and WW treatment, solid waste)
- Target customers (e.g. institutions, industry or the rural and semi-urban population)
- Strategies (e.g. public service provision, private sector participation or involvement)
- Infrastructure (sewers, DWWTPs, reuse systems)
- Organizational structures (e.g. public companies, subordinated water companies, municipalities, private sector (enterprises or companies), cooperatives association
- Ownership (sole property, pubic ownership, shared ownership, community)
- Capital Investment, CAPEX (private sector, public sector, municipalities)
- Source of Finance, (e.g., private sector, DBO, BOT, or government, public treasure, loans, donations, international cooperation
- WW treatment technologies (e.g. high sophisticated, natural based treatment)
- Trading practices (e.g. connection fees, emptying fees, tariffs, revenues from sales),
- Operational processes (e.g., collection, transport, treatment, reuse)

Table 1
Advantages and disadvantages of different organizational structure of DWWTP

Organizational structure	Advantages	Disadvantages	Applicability to Jordan
Public utility	Secured capital and operational costs from public budget.	Higher production costs, slow innovation adoption.	Mostly government-owned WWTPs in Jordan.
Associations	Voluntary consumer association with reporting transparency and donor financing potential.	Limited rural service coverage, potential conflicts, non-professional management.	Ideal for small rural settlements.
Municipal enterprises	Property owned by local authority, immune to bankruptcy, funding possibilities.	Political influences on tariff decisions, legislative framework challenges.	Needs capacity building and new legislation for applicability.
Municipality departments	Local authority-owned, flexibility in staff recruitment.	Lack of technical capacity, political influence on management.	Needs capacity building and new legislation; little obvious benefit.
Commercial companies	Attracts private investments, profit potential, performance management.	Reduced funding options, limited stakeholder involvement, high tariff risks.	Limited experience in Jordan; sector unattractive due to affordability constraints.
Small private operators	Efficiency through private sector expertise, but limited capacity.	Reliant on contractual basis, potential profit-driven issues.	Technical capacity solved via outsourcing and national rules.
Private sector ownership	Utilizes private expertise and capital but high land acquisition costs.	Seen in private enterprise, industry, hotels, etc., but expensive.	Existing in Jordan for private entities.

- Policies (e.g. DWWM policy, national water strategy, investment plans),
- Culture and social factors (e.g. social acceptance, willingness to cooperate, religious aspects, willingness to pay, affordability and ability to pay)

However, WW reuse offers a double value proposition if, in addition to the environmental and health benefits of WW treatment, financial returns are also important to sustain service provision. Resource recovery from these facilities in the form of energy (biogas generation, nutrients in treated effluents, reusable water, and bio-solids) represent an economic and financial benefit that contributes to the sustainability of the system and of the water utilities operating them.

The size of the revenue streams depends on the types of resources that can be recovered from WW. There is a range of options to move from a 'revenue model' to a 'business model', with costs and value recovery offering a significant advantage from a financial perspective, not only for private sector engagement, but also to the public sector. An improved sewage collection and treatment system should collect and treat the WW from a large percentage of the people in the area and thus reduce the amount of people that use a non-water tight septic tank or cesspit. This will improve the quality of the groundwater that is used as a source for water supply and irrigation and as such will be a significant environmental benefit to human health leading to a reduction of the risk and occurrence of waterborne diseases, particularly diarrhea, typhoid and cholera.

4.6. Economic and financial viability of business model

Rasoon village was chosen as a pilot project, located in Ajloun Governorate, stands as a noteworthy site for detailed investigations owing to available data and its features—848 households with 4327 inhabitants in 2022, a rural backdrop, and recognition as a vulnerable groundwater hot-spot in Jordan. This setting offers a prime platform to showcase decentralized solutions typical of rural Jordanian conditions. Envisioning that roughly 75% of households would link to a traditional gravity sewer system, the remaining 25% faced elevation challenges necessitating regular emptying of their collection tanks. This assumption was made based on the incapability of about a quarter of houses to connect to street sewers due to elevation constraints, with a total assumed sewer length of 12 km. In this illustrative case, a 2-stage vertical flow constructed wetland, known as the "French System," was selected. The effluent quality met secondary wastewater quality criteria as well as WHO Guide[30] and local standards for wastewater reuse in agriculture[31]. A simple operational modifications to vertical system proved to be effective for improving total nitrogen removal in arid climate. However, the final usage of the effluent is irrigating fodder crops, it was no need to modified the system.

Various business model options under different assumption were analyzed concerning sewer system operation and maintenance, including wastewater conveyance and treatment. Option (1), focuses on managing sewer systems and wastewater treatment plants (DWWTPs) with funding reliant on tariffs or state budgets and sale of treated effluent. Option (2), explores selling treated wastewater for agricultural use, requiring maintenance and sales activities. The challenge in developing wastewater (WW) solutions lies in creating technologically efficient designs. Efficient infrastructure design requires comprehensive data considering factors like volume and quality of WW, local conditions, legal requirements, and cultural acceptance. Private sector involvement aims to enhance operations, reduce public burden, and ensure economic feasibility and financial sustainability through adapted business models. Ownership models range from full private ownership with state-regulated rates to publicly owned systems managed without economic regulation, prevalent in Jordan's larger cities.

The comparison of wastewater treatment frameworks between arid and more water-abundant regions reveals significant disparities in water consumption and treatment requirements. In arid countries like Jordan and GCC countries, where water usage is low and wastewater is highly concentrated, traditional treatment paradigms designed for higher water consumption rates, as seen in Europe, may not be suitable [3,32,33]. This necessitates the adaptation of decentralized wastewater treatment designs to minimize water loss while still meeting treatment objectives. Moreover, the primary goal in arid climates often shifts towards local water reuse, emphasizing the need for wastewater treatment frameworks that facilitate safe and efficient reuse practices. Additionally, the reuse of treated wastewater in GCC countries can yield environmental advantages by combating desertification and preserving biodiversity. To address these challenges, ongoing technological innovation is essential, focusing on the development of new treatment technologies tailored to water-scarce environments and the integration of renewable energy sources to minimize environmental impact. Ultimately, a nuanced understanding of the unique challenges and requirements of each region is crucial for developing effective and sustainable wastewater treatment solutions in arid climates.

Financial incentives like subsidies or tax reliefs can incentivize private sector and community engagement in planning, establishing, and maintaining WW infrastructure [2]. Full privatization, where facilities are privately owned and operated, isn't commonly accepted by policy decision-makers. Moreover, most users of public WW services haven't paid the true cost. The total capital investment costs for small scale DWWM in Rasson are estimated with about JD 1.54 million, the annual operational expenditure JD 45,800 to treat about 98,000 m^3/y and potential reused effluent amounted to 82,000 m^3/y. The model operates on the premise that the operator shoulders all operating costs, which are then passed on to consumers through tariffs. Among these costs, an annual management charge of JOD 12,000 is included, encompassing an assumed salary for a professional engineer and associated social and miscellaneous expenses.

The financial model primarily relies on annual cash flows, with tariffs adjusted yearly to cover operational expenses, capital maintenance, return on investment, and a predetermined profit margin. However, capital investments made by the service provider are treated differently, applying current cost depreciation to spread the investment costs over the asset's useful life. This net written down value is included in an asset base, allowing for a return on capital to cover financing costs or the opportunity cost of capital for the service provider.

The tariff structure includes a breakdown of revenue requirements for each activity, encompassing operational costs, network capital maintenance, current cost depreciation, return on capital, and a set profit margin. To arrive at the base revenue requirement for each activity, revenue from cost-reflective treatment charges and income from other sources are deducted from this value. The financial analysis of the selected business models reveals several key points:

- The average incremental cost (AIC) stands at approximately JD 0.77±0.05/m^3. Running different scenarios of project life span from 15 years to 20, and 25 years reduce the AIC to JD 0.71±0.04 and JD 0.63±0.04, respectively.
- Operational costs for smaller, dispersed areas are significantly higher than in larger urban areas, necessitating higher tariffs (0.55±0.3 JD/m^3), even though these remain within estimated affordability constraints.
- Limited opportunities exist to alleviate consumer burdens, such as selling wastewater to agriculture, but these are insufficient to match tariff levels elsewhere in Jordan.
- Until substantial market price increases, these schemes pose high uncertainty and risk, deterring operator interest.
- An approach to enhance efficiency involves expanding larger urban utilities' roles to encompass smaller communities, improving scope and scale economics.

4.7. Private-sector partnerships

Different partnership business models within the private sector are deliberated with stakeholders and outlined in Table 2. Stakeholders are invited to articulate their preferences by presenting arguments for their favored model.

Stakeholders resist full wastewater treatment privatization due to worries about profit-driven priorities, limited access, and unequal distribution. A solution could involve a balanced approach, merging private efficiency with public oversight to ensure affordability, quality, and accountability.

4.8. Proposed management of DWWMs

Service contracts cover labor for repair and maintenance of water facilities, requiring the facility owner to purchase equipment. Preventive maintenance and some operations are part of the agreement, but major equipment installation remains the owner's responsibil-

Table 2
Common public-private partnership business model

Partnership option	Description
Acquisition, divestiture	Public partner sells facility to private partner for private ownership and operation.
Joint venture	Private partner co-owns facility with public partner.
Concession or BOT	Private partner builds, owns, operates facility; transferred to public partner after a specified period.
Turnkey facility	Private partner designs, constructs, operates facility; public partner retains ownership, assumes financing risk.
Full-service contract	Public partner contracts private partner for facility operation and maintenance, public retains ownership.
Contract operations	Private partner operates and maintains public partner's facilities.
Contract management	Private partner manages and supervises public partner's personnel.
Operations assistance	Private partner aids in transition or program management to enhance public partner's operations.

ity. A preventive maintenance service contract involves fixed-fee services for scheduled rigorous activities like inspections, equipment overhauls, and calibration. The contractor typically provides necessary materials. Emergency repairs may or may not be included. The aim is to maintain optimal equipment performance and minimize unexpected failures. While initially cost-effective and focused on quality maintenance, budgeting for emergency repairs becomes challenging. This contract type places most risk on the owner, requiring a clear understanding of requirements for effective setup.

An inspection service contract involves fixed annual inspections of wastewater treatment plants (WWTPs) and related installations, focusing on basic checks for issues like blockages or structural integrity. It's the least expensive contract type but may lack effectiveness. Contractors might or might not provide some materials, and emergency repair agreements may or may not be included. While cost-effective, this contract type can carry operational risks, potentially affecting public safety. In Jordan, this contract is used for monitoring wastewater effluents in various private sector DWWTPs [34].

Private sector involvement in O&M through management contracts doesn't necessitate capital investment. Funding for infrastructure can come from various sources like the public budget or external financing. The management firm typically covers future reinvestment needs and repairs. Contract operations, maintenance, and management (OM&M) involve privately operated facilities owned by the municipality. The private firm manages operations, ensures compliance, and may handle design, construction, and financing of the facility while the municipality maintains ownership. The advantage and disadvantage related to WW sector in Jordan are displayed in Table 3.

4.9. Regulation and control

This section emphasizes the need to revise laws, regulations, policies, and standards to ensure sustainable water management in Jordan. It proposes assigning clear roles to stakeholders and institutions, defining their responsibilities, and fostering improved communication and collaboration among them to effectively implement water management initiatives.

4.9.1. Setting standards for DWWM

Jordan currently has standards, notably JS893/2006, suitable for centralized WWTPs. However, there's a need for specific standards tailored to effluents from DWWTPs. Alongside this, establishing a distinct monitoring framework based on existing sector frameworks and indicators is crucial for effectively implementing this plan.

4.9.2. Establishment of a monitoring system for DWWM

Reliable monitoring technology is vital for efficient DWWM systems, addressing challenges in personnel requirements and treatment reliability. Advanced remote monitoring tech minimizes these demands, enabling remote control of distant DWWTPs. A monitoring body can ensure comprehensive oversight, reporting findings regularly to decision-makers.

4.9.3. Update and amendment of legislations

Introducing a penalty system for non-compliance with effluent standards, following polluter-pay principles for influents, and compensating or adjusting treatment fees for treated effluents can deter violations.

4.9.4. Certification body for technology and operation

It is required to establish a certification body (could be JSMO). Once a technology certification system is established in Jordan, the monitoring frequency shall be further reduced.

4.9.5. Contract Based Service Performance

Jordan should establish a competitive market for outsourcing O&M services for smaller DWWTPs to the private sector, relieving the burden on the public sec-

Table 3
Benefits and drawbacks of management and service contracts in DWWM in Jordan

Options	Benefits	Drawbacks
Management contracts	Enhance services and reduce government risks Improve system efficiency and service quality Drive organizational reforms Initial step for private sector involvement	Government finances capital and some operational investments
Service contracts	Grant public sector access to private expertise Lead to efficiency improvements Widely used and relatively simple	Limited impact on overall utility management Cannot solve issues like tariff rate design or cost recovery Requires careful management and monitoring

Source: Stakeholders consultations

tor. Oversight by a national regulator is vital to uphold quality and standards.

4.9.6. Institutional Coordination and Clear Roles and Responsibility

Skilled operators and staff for O&M with the ability to select appropriate WW management systems and O&M schemes are essential to successful implement and sustainable manage decentralized WW infrastructure.

5. Conclusions

The current governance structure for DWWM in Jordan lacks clear institutional and legal arrangements, leading to confusion about responsibilities despite the MWI assigning DWWM management to WAJ. However, WAJ indicates this isn't their responsibility. Promoting DWWM in rural communities regardless of size should be prioritized based on multiple factors. Small-scale operations in low-density areas incur higher wastewater service costs than urban regions, leading to tariffs exceeding urban rates, making sustaining services challenging without substantial subsidies. Despite higher tariffs, they remain within affordability estimates.

Exploring revenue avenues proves limited. Options like selling wastewater to agriculture or obtaining carbon credits are insufficient to reduce tariffs. Financial viability for operational cost recovery in DWWM could be achieved if public budgets cover capital investments, making it appealing to private investors. Service contracts for smaller areas require specific regulations and economic incentives like fixed fees per treated cubic meter.

Continuous high-quality DWWM services depend on securing adequate financing, which influences various business models. Financial incentives like subsidies, tax deductions, and special depreciation encourage private and community engagement. The success of PPPs in wastewater management hinges on reshaping roles across sectors and overcoming implementation barriers. Privatization of WW Management Service by PPP in a form of BOT, BOOT, DBO, DBFO, DCMF are applicable for large scale WW projects, but can be also applicable to DWWM if sufficient revenues are guaranteed and certain, and a specific amount of WW to be treated is guaranteed as a minimum.

Comparing wastewater treatment frameworks across different contexts requires a nuanced understanding of the specific challenges and requirements associated with each region. In arid countries, where water scarcity is a primary concern, the adaptation of existing design paradigms, the promotion of water reuse goals, and the consideration of broader environmental impacts are essential factors to consider in developing effective and sustainable wastewater treatment solutions.

Comparing the framework for decentralized wastewater management with international best practices reveals key areas for improvement. Aligning regulatory frameworks, enhancing private sector engagement, and ensuring meaningful community involvement are essential considerations. Addressing implementation challenges such as financial sustainability and capacity building requires innovative strategies aligned with successful models. Assessing adaptability to diverse contexts is crucial for scalability and relevance. This comparative analysis guides policymakers and stakeholders in refining strategies to achieve improved water quality and sanitation globally. Stakeholders can identify strengths, weaknesses, and opportunities for enhancing decentralized wastewater management strategies. This comparative analysis can inform policy development, implementation strategies, and capacity-building efforts to improve water quality and sanitation outcomes globally.

6. Recommendations

This study recommends establishing a dedicated monitoring body or unit for decentralized wastewater management in Jordan within the MWI, connected to the National Water Information System. Currently, multiple institutions handle wastewater monitoring, necessitating clear roles and strong coordination for effective DWWM management. Efficient wastewater management through DWWM can be achieved by several means:

- Encouraging Public-Private Partnership (PPP) schemes can serve as off-budget mechanisms for infrastructure development, involving the private sector in construction and contract-based sanitation system management, reducing immediate cash spending.
- Site-specific, economically feasible, and environmentally sustainable wastewater systems should be considered. Small-scale, decentralized setups can lower environmental impact and health risks while potentially increasing wastewater reuse. A structured technology selection approach aids in navigating available options.
- Introducing certification procedures for technology and operations ensures adherence to standards, thereby enhancing reliability.
- Implementing reliable remote monitoring systems using advanced sensor technology aids in managing decentralized systems by enabling distant facility control and reducing onsite monitoring needs.
- The financing models for DWWM vary, with full privatization proving unattractive to investors and public operation facing challenges due to limitations in public entities' capabilities. Government interven-

tions like subsidies, service leasing, tax exemptions, and revenue collection must incentivize private sector involvement. Financial feasibility relies on a mix of central budget taxes, user charge revenues (tariffs), and international assistance for capital investment.

- Regulations that consider the variability of treatment efficacy of small and decentralized treatment systems and recognize the importance of decentralized wastewater treatment in Jordan would help promote wastewater treatment and reuse on a local scale.

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Balaban Desalination Publications

مؤتمر الخليج الخامس عشر للمياه
The 15th Gulf Water Conference

(2025) 344
doi: 10.5004.dsal.2025.700113

WSTA 15th Gulf Water Conference
Water in the GCC, The Role of Technology in Effective Water Management
28–30 April 2024, Doha, Qatar

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Water Sciences and Technology Association (WSTA)

Introduction

The Water Sciences and Technology Association (WSTA) was formed as a result of individual efforts of some of those concerned with water affairs in the Gulf Cooperation Council (GCC) Countries with an objective mainly to encourage and promote interest in water sciences and strengthen scientific ties among water professionals, encourage scientific research, training programs, and the development of local capabilities in the different fields of water sciences and technology.

The Government of Bahrain consented to register the Association in Bahrain, and the Association was formally founded in September 1987, to be the first scientific association in the field of water sciences and technology in the Arabian Gulf region. WSTA is a non-government organization, and its membership is open to all water professionals in the GCC, water-related national and international organizations, educational institutes, consultants, and companies.

Activities & Achievements

1. Conferences

WSTA has organized a series of conferences under the title Gulf Water Conference, where the first one was held during the period 10–13 October, 1992 in Dubai, UAE, under the theme "Water and Development in the Gulf Region, Challenges of the Nineties".

Following the success of its first conference, WSTA decided to organize this Regional conference biannually alternating in each of the GCC countries. The 2nd Conference was held in Bahrain during 5–9 November 1994, under the theme "Water in the Gulf, Towards an Integrated Management".

The 3rd Conference was held in Muscat during 8–13 March 1997 under the theme "Towards Efficient Utilization of Water Resources in the Gulf".

The 4th Conference was held in Bahrain again, during 13–19 February 1999, under the theme "Water in the Gulf, Challenges of the 21st century".

The 5th Conference was held in Doha, during 24–28 March 200, under the theme "Water Security in the Gulf".

The 6th Conference was held in Riyadh, during 8–12 March,2003, under the theme "Water in the GCC... Towards Sustainable Development".

The 7th Conference was held in Kuwait during 19–23 November 2005, under the theme "Water in the GCC… Towards an Integrated Water Resources Management".

The 8th Conference was held in Bahrain during 3–6 March 2008, under the theme "Water in the GCC... Towards an Optimal Planning and Economic Perspective".

The 9th Conference was held in Muscat, during 22–25 March 2010 under the theme "Water Sustainability in the GCC Countries — The need for a Socio-Economic and Environmental Definition".

The 10th Conference was held in the period 22–24 April 2012 in Doha, Qatar under the theme "Water in the GCC... Water-Energy-Food Nexus".

The 11th Conference was held in Muscat, Sultanate of Oman during 20–22 October 2014 under the theme "Water in the GCC States… Towards an Efficient Management".

The 12th Conference was held in Manama, Kingdom of Bahrain during 28–30 March 2017 under the theme "Water in the GCC...Towards an Integrated Strategy".

The 13th Conference was held in Kuwait during 12–14 March 2019 under the theme "Water in the GCC: Challenges and Innovative Solutions".

The 14th Conference was held in Riyadh, KSA, from 13–15 February 2022 under the theme "Water in the GCC... Challenges and Innovative Solutions".

The 15th Conference was held in Doha, State of Qatar, from 28–30 April 2024 under the theme "Water in GCC….Embracing Technological Progress".

2. Symposiums & Workshops

The WSTA has organized many symposiums and training workshops. The followings are a list of these:

"Symposium on Water Supply Fluoridation" held in October 1996, Kuwait;

"Future of Desalination in the GCC Countries Workshop", held on 8th March 1998, Bahrain;

"The Future of Desalination Research Workshop", organized in co-operation with the European Desalination Society (EDS), held during 8–11 September 2002, in L'Aquilla, Italy, titled "Operation and Maintenance: Performance Problems Workshop";

The second workshop was held during 24–27 August 2003, in Amsterdam, Holland;

The third workshop titled "Capacity Building workshop", was held during 1–2 December 2004, in Bahrain.

The workshop "Environmental Impact Assessment workshop" was held in collaboration with UAE University during 3–4 April 2013, Al-Ain, UAE.

Training course on "Using Mathematical Dynamic Modelling for Integrated Water Resources Management Using the program WEAP 20 October 2014 in the Sultanate of Oman in cooperation with the Ministry of Regional Municipalities and Water Resources.

WSTA conducted a Regional Training Course on "Water Footprint Assessment in the Gulf Cooperation Council" during 20–22 April 2015, in the Kingdom of Bahrain, in cooperation with AWARENET, AGU, MENA NWC, ESCWA and Cap-Net UNDP.

Further, a training workshop on "Non-Revenue Water" was held during 15–19 November 2015 in the Kingdom of Bahrain, in cooperation with the Arab Countries Water Utilities Association (ACWUA).

Moreover, WSTA conducted many training workshops, either during its conferences or separately. The Association held a workshop and training course on the "Quality of Irrigation Water in Oman" for a group of workers in the field of agriculture in April 2018, in cooperation with the Ministry of Agriculture and Fisheries in the Sultanate.

In addition to the workshops, WSTA had organized a Seminar on "Bottled Water Consumption in the GCC Countries", in collaboration with KISR and KFAS on 9th January 2020, followed by a virtual seminar on "The Experience of Artificial Recharge in the Countries of the Gulf Cooperation Council," organized in cooperation with KISR, 17 March 2021.

In addition, a virtual seminar on "Investment Opportunities in Brine Water", was held on 8 April 2021.

Recently, a webinar on “Produced Water Management, Challenges and Opportunities” was held on 25th October 2021, organized jointly with WSTA and Omani Water Society.

In 2022, WSTA organized a Training workshop entitled “The Role of Media Professionals in Raising Community Awareness on Water Challenges in the Gulf Cooperation Council Countries” held in Muscat during 28–29 September 2022.

This was followed by the 2nd Seminar on Bottled Water Consumption in the GCC Countries held in Doha, Qatar, during 30 April–1 May 2023, in cooperation with the Ministry of Environment and Climate Change.

The Association also organized a symposium on “The Problem of Shallow Water Table Rise in the Urban Areas in the GCC Countries” in Doha, State of Qatar in collaboration with the Public Work Authority (ASHGHAL) on 17 September 2023.

3. Affiliations

The Association is affiliated with a number of Regional and International NGO’s and Institutions addressing the global water issues, most notably the European Desalination Society EDS, International Desalination Association IDA, Arab Countries Water Utilities Association ACWUA and Oman Water Society OWS.

In addition, WSTA has established strong ties with many UN organizations (UNESCO, ESCWA, UNDP, UNEP, FAO and many more) working in the water sector to enforce its position as a pioneer in addressing the importance of conserving water and protecting water resources in the Gulf Region.

The WSTA Board of Directors:

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For further information, please visit the WSTA website at https://wstagcc.org/