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Water Resources In Arid Regions: Challenges, Vulnerability, and Sustainable Management Strategies in The Mutla'a-Jahra Coastal Area, Kuwait

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WATER RESOURCE sustainability poses challenges in arid regions due to limited freshwater availability, climate variability, and growing demand. Kuwait, as a predominantly arid country, faces acute water management challenges driven by heavy reliance on desalination, rapid urbanization, and groundwater depletion. The Mutla'a-Jahra coastal area is particularly vulnerable to these pressures, emphasizing the need for comprehensive water resource assessments. Despite previous research on groundwater and desalination, there is a gap in integrating hydrological, environmental, and sustainability-focused analyses to address these challenges holistically.

This study aims to bridge this gap by evaluating key challenges affecting water resource sustainability in the Mutla'a-Jahra coastal area. Using a multidisciplinary approach, the research investigates the impacts of climate change, groundwater depletion, and desalination dependency. The strengths, weaknesses, opportunities, and threats (SWOT) framework, and the water evaluation and planning (WEAP) model were employed to assess water supply and demand dynamics.

Findings reveal that desalination operations, primarily at the Doha East and West plants, were found to be energy-intensive, with multistage flash (MSF) systems emitting twice the carbon footprint of reverse osmosis (RO) systems while consuming more energy and chemical resources. However, treated wastewater from the Sulaibiya and Kabd plants meets regulatory standards, making it a viable alternative for agricultural irrigation and reducing dependency on desalinated water.

To address these challenges, the study proposes integrating renewable energy, adopting energy-efficient technologies, and implementing sustainable water practices. These strategies align with Kuwait's Vision 2035, providing actionable pathways to ensure water sustainability in arid regions.

Keywords: Water Resource Management, Climate Change Impact, Groundwater Depletion, Desalination Sustainability.

1. Introduction

Arid regions, characterized by high evaporation rates, water scarcity, and land degradation, cover approximately 41% of the Earth's surface and support nearly one-third of the global population (Kuwait Vision 2035: New Kuwait, 2022), (Kelly, 1951), (Nazih, 2022).Water scarcity is one of the most pressing challenges of the 21st century, exacerbated by climate change, which continues to deplete freshwater resources, particularly in arid and semiarid regions (IEA, 2012), (United Nations, 2015a), (United Nations, 2015b), (United Nations, 2019), (United Nations , 2021). The increasing frequency of extreme weather events, declining precipitation, and rising temperatures further contribute to groundwater depletion and increased salinity, placing additional stress on water systems and highlighting the urgent need for sustainable water management strategies (El-Baz & Al-Sarawi, 1996), (Water, 2020). By 2025, nearly half of the global population is expected to experience water stress (United Nations, 2015a), with regions like Kuwait being particularly vulnerable due to their reliance on nonrenewable water sources. Kuwait has one of the highest evaporation rates in the

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world and minimal groundwater recharge, making it dependent on desalinated water for domestic use and treated wastewater for agriculture (Al-Sulaimi, Viswanathan, Naji, & Sumait, 1996), (OECD, 2021), (United Nations, 2015b). While desalination provides a reliable water source, it poses environmental risks, including high carbon emissions, brine discharge, and adverse impacts on marine ecosystems (Al-Mutairi, Rashed, El-Halwany, & Mosaad, 2024), (Nazih, 2022). Also, groundwater extraction is hindered by high salinity and total dissolved solids (TDS), further limiting its usability for agricultural and domestic purposes (United Nations, 2015a).

Several studies have examined Kuwait's groundwater resources, focusing on geology, hydrogeology, and water quality (Al-Senafy, 2011), (Al-Sulaimi & Akbar, 1999), (Mukhopadhyay, Al-Sulaimi, & Al-Awadi, 1996), as well as the impacts of irrigation on brackish groundwater lenses (Al-Sulaimi & Mukhopadhyay, 2000), (Mukhopadhyay, Al-Sulaimi, & Barat, 1994). These studies have established that groundwater in Kuwait is highly saline, with limited recharge potential due to the arid climate and excessive extraction. Irrigation practices have further exacerbated salinization, reducing groundwater quality and availability. However, significant gaps remain in understanding the long-term sustainability of groundwater reserves, the cumulative impact of climate change, and the effectiveness of integrated water management strategies. Addressing these challenges requires a multidisciplinary approach that integrates geological, hydrological, and sustainability-focused analyses.

Effective water management necessitates the integration of geological and geomorphological data with predictive modeling tools to evaluate water resource sustainability under various scenarios (Al-Sulaimi & Akbar, 1999), (Al-Sulaimi, Khalaf, & Mukhopadhyay, 1997). Previous studies on surface and near-surface geology, as well as aquifer dynamics, have contributed to a foundational understanding of Kuwait's groundwater systems, (El-Anbaawy, Abdelhalim, & Al-Sarawi, 2017 a), (Shatat & Riffat, 2014). However, these studies often lack an integrated framework that considers both environmental impacts and long-term resource planning. Recent advancements, including renewable energy integration and data-driven optimization techniques, offer new opportunities for improving water management efficiency (Shatat & Riffat, 2014).

To bridge this gap, this study employs a comprehensive, multidisciplinary approach that combines SWOT analysis to assess strategic strengths and weaknesses, and the Water Evaluation and Planning (WEAP) model to analyze long-term water supply-demand dynamics. Kuwait's Vision 2035 further emphasizes the importance of adopting innovative technologies and sustainable water practices to secure long-term water availability.

This study aims to evaluate and enhance integrated water management strategies in Kuwait's Mutla'a-Jahra coastal area by assessing groundwater quality, resource availability, and the environmental impact of existing water systems. By utilizing a multidisciplinary framework that incorporates SWOT analysis, and the WEAP model, the research identifies key challenges related to groundwater depletion, desalination dependency, and climate change impacts. The findings contribute to the development of sustainable, data-driven water management strategies tailored to arid environments, ensuring long-term resilience and efficiency.

This study assesses the environmental impacts of desalinated and treated wastewater on coastal ecosystems. By integrating hydrogeological assessments with sustainability models, the research provides a comprehensive evaluation of Kuwait's water resources and offers practical recommendations for optimizing groundwater extraction, improving desalination efficiency, and promoting sustainable wastewater reuse.

The findings provide valuable insights for policymakers, researchers, and water management authorities, guiding future efforts towards more sustainable and efficient water systems in Kuwait and other arid regions.

2. Study Area

2.1 Introduction to the Study Area

Kuwait, located in the northwestern Arabian Gulf (Fig. 1), spans an area of 17,600 km² and is bordered by Iraq to the north and Saudi Arabia to the south. The Mutla'a-Jahra coastal area, covering 2,301 km² near Kuwait Bay, is characterized by flat, gravelly, sloped terrain with Miocene to recent rock formations. This region plays a critical role in Kuwait's water resource management and urban development due to its unique geological and hydrological characteristics.

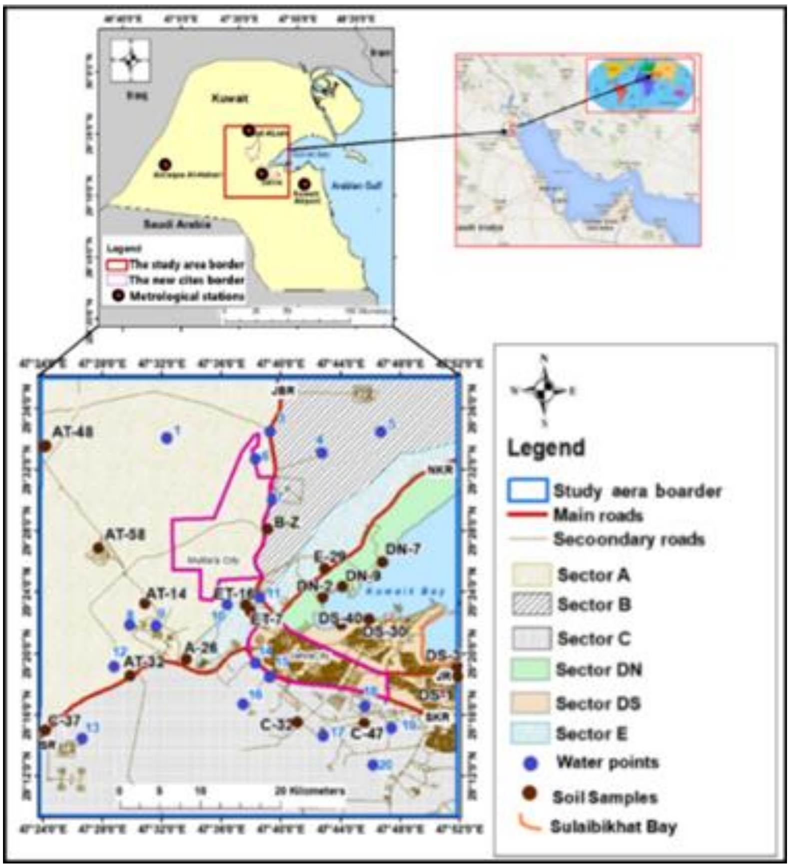

Fig. 1. Study location in the Al Jahra–Al Mutla'a District of Kuwait, showing the selected meteorological station locations.

2.2 Physiographic Sectors and Development Challenges

The study area is divided into six physiographic sectors, delineated by major roads, including Al-Salmi Road (SR), Al-Jahra Road (JR), Jaber Al-Ahmad Road (JBR), Naser Al-Kharafi Road (SKR), and Saad Al-Abdullah Road (NKR). These roads align with natural topographic and geological boundaries, ensuring a structured analysis of sector-specific influences on water resources and infrastructure. Each sector exhibits distinct physiographic characteristics: **Sector A:** Includes Mutla'a City, the Al-Rigsah Depression, and the Al-Liyah Escarpment, where depressions serve as natural basins facilitating water accumulation and groundwater recharge, while the escarpment alters surface runoff and soil moisture retention (Al-Sulaimi & Pitty, 1995). **Sector B:** Features the Umm Al-Rimmam and Zaglah Depressions, crucial for water retention and recharge. **Sector C:** Houses the Kabd and Sulaibiya wastewater treatment plants, which support agricultural development. **Sector E:** Comprises Jal-Az-Zor and its escarpment, playing a vital role in water recharge during seasonal rains. **Sector DN (North of Kuwait Bay):** Plays a crucial role in transportation and coastal activities, supporting economic and environmental functions. **Sector DS (South of Kuwait Bay):** Encompasses major urban centers such as Al-Jahra City, Saad Al-Abdullah, and Jaber Al-Ahmad City, which rely on desalinated water supplied by the Doha desalination plants.

3. Methodology

3.1 WEAP Analysis

The Water Evaluation and Planning (WEAP) model was adapted from ((KISR), 2012), (IPCC, 2018) to assess future water demand and supply trends in Kuwait and the Mutla'a-Jahra coastal region, considering different population growth scenarios and climate change projections. The model integrates historical hydrological data, demographic trends, and climate impact projections to evaluate potential challenges in water resource sustainability.

Four scenarios were developed to analyze the combined effects of demographic growth and climate change on water availability and demand in both

Kuwait as a whole and the Mutla'a-Jahra coastal study area. The scenarios were selected based on official national statistics, regional climate projections, and strategic development plans.

3.2 Environmental Assessment

Brine discharge data from the Doha East and West desalination plants and water quality parameters from the Sulaibiya and Kabd WWTPs and the Al-Jahra pumping station (PS) were assessed and compared with the Kuwait Environmental Public Authority (KEPA) standards. The saturation index (SI) of groundwater minerals was calculated using the following formula (Davis & Dewiest, 1966):

Equation (7): $SI = log\frac{K_{iap}}{k_{sp}}$, where K_{iap} is the ion activity product of dissociated chemical species in solution and K_{sp} is the mineral solubility product.

3.3 Strategic Planning

The Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis was incorporated into this study to provide a structured framework for evaluating the sustainability of water resource management strategies in the Mutla'a-Jahra coastal area of water resource systems was performed.

4. Results

4.1 Water Desalination: Energy and Environmental Impacts

4.1.1 Energy Demand and Carbon Footprint

Kuwait's reliance on desalination, which produces approximately 307 million m³/day, is critical for freshwater supply but is energy intensive. MSF systems consume 5.389 kWh/m³, producing a carbon footprint of 2.6945 kg CO_2/m³, while RO systems are more efficient, consuming 2.580 kWh/m³ and generating 1.29 kg CO_2/m³. These findings underscore the need for energy-efficient technologies and renewable energy integration to reduce environmental impacts.

4.1.2 Environmental Challenges Associated with Brine Discharge

Desalination plants, such as Doha East and West (Fig. 2), discharge high-salinity brine (70,000–75,000 ppm) into Kuwait Bay, exceeding the average seawater salinity of 45,000 ppm. These discharges, combined with thermal pollution from the plants, harm marine ecosystems. Limited circulation in shallow bays exacerbates pollutant accumulation, necessitating continuous monitoring and a transition to advanced, eco-friendly technologies.

4.2 Treated Wastewater: Opportunities and Compliance

The study area comprises three key wastewater treatment plants (WWTPs) (Fig. 3): the Sulaibiya plant, the Kabd plant, and the Al-Jahra plant. Although the Al-Jahra plant was decommissioned as a WWTP in 2010 because it could no longer handle the rising demand, it was repurposed into a primary pumping station. This change highlights the challenge of increasing water demands and illustrates how infrastructure is adapted over time. The areas served by these facilities—832 km² for Sulaibiya, 640 km² for Kabd, and 13.2 km² for the converted Al-Jahra site—demonstrate their distinct roles within Kuwait's comprehensive water management strategy.

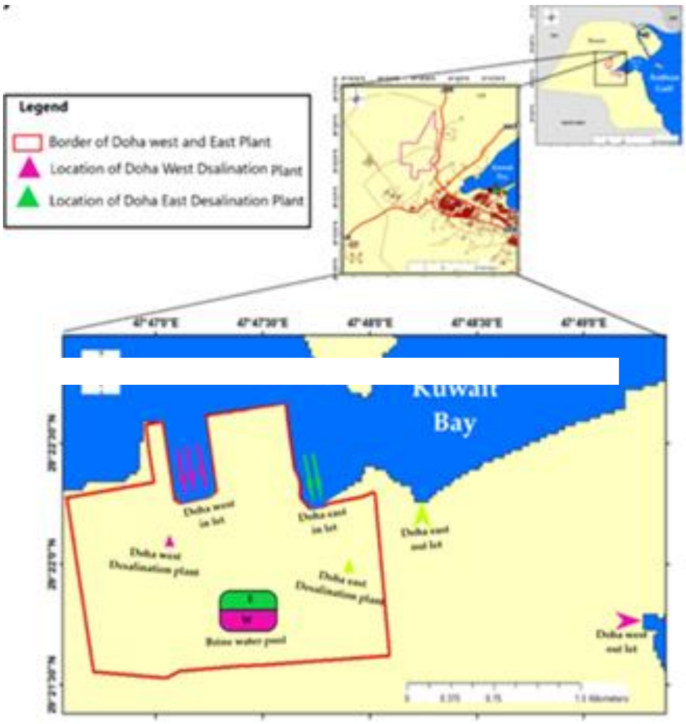

Fig. 2. Location map of the Doha East and West desalination plants showing the inlet sites.

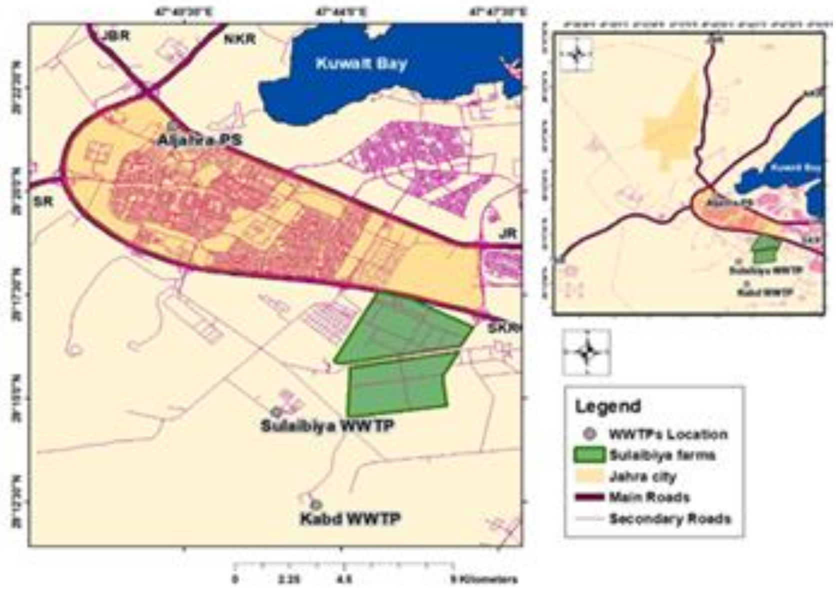

Fig. 3. Locations of wastewater plants.

4.2.1 Wastewater Treatment Plant Performance

The Sulaibiya WWTP processes 57% of Kuwait's wastewater using advanced RO and UF, whereas the Kabd WWTP employs a vertical activated sludge technique. Both plants meet most of the KEPA standards, although treated wastewater from the Kabd plant exhibits elevated ammonia nitrogen levels (25.2 mg/l vs. the standard of 15 mg/l), indicating the potential for optimization (Table 1).

4.2.2 Environmental Compliance and Reuse Potential

Based on the study results, the Sulaibiya plant consistently meets KEPA standards—with an average TSS of 0.009 mg/l and TDS of 37.79 mg/l, both far below the respective limits of 15 mg/l and 1500 mg/l. In contrast, the Kabd plant shows an average ammonia nitrogen (NH_4-N) concentration of 19.7 mg/l, which exceeds the KEPA limit of 15 mg/l. Therefore, focusing on enhancing the nitrification process at the Kabd plant to reduce ammonia nitrogen levels could ensure full compliance with KEPA standards and promote the safe reuse of treated water for agricultural purposes.

Table 1. Statistical summary of wastewater treatment plant effluent parameters.

Parameter	Sulaibiya			Kabd			*KEPA Standard Value
	Max	Min	Average	Max	Min	Average	
PH	7.4	6.13	6.684	6.88	6.72	6.802	6.5–8.5
TSS (mg/l)	0.2	0	0.0494	115	12	47.4	15
TDS (mg/l)	55	27.9	38.654	900	716	841.4	1500
O&G (mg/l)	0.06	0	0.0278	0.1	0.073	0.0854	5
NH_4-N (mg/l)	0.64	0	0.324	34.98	16.57	25.204	15
NO_3-N (mg/l)	1.32	0.41	0.932	9.3	0.421	4.9802	-
PO_4-P (mg/l)	0.73	0	0.26	5.6	0.8	3.74	30
CaCO3 (mg/l)	3.58	1.46	2.394	10.2	4.5	6.664	500
T.C (µg/l)	0.06	0	0.0132	1.02	0.53	0.866	200
BOD_5 (mg/l)	0.61	0	0.3346	129	27	59.8	20

(K-EPA, 2001)

4.3 Water Management and Resources Chalenges

Kuwait's water system was analyzed using the WEAP model, integrating climatic and hydrological data to support strategic planning and resource management ((KISR), 2012). Such efforts highlight the urgent need for sustainable water management strategies to address increasing demand, driven by a 24.7% population growth from 1960 to 2023 (Fig. 4).

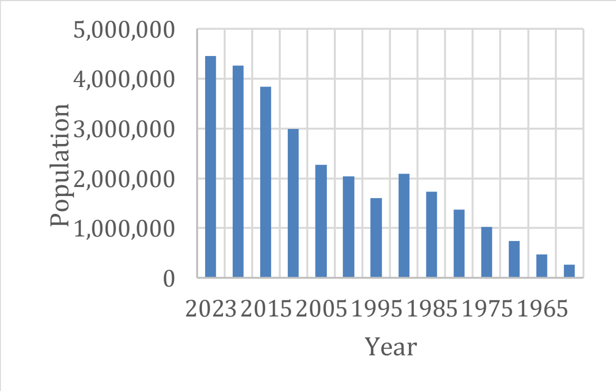

Fig. 4. Population of Kuwait over time.

4.3.1 SWOT Analysis of Water System

The experimental rationale was to identify critical factors influencing water resource sustainability and management. The SWOT analysis highlights the following key findings:

Strengths: The presence of brackish groundwater fields, such as those in Atraf, supports irrigation, while the high-quality seawater available facilitates efficient desalination. **Weaknesses:** Challenges such as groundwater depletion, increased salinity, contamination issues, and reliance on outdated water quality data impede effective policymaking. **Threats:** Over-extraction poses risks like seawater intrusion, and ecological stress is induced by desalination discharges and agricultural runoff. Additionally, climate change exacerbates

water scarcity and increases dependence on costly water production measures. **Opportunities:** Implementing advanced infiltration and artificial recharge systems can enhance groundwater sustainability and integrating renewable energy sources into water systems can reduce energy use and emissions.

4.3.2 WEAP Model

The WEAP model projections indicate a significant rise in water demand in both Kuwait as a whole and the Mutla'a-Jahra coastal study area due to population growth and climate change impacts.

Population Growth Trends (2022–2042)

The annual population growth rate (Table 2) is projected to remain relatively stable at 0.09% under normal conditions and 0.1% under high-growth scenarios. By 2042, Kuwait's total population is expected to increase from 4.27 million in 2022 to 5.0 million under normal growth or 5.2 million under high-growth conditions. Similarly, in the Mutla'a-Jahra study area, the population will rise from 1 million in 2022 to between 1.13 and 1.2 million, depending on the scenario.

Water Consumption Trends (2022–2042)

- Under normal conditions, without climate change, per capita water consumption is expected to increase from 480 to 495 Liters per day in Kuwait and from 120 to 124 Liters per day in the study area.
- With climate change impacts, per capita water demand is projected to rise further, reaching 500 Liters per day in Kuwait and 242 Liters per day in the study area, particularly under high population growth scenarios.
- The total water consumption in Kuwait is expected to increase from 485 million m³ to 911.04 million m³ under high population growth. In the study area, total demand could rise from 219 million m³ to 233 million m³ by 2042. Figure 5 illustrates the distribution of these sources and their integration within Kuwait's physiographic sectors.

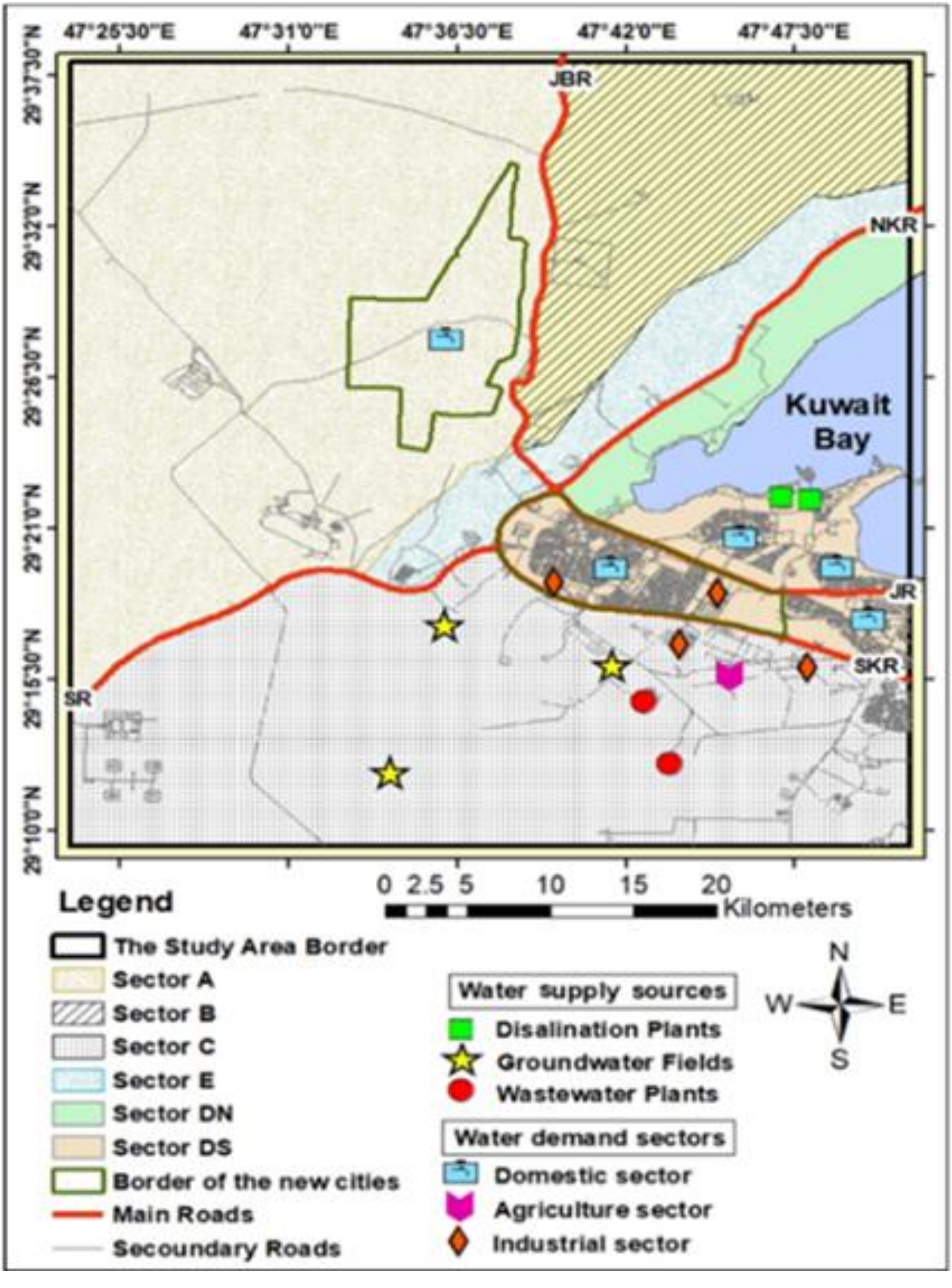

Fig. 5. Distribution of water supply sources and water demand sectors within the physiographic sectors of the study area.

Table 2. Annual population growth and water consumption levels in Kuwait and the study area.

Parameters	With out climate change				With climate change			
	*Kuwait		**The study area**		*Kuwait		**The study area**	
	Normal growth of population	High population growth	**Normal growth of population**	**High population growth**	Normal growth of population	High population growth	**Normal growth of population**	**High population growth**
Annual population growth rate 2022-2042	0.09%	0.1%	**0.09%**	**0.1%**	0.09%	0.1%	**0.09%**	**0.1%**
Total population in million people	From: 4.27 in 2022 to 5 in 2042	From: 4.27 in 2022 to 5.2 in 2042	**From: 1 in 2022 to 1.13 in 2042**	**From: 1 in 2022 to 1.2 in 2042**	From: 4.27 in 2022 to 5 in 2042	From: 4.27 in 2022 to 5.2 in 2042	**From: 1 in 2022 to 1.13 in 2042**	**From: 1 in 2022 to 1.18 in 2042**
Per-capita water consumption level (current)	480 L/D	480 L/D	**120 L/D**	**120 L/D**	From: 480 to 495 liter per-capita per day in 2022 to 2042	From: 480 to 500 liter per-capita per day in 2022 to 2042	**From: 120 to 124 liter per-capita per day in 2022 to 2042**	**From: 120 to 242 liter per-capita per day in 2022 to 2042**
Water consumption in 2042 Million m^3	485 L/D	911.04 L/D	**219 L/D**	**230 L/D**	885 L/D	932 L/D	**221.3 L/D**	**233 L/D**

*****Modify after ((KISR), 2012)

5. Discussion and Recomendation

This study aimed to evaluate and enhance integrated water resource management strategies in Kuwait's Mutla'a-Jahra coastal area by assessing groundwater quality, resource availability, and the environmental impact of existing water systems. Using a multidisciplinary approach incorporating the Strengths, Weaknesses, Opportunities, and Threats (SWOT) framework, and the Water Evaluation and Planning (WEAP) model, the research identified key challenges related to groundwater depletion, desalination dependency, and climate change impacts. The findings underscore the urgent need for sustainable water management strategies that integrate renewable energy, improve water efficiency, and mitigate environmental impacts.

Strategic Recommendations

Enhanced Monitoring and Data-Driven Decision-Making

The study highlighted significant groundwater quality limitations, with high salinity and total dissolved solids (TDS) concentrations making much of the available water unsuitable for direct agricultural or domestic use without advanced treatment. Results indicate that TDS levels in Sulaibiya B reached 10,503 mg/L, far exceeding acceptable limits. These findings align with the previous studies highlighted Kuwait's limited groundwater recharge potential due to arid climatic conditions and over-extraction. To address this, establishing GIS-based monitoring programs can improve tracking of water quality and hydrological changes across groundwater, desalination, and wastewater treatment systems. Periodic chemical and hydrological assessments will enhance compliance with environmental standards and provide critical data for policymaking.

Integrated Water Resource Management

The WEAP model projections underscore the urgency of implementing integrated water management strategies to balance water use among groundwater, desalination, and treated wastewater sources. Population growth and climate change are expected to exacerbate water scarcity, necessitating the modernization of irrigation systems. The study identified that brackish water techniques and optimized irrigation can help reduce losses in agricultural use. Implementing strategies such as training programs for farmers and policy-driven incentives for efficient water use will be crucial in ensuring resource sustainability.

Adoption of Renewable Energy and Sustainable Technologies

Desalination remains Kuwait's primary source of freshwater but is associated with high energy demands and environmental concerns. The study revealed that multistage flash (MSF) desalination consumes significantly more energy than reverse osmosis (RO) systems, generating a carbon footprint nearly twice as high. Global sustainability initiatives advocate for the transition to low-carbon water management solutions and integrating renewable energy sources such as solar and wind into desalination plants and wastewater treatment plants (WWTPs) can reduce carbon emissions. Additionally, investing in energy-efficient RO desalination systems and sustainable construction materials will help minimize environmental impacts.

Improving Groundwater Recharge

Given the limited natural recharge potential of Kuwait's groundwater resources, implementing artificial recharge techniques is essential. The study suggests that strategic excavation and management of retention sites in areas such as Umm-Al-Rimmam and Jal-Az-Zor could enhance aquifer recharge. Monitoring rainfall and runoff patterns can further optimize stormwater collection efforts. These initiatives align with the best global practices in managed aquifer recharge (MAR), which have demonstrated success in other arid regions.

Community Engagement and Policy Development

Public awareness and policy-driven solutions play a critical role in addressing water scarcity. The study found that while treated wastewater meets Kuwait Environmental Public Authority (KEPA) standards for irrigation, elevated ammonia nitrogen levels at the Kabd facility indicate a need for process optimization. Promoting water conservation campaigns, launching educational initiatives on climate change, and developing policies that incentivize innovation in water management technologies will be crucial steps toward sustainability. Funding for research and development can further support technological advancements in water efficiency.

By integrating innovative technologies, advanced modeling tools, and renewable energy, Kuwait can address water scarcity while aligning with global sustainability goals such as the SDGs and Vision 2035. Future research should focus on refining models and exploring emerging technologies to enhance sustainability in arid regions.

6. Conclusion

This study has examined water resource management challenges and opportunities in Kuwait, an arid environment, with a focus on groundwater, desalinated water, and treated wastewater. By integrating hydrographic, geomorphological, and chemical analyses with tools such as LCA, SWOT analysis, and WEAP modeling, this research addresses sustainability issues linked to climate change and population growth.

Another major finding is the environmental footprint of desalination technologies, with MSF desalination exhibiting significantly higher carbon emissions than RO systems. The results reinforce global calls for transitioning to energy-efficient and renewable-powered desalination methods. By demonstrating the feasibility of integrating renewable energy sources into desalination and wastewater treatment processes, this research supports broader sustainability goals aligned with Kuwait Vision 2035 and the United Nations Sustainable Development Goals (SDGs).

Beyond these key findings, this study also contributes to the broader knowledge base in water management by adopting a multidisciplinary framework that holistically evaluates Kuwait's water systems. Unlike previous studies that focused on isolated aspects of water management, our approach integrates diverse methodologies to provide a more comprehensive understanding of water sustainability challenges. These insights are essential for policymakers and water management authorities, as they offer actionable strategies for optimizing resource use, reducing environmental impact, and enhancing long-term water security in Kuwait and similar arid regions.

Looking forward, future research should expand on the socio-economic dimensions of water management, particularly exploring public acceptance, policy implications, and cost-benefit analyses of alternative water sources. Additionally, further refinement of hydrological and climate models could enhance predictive capabilities for long-term water sustainability in Kuwait and similar arid regions. By continuing to develop interdisciplinary strategies, researchers and policymakers can work toward achieving resilient and sustainable water resource management systems globally.

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موارد المياه في المناطق الجافة: التحديات، مواطن الضعف، واستراتيجيات الإدارة المستدامة في منطقة سهل المطلاع الجهراء الساحلية، الكويت

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تواجه إدارة الموارد المائية في المناطق القاحلة تحديات كبيرة بسبب ندرة المياه العذبة، وتغير المناخ، والطلب المتزايد. تعد الكويت واحدة من الدول التي تعاني بشدة من هذه التحديات، نظرًا لاعتمادها الكبير على تحلية المياه، والتوسع العمراني السريع، واستنزاف المياه الجوفية. يركز هذا البحث على منطقة **الساحل الممتد بين المطلاع والجهراء**، باعتبارها منطقة حساسة لهذه الضغوط، مما يستدعي تقييمًا شاملًا لمواردها المائية.

على الرغم من الأبحاث السابقة حول المياه الجوفية وتحلية المياه في الكويت، إلا أن هناك فجوة في دمج التحليل الهيدرولوجي والبيئي والاستدامة لتقديم حلول متكاملة لهذه التحديات. يسعى هذا البحث إلى سد هذه الفجوة من خلال تقييم التحديات الرئيسية التي تؤثر على استدامة المياه في منطقة الدراسة، مع استخدام نهج متعدد التخصصات لتحليل تأثيرات تغير المناخ، واستنزاف المياه الجوفية، والاعتماد على تحلية المياه.

تم استخدام **تحليل نقاط القوة والضعف والفرص والتهديدات (SWOT)** ونموذج **تقييم وتخطيط المياه (WEAP)** لتحليل ديناميكيات العرض والطلب على المياه. أظهرت النتائج أن محطات التحلية، لا سيما في **محطتي الدوحة الشرقية والغربية**، تعتمد على أنظمة **التحلية بالتقطير متعدد المراحل(MSF)** ، التي تستهلك ضعف كمية الطاقة وتنتج انبعاثات كربونية أعلى مقارنة بأنظمة **التناضح العكسي (RO)** من ناحية أخرى، أظهرت **محطات معالجة مياه الصرف الصحي في الصليبية وكبد** قدرتها على إنتاج مياه معالجة تتوافق مع المعايير البيئية، مما يجعلها خيارًا مستدامًا للري الزراعي وتقليل الاعتماد على المياه المحلاة.

لمواجهة هذه التحديات، يقترح البحث عدة استراتيجيات تشمل **دمج الطاقة المتجددة** في عمليات التحلية، واعتماد **تقنيات كفاءة الطاقة**، وتعزيز **الممارسات المائية المستدامة**، بما يتماشى مع **رؤية الكويت ٢٠٣٥** .كما يؤكد البحث على الحاجة إلى **مراقبة جودة المياه الجوفية، وتطوير نماذج تنبؤية للتغيرات المناخية، وتحسين عمليات إعادة تغذية الخزانات الجوفية** عبر تقنيات حديثة.

تقدم هذه الدراسة مساهمة علمية متميزة في مجال إدارة المياه في المناطق الجافة، من خلال تبني إطار متكامل يجمع بين التحليل الجيولوجي، والهيدرولوجي، والبيئي، والاستراتيجي. تسهم النتائج في توجيه صناع القرار نحو سياسات أكثر كفاءة واستدامة، وتسهم في تحسين التخطيط المستقبلي للمياه في الكويت ومناطق أخرى تعاني من نفس التحديات المناخية والبيئية.

الكلمات المفتاحية: إدارة الموارد المائية، تأثير تغير المناخ، استنزاف المياه الجوفية، استدامة تحلية المياه.