Sustainable Water Resources Management in Saudi Arabia

Subjects: Water Resources
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Saudi Arabia is one of the most water-scarce nations in the world, with a huge demand-supply gap, and the situation is expected to worsen due to climate change. Conventional surface water resources are limited, while nonrenewable groundwater sources are depleted. To build a more resilient and sustainable water sector, the production of non-conventional water resources, specifically desalinated seawater and treated domestic wastewater, has steadily increased in recent years. As the country lacks perennial water resources, such as rivers or water bodies, it relies mainly on nonrenewable groundwater and desalinated water to meet its daily requirements. Although the government is attempting to regulate the agricultural sector, water consumption in agriculture remains relatively high. It presents an environmental challenge due to its heavy reliance on non-renewable groundwater resources. The anticipated increase in temperature and highly uncertain changes in the rainfall patterns in Saudi Arabia could lead to greater uncertainty when attempting to develop effective water resource management plans.

Keywords: water resources ; climate change ; sustainability ; arid regions ; Saudi Arabia

1. Introduction

The Kingdom of Saudi Arabia (KSA) faces a significant challenge due to absolute water scarcity. The country primarily relies on four water sources: surface water, groundwater (renewable and non-renewable), desalinated water, and treated wastewater. KSA is the largest country without any perennial rivers or lakes worldwide [1], which makes it heavily reliant on primarily non-renewable groundwater and desalination resources to fulfill its daily needs, including drinking and agricultural requirements. Most agriculture activities are satisfied from depleted groundwater sources with almost negligible natural recharge [2][3]. Depleting the pivotal deep groundwater aquifer at the current rate in the Kingdom threatens its sustainable agriculture and food production [4]. Due to the limited conventional resources (i.e., surface water and groundwater), non-conventional water resources (i.e., desalinated water and treated wastewater) have been utilized as a viable solution to substitute for water deficiency.

Contrary to its enormous oil reserves, Saudi Arabia has long struggled with its limited freshwater water resources due to its arid climate and high demand for water for agriculture and domestic use. This desperation led to exploring unconventional solutions, such as towing icebergs from Antarctica to the Saudi Arabian coasts as a potential source of freshwater during the 1970s. However, the plan was eventually deemed impractical due to its high cost and logistical challenges [5]. The country is characterized by arid and semi-arid regions, with an average annual rainfall of about 100 mm. Approximately 81% of the country’s water resources consist of conventional sources (i.e., nonrenewable groundwater and surface water bodies) (**Figure 1**). In contrast, nonconventional sources (i.e., desalinated water and treated wastewater) account for nearly 19% of the country’s water resources. This has made water a valuable resource in the country, and the government has been working to manage it sustainably.

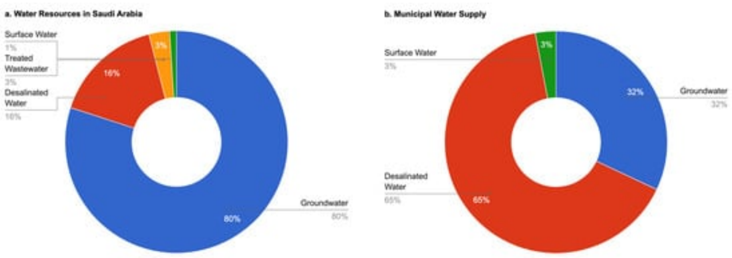

Figure 3. Charts representing data in 2021: (**a**) water resources in KSA with their share, and (**b**) municipal water supply (Data source: MEWA Annual Report [6]).

In 2021, the annual water demand in KSA was estimated to be 14.264 BCM/year (**Table 1**). Despite water scarcity being a concern in the country, irrigation accounts for around 78% (11.4 BCM/year) of the total annual consumption. The annual domestic and industrial water needs were about 25% (3.556 BCM) and 4.4% (0.628 BCM), respectively. Most of the demand was satisfied by nonrenewable resources (about 70%, or 10.08 BCM/year). Although the dams in the country have a combined capacity of 2.446 BCM, they only contributed 0.112 BCM in 2021, equivalent to 3% of the domestic water supply [6]. Thus, the benefits of such dams in a country with minimal surface water and low annual rainfall are constantly questioned. The annual water demand was 24.83 BCM/year in 2015, growing steadily at 7% per year, with about 84% (20.83 BCM/year) used for agricultural purposes. However, the decline in annual water demand in 2021 was mainly due to a governmental program by the Ministry of Environment, Water, and Agriculture (MEWA) to regulate the agricultural sector.

Table 1. Water demand by various sectors in KSA in 2021 (Data source: MEWA [6]).

Sector	Quantity (BCM per Year)	Percentage (%)
Agricultural [1]	**11.4**	**79.9%**
Domestic [2]	**3.556**	**24.9%**
Industrial [3]	**0.628**	**4.4%**
Total water demand	**14.264**	**100.0%**

[1] Initial estimations from renewable, non-renewable, and reused treated wastewater.
[2] Initial estimations based on the National Water Strategy 2030.
[3] Initial estimations based on a daily demand of 1.72 MCM/day at the beginning of 2022.

Climate change is expected to have significant implications for Saudi Arabia, particularly for its water resources. As reported in the literature, some anticipated consequences of climate change on water resources in KSA are listed below:

- One of the primary impacts of global warming is the rise in water demand across all sectors. For example, agricultural water demands are likely to increase by 1 to 3 BCM/year to maintain the current level of agricultural production [7][8]. Rising temperatures are also expected to lead to higher domestic water demand [9]. However, the exact extent of the latter's impact locally remains uncertain and needs further investigation.

- A reduction in surface runoff by 0.115–0.184 BCM/year (0.600–0.960 BCM/year) could be experienced if the average temperature rises by 1 °C (5 °C) [10].

- If the temperature rises by 1 °C (5 °C), it can lead to a decrease of approximately 0.0914 BCM (0.475 BCM) in the annual groundwater recharge values [11].

- Rising temperatures can lead to a higher rate of evaporation from open reservoirs [9], affecting the limited usability of the existing 544 dams. However, the exact extent of this impact on local basins remains undetermined.

- The rise in temperature will likely cause more evapotranspiration (ET_o) by up to 50% [7], while El-Rawy et al. [8] predicted a relatively smaller increase based on the SSP2-4.5 and SSP5-8.5 scenarios.

- The soil moisture may decrease by 0.181 m/year by 2050 [7].

- Water quality parameters could be negatively affected (e.g., reduction in dissolved oxygen (DO), increase in dissolved organic matter (DOM), nutrient load increase, and microorganism load increase) [7][12][13].

- An increase in seawater salinity in the Arabian Gulf could be brought about by climate change, which, in turn, may decrease the desalination process's efficiency and energy consumption [14].

- The frequency and intensity of climatic and hydrological extremes will increase, such as heavy precipitation events [15]. Moreover, in the design of critical urban infrastructure and water systems, the probability of climate change-induced events must be considered [16].

- Marine biodiversity in the Arabian Gulf will be adversely affected, and there is a risk of local extinction of some habitat species [14].

2. Sustainable Water Resources Management in a Changing Climate

2.1. Managing Agricultural Demands

The predominant means for irrigated agriculture remain unjustifiable water-intensive conventional surface methods such as flood irrigation with low water productivity [17][18]. Such large water losses in the irrigation sector are due to several factors, including inefficient irrigation systems, farmers' awareness, low-skilled laborers, and a lack of capacity at the administration level, according to Al-Omran et al. [19]. Al-Subaiee et al. [20] found that farmers' adoption of modern irrigation methods in Qassim, a region with high agricultural activity, is positively correlated with educational levels but negatively correlated with farmers' age and years of experience.

In order to address the rising demand for water due to climate change, it is necessary to implement the best water management approaches in the irrigation sector. These strategies may include scheduling irrigation, improving irrigation efficiency, decreasing evaporation, and eliminating non-economical crops [19]. Modern irrigation systems, such as drip irrigation or pivot sprinklers, have been proven to conserve water without impacting crop yields. For instance, drip irrigation systems have enabled farmers worldwide to reduce their water consumption by 30 to 70% while increasing their crop yields by more than 20% [21]. On a national scale, it is necessary to conduct an urgent, thorough assessment of the current irrigation water usage and efficiency [19].

The Saudi Organization for Irrigation (SIO), a public governmental institution with legal, financial, and administrative independence associated with MEWA, is currently reforming the legislative and institutional structure of the irrigation sector with the assistance of the Food and Agriculture Organization (FAO). Moreover, an initiative by SIO for water consumption reduction in agriculture includes several projects such as providing water-saving devices to farmers to improve irrigation efficiency, conducting studies and research to increase irrigation efficiency, developing the SCADA system along with a central operations control and monitoring headquarters, setting up a technical center for the advancement of irrigation practices and methods, and launching awareness campaigns and providing information to the public. MEWA launched a leading initiative to install electronic meters on selected farm groundwater wells in line with the National Water Strategy 2030 objectives. Currently, there are no charges for irrigation water consumption. However, under the recently-released Saudi Water Law in Article 10, MEWA is authorized to impose charges for any water usage that exceeds the “allocated water ration”. The ministry will determine the allocated water ration based on the water requirements of various crops.

Improving water use efficiency by adopting modern irrigation techniques, enhancing soil properties, and implementing deficit irrigation is not a choice but a necessity [19]. It has become imperative to prioritize “water security” over the old policy of “food security”. This shift in focus is crucial for ensuring the sustainability of depleted resources and the well-being of the community.

2.2. Reuse of Treated Wastewater

In regions with limited water resources, treated wastewater is an essential and practical solution to address the water scarcity issue. Wastewater reuse enables the environmentally conscious and sustainable reutilization of scarce water resources for non-drinking purposes in areas such as industry, agriculture, and environmental improvement. The development of wastewater infrastructure is growing rapidly on a local scale. Given the projected annual growth rate of 4% in sewage effluent volumes between 2025 and 2050 [22], the opportunity is huge. The Kingdom of Saudi Arabia has recently embraced sustainable water management as a priority, including the reuse of treated sewage effluent as a self-sustainable component of integrated water management [23]. For instance, the “Riyadh Green Project” aims to add more green space by planting 7.5 million trees in the city using recycled water.

As of 2018, only about 60% of households had access to wastewater connections, which falls short of the benchmark goal of serving at least 98% of households [24]. Although there has been an increase in wastewater treatment in KSA recently, only a small fraction of the treated wastewater (22% as of 2021) is utilized for agriculture and industry purposes [6], which also falls short of the benchmark goal of utilizing at least 60% [24]. The majority of the treated wastewater is left unused. According to UN-WWAP [25], high-income countries treat approximately 70% of the municipal and industrial wastewater they produce.

Moreover, one of the challenges is the low public acceptance of reusing gray and mixed wastewater, even among well-educated individuals [26]. Greywater has fewer pathogens than blackwater, making it safer to handle and easier to treat and reuse onsite for non-potable purposes such as toilet flushing, car washing, and landscaping.

Therefore, changing people’s pessimistic outlooks, particularly toward gray water, is paramount. Furthermore, the absence of local environmental regulations and legal frameworks regarding utilizing these resources poses a significant issue [24]. To our knowledge, studies have yet to be conducted on the health and environmental impacts of using treated water in the region in the future.

2.3. Evaporation Reduction Technologies

KSA has high potential evaporation rates, with an average annual rate ranging from 2500 mm to 3000 mm [27][28]. The volume of water lost through evaporation from the existing 544 dam reservoirs in KSA each year is enormous. In arid regions, it is vital to adopt evaporation reduction technologies to minimize water loss, help conserve the already limited surface water resources, and improve water use efficiency. The most commonly used evaporation reduction technologies include physical and chemical covers.

The function of physical covers is to reduce the amount of direct sunlight and wind exposure that water surfaces are exposed to. Craig et al. [29] found that implementing physical covers significantly minimized evaporation, particularly for small reservoirs with an area of less than 10 hectares. Yao et al. [30] stated that a fully-covered dam using suspended (floating) covers could substantially reduce annual evaporation by 76% (68%). Physical covers can also be utilized for large reservoirs; however, they would not be cost-effective.

One of the available options for physical covers is the use of floating photovoltaic (PV) panels. They have been receiving increasing attention due to their many benefits, such as reducing evaporation, conserving valuable land in agricultural areas, and possibly producing more energy due to less obstruction to sunlight and a lower panel temperature [31]. They have been installed on various water bodies, including irrigation canals, lakes, and dams, as demonstrated in recent studies by Baradei & Sadeq [32], McKuin et al. [33], and Khan et al. [34].

To make the use of physical covers more economical, locally sourced materials as the cover have been proposed, such as palm trees, which are widely distributed throughout the country (estimated to be more than 21 million trees) due to their ability to survive a harsh climatic environment [35][36]. Alam and AlShaikh [36] used double-layer palm-frond sheets and observed about a 58% average reduction in evaporation when the water surface was fully covered. Al-Hassoun [37][38] used the same local materials and reported comparable findings with no significant impact on water quality.

Another approach to reducing evaporation is using surface chemical coatings such as monolayers, which form a thin layer on the surface of the water and can reduce the evaporation rate. Coatings are usually composed of natural or synthetic substances that are harmless to both people and the environment [39]. The monolayer technique, in particular, is widely used because it is both cost-effective and readily available, making it economically feasible [40]. The efficiency of this technique in arid regions was investigated in Algeria in laboratory conditions, and a 22% reduction was observed [40]. One downside of using these covers is that the materials need to be reapplied frequently. Additionally, wind conditions during the application process can affect their effectiveness on the water surface [39].

However, it is crucial to acknowledge that the use of chemicals or physical covers on water bodies may affect the aquatic ecosystem [28][30][38][41][42][43]. Therefore, the applicability of some of these techniques in the KSA environment needs to be further investigated. Apart from technological solutions, implementing efficient management practices can also decrease evaporation in arid regions. This can be achieved by optimizing irrigation techniques to avoid overwatering and reducing the exposed surface area of water bodies.

2.4. Subsidies in Domestic Water Supply

In KSA, subsidies are provided for domestic water supply to ensure social welfare and reduce the financial burden on households, particularly those with low and fixed incomes. However, the heavy subsidies on domestic water supply and low tariffs have also led to overconsumption and waste, as proven by the high average per capita water consumption, as consumers do not face the true cost of water and therefore have little incentive to conserve it [44]. On average, households in the KSA consume 222 m^3 of water per month. It has been observed that Saudi households consume more water than non-Saudi households [45].

In 2015, the government took steps toward reducing these subsidies and introducing more cost-effective pricing policies. This included imposing an updated increasing-block tariff based on consumption levels (cf. **Table 2**). Ultimately, the main goal of the new rates is to strike a balance between meeting the demand of consumers and conserving water resources, as well as promoting sustainable development in KSA. The current subsidized potable water (and sewer) cost is \$0.04/m^3 (for less than 15 m^3/month consumption). Still, consumers pay only a fraction of the water production and transmission costs (including the highest consumption tier), as the actual cost is around \$3.4/m^3 [24]. The average global cost of potable water is around \$6/m^3 [46].

Table 2. Old and new water consumption rates (per m^3) in **SAR** (US\$).

Old Tariff [A]		**New Tariff** [B]	
Tier (m^3/Month)	**Consumption Tariff (SAR/m^3/Month)**	**Tier (m^3/Month)**	**Consumption Tariff (SAR/m^3/Month)**
Up to 50	**0.1 (0.03)**	**Up to 15**	**0.15 (0.04)**
>50–100	**0.15 (0.04)**	**>15–30**	**1.5 (0.4)**
>100–200	**2 (0.53)**	**>30–45**	**4.5 (1.2)**
>200–300	**4 (1.07)**	**>45–60**	**6 (1.6)**
More than 300	**6 (1.60)**	**More than 60**	**9 (2.4)**

[A] **There is no sewer consumption charge.**
[B] **The sewer consumption rate is included (as 50% of the water consumption rate).**

If there is an increase in demand for tap water, it will be met only by the operation of more desalination plants [47]. Considering the expenses involved in producing and delivering desalinated water in Saudi Arabia, it is logical to factor in the marginal cost of municipal water, particularly for high-volume users, towards a sustainable water pricing policy considering the local socio-economic characteristics.

2.5. Rainfall Harvesting

Although intense rainfall events are rare in Saudi Arabia and characterized by random temporal and spatial distributions, they can still cause substantial flash floods that result in large amounts of surface water. As rainfall surplus increases and wet periods become more prolonged due to climate change [48], flash floods are expected to occur more frequently. Therefore, it is crucial to consider proactive measures to exploit rainwater harvesting opportunities. Rainwater harvesting is a practical and eco-conscious method of collecting and storing rainwater for future use. This sustainable practice not only helps to conserve water resources but also minimizes the impact of stormwater runoff on the environment. Several ways to achieve this goal include rooftop collection systems, storage tanks, and filtration systems (e.g., [49]). Harvested water from a rainfall event can be used for non-potable purposes, such as irrigation, flushing toilets, or washing clothes, to reduce municipal water demand and help conserve water resources. An alternative option is transitioning from the prevailing gray infrastructure to green infrastructure. The latter method uses permeable surfaces that can be exploited for harvesting and reusing stormwater.

Effective management of the limited rainwater in both rural and urban areas has become a crucial aspect of water resource management in the KSA as the only natural supplier to groundwater reservoirs. Ghazaw [50] and Rabeiy et al. [3] suggested that rainwater resulting from heavy rainstorms and stored in existing bonds in the Qassim region has the potential to help artificially replenish the groundwater of the Saq Aquifer using injection wells and reduce water loss caused by evaporation from surface storage. Another method of groundwater recharge in KSA is using recharge dams, which capture and store surface water during periods of high rainfall and release it gradually into the ground, allowing it to recharge the underlying aquifers.

Groundwater in shallow alluvial aquifers can be naturally recharged more quickly and frequently than in deep aquifers, although their supply is limited and depends on rainfall and surface runoff. According to a 2012 report by the Ministry of Water and Electricity (MWE) [51], now known as MWEA, it has been estimated that these aquifers have an average annual recharge of 1.196 BCM with storage of about 84 BCM. This suggests that these sources can potentially provide a viable solution for sustainable water usage, particularly for inner cities.

However, the current recharge methods (and rainfall harvesting) offer information for a specific location but have yet to be able to comprehensively evaluate the complex dynamics of groundwater replenishment on a regional scale [52]. Additionally, there is a concern about polluting these fossil aquifers [53]. To address such limitations, further research and technological advancements are needed. One potential solution could be the development of advanced modeling techniques that can accurately assess recharge rates and patterns across larger geographical areas. This would require integrating various data sources, such as precipitation data, land use patterns, soil characteristics, and hydrological parameters, into comprehensive models.

2.6. Better Technologies in Desalination

By replacing the energy-intensive thermal technologies in most plants with cost-effective and eco-friendly RO technologies, SWCC has successfully achieved an 80% reduction in energy consumption. The SWCC's goal is to attain energy consumption levels lower than 2 kWh/m^3 for agricultural production facilities by the end of 2023, 2.1 kWh/m^3 for small-scale and mobile production plants by 2024, and 2.5 kWh/m^3 for large-scale production plants by 2025 [54]. Nevertheless, fuel consumption in water desalination still represents more than 25% of the volume of national fuel production, according to the National Water Strategy 2030 [24].

Although some desalination methods (i.e., reverse osmosis, multistage flash, and multi-effect distillation) have been utilized for a long time, adopting newer and more advanced techniques to achieve better efficiency, lower costs, and minimal environmental impact is necessary. Moreover, relying on fossil fuels to produce freshwater is economically and politically unsustainable [55]. It is crucial to have a dependable desalination industry that is powered by sustainable energy. Some promising methods include using geothermal energy [55] or nuclear power [56][57] to meet the growing freshwater demand.

2.7. Water Conservation

Water conservation is an essential aspect of managing scarce water resources. Many water-stressed countries have prioritized large-scale technical solutions to augment the water supply from alternative sources instead of implementing water conservation methods [58]. In countries such as the KSA, water conservation is no longer a choice but a necessity [59]. As irrigation is the dominant water consumer by far, pervasive water-liberal irrigation practices such as "flood irrigation" continue to be the dominant production system for irrigated agriculture [17][18][19]. Before 1994, potable water in KSA was provided without charge, and low-priced water tariffs were only introduced then to raise consumers' awareness about water's value [60]. Ouda et al. [59] conducted a survey and found a relatively low level of awareness regarding the issue of water scarcity in the Kingdom. In addition, the non-revenue water (quantities lost before reaching customers) in the municipal distribution network is still high due to network losses (20% and 40% of the total volume of the distributed water) [61].

Nevertheless, the government has implemented several measures to promote water conservation, such as increasing tariffs on water usage, promoting the use of water-efficient technologies, encouraging the reuse of treated wastewater, and implementing awareness campaigns to educate the public on the importance of water conservation. Some examples of conservation measures implemented in the domestic domain thus far are as follows:

- Some of the treated wastewater effluents (22% of the total treated wastewater effluents) have been used either for irrigation by SIO (95.6% of reused treated wastewater) or for industrial purposes (4.4% of reused treated wastewater) [6].
- Some efforts have been made to minimize water leakage losses from the water supply networks.
- Toilet flushing at the Holy Mosque in Makkah has adopted a conservation measure whereby highly saline water from Wadi Malakan near Makkah is used instead of expensive desalinated water [62].
- The government launched a nationwide campaign in 2004 to provide free water conservation tools (including water-saving showerheads and faucets, replacement bags for 3-L toilet tanks, and pills for detecting leaks) to targeted sectors, including residential, government/public, and private. However, the efficiency of this campaign is questionable [59].
- Qatrah, which means “droplet” in Arabic, is one of the latest water conservation programs to promote water conservation practices in the industrial and residential sectors. The program aims to decrease daily water usage from 263 L per capita per day (LPCD) in 2019 to 200 LPCD by 2020 and 150 LPCD by 2030.
- The Saudi Green Building Code (SBC 1001-CR), introduced in 2018 as a voluntary part of the new Saudi Building Code (SBC), addresses, among other environmental requirements, water resource quality and efficiency [63].

However, the aforementioned programs’ efforts and others have fallen mostly short of their intended objectives. The reported per capita consumption of 278 LPCD in 2021 [6] suggests that there is still much work to be conducted in the realm of water conservation policies.

As approximately 20% to 40% of the water supplied in the country is lost due to leakage in water distribution systems as water flows from sources to end-users, greater efforts are needed to achieve the 8% national benchmark of water loss [64][65]. For instance, installing modern technology to detect and repair leaks in the water distribution systems promptly is warranted. It is recommended to continuously maintain and inspect old pipes or replace them with new, more durable ones that are less prone to leakage. Moreover, public awareness of conserving the extremely scarce water and reporting any leaks they observe to local authorities is essential.

It is imperative that further measures are implemented to maintain the sustainability of water resources. This can be achieved by disseminating awareness campaigns across various (social and traditional) media platforms and educational systems to alert the masses, particularly young generations, about the importance of water conservation.

References

1. Llamas, R.; Custudio, E. Intensive Use of Groundwater: Challenges and Opportunities; A.A. Balkema Publishers: Lisse, The Netherlands, 2003; p. 481.
2. Alataway, A.; El Alfy, M. Rainwater Harvesting and Artificial Groundwater Recharge in Arid Areas: Case Study in Wadi Al-Alb, Saudi Arabia. J. Water Resour. Plan. Manag. 2019, 145, 05018017.
3. Rabeiy, R.; Alfawzan, M.; Bakri, M. Artificial Recharge Modelling of Groundwater Aquifer in Arid Regions. Civ. Environ. Eng. 2022, 18, 301–311.
4. Ghanim, A.A. Water resources crisis in Saudi Arabia, challenges and possible management options: An analytic review. Int. J. Environ. Ecol. Eng. 2019, 13, 51–56.
5. Weeks, W.F. Iceberg water: An assessment. Ann. Glaciol. 1980, 1, 5–10.
6. Ministry of Environment, Water, and Agriculture (MEWA), Saudi Arabia (2022) MEWA Statistical Report 2021. Available online: https://mewa.gov.sa/ar/InformationCenter/Researchs/Reports/GeneralReports/%D8%A7%D9%84%D9%83%D8%AA%D8%A7%D8%A8% (accessed on 21 March 2023).
7. Chowdhury, S.; Al-Zahrani, M. Implications of Climate Change on Water Resources in Saudi Arabia. Arab. J. Sci. Eng. 2013, 38, 1959–1971.
8. El-Rawy, M.; Batelaan, O.; Al-Arifi, N.; Alotaibi, A.; Abdalla, F.; Gabr, M.E. Climate change impacts on water resources in arid and semi-arid regions: A case study in Saudi Arabia. Water 2023, 15, 606.
9. Tarawneh, Q.Y.; Chowdhury, S. Trends of climate change in Saudi Arabia: Implications on water resources. Climate 2018, 6, 8.
10. Abderrahman, W.A.; Al-Harazin, I.M. Assessment of climate changes on water resources in the Kingdom of Saudi Arabia. In Proceedings of the GCC Environment and Sustainable Development Symposium, Dhahran, Saudi Arabia, 28–30 January 2008; pp. D-1-1–D-1-13.

11. Sen, Z.; Al Alsheikh, A.; Al-Dakheel, A.M.; Alamoud, A.I.; Alhamid, A.A.; El-Sebaay, A.S.; Abu-Risheh, A.W. Climate change and Water Harvesting possibilities in arid regions. Int. J. Glob. Warm. 2011, 3, 355–371.
12. Alkolibi, F.M. Possible Effects of Global Warming on Agriculture and Water Resources in Saudi Arabia: Impacts and Responses. Clim. Chang. 2002, 54, 225–245.
13. Ragab, R.; Prudhomme, C. Sw—Soil and Water: Climate change and water resources management in arid and semi-arid regions: Prospective and challenges for the 21st century. Biosyst. Eng. 2002, 81, 3–34.
14. Wabnitz, C.C.; Lam, V.W.; Reygondeau, G.; Teh, L.C.; Al-Abdulrazzak, D.; Khalfallah, M.; Pauly, D.; Palomares, M.L.D.; Zeller, D.; Cheung, W.W. Climate change impacts on marine biodiversity, fisheries and society in the Arabian Gulf. PLoS ONE 2018, 13, e0194537.
15. Almazroui, M.; Şen, Z.; Mohorji, A.M.; Islam, M.N. Impacts of climate change on water engineering structures in arid regions: Case studies in Turkey and Saudi Arabia. Earth Syst. Environ. 2019, 3, 43–57.
16. Salimi, M.; Al-Ghamdi, S.G. Climate change impacts on critical urban infrastructure and urban resiliency strategies for the Middle East. Sustain. Cities Soc. 2020, 54, 101948.
17. DeNicola, E.; Aburizaiza, O.S.; Siddique, A.; Khwaja, H.; Carpenter, D.O. Climate change and water scarcity: The case of Saudi Arabia. Ann. Glob. Health 2015, 81, 342–353.
18. Gabr, S.S.; Farg, E.F.; Habeebullah, T.M.; Arafat, S.M. Irrigation water consumption and its impact on the groundwater aquifer of Wadi Uranah, Makkah, Saudi Arabia using remote sensing techniques. Egypt. J. Remote Sens. Space Sci. 2020, 23, 167–180.
19. Al-Omran, A.M.; Al-Khasha, A.; Eslamian, S. Irrigation water conservation in Saudi Arabia. In Handbook of Water Harvesting and Conservation: Case Studies and Application Examples; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2021; Chapter 25; pp. 373–383.
20. Al-Subaiee, F.S.; Al-Ghobari, H.M.; Baig, M.B.; Ei-Hag, E.A.; Abu-Riziga, M.T. Studies on adoption of irrigation methods by the date palm farmers in Al-Qassim area-Kingdom of Saudi Arabia. Bulg. J. Agric. Sci. 2013, 19, 1337–1345.
21. Postel, S.; Polak, P.; Gonzales, F.; Keller, J. Drip irrigation for small farmers: A new initiative to alleviate hunger and poverty. Water Int. 2001, 26, 3–13.
22. Alkhudhiri, A.; Darwish, N.B.; Hilal, N. Analytical and forecasting study for wastewater treatment and water resources in Saudi Arabia. J. Water Process Eng. 2019, 32, 100915.
23. Kreutzberger, W.; Robinson, J.; Bkayrat, R.; Bacon, E. Comprehensive study of water reuse role in integrated water resources management—Kingdom of Saudi Arabia. In Proceedings of the World Environmental and Water Resources Congress 2012: Crossing Boundaries, Albuquerque, NM, USA, 20–24 May 2012; pp. 3366–3377.
24. National Water Strategy. 2018. Available online: https://mewa.gov.sa/en/ministry/agencies/thewateragency/topics/pages/strategy.aspx (accessed on 20 March 2023).
25. UN-WWAP (United Nations World Water Assessment Programme). The United Nations World Water Development Report 2017. Wastewater: The Untapped Resource. Paris, UNESCO. 2017. Available online: https://unesdoc.unesco.org/ark:/48223/pf0000247153 (accessed on 3 July 2023).
26. Mu'azu, N.D.; Abubakar, I.R.; Blaisi, N.I. Public acceptability of treated wastewater reuse in Saudi Arabia: Implications for water management policy. Sci. Total Environ. 2020, 721, 137659.
27. Al-Yamani, M.S.; Sen, Z. Regional variation in monthly rainfall amounts in the Kingdom of Saudi Arabia. Earth Sci. 1993, 6, 113–133.
28. Elsebaie, I.H.; Fouli, H.; Amin, M. Evaporation reduction from open water tanks using palm-frond covers: Effects of tank shape and coverage pattern. KSCE J. Civ. Eng. 2017, 21, 2977–2983.
29. Craig, I.; Aravinthan, V.; Joseph, P.; Baili, C.; Beswick, A. Evaporation, seepage and water quality management in storage dams: A review of research methods. J. Environ. Health 2007, 7, 84–97.
30. Yao, X.; Zhang, H.; Lemckert, C.; Brook, A.; Schouten, P. Evaporation Reduction by Suspended and Floating Covers: Overview, Modelling and Efficiency; Urban Water Security Research Alliance Technical Report No 28; Urban Water Security Research Alliance: Brisbane, Australia, 2011; ISSN 1836-5566.
31. Abdelal, Q. Floating PV; an assessment of water quality and evaporation reduction in semi-arid regions. Int. J. Low-Carbon Technol. 2021, 16, 732–739.
32. Baradei, S.E.; Sadeq, M.A. Effect of solar canals on evaporation, water quality, and power production: An optimization study. Water 2020, 12, 2103.
33. McKuin, B.; Zumkehr, A.; Ta, J.; Bales, R.; Viers, J.H.; Pathak, T.; Campbell, J.E. Energy and water co-benefits from covering canals with solar panels. Nat. Sustain. 2021, 4, 609–617.
34. Khan, I.; Guanghua, L.; Sahito, A.A.; Memon, A.A.; Hao, C.; Soomro, A.H.; Shah, S.H.H. Analysis of Jamrao canal for potential of hybrid photovoltaic/hydrokinetic turbine system. Energy Rep. 2023, 10, 419–430.
35. Al-Juruf, R.S.; Ahmed, F.A.; Alam, I.A. Development of heat insulating material using date palm leaves. J. Therm. Insul. 1988, 11, 158–159.

36. Alam, S.; AlShaikh, A.A. Use of palm fronds as shaded cover for evaporation reduction to improve water storage efficiency. J. King Saud Univ.-Eng. Sci. 2013, 25, 55–58.

37. Al-Hassoun, S.A.; Mohammed, T.A.; Nurdin, J. Evaporation reduction from impounding reservoirs in arid areas using palm leaves. J. Eng. Appl. Sci. 2009, 4, 247–250.

38. Al-Hassoun, S.A.; AlShaikh, A.A.; Al Rehaili, A.M.; Misbahuddin, M. Effectiveness of using palm fronds in reducing water evaporation. Can. J. Civ. Eng. 2011, 38, 1170–1174.

39. McJannet, D.; Cook, F.; Knight, J.; Burn, S. Evaporation reduction by monolayers: Overview, modelling and effectiveness. Urban Water Secur. Res. Alliance Tech. Rep. 2008, 6, 1–32.

40. Saggaï, S.; Bachi, O.E.K. Evaporation reduction from water reservoirs in arid lands using monolayers: Algerian experience. Water Resour. 2018, 45, 280–288.

41. Maestre-Valeroa, J.; Martinez-Alvarez, V.; Gallego-Elvira, B.; Pittaway, P. Effects of a suspended shade cloth cover on water quality of an agricultural reservoir for irrigation. Agric. Water Manag. 2011, 100, 70–75.

42. Maestre-Valero, J.; Martinez-Alvarez, V.; Nicolasb, E. Physical, chemical and microbiological effects of suspended shade cloth covers on stored water for irrigation. Agric. Water Manag. 2013, 118, 70–78.

43. Bakhtiar, M.; Aminzadeh, M.; Taheriyoun, M.; Or, D.; Mashayekh, E. Effects of floating covers used for evaporation suppression on reservoir physical, chemical and biological water quality parameters. Ecohydrology 2022, 15, e2470.

44. Baig, M.B.; Alotibi, Y.; Straquadine, G.S.; Alataway, A. Water resources in the kingdom of Saudi Arabia: Challenges and strategies for improvement. In Global Issues in Water Policy; Springer: Berlin/Heidelberg, Germany, 2020; Volume 23, pp. 135–160.

45. Al Qahtani, S.; Ismaiel, S.; Sofian, B. The impact of reforming municipal water tariff on water rationing and consumer welfare in Saudi Arabia. J. Water Clim. Chang. 2016, 7, 788–795.

46. Taleb, H.M.; Sharples, S. Developing sustainable residential buildings in Saudi Arabia: A case study. Appl. Energy 2011, 88, 383–391.

47. Ouda, O.K. Review of Saudi Arabia municipal water tariff. World Environ. 2013, 3, 66–70.

48. Almazroui, M.; Islam, M.N.; Balkhair, K.S.; Şen, Z.; Masood, A. Rainwater harvesting possibility under climate change: A basin-scale case study over western province of Saudi Arabia. Atmos. Res. 2017, 189, 11–23.

49. Khalid, B.; Alodah, A. Multivariate Analysis of Harvested Rainwater Quality Utilizing Sustainable Solar-Energy-Driven Water Treatment. Sustainability 2023, 15, 14568.

50. Ghazaw, Y. Harvesting runoff from rainfall for groundwater recharge in Saudi Arabia. In The International Conference on Water Conservation in Arid Regions ICWCAR09; King Abdulaziz University, Water Research Center: Jeddah, Saudi Arabia, 2009; pp. 12–14.

51. MWE (Ministry of Water and Electricity). Supporting Documents for King Hassan II Great Water Prize. Riyadh, KSA. Retrieved 30 November 2014. 2012. Available online: http://www.worldwatercouncil.org/fileadmin/wwc/Prizes/Hassan_II/Candidates_2011/16.Ministry_SA.pdf (accessed on 8 May 2023).

52. Al-Saud, M.; Teutsch, G.; Schüth, C.; Rausch, R. Challenges for an integrated groundwater management in the Kingdom of Saudi Arabia. Int. J. Water Resour. Arid Environ. 2011, 1, 65–70.

53. Masoud, M.H.; Basahi, J.M.; Rajmohan, N. Impact of flash flood recharge on groundwater quality and its suitability in the Wadi Baysh Basin, Western Saudi Arabia: An integrated approach. Environ. Earth Sci. 2018, 77, 395.

54. Saline Water Conversion Corporation (SWCC). Sustainability Report. 2022. Available online: https://www.swcc.gov.sa/uploads/SustainabilityReport2022-en.pdf (accessed on 4 July 2023).

55. Chandrasekharam, D.; Lashin, A.; Al Arifi, N.; Al Bassam, A.; Varun, C. Desalination of seawater using geothermal energy to meet future fresh water demand of Saudi Arabia. Water Resour. Manag. 2017, 31, 781–792.

56. ALQahtani, M.; Alhuzaymi, T. A Cost Analysis Study of Nuclear Reactor Powered Desalination Process by DEEP Analysis—A Case Study of Saudi Arabia. In Sustainable Development of Water and Environment: Proceedings of the ICSDWE2022; Springer: Cham, Switzerland, 2022; pp. 179–190.

57. Khan, S.U.-D.; Najib, A.; Orfi, J. Performance analysis of nuclear powered desalination unit based on MED-TVC: A case study for Saudi Arabia. Kerntechnik 2023, 88, 302–315.

58. Sowers, J.; Vengosh, A.; Weinthal, E. Climate change, water resources, and the politics of adaptation in the Middle East and North Africa. Clim. Chang. 2011, 104, 599–627.

59. Ouda, O.K.; Shawesh, A.; Al-Olabi, T.; Younes, F.; Al-Waked, R. Review of domestic water conservation practices in Saudi Arabia. Appl. Water Sci. 2013, 3, 689–699.

60. Zaharani, K.H.; Al-Shayaa, M.S.; Baig, M.B. Water conservation in the Kingdom of Saudi Arabia for better environment: Implications for extension and education. Bulg. J. Agric. Sci. 2011, 17, 389–395.

61. Al-Zubari, W.; Al-Turbak, A.; Zahid, W.; Al-Ruwis, K.; Al-Tkhais, A.; Al-Muataz, I.; Abdelwahab, A.; Murad, A.; Al-Harbi, M.; Al-Sulaymani, Z. An overview of the GCC unified water strategy (2016–2035). Desalination Water Treat. 2017, 81, 1–18.

62. Abderrahman, W.A. Water demand management in Saudi Arabia. Water Manag. Islam 2001, 1, 61.
63. Jamoussi, B.; Abu-Rizaiza, A.; Al-Haij, A. Sustainable Building Standards, Codes and Certification Systems: The Status Quo and Future Directions in Saudi Arabia. Sustainability 2022, 14, 10314.
64. Haider, H.; Al-Salamah, I.S.; Ghazaw, Y.M.; Abdel-Maguid, R.H.; Shafiquzzaman, M.; Ghumman, A.R. Framework to establish economic level of leakage for intermittent water supplies in arid environments. J. Water Resour. Plan. Manag. 2019, 145, 05018018.
65. Haider, H.; Almutlaq, M.A.; Alodah, A.; Ghumman, A.R.; AlSalamah, I.S.; Ghazaw, Y.M.; Shafiquzzaman, M. Risk-Based Inspection and Rehabilitation Planning of Service Connections in Intermittent Water Supply Systems for Leakage Management in Arid Regions. Water 2022, 14, 3994.