



Review

Balancing Sustainability and Scarcity: Saudi Arabia's Water Policies on Desalination and Groundwater Management

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Abstract: Saudi Arabia is among the countries facing huge challenges in meeting the water needs of its fast-growing population and economy. This paper examines the policies adopted by the Kingdom in terms of water management, with special focus on its reliance on desalination processes and the exploitation of subterranean aquifers. Being the world's largest producer of desalinated water, Saudi Arabia has invested much in high-tech solutions for reliable and sustainable sources of water. Nevertheless, excessive extraction of fossil groundwater is a significant problem, which enhances the depletion of non-renewable water resources. This study analyzes the balance between these two approaches, exploring their economic, environmental, and policy implications. Specifically, it focuses on the improvements in desalination technologies, such as energy-efficient reverse osmosis and the integration of renewable energy sources, but it also examines the environmental impact of overexploiting groundwater. This paper highlights the critical role of sustainable water management practices and policy innovation in addressing water scarcity within arid regions through an evaluation of Saudi Arabia's strategic initiatives and challenges. The findings provide insights into how the Kingdom's approach can inform broader global strategies for managing water resources in similarly water-stressed environments.

Keywords: Desalination, Water Scarcity, Middle East, Sustainable Water Management, Renewable Energy, Regional Cooperation.

1. Introduction

Water scarcity defines the 21st century, and perhaps nowhere is this more evident than in the Middle East. With arid landscapes, limited renewable freshwater resources, and rapidly growing populations, the region is on the leading edge of global efforts to develop sustainable solutions to manage water. The shortage of water is not only an environmental concern; it is a critical issue with profound social, economic, and political implications. As traditional sources fail to meet the increasing demands, innovative approaches have become vital in ensuring water security and stability.

Desalination, which, as known is the process of removing salt and other impurities from seawater to make it drinkable, has become a game-changing solution to tackle one of the most pressuring challenges of our times: water scarcity. Among the nations pioneering this process, Saudi Arabia stands out as one of the most advanced and prominent regional players. This country, whose geography and climate have made traditional water supply rather difficult, has undertaken decisive advancements in recent years regarding water technology. Not only have important investments been poured in, but also concrete strategic long-term visions have been implemented in infrastructures and advanced technologies on a national level. As a result, Saudi Arabia can presently be considered the biggest producer of fresh desalinated water in the world. Furthermore, the exploitation of Saudi Arabia's rich aquifers, a legacy of a very ancient past, has allowed Riyadh to have access to an additional source of supply.

This has allowed Saudi Arabia to have a diversified water supply chain - represented by desalination and underground storage - very unusual in the Middle East.

This article addresses the role of desalination in Saudi Arabia, examining its technological advances, economic impacts, and environmental considerations. Additionally, it analyzes the Kingdom's reliance on groundwater resources and the challenges of their over-extraction. By exploring the connection between desalination and groundwater management, the study highlights the delicate balance needed to achieve sustainable water security. Further, it comments on how these aspects of the policy framework, renewable energy integration, and regional cooperation could contribute toward enhancing the effectiveness and sustainability of approaches meant to counteract water-scarcity within the Middle East region.

2. Methodology

The present research involves a mixed methodology with an emphasis on qualitative research supported by moderate usage of quantitative analysis. This article investigates the role that desalination plays in water shortage mitigation within the Middle East, using Saudi Arabia as the specific case under investigation. The qualitative part aimed to understand the socioeconomic, environmental, and political influences; the quantitative parts, on the other hand, provided contextual support through data analysis. In this regard, qualitative data was gathered through an in-depth review of academic literature, government publications, and industry-specific publications. This review placed Saudi Arabia's desalination projects in both regional and international contexts of water resources management. Moreover, international organizations' reports provided different and de-politicized perspectives on the implementation of major projects, technological developments, and socioeconomic impacts.

A comprehensive case study was carried out on the major water strategies of Saudi Arabia, with a specific mention regarding water desalination and the exploitation of underground water reservoirs. Thematic analysis was applied in order to find common patterns that included technological innovation, energy efficiency, environmental mitigation, and socio-economic benefits of these projects. The results were cross-checked in order to validate the findings and compare it with actual statistics. Quantitative data collected from government and international organizations, included measures of desalination capacity, amounts of water produced, and levels of energy use. The descriptive analysis of these measures with a quantitative approach was helpful in fully complement the qualitative findings, as it illustrated trends in desalination production and efficiency. Such a mixed approach, which was based on the combination of both qualitative and quantitative methodologies, provided considerable breadth while, at the same time, minimizing potential biases and maximizing reliability through triangulation. This methodological technique offered a detailed analysis of the strategic implementation of desalination by Saudi Arabia to tackle water scarcity integrating comprehensive qualitative analysis with specific quantitative corroboration as well as the examination of the impacts of groundwater's withdrawals.

This research will contribute to the existing literature with a detailed analysis of the strategic methodology implemented by Saudi Arabia in desalination as the chosen means to approach water shortage alleviation, encompassing all issues related to technology, policy, and sustainability. This paper increases awareness of how a country with finite resources uses modern desalination technologies with a view into the broader national goals, especially those established in Vision 2030. Saudi Arabian efforts will contextualize the region, highlighting particularly how innovations and policy might usefully influence the regional, indeed global, pursuit of optimum strategies of water management. Such qualifications would intermesh a fine-tuning into qualitative analysis and selective quantification of data to bridge theory and practice. This contribution will, therefore, help to bridge the gaps in the literature concerning the scalability and replicability of the different advanced desalination technologies and their place within comprehensive water management frameworks.

3. Saudi Arabia's Water Policies

A huge desert land and abundant oil. These are the first characteristics that usually come to mind when referring to Saudi Arabia. To a greater extent, both these stereotypical concepts are correct, even if incomplete. The Kingdom of the Saudis is, in fact, one of the most inhospitable countries on the planet in terms of climate, with an average annual temperature of about 32 degrees Celsius and very low rainfall, between 50 and 75 mm per year (Al-Addous et. al, 2024; Rayan et al., 2024). In terms of oil, the large Arab Kingdom has about a quarter of

the world's proven crude oil reserves and is the main producer and exporter. These facts and figures are incontrovertible, and of public domain; for a long time, they have had a stereotyped impact on the notions of geography relating to the kingdom of the Saudis, considered by many as a large, mostly inhospitable territory that owes most of its political and financial fortunes to the undoubted wealth of its subsoil. However, it ought to be underscored that the subsoil of Saudi Arabia is not only richly endowed with the so-called "black gold", but also with water. The Saudi aquifers contain billions of cubic meters (hereafter CM) of water, a legacy of thousands of years ago when the entire Arabian Peninsula was a huge green expanse where forests, lakes and rivers were widespread (Al-Addous et al., 2024; Rayan et al., 2024).

For some years already, Ryad has achieved unexpected agricultural-food self-sufficiency. In recent times, the Saudis have even become net exporters of agricultural products. The reason for such a stunning achievement, in some ways, is due in large part to the water policies that have been implemented over the past decades (Alshawaf et al., 2024). The strategies adopted, mainly focusing on large-scale desalination and massive exploitation of ancient aquifers, have indeed brought undoubted benefits both socially and economically. Nevertheless, there are many questions that arise about the sustainability of such water policies, which are geared toward achieving medium to short-term effects with little interest in the long term (Alshawaf et al., 2024).

According to various reports (FAO, 2024; UN, 2024), by 2050, Saudi Arabia's current population of 36 million individuals will be around 77 million. Such predictions have been taken into account since the early 2000s, namely when the Kingdom's population began to grow with some regularity. This situation presented the Saudi royal house with a dilemma: to continue importing agricultural products in exchange for oil, which was done more or less until the early 1990s, or to invest in the search for more sustainable and self-sufficient methods of agricultural production (UN, 2024; Salomons et al., 2023). Until the second half of the 1980s, the Saudis were net importers of almost all (80%) of the food needed to sustain their population. The main reason for this was due to the lack of substantial alternatives. Desalination was struggling to take hold, and intensive exploitation of groundwater began only in the mid-1980s (Rayan et al., 2023). Aware of the demographic and social challenge that awaited the country in the following years, the Saudi royals began, over time, to change course and lay the groundwork for food self-sufficiency. The first step in this direction was the adoption of an audacious water policy that would be able to guarantee satisfactory results in a short period of time. Indeed, according to the data, Ryad is currently not only totally self-sufficient but is also able to guarantee a growing number of countries, both in Africa and Asia, respectable agricultural exports (FAO, 2024; UN, 2024).

The first pillar of Saudi water policies has been the large-scale use of desalination plants. The abundance of seawater ensures that the Arabian Peninsula has ample availability of marine-type water resources. Once industrial desalination became a widespread measure in the global context, Riyadh made extensive use of it (Janowitz et al., 2022). This situation is well captured by the numbers. The Saline Water Conversion Corporation (SWCC), a Saudi corporation founded in 1974, is the largest seawater desalination company in the world. SWCC has about 30 large desalination plants operating throughout the country, has more than 4,000 kilometres of aqueduct, employs about 10,000 Saudis, is the Kingdom's second-largest power provider, and has a commercial value of more than \$20 billion (Janowitz et al., 2022; Al-Addous et al., 2024). These are, indeed, impressive numbers that demonstrate how important desalination is in the socio-energy dynamics of the Arab Kingdom. The plants managed by SWCC produce more than three billion CM of drinking water per day, supply 70% of the water needs of all Saudi cities and also play a primary role in the use of non-saline water resources in national industry. In essence, the Saline Water Conversion Corporation is a "giant entity" that has allowed Riyadh to count on a lot of desalinated water used in the most diverse sectors (Janowitz et al., 2022; Al-Addous et al., 2024).

While SWCC has had an impact mainly in cities and in power generation, the exploitation of the rich Saudi aquifers has instead guaranteed the Kingdom an additional source of water to be used mainly in the countryside (Alsaden, 2022). The second pillar of Riyadh's water policies is the use of groundwater to source the precious liquid and use it in irrigation (Alsaden, 2022). The first large underground water deposits were discovered in the late 1960s when the government commissioned a number of oil companies to explore the subsoil for crude oil. In addition to the latter, technicians found vast underground areas where water abounded. On average, the aquifers from which water could be drawn had an estimated depth of 250 to 450 meters; this meant that there was the possibility of using trapped water with the support of simple wells. As a result of this important discovery, many

small and medium-sized wells were built from which it was possible to draw water without special engineering techniques. (Alsaden, 2022; Janowitz et al., 2022; Al-Addous et al., 2024).

Initially, the discovery of vast groundwater created some uncertainty within the Saudi political scenario. After having identified an unexpected and rich source of water, a clear environmental and political strategy on how to use it was necessarily going to be developed, especially regarding agricultural production (Alshawaf, et al., 2024; Salomons et al., 2023). Until a few decades ago, dates were the “main” product of the Saudi agricultural sector (FAO, 2024). This is because it is a palm fruit that requires little water to grow and provides important energy sustenance. After the discovery of underground water deposits, the so-called “rules of engagement” changed; the resources that Riyadh could rely on increased exponentially. This required real agricultural planning, which had not occurred since the Kingdom’s origins because of the limited water reserves that Saudi farmers could rely on (Alshawaf et al., 2024; Salomons et al., 2023).

After a few years of uncertainty, the royal household decided to invest not so much in the production of some specific agricultural products but in the use of a specific irrigation technique: Center Pivot Irrigation - CPI (Alsaden, 2022; Janowitz et al., 2022). Invented in 1940 by U.S. farmer Frank Zybach, this method uses a mechanical system consisting of a movable pipe, rotating around a fixed point, from which water flows out using the sprinkler irrigation technique. This provides the ability to circumscribe the land to be cultivated and to employ moderate water resources to produce a given agricultural product. Saudi Arabia has made copious use of this technique to diversify its food production, avoiding focusing on the few products that would have been grown by traditional methods. Since the late 1980s, Riyadh has extensively resorted to Center Pivot Irrigation for the purpose of providing a growing population with various agricultural products (Alsaden, 2022; Janowitz et al., 2022).



Fig.1. AI - generated prototype of a Center Pivot Irrigation technique in a vast agricultural field



Fig.2. AI-generated image depicting center pivot irrigation in a semi-arid environment

The CPI technique, in addition to ensuring an aesthetically pleasing result, guarantees high rates of production efficiency. For about fifteen years, Saudi Arabia has been completely self-sufficient from an agricultural-food point of view. The discovery and subsequent exploitation of the ancient water reservoirs, together with the adoption of Center Pivot Irrigation, have constituted the perfect combination in this regard.

The excellent results in terms of agricultural production have enabled the Saudis to achieve two other important successes. First, as mentioned earlier, after fully providing for the domestic market, Riyadh is now a reliable exporter of various products, including wheat, milk and, dairy products, meat, and eggs. This has been aided by the significant investments the government has made to improve rural roads and communication routes that connect ports with places of agricultural production (Gözüm et al., 2023). Not only food products but also other types of products, such as flowers, are regularly exported from Saudi Arabia to the Horn of Africa and Southeast Asia. Secondly, precisely because of the high agricultural production provided by the factors we have mentioned, the Saudis have been able to change the eating habits of their people (Esmailion et al., 2021). To some extent, especially at the socio-anthropological level, this is an even more important achievement than the agricultural export that has distinguished Riyadh for a number of years now. Nowadays, the Saudi diet consists of plenty of vegetables, milk, eggs, wheat, poultry, and various kinds of meat. This all seems unbelievable when compared to a few decades ago, when the vast majority of these products were imported from outside the country and, consequently, had a cost that only a few families could afford (Esmailion et al., 2021; Gözüüm et al., 2023). In the past, the main foods that could be easily sourced locally were dates, desert grapes and dromedary meat. Of course, imports brought other types of food into the Saudi domestic market, so there was still plenty of choice. However, as mentioned, these were not domestic products but imported goods. As a consequence of new irrigation techniques and the exploitation of the vast water deposits in its subsoil, Saudi Arabia today can guarantee its growing population a wide range of agricultural products generated entirely within its national borders (Esmailion et al., 2021; Gözüüm et al., 2023).

4. Discussion

Saudi Arabia's water and food achievements in recent years, as described above, are rather evident. However, it is worth pointing out a number of critical issues that these bold water policies have caused at the environmental and diplomatic levels. First of all, it ought to be considered that the high use of industrial desalination plants generates high rates of air and marine pollution (Hafidi et al., 2024). To operate at the impressive rates imposed by Saudi policies, the SWCC plants employ very high amounts of fossil energy day and night. According to some studies (Jaber, 2024; Bhardwaj et al., 2024), about one-third of the oil extracted in the country is used in the production of desalinated water. This figure lends itself to a dual reading. On the one hand, in fact, Saudi Arabia has the fuel needed to run its desalination industry. Being an oil-rich nation, production costs are reduced because resources that are already in the material disposition of the Kingdom are used (Esmailion et al., 2021; Gözüüm et al., 2023). If, for example, the crude oil needed to produce billions of CM of water daily were to be imported, production costs would rise exponentially, effectively making the first pillar of Saudi water policy unsustainable and unfeasible (Esmailion et al., 2021; Gözüüm et al., 2023).

On the other hand, the massive use of a highly polluting energy source generates a lot of waste that has a profound environmental impact. For example, in 2016 alone, Saudi Arabia released more than 517 million tons of CO₂ into the atmosphere, confirming it as one of the most polluting countries in the global context (Hafidi et al., 2024). Desalination plants are primarily responsible for this high number of emissions. In addition, numerous pollution issues are also found at the marine level. Brine, which is a hyper-saline industrial waste from the desalination process, is regularly disposed of at sea since other disposal methods would make the whole process very expensive. This causes high rates of marine environment pollution, especially near coastlines and desalination plants. The waste that is dumped into the sea alters the salinity of the waters, causing extensive damage to marine flora and fauna (Hafidi et al., 2024).

The massive exploitation of groundwater that has occurred in recent decades should also be considered regarding the perspective of environmental sustainability. The water in the Saudi subsoil, while abundant, is certainly not infinite. On the contrary, according to some published reports, groundwater levels in the Kingdom have already been reduced by 15% as a result of heavy use in recent years (Ammar, 2022; Sommer et al., 2024). Then,

being a country where annual rainfall is very low, there is an evident difficulty in replenishing underground reserves again. In essence, Ryad is gradually draining its groundwater, which contains fossil water deposited over the past millennia, due to the high rates of extraction for irrigation purposes. Suppose this pace of extraction rates continues to be so high. In that case, it is predicted that as early as around 2050, which is when the Saudi population will touch almost 80 million, the water contained in the subsoil will have undergone massive decreases amounting to about 40-45% of the total (Ammar, 2022, Sommer et al., 2024).

The use of water resources found underground also involves serious problems at the level of international relations, especially if the aquifer being exploited is transboundary in nature. With an area of 2,149,690 km², Saudi Arabia is by far the largest country in the Arabian Peninsula (3,237,500 km²). Some aquifers may be shared with multiple nations residing in this vast desert. When this occurs, serious tensions can arise between the governments of the countries involved, which seek to exploit as much of the water resources found underground with little regard for each other or the other “competitors.” Among the various cases over time, reference should be made to the tensions that have arisen between Saudi Arabia and Jordan over the exploitation of the Disi aquifer. The latter is a large freshwater deposit discovered in 1969 during a UNDP (United Nations Development Program) study mission (UN, 2024). Riyadh immediately put an exploitation strategy into practice as early as the mid-1980s, that is, when the Saudi Kingdom began to consider adopting more structured water policies seriously. A few years later, Jordan also began using Disi’s water to limit the recurring water supply crises that characterize its territory (Ammar, 2022; Sommer et al., 2024).

The use of this immense aquifer for a country like Jordan is of particular relevance. In fact, Amman is the capital of a state virtually surrounded by desert (80% of its territory) that has little capacity to store rainwater, which moreover evaporates almost entirely (Bhardwaj et al., 2024; Bourhrous et al., 2023). The capital, the primary urban center where much of the kingdom’s population is concentrated, is 40-50% supplied by water from the Jordan Valley (pumped through the King Abdullah Canal), from the Zarqa and Mafraq aquifers, or from new aquifers in the south. It is thus evident how Jordan suffers from endemic water scarcity. Moreover, lacking industrial and desalination capacity comparable to that of Saudi Arabia, the Disi aquifer represents a nearly vital resource for the Hashemite royal house (Bhardwaj et al., 2024; Bourhrous et al., 2023).

Indeed, there has been no shortage of tensions between the Saudis and Jordanians over the management of the large fossil water reservoir over time. Ryad has significant annual pumping rates of about a billion CM. Such a situation is similar in the case of Amman, which currently stands at about 800 million CM drawn annually (Esmailion et al., 2021; Maftouh et al., 2023). “Cold” tensions between the two Arab nations intensified when Jordan began to consider expanding its use of the Disi aquifer in order to supply its capital city and support the development of its agricultural sector, given the dwindling inflow of water from the Jordan River. According to Jordanian development plans, a 325-km aqueduct should be built in the next few years, which will be fed by 65 wells in the Disi Basin that will go as deep as 500 meters to find water. In addition to this, a 12,000-CM reservoir will collect all the water resources withdrawn, storing them before passing them to the central pumping station from which they will be sorted. This project is expected to provide an average of 100 million CM of high-quality drinking water annually to the capital city of Amman (Esmailion et al., 2021; Maftouh et al., 2023).

Saudi Arabia frowns upon Jordanian plans to make greater use of Disi water. This large reservoir plays an important role for all agricultural production located in the north of the Kingdom, which has historically been very poor in water resources (Olawuyi, 2022; Sommer et al., 2024). It seems, for the moment, that the two countries have almost completely ignored each other in this affair; tensions, perceptible from the climate of ill-concealed suspicion that still characterizes Saudi and Jordanian actions, have not emerged openly. However, in order to avoid the disorganized depredation of a basin that receives no precipitation and is therefore destined to be ineluctably depleted, it would be desirable for Ryad and Amman to cooperate to agree diplomatically and officially on how much water to withdraw each year. Currently, it is advisable for both to drastically reduce pumping in the Disi Basin. At a later stage, it would be exceedingly desirable for the dignitaries of the two states to intensify negotiating talks on how much water they intend to withdraw (Olawuyi, 2022; Sommer et al., 2024).

5. Conclusion

As analyzed in this article, Saudi Arabia, in recent decades, has been able to extricate itself from a problem that many Middle Eastern and African nations still have today: the water supply crisis. Thanks to significant industrial capacity, the use of revolutionary irrigation techniques and the presence of much fossil water in its subsoil, Riyadh can be considered a true hegemonic power from a water perspective in the Middle Eastern context. As proof of this, not only has the domestic agricultural market been fully developed, but also, from the export point of view, the Saudis can be beyond satisfied.

However, this favorable situation holds dangerous side effects in multiple aspects. If we rank the severity of these effects, we will probably dwell on the aspect of bilateral relations. Indeed, on the environmental front, while this is a serious condition that deserves to be constantly monitored, we will see a significant improvement in the near future. New desalination plants, which are less polluting and more environmentally sustainable, are being brought to market every year. We also take into account solar energy technologies that would find optimal use in those regions. This means that we should see a positive glimmer in terms of CO₂ emission and in the marine sphere before long. The new desalination plants no longer adopt the “reverse osmosis” technique, which is very impactful on the land, but the so-called “membrane distillation,” which allows more desalinated water to be generated at lower production costs with less impact on the environment. In addition, new engineering technologies have favored the construction of plants that will use renewable energy, especially wind and solar, instead of oil.

Regarding international relations, the situation is decidedly more serious. In this regard, as a result of the water exploitation that has occurred in recent decades, the Saudis gave the impression of “overperforming”. The case of the Disi aquifer is a clear sign of such a scenario. While waiting to agree on joint management with Jordan, a country that really has pressing water needs and has not yet found a viable strategy to deal with severe cases of water scarcity, Riyadh has given the impression that it is undauntedly continuing to exploit its own portion of the territory with insufficient regard for its Arab neighbor. This, for the time being, has not generated any noteworthy diplomatic crises. However, in the future when both the Jordanian and Saudi populations grow and, consequently, in anticipation of more significant water and agricultural needs, problems may arise in a much more pressing manner. Moreover, the long-standing demand for water by the Saudis has meant that they care exclusively for the most immediate outcome with less attention to the long term. This is evidenced by the evident desire to exploit groundwater not only to produce domestic goods but also with a view to export. Underground water should be held in extreme regard, like the gold reserves that every national bank keeps in its vaults. It is wise for such reserves to be used only when needed and not only with a view to economic development. Similarly, it is wise for aquifers to be used sparingly, especially if they are reservoirs that are difficult to replenish because of the low rainfall that characterizes Saudi Arabia.

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