sustainability

Review

Towards Sustainable Water Resources Management Considering Climate Change in the Case of Saudi Arabia

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Abstract: 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. In this work, we review the status of the present and future of water resources and the challenges local authorities face in managing water resources amidst a changing climate in Saudi Arabia. This study employed a narrative research methodology, utilizing various databases, including Scopus, Web of Science, and Science Direct, to extract relevant articles within the subject area. This study proposes a number of recommendations and conclusions aimed at improving decision-makers' ability to adapt to and mitigate the anticipated adverse impacts of climate change to manage scarce water resources sustainably.

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

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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.

The anticipated changes in the climate regime, coupled with a fast increase in population size and rapid urbanization, would add more stress to the already exhausted water situation [5]. Saudi Arabia is expected to experience a significant adverse impact on its agriculture sector, which could threaten food and water security [6]. With the country experiencing substantial population growth due to swift economic development, KSA is presently facing the daunting task of fulfilling the subsequent surge in water demand.

Between 2010 and 2022, the population of KSA increased by nearly 20%, from around 27 million to 32.2 million, with an average annual growth rate of 2.5%, according to the latest report by the General Authority for Statistics in 2023 [7]. Consequently, the demand for freshwater has escalated drastically over the past two decades, mostly fulfilled by fossil groundwater resources. Moreover, the country has experienced a range of impacts on its ecosystems, including rising temperatures, changes in precipitation patterns, and an increase in the frequency and severity of climate-induced extreme events [8–12]. Awareness of the relationship between climate variables and the environment can help to reduce vulnerability by implementing more effective management strategies for water resources [6,13].

In the 1970s and 1980s, Saudi Arabia conducted a comprehensive evaluation of water resources, including mapping potential aquifers and assessing their capacity, leading to the drilling of deep wells for urban and agricultural purposes. This resulted in a significant increase in wheat exports during the 1980s [14]. However, due to growing water demand, a reassessment of resources and sustainability became necessary. In 2002, the Ministry of Water and Electricity initiated a project to examine all aquifers, leading to the adoption of a new agricultural policy.

Due to the current non-renewable groundwater extraction rates, primarily for agriculture, several regions in the KSA are expected to experience a depletion of their reserves within the next 12 years, according to the National Water Strategy 2030 [15]. Apart from the water consumption levels, there is also an issue with the efficiency of crop productivity in KSA. In Saudi Arabia, fodder productivity is below the global average in some areas, while grain production aligns with the global average. Additionally, the average irrigation efficiency in the country has been around 50% over the past decade [15], whereas international best practices recommend achieving levels of 75% to 85%.

The assessment of freshwater availability, considering the changing climate in KSA as a water-stressed region, is crucial for the future of the region's growing population. Climate change has recently become increasingly evident, and it is now widely acknowledged that human activities are contributing significantly to the alteration of the climate, in addition to natural variability. The observed changes in global and regional mean temperatures over the past century have been well documented (e.g., [16,17]). According to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), the global average surface temperature has increased by approximately 1.1 °C since the pre-industrial era (1850–1900) [6]. However, regional warming has accelerated faster, reaching around 1.4–1.5 °C compared to pre-industrial levels [18]. If global temperatures keep increasing, some environmental changes may become inevitable and irreversible. Accordingly, there is an increased interest in assessing the projected impacts of climate change on the water sector in the region [13]. Currently, the concentration of carbon dioxide in the atmosphere exceeds any recorded levels from the past 650,000 years. If significant measures are not taken, it is predicted to rise to 540–970 ppm (140–263% relative to 2000 levels) by the year 2100 [19]. The average global temperature is projected to increase by 1.4 to 5.8 degrees Celsius by 2100 compared to pre-industrial levels [20]. This will consequently intensify the hydrological cycle and alter moisture advection, leading to significant changes in precipitation patterns [21]. The impact of global warming on water resources globally and regionally is significant and has already caused noticeable depletion, as reported in many studies [5,22–26]. This trend is likely to continue, with potentially severe consequences for natural ecosystems and human populations relying on these resources. Such an effect of climate change on water resources is among the most critical areas that require adaptation measures [27,28].

With a high level of confidence, climate change has caused modifications to every aspect of the global hydrological cycle over the past few decades [6,29]. Under RCP 4.5 (RCP 8.5) greenhouse gas emissions for the period 2023–2080, the water requirements for some crops will increase between 5.1% and 5.9% (7.7 and 9.7%), compared to the current requirements in Egypt [30]. Locally, the country has experienced record-breaking weather events in the past decades, including extreme heatwaves, heavy rainfall events, and devastating flash floods. Jeddah, the largest coastal city on the Red Sea, experienced severe flash floods in 2009, 2011, and 2022, which brought about widespread damage to infrastructure, the economy, the environment, and most significantly, people's lives [31]. Floods have been responsible for seven out of the ten most catastrophic events in KSA between 1900 and 2011, regarding the number of casualties and people affected [32]. Moreover, there are significant positive trends in the duration of heatwaves in the Middle East [33]. Recent regional climate projections indicate that extreme precipitation events are expected to occur less frequently but more severely [32,34–36].

Kompas et al. [37] conducted a study that concluded that the RCP6.0 (medium-high emission) scenario, which predicts a global warming of 3 °C by 2100, would lead to significant long-term economic strain, resulting in a reduction of the Kingdom's gross domestic product (GDP) by over 5% by the end of the century. In such a scenario, cooling during electricity production would decrease oil exports and subsequently reduce the revenue generated [38,39]. Therefore, it is crucial to prioritize the potential impacts of such events and take the required preventive measures. It is worth mentioning that the farmers in Saudi Arabia are well aware of the pressing issue of climate change [40]. According to a recent study conducted by Alotaibi et al. [41], most farmers in KSA associate climate change with releasing greenhouse gases and pollution. Through heightened awareness, we can efficiently strategize for the sustainable management of precious water resources. Arnout [42] emphasizes the importance of improving climate communications to enhance the understanding of climate change in the KSA.

A comprehensive understanding of the current and projected water resource situation in Saudi Arabia is essential for policymakers and water managers to develop effective water management strategies to ensure water resources' sustainability and meet the increasing water demand. This paper reviews various scientific studies conducted by different researchers to (1) identify and discuss the existing water demand and supply, (2) project future changes in hydroclimatic variables and their implications on water resources, (3) propose adaptation strategies that can be implemented in the water sector of Saudi Arabia to cope with potential risks amid changing environmental conditions, and (4) highlight research gaps and challenges that researchers and decision-makers face.

2. Methods

In this work, a narrative review approach, which relies on existing primary research studies, is adopted. This narrative review aims to address broad research topics on water resource availability with a focus on Saudi Arabia in relation to the impacts of climate change. Unlike other review methodologies, a narrative review does not follow a strict protocol, and its design is dependent on the work's objectives. There is no consensus on the standard structure of narrative reviews; however, their primary purpose is to enhance understanding within a specific research area by identifying and summarizing published studies [43,44]. They are commonly used to explore existing debates, evaluate previous studies, identify knowledge gaps, and speculate on recent interventions.

To gather relevant papers, we conducted a search on the Web of Science, Scopus, the Saudi Digital Library (SDL), and Science Direct databases using the keywords "climate change", "Saudi Arabia", and "water resources" without any time constraints. After removing duplicates and non-English papers, we carefully reviewed the abstracts and selected about 120 papers that focused on the topics of "climate change" and "water resources" for further analysis. From our comprehensive narrative review, we identified five key review areas: "current water resources in KSA", "observed changes in climatic variables in Saudi Arabia", "projected changes in climatic variables in Saudi Arabia", "implications of climate change in Saudi Arabia," and "sustainable water resources management in a changing climate". These topics emerged as central themes based on the findings and insights derived from the reviewed papers.

3. Study Area and Climate Data Sources

The Kingdom of Saudi Arabia (KSA), known colloquially as Saudi Arabia, is the largest Arab state in Western Asia in terms of land area, covering approximately 2,150,000 square kilometers. KSA is located between 17° and 32° N and 35° to 55° E and occupies almost 80% of the Arabian Peninsula (AP), making it the second-largest country in the Arab world [45]. The country is home to some of the most important Islamic holy sites, namely the cities of Makkah and Madinah, which attract millions of Muslim pilgrims worldwide every year. KSA shares borders in the north with Jordan and Iraq, Kuwait to the northeast, Qatar, Bahrain, and the United Arab Emirates to the east, Oman to the southeast, and Yemen to the south.

Geologically, KSA is located within the boundaries of the so-called Arabian Plate. The tectonic Arabian Plate comprises two distinct geological regions: the Arabian Platform or Shelf (covering two-thirds of the peninsula), located in the east, and the Arabian Shield (covering one-third of the peninsula), which borders the Platform towards the west (Figure 1). The Arabian Shield primarily consists of a crystalline basement of Precambrian continental crust. The amount of groundwater available on the Shield is very limited compared to the Platform, which has a greater supply.

Figure 1. A map of KSA shows the geographical areas where groundwater and most surface water can be found in the Arabian Platform and the Arabian Shield, respectively, as well as the locations of desalination plants.

The AP is characterized by a hyper-arid moisture regime on approximately 32.02% of its land, with 66.72% classified as having an arid moisture regime [19]. The climate of the AP can be classified into two primary seasons, each followed by a transition period. These seasons are the summer season (June to September), followed by the fall (October to November), and the winter (December to March), followed by the spring (April to May) [46].

The data used in this section are the latest monthly high-resolution gridded multivariate climate datasets from the Climatic Research Unit gridded Time Series (CRU-TS) on a 0.5° latitude by 0.5° longitude grid of the University of East Anglia [47]. The climate of Saudi Arabia varies depending on the region; however, it is predominantly arid or semi-arid, with hot and dry summers and mild and somewhat wet winters. The temperature range in the region varies from −5 °C, particularly in the southwestern regions, and exceeds 50 °C in the summer [46]. The monthly temperature and rainfall amounts averaged over KSA are represented in Figure 2.

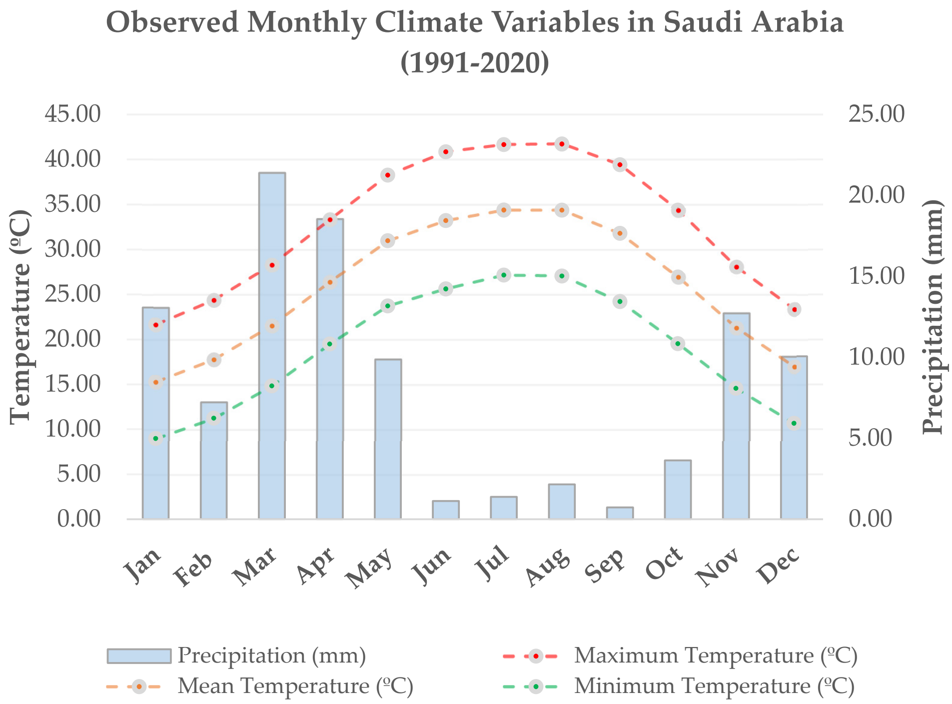

Figure 2. Annual cycle of the country-averaged monthly temperature (in °C) and precipitation amount (in mm). Data source: Climate Research Unit gridded observations over land [47].

The country receives almost no precipitation in the summer months (June to September), when the temperature is north of 40°, except in the southwestern parts. The annual precipitation fluctuates between less than 50 mm in the uninhabitable Empty Quarter (al Rub' al Khali) desert and as much as 600 mm in the southwestern parts that experience monsoon-like conditions. Most rainfall happens from November to May, and there is typically little to no rainfall during the summer, except in the country's southwest region.

4. Current Water Resources in KSA

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 [48]. 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 3a). 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. In this section, we will discuss the current water resources in KSA. Most of the conventional water resources in the country come from non-renewable groundwater due to the limited availability of surface water. Given the annual variability of surface water depending on rainfall received, this source should be reevaluated.

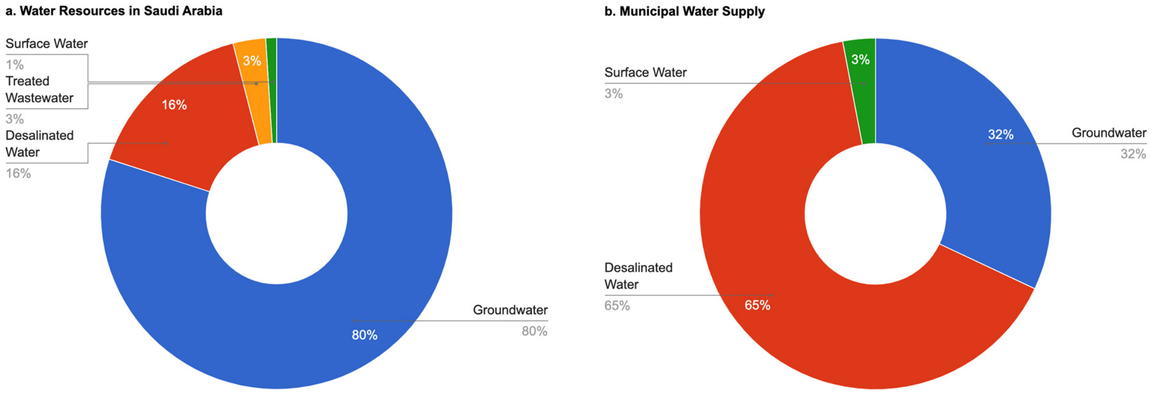

Figure 3. Charts representing data in 2021: (**a**) water resources in KSA with their share, and (**b**) municipal water supply (Data source: MEWA Annual Report [49]).

4.1. Conventional Water Sources

4.1.1. Groundwater Resources

Groundwater is the primary water source in SA, accounting for approximately 80% of the country's water resources (Figure 3a) and 32% of its municipal water demand (Figure 3b) in 2021. It is found in aquifers, underground layers of porous rock, sand, or gravel holding water. Groundwater can be found in both shallow and deep aquifers (mostly fossil water), each with varying levels of potential for water extraction depending upon several factors, including its geologic properties, depth, and proximity to other water sources. The major non-renewable aquifers in the country are Saq, Tabuk, Wasia-Biyadh, Minjur-Dhruma, Wajid, Dammam, Umm Er Radhuma, and Neogene [50]. The secondary non-renewable aquifers include Al-Jauf, Al-Khuff, Al-Jilh, the upper Jurassic, Sakaka, the lower Cretaceous, Aruma, and Basalts [50]. Many of the aquifers are situated on the Arabian Platform and stretch towards the eastern regions of the nation. The Saq/Disi aquifer is a transboundary aquifer shared by Jordan and Saudi Arabia. A 2015 agreement regulates its use and restricts abstraction within a buffer area on both sides of the border [51,52].

The quality of sorted water in these aquifers varies, and total dissolved solids (TDS) levels range from 300 to over 10,000 ppm [50]. The excessive withdrawal from groundwater caused some deterioration in water quality [53]. The thickness of aquifers ranges from a few hundred to over 5000 m, with estimated total reserves of about 2185 BCM [50]. The Wasia-Biyadh aquifer, the largest aquifer, holds 590,000 MCM of water, while the Saq aquifer reserves 290,000 MCM [50].

The overuse of groundwater due to the increased cultivated lands has led to a depletion of this resource at an alarming rate. Non-renewable groundwater sources have been overexploited to bridge the gap between national water demand and supply. Extraction rates that exceed annual recharge by over 100 times have led to a significant decline in groundwater levels [54,55]. Over the last five decades, the Saq aquifer, the second-largest fossil aquifer in the AP with negligible recharge of less than 2 mm/year [56], has been significantly overexploited mainly by irrigation, leading to a regional drawdown of groundwater levels of up to 150 m [57]. However, the groundwater recharge in the southwest, the wettest region in KSA, is relatively higher, ranging from 1.22 to 6.97 m per annum, brought about by flash floods in the wet season [58]. Currently, the inability to fully recharge groundwater storage across the country has resulted in fossil aquifers being classified as "storage-dominated" instead of "recharge-flux-dominated" [59]. Al-Saud et al. [60] emphasized the need for "immediate action" to prevent the excessive depletion and over-extraction of the country's fossil groundwater resources.

4.1.2. Surface Water Resources

In KSA, surface water resources (i.e., rivers, lakes, and other bodies of water on the earth's surface) are scarce to absent, as the country is primarily arid and receives little precipitation annually. Given that all Saudi Arabian rivers are ephemeral, runoff is governed by rainfall patterns and topographic features and occurs in the form of intermittent flash floods following heavy rainfall events to drain inland. Most of the surface water resources in the country are found in the western and southwestern regions, where mountain ranges capture precipitation, feed into wadis (dry valleys), and streams eventually drain into the sea.

Despite the limited availability of surface water resources, the Saudi Arabian government has invested in several projects to improve their management and increase efficiency, including constructing dams and reservoirs to harvest rainwater. By the end of 2021, the country had 544 dams; however, their total capacity still needs to be improved (2445.85 km^3) [49]. Considering the additional 20 dams under construction, the total capacity will increase slightly to 2537.64 km^3. As of 2017, the primary purposes of dams are groundwater recharge (67.7% of dams), water supply (12.4%), irrigation (0.4%), and flood control (19.5%) [61]. Considering the relatively low levels of precipitation and the high rate of evaporation, which ranges from approximately 2.5 mm/day in winter to about 17 mm/day in summer [50], there may be some uncertainty surrounding the efficacy of dams as a means of water conservation.

4.2. Non-Conventional Water Sources

4.2.1. Desalination Sources

Some regions that experience water scarcity, as in the case of SA, heavily depend on non-conventional, non-renewable water from desalination to increase the availability of potable water and meet their domestic water needs, particularly in urban areas beyond what is naturally accessible. Desalination is a method of removing salt and other minerals from seawater in order to create fresh drinking water. This country is the biggest manufacturer of desalinated water worldwide, contributing 22% of the total global capacity [62]. The KSA currently has 30 desalination plants along its coastlines on the Red Sea and the Arabian Gulf (Figure 1), with a current production capacity of 7.5 MCM of water per day under the management of the Saline Water Conversion Corporation (SWCC) [63]. Desalinated water is transported from coastal desalination plants to beneficiary cities via a network of pipelines. The pipelines have varying diameters, ranging from 200 mm to 2000 mm, and span approximately 5600 km. This robust infrastructure ensures a reliable and consistent supply of fresh water to these urban centers, which is essential for the well-being and prosperity of their inhabitants.

The desalination process in KSA is mainly carried out using membrane and thermal technologies. Thermal desalination is a method that entails heating seawater to generate steam. This steam is then condensed to produce freshwater. Certain plants use multi-stage flash (MSF) distillation as a method of extracting fresh water. This process requires the seawater to be pumped to a higher pressure and heated to almost boiling. As the seawater passes through several stages, its pressure is gradually reduced, producing vapor, which is then condensed by the incoming seawater [64]. Other thermal plants use the so-called Multi-Effect Distillation (MED) technique, which utilizes steam-generated heat to evaporate seawater in multiple stages under reduced pressure. On the other hand, membrane desalination involves using a semi-permeable membrane to filter out salt and other impurities from seawater. In recent years, SWCC has increasingly adopted a more energy-efficient process, compared to thermal technologies, that uses high-pressure membranes to filter out salt and other impurities from seawater without heating, called reverse osmosis (RO) [65].

Despite the advantages of desalination and the continuous development of its technologies, desalination is still energy-intensive and costly. It consumes approximately one-fourth of the country's domestic oil production [55,66,67]. Moreover, the pumping costs of transmitting water from coastal areas to inland regions, where a significant portion of the population lives mainly in cities such as Riyadh, Makkah, and Medina, further worsen the issue [68]. Additionally, as the desalination sector relies heavily on fossil fuels, its operations have a considerable environmental impact. Thus, SWCC is exploring alternative renewable energy sources, such as solar and wind, to power its desalination plants. The National Renewable Energy Program includes an initiative to integrate renewable energy into the energy mix by increasing the share of renewable energy sources by 50%. This transition is estimated to result in a 27% decrease in indirect greenhouse gas emissions from desalination facilities [63]. In addition, the SWCC is considering some "Carbon Capture, Storage, and Utilization" (CCUS) techniques to reduce GHG emissions in the remaining two desalination plants that implement the MSF technique [63].

4.2.2. Treated Wastewater Resources

In the Kingdom of Saudi Arabia, the utilization of treated wastewater has become a subject of great interest due to its potential to address the incessant water shortage. This approach is a promising solution to bridge the widening gap between water demand and supply [69]. This non-conventional water source is used mainly for irrigation, landscaping, and industrial purposes. During the 1990s, approximately 40% of wastewater was released into the environment without undergoing any form of treatment [70]. In that period, the typical wastewater treatment method in Saudi Arabia was secondary treatment technology [69]. The amount of wastewater increased by almost 200% from 2007 to 2018 and is predicted to have an annual growth rate of 4% between 2025 and 2050 [61].

As of 2021, the Saudi Arabian government has made significant investments in wastewater treatment infrastructure, resulting in 133 wastewater treatment plants and a network of pipelines with more than 46,106.45 km [49]. On average, 5,137,334 m^3/day are currently treated with tertiary treatment technology (or 1.875 BCM per year) [49]. The technologies used in wastewater plants include tricking filter activated sludge, activated sludge, clarification and filtration, media filtration, oxidation ditch, and tertiary treatment [61]. In 2021, only 22% of the treated wastewater was utilized in agriculture and industry, with a volume of 0.419 BCM out of 1.875 BCM, as reported by MEWA [49]. Most of the reused recycled wastewater, specifically 95.6%, or 0.401 BCM, was used for agricultural purposes, while the remainder was used for industrial purposes [49].

5. Current Water Demands in KSA

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 [49]. 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 [49]).

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.

5.1. Agricultural Water Demand

Since the mid-1970s, the water demand for agriculture has grown significantly. Cultivated areas have expanded from less than 400,000 hectares in 1971 to approximately 1.6 million hectares in 1992 and are primarily satisfied by nonrenewable groundwater resources [71]. The significant growth experienced was a direct result of the agricultural sector receiving a massive governmental support policy. This policy was part of a comprehensive model of development that aimed to achieve self-sufficiency, enhance food security, and ultimately improve the livelihoods and prosperity of rural communities by substituting imports with local production [71,72]. At that time, the country was even able to export a variety of produce, such as cereals, vegetables, and fruits. However, the KSA government realized later that the aforementioned agricultural policy was at the expense of non-renewable water resources.

In 2000, Saudi Arabia conducted an in-depth review of its food self-sufficiency policy and irrigation water conservation programs to mitigate excessive irrigation water consumption, which decreased groundwater extraction [73]. Therefore, a new policy was implemented in 2008 by halting the cultivation of water-intensive crops, mainly wheat, and instead encouraging the cultivation of high-value crops such as fruits and vegetables [72]. A few of these crucial steps include putting a halt to land distribution, cutting back on generous subsidies, and imposing well licensing. However, many farmers perceive obtaining drilling authorizations as a complicated and bureaucratic process and resort to drilling without following the proper procedures. Furthermore, the government has incentivized farmers to adopt more water-conserving techniques (e.g., drip irrigation and soil moisture sensing equipment).

In 2021, this sector still consumed about 80% of the annual water demand (11.4 BCM) satisfied by renewable, non-renewable, and reused treated wastewater. The high agricultural demand may be acceptable in areas with abundant water resources [74], but not in water-stressed Saudi Arabia. However, the decline in agricultural water demand in 2021 was mainly due to a governmental program by the Ministry of Environment, Water, and Agriculture (MEWA) to regulate green fodder production, mainly alfalfa. Another measure MEWA took to minimize agricultural uses was banning exports of some crops and their products (fresh or processed) known for their high consumption of water (e.g., potato, tomato, corn, and watermelon). Furthermore, to regulate the consumption of non-renewable aquifers, MEWA recently launched a leading initiative to install electronic meters on selected farm groundwater wells in line with the objectives of the National Water Strategy 2030 [15].

5.2. Domestic Water Demand

The domestic water needs were about 25% of the total demand (3.556 BCM) in 2021. Most of this demand, specifically 65%, was met through desalinated seawater production, which amounts to 2.305 BCM, by the SWCC. The remaining 32% of the demand is satisfied by groundwater resources, totaling 1.139 BCM/year. The Kingdom-wide average per capita water consumption is considered very high at 278 L per capita per day (LPCD) (or

101.5 cubic meters per year) in 2021, similar to countries with abundant fresh water [75]. As per the United Nations Committee on Economic, Social, and Cultural Rights [76], "sufficient, safe, acceptable, physically accessible, and affordable water for personal and domestic uses" is a fundamental human right to ensure sustainable, healthy urban living. For basic drinking needs, food preparation, hygiene, and sanitation, as determined by the World Health Organization (WHO) [77], 20 to 50 LPCD are deemed sufficient in underdeveloped nations without a continuously supplied potable water service. According to Crouch et al. [78], a water consumption rate of 175 LPCD is considered more practical for the present-day lifestyle of developed countries and the standard household water-use fixtures. While the country planned to decrease it to 150 LPCD by 2030, it has increased by 20% since 2010. According to a study conducted by Alotaibi et al. [79], the demand for domestic water is expected to double by the year 2035.

5.3. Industrial Water Demand

The Kingdom has experienced significant industrial growth in recent years, which has led to a sharp increase in water demands. The industrial sector encompasses a range of industries, including petrochemicals, cement, steel, fertilizers, mining, basic metals, textiles, and food and beverage production [50]. Industrial water demands have increased significantly since 1980, from 0.056 BCM to 0.628 BCM in 2021. This trend is predicted to continue, reaching 2.375 BCM by 2060 [50]. To meet these growing demands, desalination plants and non-renewable groundwater resources have been primarily utilized.

6. Observed Changes in Climatic Variables in Saudi Arabia

While an increase of 1.1 °C was observed globally compared to the early 1900s [6], regional warming has now reached around 1.4–1.5 °C [18]. According to the study by Haque and Khan [12], from 1967 to 2016, the average temperature in KSA increased by 1.9 °C. Until the beginning of the 1990s, the mean annual temperature in the AP had risen linearly by 0.638 °C over the past century [80]. However, based on the gridded observations by CRU-TS, our analysis provides clear evidence that the rate of warming in KSA has accelerated more rapidly in the last 30 years compared to the 90 years preceding the mid-1990s (Figure 4). The observed changes in the annual mean temperature of KSA over the past 121 years are significant, with a trend of 0.116 °C/decade, and follow a somewhat similar pattern to the global trend. The rate of increase in mean annual temperature was barely noticeable at 0.045 °C per decade between 1900 and 1990; however, it sharply rose to 0.43 °C per decade after that. These findings are consistent with several studies that have reported accelerated warming in the region recently (e.g., [11,18,81–83]).

Table 2 lists some papers that investigated the observed changes in climatic variables in and near SA, namely: annual precipitation (PCP_{annual}), mean annual maximum temperature (Tmax), mean annual minimum temperature (Tmin), and mean annual temperature (Tmean). Based on the findings of the IPCC 2022 report [6], it has been noted with a high level of confidence that there have been significant rises in temperature extremes in West and Central Asia, including the AP region. The reported average trend for all temperature indices was around 0.6 °C per decade, more than twice the average global trend (0.27 °C per decade) [18]. The observed trends vary in magnitude, which can be interpreted by the influence of factors such as the location and geographical features of this study area, the type of dataset used, the season being examined, and the reference period being analyzed. Nevertheless, the Middle East region, in general, has been found to have significant positive trends ranging from 0.1 °C to 0.6 °C per decade (e.g., [84,85]), with an average of 0.45 °C/decade for 1981–2019 in the Eastern Mediterranean and Middle East region [18].

The accumulated annual precipitation decreased significantly at a rate of 47.8 mm per decade between 1995 and 2009 [86]. However, the region was hit by several extreme events, such as the 2009 and 2011 events when Jeddah, the coastal city in the west, was flooded after unexpected heavy rainfalls, resulting in many losses in properties and infrastructure [87]. This indicates the necessity for a modification of calculating intensity-duration-frequency

(IDF) curves to adopt the likely future increase in the intensity and frequency of extreme precipitation events [88]. Observed daily datasets of climate variables have not been extensively used to analyze the variability of extreme events in the Arabian Peninsula, in contrast to many other regions of the world [89].

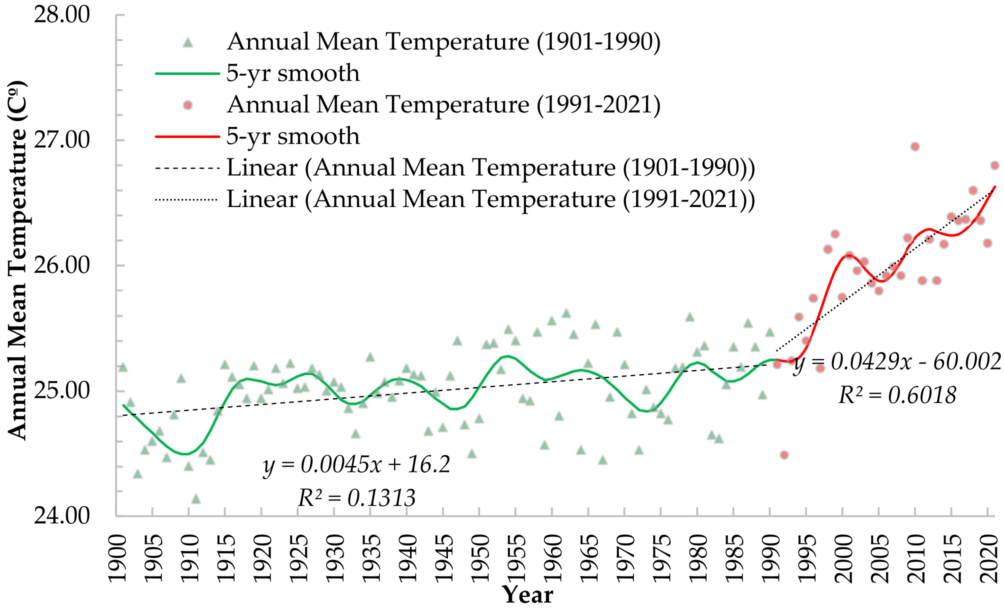

Figure 4. Observed mean annual temperature (Tmean) in Saudi Arabia in the period 1900–2021. Data source: Climate Research Unit gridded observations over land [47].

Table 2. Observed changes in climate variables based on previous findings in the literature reviews (in chronological order).

Reference	*Time Period*	*Location(s)*	*Data Type? Observed, Reanalysis or Gridded Data*	*PCP_{annual}*	*Tmax*	*Tmean*	*Tmin*
Nasrallah and Balling [80]	1891–1990	Average over the Arabian Peninsula	Gridded dataset	Insignificant decrease	----	+0.63 °C during the period	----
Rehman [90]	1970–2006	Dhahran station, Eastern part of Saudi Arabia	Observations *	Insignificant decrease	+0.6 °C per decade	+0.5 °C per decade	+0.4 °C per decade
AlSarmi and Washington [91]	1980–2008	Average over the Arabian Peninsula	Observations *	----	+0.32 °C per decade	+0.48 °C per decade	+0.55 °C per decade
Almazroui et al. [86]	1978–2009	Average over Saudi Arabia	Observations *	−47.8 mm per decade	+0.71 °C per decade	+0.48 °C per decade	+0.60 °C per decade
Athar [92]	1979–2008	Average of Saudi Arabia	Observations *	----	0.83 °C per decade	0.66 °C per decade	+0.49 °C per decade
Krishna [8]	1984–2013	Riyadh, Saudi Arabia	Observations *	----	+0.38 °C per decade	+0.643 °C per decade	+0.562 °C per decade
Alghamdi and Moore [93]	1985–2010	Urban (*rural*) stations in Riyadh, Saudi Arabia	Observations **	----	+0.45 (*0.69*) °C per decade	----	+0.68 (*0.83*) °C per decade
Islam et al. [9]	1981–2010	Average of Saudi Arabia	Observations ***	----	+0.86 °C per decade	+0.73 °C per decade	+0.58 °C per decade
Almazroui [11]	1978–2019	Average of Saudi Arabia	Observations ***	----	+0.6 °C per decade	+0.63 °C per decade	+0.64 °C per decade
Range of reported changes in temperature variables (°C per decade):					0.59 ± 0.27	0.61 ± 0.12	0.59 ± 0.1

* Annual mean of monthly data.
** Data were obtained from the Saudi Presidency of Meteorology and Environment (SPME).
*** Data were collected and provided by the General Authority of Meteorology and Environmental Protection (GAMEP).

7. Projected Changes in Climatic Variables in Saudi Arabia

The IPCC AR6 evaluated the estimated temperature and precipitation results of five scenarios using the SSP framework. These scenarios are named after the associated SSP (SSP1 to SSP5) and the expected radiative forcing level in 2100 (ranging from 1.9 to 8.5 W/m^2) [94]. The climate change data were extracted from the database of the World Bank Group's Climate Change Knowledge Portal (WB-CCKP), incorporating climate projections from the Coupled Model Inter-comparison Project Phase 6 (CMIP6) at a 1.0° × 1.0° (100 km × 100 km) resolution and different projected Shared Socioeconomic Pathways (SSPs). The CCKP serves as a comprehensive resource offering access to climate data and information at the global, regional, and country-levels, providing a centralized hub for all pertinent information (URL: https://climateknowledgeportal.worldbank.org/ (accessed on 15 June 2023)).

The historical (reference) period in our analysis is between 1995 and 2014. The future is divided into three periods: short-period (2026–2050), mid-period (2051–2075), and long-period (2076–2100). The predictions presented here are based on a combination of multiple models (ensemble) to showcase the potential variations (the mean, the 10th, and the 90th percentile range) of the most plausible anticipated effects on the climate system based on different SSPs. The difference between the reference temperature and the future temperature on an annual basis is the temperature anomaly. It is a measure used to assess whether a specific region is experiencing temperatures that are warmer or cooler than what would be expected based on historical climate data. In terms of precipitation, it is common to express changes in terms of percentages rather than anomalies. The visual representations of such anomalies/changes provide insights into potential changes in climate patterns and trends.

In terms of temperature variables, it was observed that the temperatures (mean, max, and min) are projected to increase throughout the 21st century in all emission scenarios (Figure 5a–c). Based on the SSP5-8.5 scenario, which assumes continued reliance on fossil fuels, the mean annual temperature could rise 6.6 °C in the long-term period relative to the reference period (Table 3). It is also expected that both Tmax and Tmin will continue to increase throughout the century (Tables 4 and 5). It is anticipated that Tmin will experience a more rapid increase than both Tmean and Tmax.

Table 3. Projected annual Tmean and anomaly (in °C) in the short, mid, and long periods relative to the historical period (mean: 25.47, 10th percentile: 24.88, and 90th percentile: 26.01).

Variable: Tmean	SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
			Short Period		
Mean	26.55	26.70	26.79	26.81	27.08
Anomaly	1.08	1.23	1.32	1.34	1.61
10th Percentile	25.61	25.85	25.98	26.06	26.16
Anomaly	0.73	0.97	1.10	1.18	1.28
90th Percentile	27.25	27.46	27.54	27.56	27.98
Anomaly	1.24	1.46	1.53	1.55	1.97
			Mid Period		
Mean	26.54	27.00	27.65	28.11	28.81
Anomaly	1.07	1.53	2.18	2.64	3.34
10th Percentile	25.29	26.07	26.71	27.27	27.65
Anomaly	0.42	1.19	1.83	2.39	2.77
90th Percentile	27.27	27.90	28.61	29.13	30.05
Anomaly	1.27	1.90	2.60	3.13	4.04
			Long Period		
Mean	26.29	26.95	28.20	29.59	30.84
Anomaly	0.82	1.48	2.73	4.12	5.37
10th Percentile	25.31	25.97	27.22	28.56	29.31
Anomaly	0.43	1.09	2.34	3.68	4.43
90th Percentile	27.09	27.97	29.42	30.93	32.61
Anomaly	1.08	1.96	3.41	4.92	6.60

Table 4. Projected annual Tmax and anomaly (in °C) in the short, mid, and long periods relative to the historical period (mean: 31.78, 10th percentile: 31.16, and 90th percentile: 32.36).

TMAX	SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
			Short Period		
MEAN	32.84	33.00	33.11	33.10	33.33
ANOMALY	1.06	1.22	1.33	1.32	1.55
10TH PERCENTILE	31.77	32.14	32.23	32.37	32.18
ANOMALY	0.62	0.99	1.07	1.21	1.02
90TH PERCENTILE	33.62	33.80	33.89	33.91	34.24
ANOMALY	1.26	1.44	1.53	1.55	1.88
			Mid Period		
MEAN	32.87	33.34	33.97	34.35	34.99
ANOMALY	1.09	1.56	2.19	2.57	3.21
10TH PERCENTILE	31.49	32.35	32.94	33.46	33.53
ANOMALY	0.34	1.19	1.79	2.30	2.38
90TH PERCENTILE	33.64	34.25	34.88	35.41	36.15
ANOMALY	1.27	1.89	2.52	3.05	3.79
			Long Period		
MEAN	32.64	33.32	34.52	35.73	36.88
ANOMALY	0.86	1.54	2.74	3.95	5.10
10TH PERCENTILE	31.50	32.28	33.42	34.61	35.02
ANOMALY	0.34	1.12	2.26	3.45	3.86
90TH PERCENTILE	33.51	34.29	35.61	37.11	38.50
ANOMALY	1.15	1.93	3.25	4.74	6.14

Table 5. Projected annual Tmin and anomaly (in °C) in the short, mid, and long periods relative to the historical period (mean: 19.22, 10th percentile: 18.60, and 90th percentile: 19.75).

Variable: Tmin	SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
			Short Period		
Mean	20.40	20.42	20.56	20.59	20.92
Anomaly	1.18	1.20	1.34	1.37	1.70
10th Percentile	19.42	19.35	19.53	19.63	19.95
Anomaly	0.83	0.75	0.94	1.03	1.36
90th Percentile	21.01	21.25	21.38	21.40	21.88
Anomaly	1.27	1.50	1.64	1.66	2.13
			Mid Period		
Mean	20.30	20.67	21.42	21.97	22.72
Anomaly	1.08	1.45	2.20	2.75	3.50
10th Percentile	19.04	19.55	20.28	20.92	21.59
Anomaly	0.45	0.95	1.68	2.33	2.99
90th Percentile	21.03	21.65	22.44	23.10	24.13
Anomaly	1.29	1.90	2.69	3.35	4.38
			Long Period		
Mean	20.03	20.58	21.97	23.50	24.80
Anomaly	0.81	1.36	2.75	4.28	5.58
10th Percentile	19.05	19.41	20.74	22.31	23.31
Anomaly	0.45	0.81	2.14	3.71	4.71
90th Percentile	20.79	21.70	23.30	25.04	26.98
Anomaly	1.04	1.96	3.56	5.29	7.23

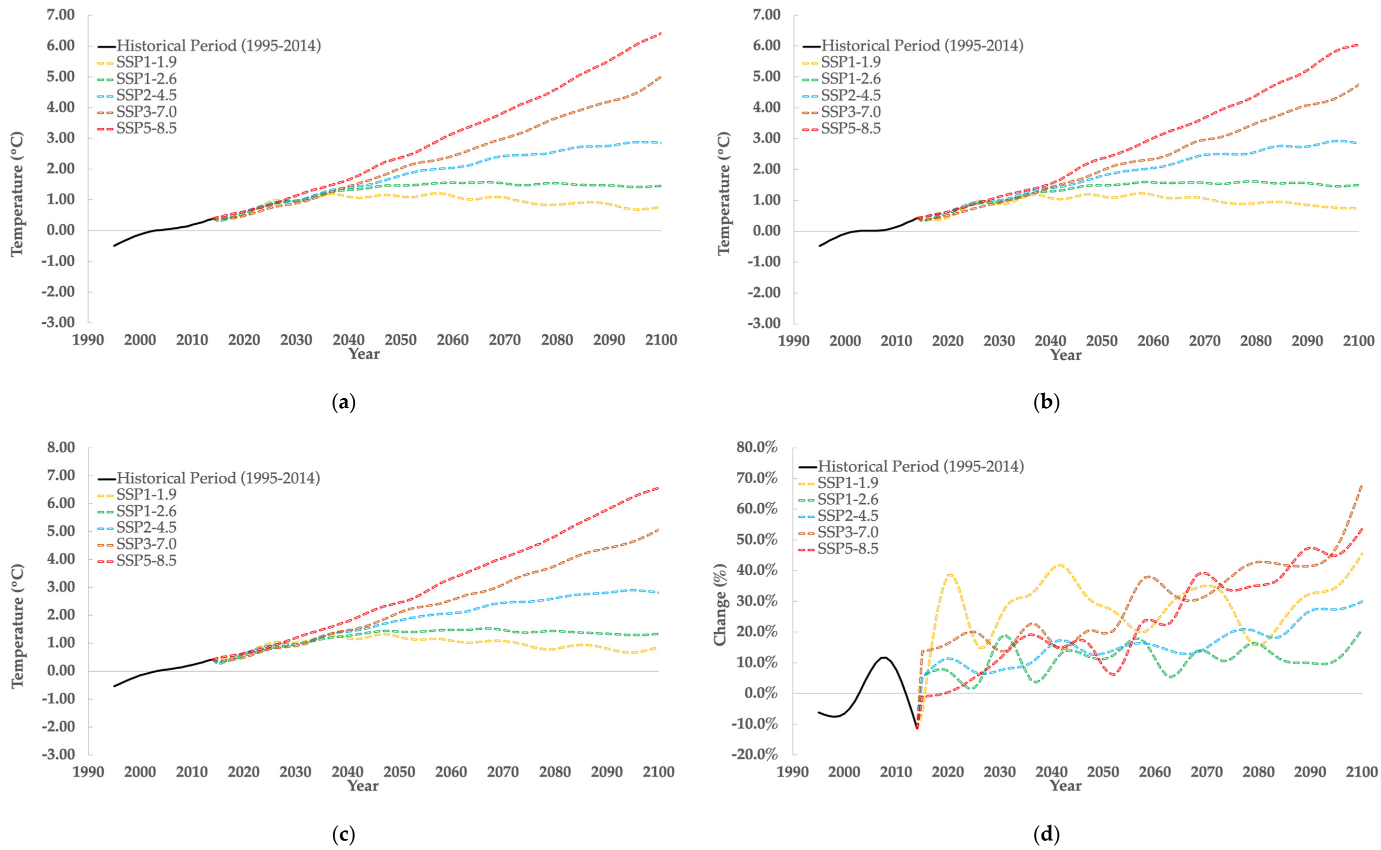

Figure 5. The projected anomalies of country-averaged annual (**a**). Tmean, (**b**). Tmax, (**c**). Tmin, and (**d**). change in $PCP_{\mathbf{annual}}$ using the mean of a multi-model ensemble and different Shared Socioeconomic Pathways (SSPs). (Authors' computation using data extracted from WB-CCKP, 2023).

Similar findings in the literature stated that the region is predicted to experience a continued rise in temperature throughout the 21st century faster than the global rates [83,95]. Based on the CORDEX-CORE regional climate projections. The IPCC's 2007 report [96] suggested a rise in the temperature of the Arabian Peninsula by as much as 1.68 °C by the year 2050. A study by Chowdhury and Al-Zahrani [97] was performed on 49 grids (2.5° Latitude × 3.75° Longitude) covering KSA and projected a mean temperature rise (1.8–4.1 °C) based on B2 and A2 scenarios by 2050. In terms of extremes, Kotwicki and Al Sulaimani [19] projected an increase in temperature in the 2050s. Other works on the larger Middle East also reported similar projections (e.g., [39,98]).

Based on the multi-model ensemble analysis of the current work, the mean annual precipitation (PCP) is projected to experience a significant increase of up to about 45%, particularly in the long period, compared to the reference period (Table 6). Although greater increases under the high-emissions SSP5-8.5 and SSP3-7.0 scenarios are generally anticipated, the magnitude of the increase needs to be clearly linked to specific emission scenarios and future periods (Figure 5d). For instance, PCP over the short period is expected to increase by 31.0% under SSP1-1.9, compared to a projected increase of only 14.4% in the case of SSP5-8.5.

Table 6. Projected mean annual precipitation (in mm) and changes (%) in the short, mid, and long periods relative to the historical period (mean: 43.0, 10th percentile: 47.90, and 90th percentile: 130.42).

Variable: PCP_{annual}	SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
			Short Period		
Mean	56.37	47.81	48.01	50.79	49.25
Change (%)	31.0%	11.1%	11.6%	18.0%	14.4%
10th Percentile	11.05	7.92	7.74	10.13	8.85
Change (%)	39.9%	0.3%	−2.0%	28.3%	12.1%
90th Percentile	145.57	140.16	148.93	141.85	149.36
Change (%)	11.6%	7.5%	14.2%	8.8%	14.5%
			Mid Period		
Mean	55.19	48.25	49.64	56.80	54.09
Change (%)	28.2%	12.1%	15.3%	32.0%	25.7%
10th Percentile	10.67	8.46	8.24	11.10	8.95
Change (%)	35.1%	7.1%	4.4%	40.5%	13.3%
90th Percentile	146.57	144.32	148.32	159.12	164.46
Change (%)	12.4%	10.7%	13.7%	22.0%	26.1%
			Long Period		
Mean	55.35	48.58	53.32	62.73	61.24
Change (%)	28.6%	12.9%	23.9%	45.8%	42.3%
10th Percentile	10.79	7.99	8.75	11.90	9.90
Change (%)	36.6%	1.1%	10.8%	50.7%	25.4%
90th Percentile	141.23	143.62	160.73	177.19	189.83
Change (%)	8.3%	10.1%	23.2%	35.9%	45.6%

The findings of this study are in line with those of previous research. There is generally a predicted increase in annual rainfall amounts. The central, western, and eastern regions are expected to experience an increase in annual rainfall (15–25 mm) by 2050 [97]. Meanwhile, Al-Zawad and Aksakal [99] predicted a 26–35 mm increase in the long period (2070–2100). The country's southwest region is projected to observe a larger increase (109.7–130.4 mm) [97], while Al-Zawad and Aksakal [99] predicted a slightly lower increase of 96.7 mm. Consistent with our findings, Tarawneh and Chowdhury [10] found variable patterns in rainfall projections in terms of emission scenarios (using representative concentration pathways, RCPs) and evaluation periods. El-Rawy et al. [100] investigated the influence of climate change in Saudi Arabia and projected an increase in the long-term period of 27% and 32% under the SSP2-4.5 and SSP5-8.5 scenarios, respectively. Numerous recent studies have consistently reported an expected rise in future rainfall amounts across various regions of the region (e.g., [19,101–104]).

8. Implications of Climate Change in Saudi Arabia

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 [97,100]. Rising temperatures are also expected to lead to higher domestic water demand [10]. 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) [105].

- 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 [106].
- Rising temperatures can lead to a higher rate of evaporation from open reservoirs [10], 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% [97], while El-Rawy et al. [100] 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 [97].
- 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) [5,97,107].
- 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 [108].
- The frequency and intensity of climatic and hydrological extremes will increase, such as heavy precipitation events [109]. Moreover, in the design of critical urban infrastructure and water systems, the probability of climate change-induced events must be considered [39].
- Marine biodiversity in the Arabian Gulf will be adversely affected, and there is a risk of local extinction of some habitat species [108].

Although the primary focus of this work is the impact of climate change on water resources, it is essential to recognize that changes in climate patterns can have broader effects. The coastal regions risk facing various consequences due to rising sea levels, as low-lying regions could be prone to flooding or erosion, causing damage to vulnerable coastal infrastructure (e.g., Jeddah city, as investigated by Almaliki et al. [110]). Countries in the Arabian Peninsula are vulnerable to rising sea levels and may face substantial inland flooding due to rising sea levels [111]. Many other sectors must be adaptable to prepare for future climate change-driven events and severe occurrences, such as food production [112,113], transportation [114], health and welfare systems [115], telecommunication systems [39], energy and power-generation systems [116], and economic growth [37]. As such, it is crucial to adopt a comprehensive approach to address climate change's far-reaching effects.

9. Sustainable Water Resources Management in a Changing Climate

In order to address the impact of climate change, this section offers recommendations for adaptation strategies that can be implemented within the water sector of Saudi Arabia. The suggested strategies aim to cope with potential risks and ensure that the water supply remains sufficient and reliable in the face of changing environmental conditions. One of the primary goals of Vision2030 [117], a governmental transformation blueprint for diversifying its economy in a sustainable manner launched in 2016, is to encourage the efficient utilization of vital water resources by decreasing consumption and expanding the use of renewable non-conventional sources of treated and renewable water in line with the United Nations Development Program to tackle water scarcity [118].

The government has already implemented some adaptation measures to improve water efficiency and reduce water consumption. These include initiatives to promote water conservation, improve irrigation techniques, and increase the use of treated wastewater for non-potable purposes. In addition, the recent implementation of some economic policies, including subsidy reforms in fuel, electricity, and water prices, could foster the adoption of new and alternative technologies, such as renewable energy [119]. An example of urban planning measurements includes land zoning, which controls population and building density, the demarcation of environmental protection zones, and the implementation of sub-urbanization in Riyadh city [120]. Moreover, the Saudi Green Building Code (SBC 1001-CR), introduced in 2018 as a voluntary part of the new Saudi Building Code (SBC), addresses water resource quality and efficiency, among other requirements [121]. Despite some progress, a significant amount of work must be accomplished.

The following subsections provide insight into some examples of areas that need improvement for sustainable water management in a changing climate.

9.1. Managing Agricultural Demands

The predominant means for irrigated agriculture remain unjustifiable water-intensive conventional surface methods such as flood irrigation with low water productivity [13,122]. 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. [123]. Al-Subaiee et al. [124] 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 [123]. 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% [125]. On a national scale, it is necessary to conduct an urgent, thorough assessment of the current irrigation water usage and efficiency [123].

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 [123]. 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.

9.2. 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 [61], 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 [126]. 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 [15]. 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 [49], which also falls short of the benchmark goal of utilizing at least 60% [15]. The majority of the treated wastewater is left unused. According to UN-WWAP [127], 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 [128]. 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 [15]. 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.

9.3. Evaporation Reduction Technologies

KSA has high potential evaporation rates, with an average annual rate ranging from 2500 mm to 3000 mm [129,130]. 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. [131] found that implementing physical covers significantly minimized evaporation, particularly for small reservoirs with an area of less than 10 hectares. Yao et al. [132] 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 [133]. They have been installed on various water bodies, including irrigation canals, lakes, and dams, as demonstrated in recent studies by Baradei & Sadeq [134], McKuin et al. [135], and Khan et al. [136].

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 [137,138]. Alam and AlShaikh [138] used double-layer palm-frond sheets and observed about a 58% average reduction in evaporation when the water surface was fully covered. Al-Hassoun [139,140] 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 [141]. The monolayer technique, in particular, is widely used because it is both cost-effective and readily available, making it economically feasible [142]. The efficiency of this technique in arid regions was investigated in Algeria in laboratory conditions, and a 22% reduction was observed [142]. 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 [141].

However, it is crucial to acknowledge that the use of chemicals or physical covers on water bodies may affect the aquatic ecosystem [130,132,140,143–145]. 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.

9.4. 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 [146]. 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 [147].

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 7). 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 [15]. The average global cost of potable water is around \$6/m^3 [148].

Table 7. 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 [149]. 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.

9.5. 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 [150], 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., [151]). 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 [152] 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) [50], 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 [60]. Additionally, there is a concern about polluting these fossil aquifers [153]. 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.

9.6. 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 [63]. 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 [15].

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 [154]. It is crucial to have a dependable desalination industry that is powered by sustainable energy. Some promising methods include using geothermal energy [154] or nuclear power [155,156] to meet the growing freshwater demand.

9.7. 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 [157]. In countries such as the KSA, water conservation is no longer a choice but a necessity [158]. 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 [13,122,123]. 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 [159]. Ouda et al. [158] 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) [160].

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) [49].
- 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 [161].
- 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 [158].
- 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 [121].

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 [49] 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 [162,163]. 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.

10. Challenges and Conclusion Remarks

In light of the challenging water conditions and hyper-arid climate in KSA, the country's future is at stake, and urgent actions must be taken to mitigate the potential adverse effects of climate change on the country's water resources. It is crucial to adopt a comprehensive, multi-faceted approach involving participation from all relevant stakeholders to tackle the potential climate alterations and reduce their effects on water resources. Although the country has inadequate renewable water resources, a staggering amount is withdrawn from fossil groundwater resources every year.

One of the challenges in dealing with climate change in general is determining the magnitude of the Earth's response to the anticipated increase in greenhouse gas emissions in this century, which remains uncertain. For instance, equilibrium climate sensitivity (ECS), a measure of how much warming (ΔT) results from a certain increase in atmospheric carbon dioxide, usually a doubling of preindustrial levels of 280 ppm [164], is still debatable (e.g., [165–168]). The IPCC's sixth assessment report (AR6) suggested that ECS is very likely to be between 1.5 °C and 4.5 °C [6]. Another source of uncertainty is future societal changes. Societal responses influence climate change impacts, including adaptation measures and mitigation efforts, as well as the evolving social, economic, and political conditions that shape future responses. Moreover, as an essential means for simulating and projecting future climate scenarios, climate models (GCMs and RCMs) inherently involve uncertainties due to simplifications and approximations of complex Earth system processes.

Despite some efforts to analyze water resources in Saudi Arabia in the context of climate change, there is still a need for further action. Here are a few key recommendations to enhance these efforts:

- Groundwater is the primary water source in Saudi Arabia, and it is being depleted at an alarming rate due to overuse. However, more comprehensive data-driven studies are needed to investigate the extent of climate change-induced impacts on the country's groundwater resources, such as changes in natural groundwater recharge.
- While climate change is expected to impact precipitation patterns and runoff volumes significantly, there is a need to understand how such changes will affect surface water availability and quality to ensure that water is accessible and safe for human consumption.
- More research is necessary to understand the water demand in Saudi Arabia, especially in urban areas, due to the expected impacts of climate change and the government's plan to substantially increase the population to 50–60 million (about 32 million in 2022), while Riyadh alone is planned to accommodate about 25 million (about 8 million in 2022) by 2030. Such research would help develop effective policies to manage water resources and ensure that water is distributed equitably.
- With increasing pressure on conventional resources, treated wastewater should play a significant role as an essential non-conventional water source in meeting SAs water demand. More efforts are needed to increase the use of treated wastewater from 22% to the government benchmark of 60%.
- Launching awareness campaigns about water and promoting the use of treated water in KSA is crucial. It can help educate the public about the scarcity of water resources and the importance of conservation, leading to more responsible water usage. In addition, promoting the use of treated water can reduce the strain on freshwater sources and ensure a sustainable supply for future generations. Moreover, raising awareness about treated water can help overcome any misconceptions or stigmas associated with its use, fostering acceptance and encouraging its widespread adoption.
- The adoption of data-driven decision-making is vital for effective climate change evaluations. However, the limited accessibility of observed climatic and hydrologic datasets has hindered comprehensive assessments. To overcome this limitation, it

is crucial to prioritize efforts that facilitate data access for researchers. This can be achieved by establishing robust data collection networks and promoting open data policies. By enhancing data accessibility, researchers can employ advanced modeling techniques to gain valuable insights into the current climate situation and make informed decisions regarding water resource management.

➢ At the government level, it is crucial to review and update existing policies and regulations to align with climate change considerations and promote sustainable water management practices. There is also a need to develop incentives and frameworks that encourage responsible water use, conservation, and the use of alternative water sources. Furthermore, it should be noted that the specific scientific basis or data supporting the government objectives were not explicitly available or provided by the governmental agencies, which is a concern that warrants further clarification.

➢ A further comparative investigation of the existing local water reforms with other plans of jurisdictions that have somehow similar conditions (e.g., the Murray–Darling Basin Plan in Australia, the National Water Program (PNH, 2020–2024) of Mexico, and water-sharing arrangements in the USA) is needed to ensure the sustainable fulfillment of the human right to water and the preservation of vital ecosystems. This comparative investigation can provide valuable insights and lessons from experiences and explore the potential applicability of successful strategies to the context of Saudi Arabia.

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