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Climate-Resilient Urban Water Systems in Arid Environments: A Policy Roadmap for Water Security

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Abstract

Water scarcity in arid regions is increasingly intensified by climate change, population growth, and pressure on limited freshwater resources. This study assesses the climate resilience of urban water systems, focusing on desalination, groundwater, wastewater reuse, and rainwater harvesting. Google Earth Engine (GEE) was used to process and visualize climate and remote-sensing datasets, including NASA GRACE MASCON, TerraClimate, and ERA5-Land, to assess changes in terrestrial water storage, evapotranspiration, and surface runoff across the Gulf region. The performance of each water source was then evaluated under baseline, projected 2050, and climate-resilient scenarios using a Climate Resilience Indicator (CRI). Under 2050 climate conditions, CRI values were 0.69, 0.82, 1.35, and 1.21 for desalination, groundwater, wastewater reuse, and rainwater harvesting, respectively, improving to 0.75, 0.87, 2.85, and 1.46 following resilience measures. The findings highlight the importance of integrated adaptation, water-source diversification, and resilient infrastructure for strengthening long-term water security in arid environments.

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1 Introduction

1.1 Background

Rapid urbanization, population growth, and climate change are placing unprecedented pressure on global freshwater resources. Rising temperatures are altering precipitation patterns, increasing drought frequency, and intensifying water scarcity. Under a 2 °C warming scenario, climate change alone is projected to increase the number of people living under absolute water scarcity by 40% [1]. These impacts are especially severe in arid regions, where freshwater resources are already limited. By 2050, countries including Saudi Arabia, Jordan, the United Arab Emirates, and Qatar may experience prolonged "Day Zero" events, during which water demand exceeds available freshwater supplies [2]. Therefore, ensuring long-term water security requires a shift toward climate-resilient water management. Rather than relying solely on infrastructure expansion, water supply systems should integrate adaptive measures, including infrastructure upgrades, alternative water sources, and improved governance, to enhance resilience under future climate conditions [3].

1.2 Why This Matters

The global population is projected to reach 9.7 billion by 2050 [4], placing increasing pressure on water resources and supply infrastructure. Consequently, the global urban population experiencing water scarcity is expected to rise from 933 million in 2016 to 1.69–2.37 billion by 2050, representing nearly one-third to one-half of the world's urban population [5]. This growing demand is further exacerbated by climate change, which not only increases global temperatures but also alters the frequency, intensity, and duration of extreme weather events. In the Gulf region, these include prolonged heatwaves, severe droughts, flash floods, sand and dust storms, marine heatwaves, and sea-level rise. In Saudi Arabia, climate change is also expected to significantly alter rainfall patterns, with the Eastern Region and Riyadh exhibiting the highest variability (CV > 100%), indicating substantial year-to-year fluctuations in precipitation [6]. These challenges highlight the need for adaptive and resilient water supply systems capable of meeting future demand under changing climatic conditions.

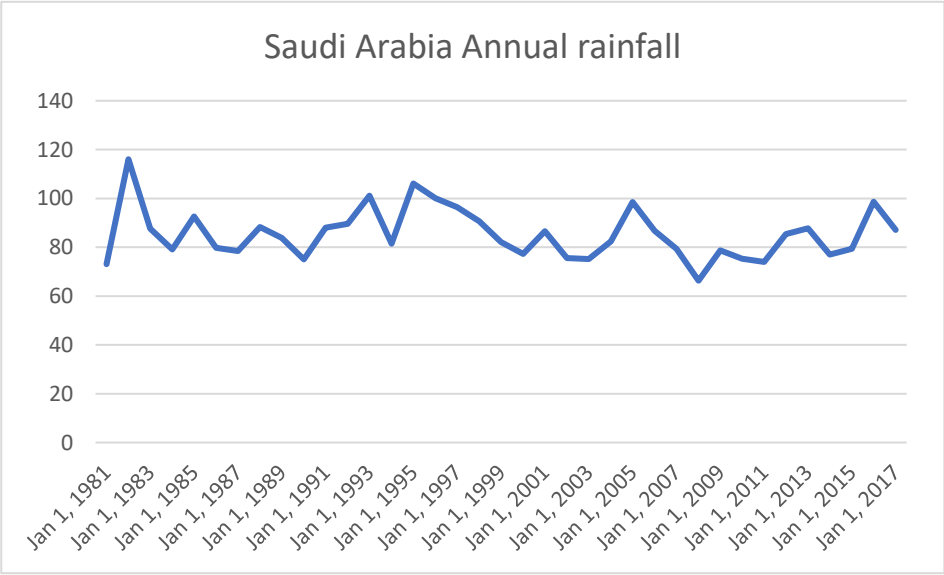


Figure 1-1: Annual precipitation across Saudi Arabia during the period 1981–2017. Source: NASA.

GULF countries is particularly vulnerable to climate change because its freshwater supply depends primarily on groundwater and seawater desalination, both of which are highly sensitive to climatic changes [7]. Groundwater is the country's primary freshwater source, supplying approximately 61% of total water demand and nearly 80% of agricultural water consumption [8]. However, decades of intensive abstraction have resulted in significant aquifer depletion. Satellite observations from 2002 to 2023 indicate groundwater declines of up to 8 cm per year in central and northern regions, including Riyadh, Al-Qassim, and Al-Jawf [9].

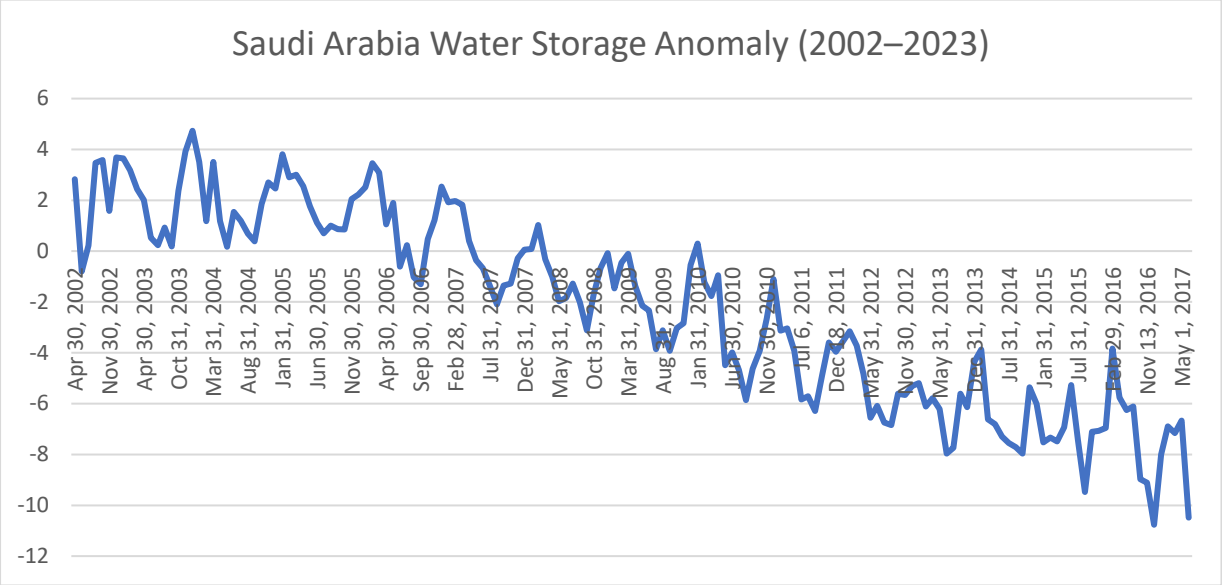


Figure 1-2: Groundwater storage anomaly in Saudi Arabia during the period 2002–2023. Source: NASA.

One of the major consequences of climate change is the increasing economic burden on water supply, particularly in Saudi Arabia, where desalination and groundwater are the primary freshwater sources. Desalination is highly energy-intensive, accounting for approximately 10–20% of the Kingdom's national electricity consumption [10]. Although groundwater extraction is generally less costly, declining groundwater levels increase pumping energy requirements. For instance, the average groundwater level in six piezometric wells within the Saq Aquifer declined from 597 m to 526 m above mean sea level between 2002 and 2013 [11], resulting in higher energy consumption and operational costs for groundwater extraction.

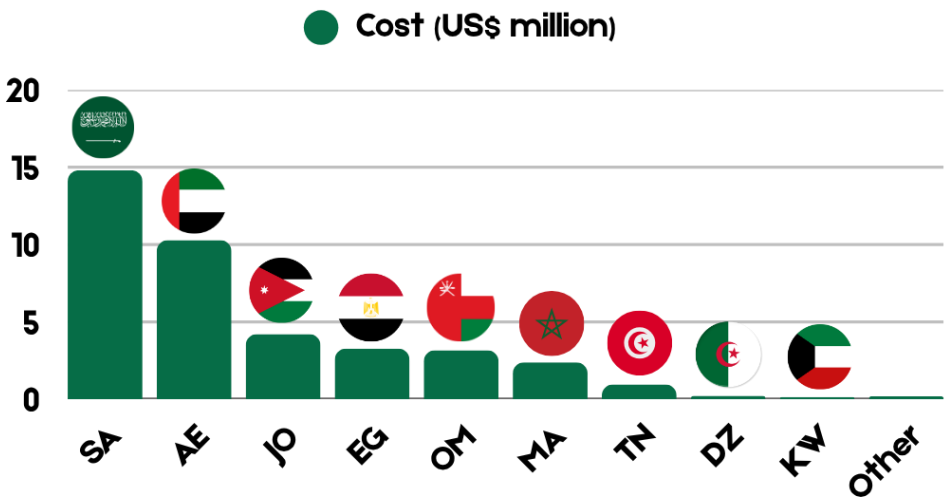


Figure 1-3: Total cost of water desalination plant projects across the Middle East and North Africa (MENA) region (US$). Source: Statista.

1.3 Purpose of The Paper

To address these challenges, this case study aims to develop a governance policy framework that integrates climate resilience into water supply system planning. The framework will evaluate climate-related risks, identify appropriate adaptation measures, assess existing policy gaps, and propose a practical roadmap to support governments in developing resilient and sustainable water systems.

2 Climate Risks to Urban Water Systems

Climate change is expected to intensify multiple threats to urban water systems, including rising temperatures, prolonged droughts, extreme rainfall and flooding, sea-level rise, and disruptions to energy systems. These hazards can reduce water availability, damage infrastructure, and increase the difficulty of meeting future water demand. Therefore, understanding these climate-related threats is essential for developing resilient and sustainable water management strategies.

To assess the impacts of climate change on water resources in the Gulf region, this study utilizes NASA datasets, including observations from the Gravity Recovery and Climate Experiment (GRACE) mission spanning 2002–2023. These data are used to evaluate changes in groundwater storage and illustrate the deterioration of water resources under changing climatic conditions.

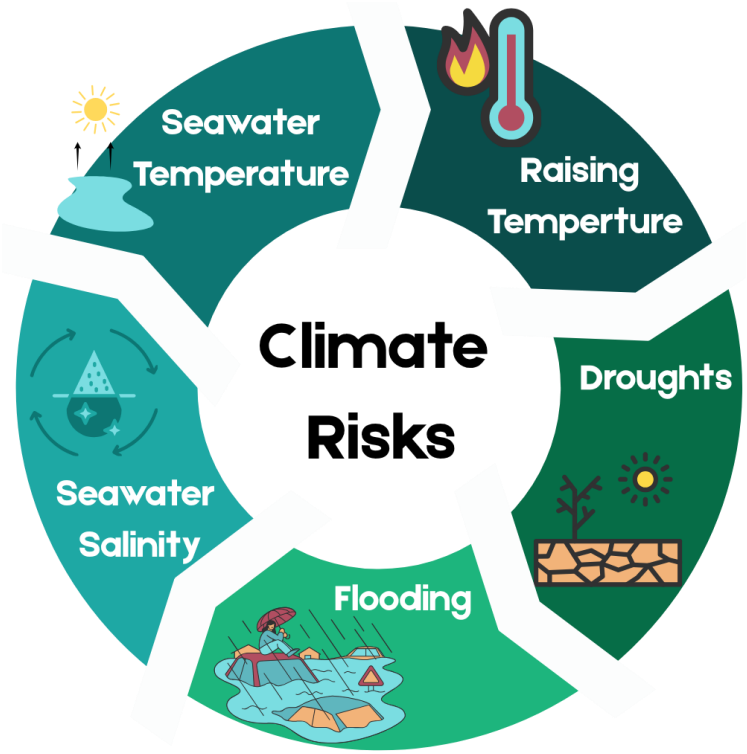


Figure 2-1: Summary of the Main Climate Risks Discussed in This Study.

2.1 Geospatial Climate Hazard Assessment

To evaluate the spatial distribution and evolution of climate-related threats across the Arabian Gulf, this study employed Google Earth Engine (GEE), a cloud-based geospatial analysis platform that enables large-scale processing of satellite observations and climate datasets. GEE was used to access, process, visualize, and compare multiple datasets representing key climate hazards between historical (2001–2004) and recent (2021–2023) periods. Three complementary datasets were selected to characterize different dimensions of climate change impacts on regional water systems, as summarized in ***Table 2-1*.**

Table 2-1: Summary of the datasets, variables, spatial resolutions, and time periods used to assess climate-related changes in evapotranspiration, terrestrial water storage, and surface runoff across the Gulf region.

Dataset	Variable	Purpose	Spatial Resolution	Time Period
TerraClimate	Actual Evapotranspiration (AET)	Assess evaporative demand and drought stress	~4.6 km	2001–2004, 2021–2023
NASA GRACE MASCON	Terrestrial Water Storage	Quantify groundwater and terrestrial water depletion	~0.5°	2001–2004, 2021–2023
ERA5-Land	Surface Runoff	Assess flood potential and runoff intensity	~9 km	2001–2004, 2021–2023

All datasets were processed within Google Earth Engine to generate spatial maps for the selected time periods using consistent visualization scales, allowing direct comparison of climate hazards over time. The resulting maps provide a spatial assessment of increasing evaporative demand, groundwater depletion, and runoff intensity, supporting the identification of areas most vulnerable to future climate-related water risks.

2.2 Climate Hazards

2.2.1 Rising Temperatures

2.2.1.1 Population Growth

Population growth and climate change are expected to place unprecedented pressure on global water resources. The global population is projected to reach 9.4–10.2 billion by 2050, representing a 22–34% increase from current levels, while total water demand is expected to increase by 20–30% [12]. These pressures will be further intensified by rising temperatures, which increase domestic, industrial, and agricultural water requirements. Gulf countries are particularly vulnerable due to their arid climate, limited renewable freshwater resources, and high-water demands associated with urban development and the oil and gas sector.

2.2.1.2 Evaporation Rates

Rising temperatures are also expected to increase evaporation rates, further exacerbating water scarcity. Ajjur and Al-Ghamdi (2021) projected that actual evapotranspiration (AET) is projected to increase by up to 0.30 mm/year by 2050 [13]. Figure 6 presents two models generated using Google Earth Engine and TerraClimate's Actual Evapotranspiration (AET) dataset to illustrate the changes in evaporation rates across the Gulf region over a 20-year period. The comparison demonstrates a clear increase in evapotranspiration, highlighting the growing influence of climate change on regional water availability.

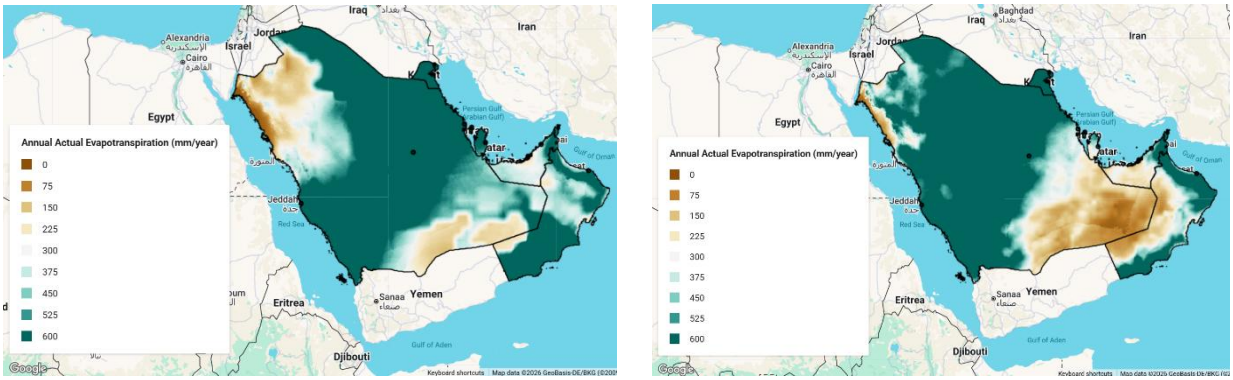


Figure 2-2: Annual actual evapotranspiration (AET) in the Gulf countries (mm/year), comparing the average conditions for 2002–2004 (left) and 2021–2023 (right).

2.2.1.3 Vulnerability of the Infrastructure

Another consequence of rising ambient temperatures is the increased vulnerability of water supply infrastructure and equipment. Bondank, Chester, and Ruddell (2018) projected that component failures could increase by 10–101% under scenarios where peak summer temperatures rise from 36°C to 44°C, resulting in a 7–91% increase in service outages [14]. These findings indicate that future temperature increases driven by climate change could pose a significant threat to existing water supply systems, highlighting the need to integrate climate-resilient measures into their planning, design, and operation.

2.2.2 Droughts

2.2.2.1 Terrestrial Water Storage (TWS)

One of the most significant impacts of climate change is the increased occurrence and severity of droughts. To assess this impact, terrestrial water storage (TWS), which represents the total amount of water stored in groundwater, soil moisture, rivers, lakes, and reservoirs, is commonly used as an indicator. Pokhrel et al. (2021) found that climate change has a substantial negative effect on TWS, projecting that nearly two-thirds of the global land area will experience declines in terrestrial water storage by the end of the 21st century under the RCP6.0 scenario [15].

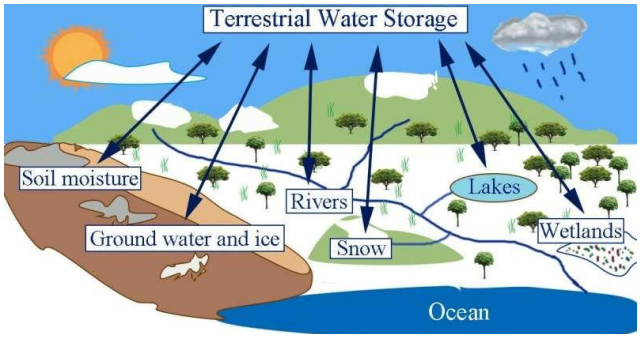


Figure 2-3: Conceptual illustration of terrestrial water storage (TWS) components in the natural environment. Source: Pokhrel et al. 2021

2.2.2.2 TWS – Terrestrial Water Storage in GULF Countries

The Gulf countries are among the region's most vulnerable to water scarcity due to the combined effects of climate change and prolonged droughts. Saharwardi et al. (2025) projected that under the high greenhouse gas emission scenarios SSP3-7.0 and SSP5-8.5, some parts of the Arabian Peninsula could experience 300–400% more frequent droughts by the end of the century, meaning that severe drought events may occur three to four times more often than they do today [16]. This increasing drought frequency is expected to intensify pressure on already limited water resources. As illustrated in Figure 7, terrestrial water storage (TWS) derived from the NASA/GRACE MASCON dataset shows a substantial decline across the Gulf region between 2002–2004 and 2021–2023, indicating a significant reduction in the amount of water stored in groundwater, soil moisture, and surface water over the past two decades.

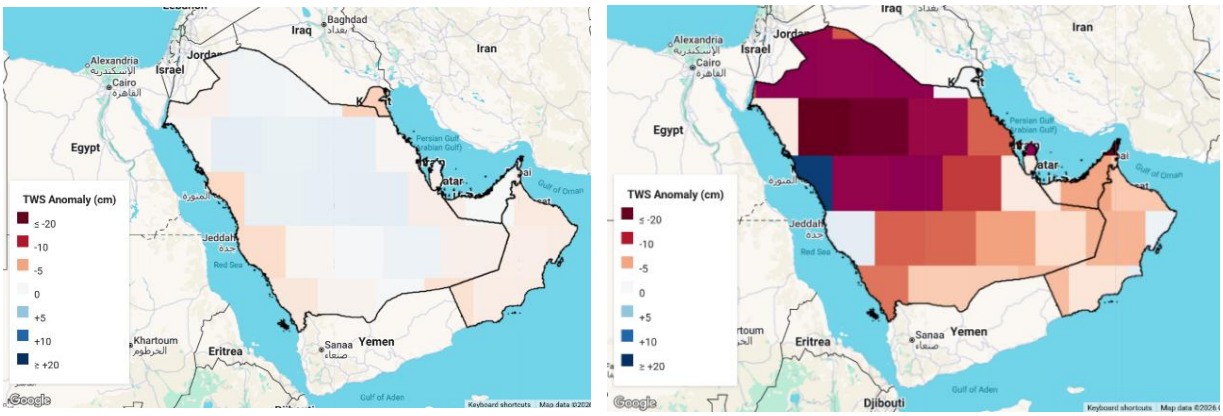


Figure 2-4: Annual terrestrial water storage (TWS) in the Gulf countries (cm) during 2002–2004 (left) and 2021–2023 (right).

2.2.3 Flooding and Extreme Rainfall

2.2.3.1 The Impact of Flooding

Flooding is one of the most significant impacts of climate change, driven by the increasing frequency and intensity of extreme precipitation events. A notable example is the 2016 Louisiana flood, where 648.3 mm of rainfall fell within three days, triggering widespread flooding that affected more than 60,600 homes and required the rescue of approximately 30,000 people [17]. This event highlights the growing risks posed by climate change and the need to incorporate flood resilience into water infrastructure planning.

2.2.3.2 GULF Countries Vulnerabilities to Flooding

Although the Gulf region is generally less susceptible to flooding due to its arid climate and low annual precipitation, climate change is increasing the risk of flooding events. Dordai et al. (2026) reported an approximately 134% increase in flood-related disasters since 1980 and a 29% increase in drought duration since 2000 [18]. Consistent with these findings, **Error! Reference source not found.** illustrates changes in runoff accumulation patterns across the Gulf region over the past two decades using Google Earth Engine and the ERA5-Land surface runoff dataset, indicating an increasing risk of localized flooding in previously less-affected areas.

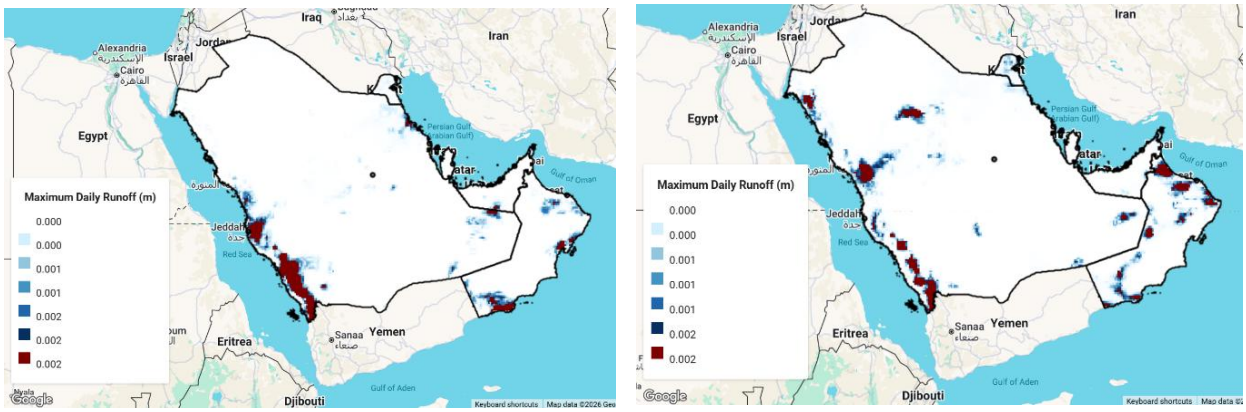


Figure 2-5: Maximum daily runoff in the Gulf region (m), comparing the average conditions during 2002–2004 (left) and 2021–2023 (right).

2.2.3.3 Flooding

In addition, much of the existing drainage and wastewater infrastructure in the Gulf region is vulnerable to overflow during extreme runoff events, posing risks to public health and the environment. According to the National Environmental Reports, 52 of the 443 discharge points along the Red Sea coast fail to comply with marine environmental standards. As runoff accumulation patterns continue to shift under climate change, the frequency and severity of these environmental and public health risks are likely to increase.

2.2.3.4 Infrastructure Damage

Flooding can severely disrupt urban water infrastructure through both direct and indirect impacts. Direct impacts include damage to water treatment plants, pumping stations, and wastewater facilities, while indirect impacts result from failures in interconnected infrastructure, particularly electricity networks that support water production and distribution. Consequently, localized flooding can trigger cascading failures that disrupt water services across wider areas [17]. These findings emphasize the need to integrate flood resilience into the planning and management of critical water infrastructure.

2.2.4 Seawater Raise

2.2.4.1 Increasing Seawater Temperature

Climate change is projected to significantly increase sea surface temperatures (SSTs) throughout the 21st century, particularly in the Northern Hemisphere, where subtropical regions may experience warming of up to 4.34°C under a high-emission scenario (RCP8.5) by the end of the century [19].

2.2.4.2 Seawater Temperature Increase in Arabian GULF

Sea surface temperatures (SSTs) in the Arabian Gulf have shown a clear warming trend over recent decades, driven by global climate change. The Gulf is recognized as one of the fastest-warming marine environments in the world due to its shallow depth, semi-enclosed basin, and limited water exchange with the open ocean. Summer SSTs frequently exceed 34–36°C, with extreme marine heatwaves becoming increasingly common and intense [20].

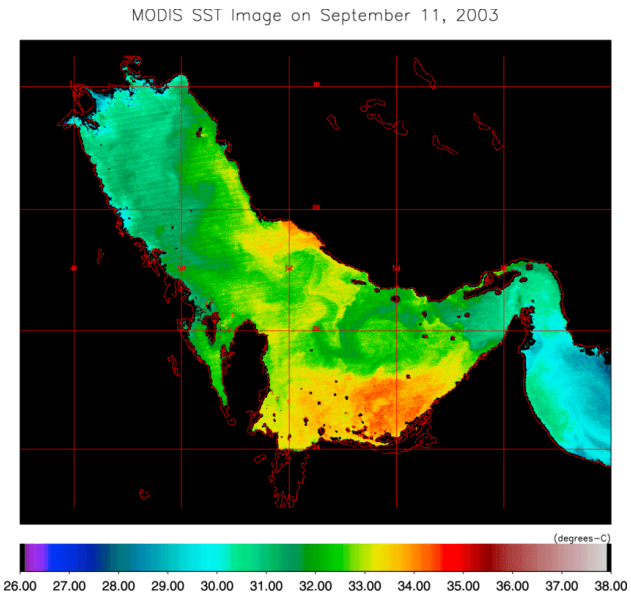


Figure 2-6: MODIS-derived sea surface temperature (SST) image of the Arabian Gulf on 11 September 2003, showing a prominent mesoscale eddy centered at 53.8°E, 22.9°N. Source: Yao and Johns 2010.

2.2.4.3 Impact of Seawater Temperature Raise

Climate projections indicate that continued greenhouse gas emissions will further increase SSTs throughout the 21st century, intensifying evaporation, increasing seawater salinity, and altering seawater chemistry. These changes have important implications for desalination systems, as warmer feedwater can reduce membrane performance, increase energy consumption, accelerate membrane fouling, and raise operational costs, highlighting the growing vulnerability of desalination infrastructure across the Gulf region [21].

2.2.5 Seawater Temperature

2.2.5.1 Increasing Seawater Temperature

Climate change is expected to alter seawater salinity, which is now recognized as a key climate-related stressor that interacts closely with ocean warming and acidification, while extreme events such as prolonged droughts further amplify salinity fluctuations in coastal regions [22]. These processes are particularly pronounced in the Arabian Gulf, resulting in naturally high salinity levels of 40,000–45,000 ppm, compared with the global ocean average of approximately 35,000 ppm [7]. Continued warming is therefore expected to further increase seawater salinity, posing additional challenges for desalination systems and coastal water resources.

2.2.5.2 Arabian GULF Salinity Effect

Because the Arabian Gulf is a shallow, semi-enclosed basin with naturally high evaporation rates, rising SSTs are expected to further intensify evaporation and increase seawater salinity [7]. These changes alter feedwater quality, increase membrane fouling and scaling, and require higher operating pressures during reverse osmosis desalination, ultimately increasing energy consumption and operational costs [23]. Together, these climate-driven changes highlight the growing vulnerability of desalination systems across the Gulf region.

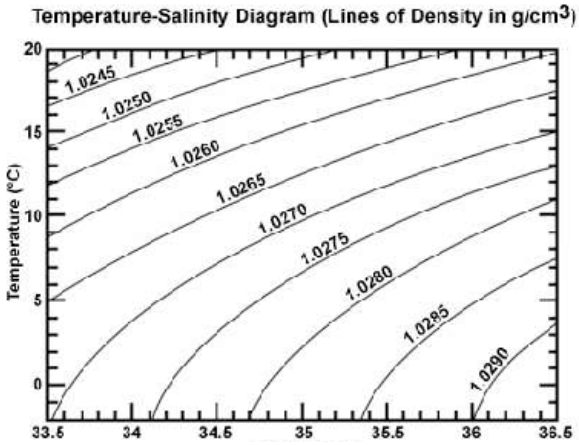


Figure 2-7: Temperature–salinity (T–S) diagram showing seawater isopycnals (lines of constant density) at constant pressure. Source: The COMET Program.

2.2.5.3 Degradation of Infrastructure

Increasing seawater salinity and higher feedwater temperatures reduce the operational efficiency of desalination infrastructure by placing greater stress on key system components. As seawater becomes warmer and more saline, osmotic pressure increases, requiring reverse osmosis (RO) systems to operate at higher pressures and increasing the workload on high-pressure pumps and pressure vessels. In addition, higher temperatures reduce the efficiency of energy recovery devices (ERDs), with one study reporting a decline in ERD efficiency from 96.2% at 15°C to 95.4% at 40°C for seawater desalination [24]. Elevated temperatures also increase the potential for membrane scaling, biofouling, and organic fouling, leading to more frequent maintenance and membrane replacement. Furthermore, membrane salt rejection deteriorates at higher temperatures, reducing permeate water quality and making it more challenging to consistently meet drinking water standards [25].

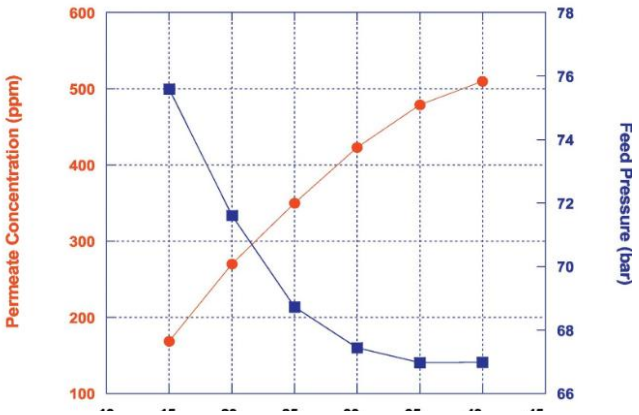


Figure 2-8: Effect of feed water temperature on feed pressure and permeate concentration for sea-water desalination. Source Koutsou et al. 2020.

3 Vulnerabilities Across the Water Cycle

Climate change poses a wide range of risks across every stage of the urban water cycle, affecting water availability, quality, infrastructure, and service reliability. In the Gulf region, rising temperatures, prolonged droughts, extreme rainfall, and sea-level rise threaten key water resources and infrastructure, including groundwater, desalination systems, water transmission and distribution networks, wastewater management, and water reuse. Understanding these interconnected vulnerabilities is essential for developing climate-resilient urban water systems and informing effective adaptation strategies. ***Figure 3-1*** summarizes the major climate change vulnerabilities discussed in this section.

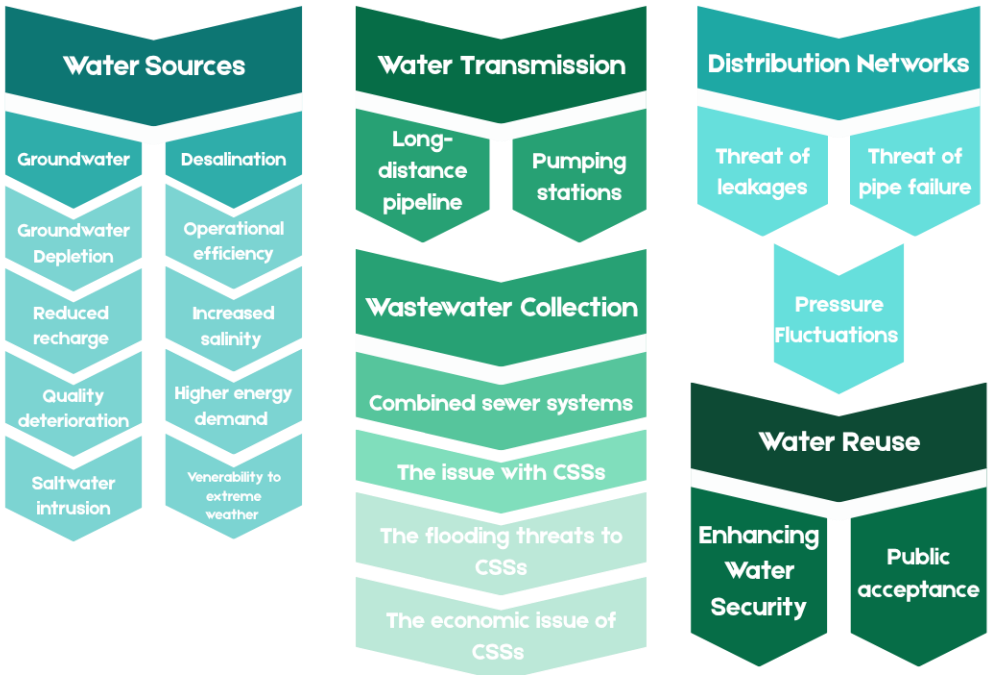


Figure 3-1: Summary of the major climate change vulnerabilities affecting different components of the urban water cycle, including water sources, transmission, distribution networks, wastewater collection, and water reuse.

3.1 Water Sources

3.1.1 Groundwater

Groundwater is one of the primary freshwater sources supporting domestic, industrial, and agricultural water demands across the Gulf Cooperation Council (GCC) countries. However, climate change, particularly rising temperatures, prolonged droughts, and declining groundwater recharge, is placing increasing pressure on regional aquifers. As a result, groundwater systems across the region face several major challenges, including groundwater depletion, reduced groundwater recharge, groundwater quality deterioration, and saltwater intrusion, all of which threaten the long-term sustainability of this critical water resource. Renewable water resources across the GCC are limited to approximately 8.83 billion m^3/year, with nearly 76% of the annual groundwater recharge occurring in Saudi Arabia [26]. Combined with continued over-abstraction, these pressures have led to widespread groundwater depletion, threatening the long-term sustainability of this critical water resource throughout the region [27].

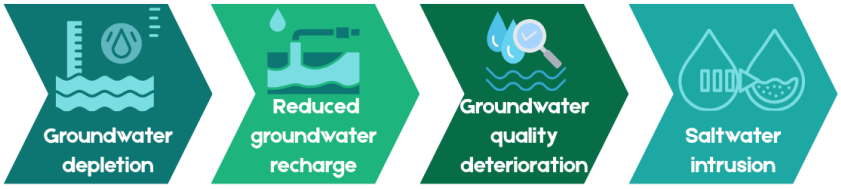


Figure 3-2: Major climate change impacts on groundwater systems.

3.1.1.1 Groundwater Depletion

One of the greatest challenges associated with groundwater dependence is the continuous decline in groundwater levels. Groundwater supplies approximately 84% of total water withdrawals across the Gulf region. However, rising temperatures, more frequent droughts, and increasing water demand have reduced groundwater recharge while accelerating groundwater abstraction. Climate change is projected to reduce the region's renewable water resources by an additional 20% by 2030, further intensifying pressure on regional aquifers [28]. As a result, many major aquifer systems across the Arabian Peninsula are being exploited beyond their natural recharge rates, leading to widespread groundwater depletion and declining water tables.

3.1.1.2 Reduced Groundwater Recharge

Another major consequence of climate change is the reduction in groundwater recharge. Aquifers are broadly classified into two categories: renewable and fossil aquifers. Renewable aquifers are replenished through the hydrological cycle and are therefore highly vulnerable to changes in precipitation and recharge patterns associated with climate change [29]. In contrast, fossil aquifers contain ancient groundwater that receives little to no natural recharge, making them effectively non-renewable. As fossil aquifers constitute the majority of Saudi Arabia's groundwater reserves [30], the country's water security depends heavily on finite groundwater resources. Moreover, groundwater recharge is an inherently slow process, making it difficult to offset increasing groundwater abstraction and the reduced recharge rates caused by climate change [31].

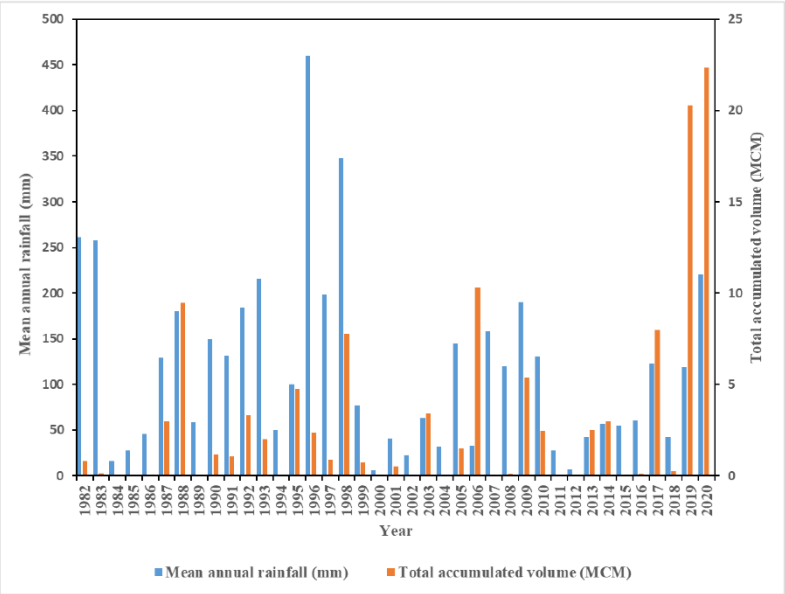


Figure 3-3: Per capita renewable water resources across the Middle East and North Africa (MENA) region in 1992, 2002, 2011, and 2020. Source: Sherif et al. 2023.

3.1.1.3 Groundwater Quality Deterioration

Another major consequence of climate change is the deterioration of groundwater quality. Rising temperatures increase groundwater temperatures, accelerating microbial activity and reducing dissolved oxygen concentrations within aquifers. These changes alter groundwater chemistry, promote more reducing conditions, and increase the mobilization of naturally occurring contaminants such as arsenic, manganese, iron, and fluoride, thereby reducing groundwater quality and increasing water treatment requirements [32]. Furthermore, sea-level rise accelerates saltwater intrusion into coastal aquifers, increasing groundwater salinity and reducing freshwater availability [33]. Together, these processes pose a growing threat to groundwater quality and long-term water security, particularly in arid coastal regions such as Saudi Arabia.

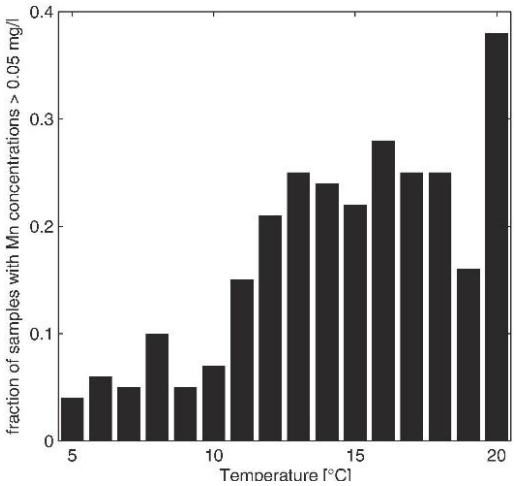


Figure 3-4: : Demonstrates that manganese (Mn) concentrations increase with groundwater temperature. Higher temperatures promote reducing conditions that mobilize Mn from aquifer sediments, increasing the proportion of samples exceeding the drinking water guideline of 0.05 mg L^{-1}. Source: Riedel 2019.

3.1.1.4 Saltwater Intrusion

Saltwater intrusion is one of the most significant climate change impacts on groundwater quality. As discussed previously, sea-level rise increases groundwater salinity, reducing freshwater availability and increasing treatment requirements. A recent study in Al-Ahsa reported that 48.15% of groundwater samples were classified as very highly polluted [34], highlighting the severity of groundwater quality deterioration. Although excessive groundwater abstraction remains the primary driver, climate change is expected to exacerbate saltwater intrusion through sea-level rise and reduced groundwater recharge, further increasing the vulnerability of coastal aquifers.

3.1.2 Desalination

Desalination is the primary source of municipal freshwater in Saudi Arabia and a cornerstone of the Kingdom's water security strategy. According to the Saudi Water Authority (SWA) Open Data Portal, approximately 2,092.214 million m^3 of desalinated water was produced in 2024, with seawater reverse osmosis (SWRO) and thermal desalination accounting for most of the production. Although desalination has enabled Saudi Arabia to overcome its limited natural freshwater resources, the sector is becoming increasingly vulnerable to climate change. The major climate-related threats to desalination include reduced operational efficiency, increased seawater salinity, higher energy demand, and greater vulnerability of coastal infrastructure to extreme weather events and sea-level rise.

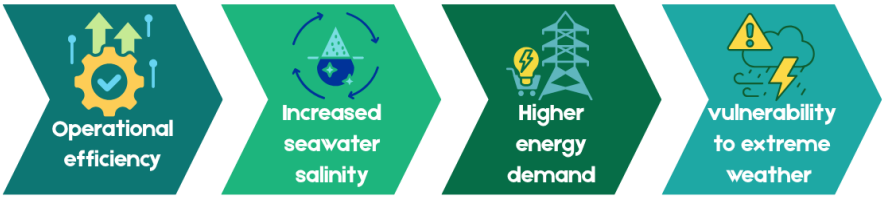


Figure 3-5: Major climate change impacts on desalination systems.

3.1.2.1 Operational Efficiency

One of the first impacts of climate change on desalination is the reduction in operational efficiency. Rising ambient temperatures, seawater temperatures, and seawater salinity are expected to reduce plant performance while increasing energy requirements. Yang et al. (2024) estimated that a 10°C increase in temperature could raise desalination energy consumption by approximately 20%, highlighting the growing energy burden under future climate scenarios [35]. As desalination is already one of Saudi Arabia's most energy-intensive water supply technologies, these changes are likely to increase operational costs and greenhouse gas emissions unless more energy-efficient technologies and renewable energy sources are adopted.

3.1.2.2 Increased Seawater Salinity

Climate change is expected to increase seawater salinity in the Arabian Gulf by intensifying evaporation while reducing the relative contribution of freshwater inputs. The Gulf is particularly vulnerable because it is a shallow, semi-enclosed, hyper-arid basin with evaporation rates of 2–5 m/year, far exceeding annual precipitation (0.15 m/year) and river inflows (0.15–0.19 m/year) [7]. Consequently, dissolved salts become increasingly concentrated, and the Gulf already exhibits salinity levels of 40,000–45,000 ppm, compared with the global ocean average of approximately 35,000 ppm [7]. Rising seawater salinity increases osmotic pressure, promotes membrane fouling and scaling, and reduces desalination efficiency, ultimately increasing energy consumption and operational costs for desalination plants across the Gulf region [10].

3.1.2.3 Higher Energy Demand

Climate change is expected to increase the energy requirements of desalination plants through rising seawater and ambient temperatures. Higher temperatures alter feedwater properties and increase the energy required for pumping, cooling, and auxiliary systems, while increasing seawater salinity raises the osmotic pressure that reverse osmosis systems must overcome [36]. A modelling study by Tahir, Al-Ghamdi, and Al-Ansari (2026) found that increasing the feedwater temperature from 25°C to 40°C increased the specific power consumption of a seawater reverse osmosis (SWRO) plant by approximately 7.5%. Given that desalination already accounts for a substantial share of electricity consumption in Gulf countries, climate-driven increases in energy demand will raise operational costs and greenhouse gas emissions unless supported by energy-efficient technologies and renewable energy integration [10].

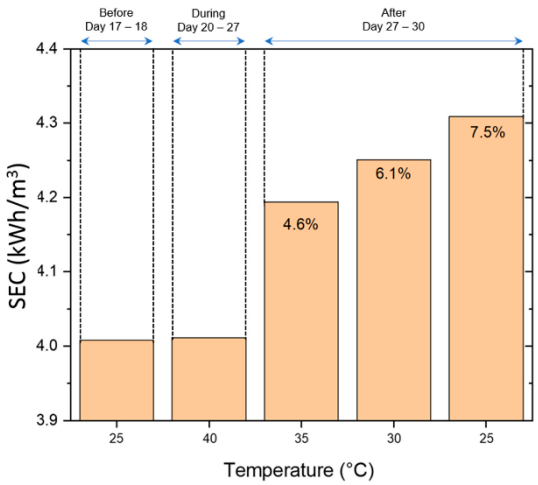


Figure 3-6: Average specific energy consumption (SEC) of a reverse osmosis (RO) desalination system before, during, and after a short-term (7-day) increase in feed seawater temperature, illustrating the impact of rising seawater temperatures on desalination energy demand. Source: Yang et al. (2024).

3.1.2.4 Vulnerabilities to Extreme Whether

Desalination plants are increasingly vulnerable to climate change because rising seawater temperatures, ocean acidification, and changes in seawater chemistry directly affect plant performance and water quality. Higher feedwater temperatures reduce reverse osmosis membrane efficiency, while lower seawater pH and increased dissolved inorganic carbon alter carbonate chemistry and pretreatment processes. Modelling studies further indicate that future climate scenarios may increase total dissolved solids, chloride, sodium, and boron concentrations in desalinated water, making it more difficult for some systems to consistently meet drinking water standards [37]. In addition, climate-induced changes in seawater chemistry can increase operational complexity and may result in greater carbon dioxide emissions during disinfection and coagulation processes, highlighting the need for more resilient desalination technologies under future climate conditions.

3.2 Water Transmission

3.2.1 Long Distance Pipes

Water transmission systems are also vulnerable to the impacts of climate change, particularly long-distance transmission pipelines. In the Gulf region, most desalination plants are located along the coast, whereas major population centres are situated inland, requiring freshwater to be transported over hundreds of kilometres. This centralized configuration increases the exposure of pipelines, pumping stations, and associated infrastructure to extreme heat, flooding, and sea-level rise, potentially disrupting water supply [38]. Moreover, the failure of a major transmission pipeline or desalination plant could interrupt potable water delivery to large population centres within days due to limited emergency water storage capacity [39]. These risks highlight the need to strengthen transmission infrastructure, expand strategic water storage, and diversify water supply systems to enhance resilience under future climate conditions.

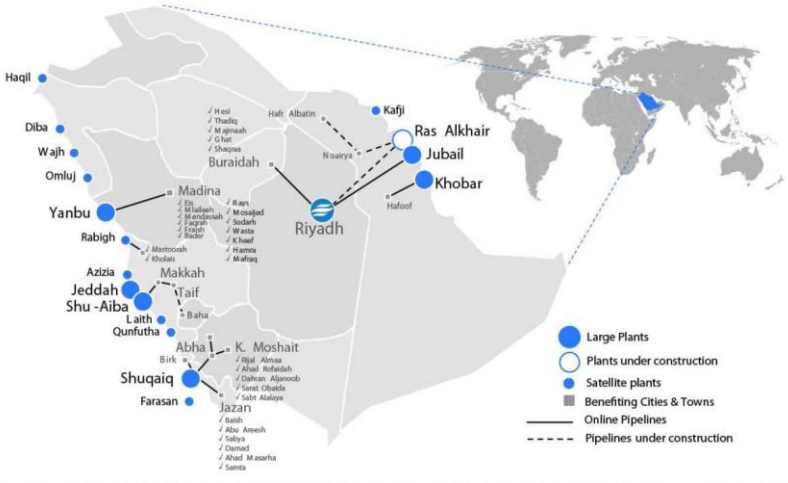


Figure 3-7: Water transmission and distribution network of Saudi Arabia. Source: Saline Water Conversion Corporation (SWCC).

3.3 Pumping Station

Rising temperatures can adversely affect the performance and reliability of water transmission pumping stations. As water temperature increases, its vapor pressure also rises, making pumps more susceptible to cavitation, a process in which vapor bubbles form and collapse within the pump, reducing hydraulic efficiency and causing vibration, noise, and mechanical damage [40]. Experimental studies have shown that the thermodynamic effects associated with cavitation become substantially more significant at elevated temperatures, with the thermodynamic effect parameter increasing by approximately 23 times as water temperature rises from 20°C to 90°C [41]. In addition, higher ambient temperatures increase cooling requirements for motors and electrical equipment, accelerate component degradation, and increase maintenance needs. These impacts reduce the reliability of pumping stations and may increase the energy required to maintain water transmission under future climate conditions [25].

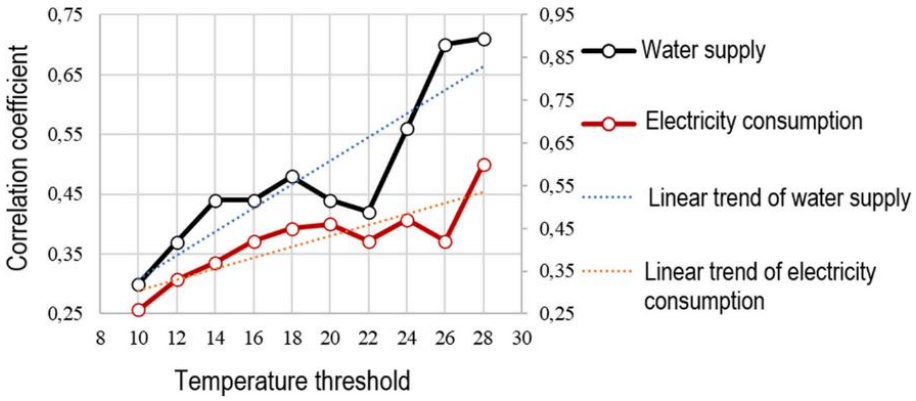


Figure 3-8: Key factors influencing urban water consumption and their implications for the energy-efficient management of pumping stations. Adapted from Identification of Easily Accessible Urban Water Consumption Factors for Energy-Efficient Management of Pumping Stations. Source: Koutsou et al. 2020.

3.4 Distribution Network

3.4.1 Threats Of Leakage

Climate change is increasing the frequency and intensity of flooding, posing a significant threat to water distribution infrastructure. Flooding can damage pipelines and increase the likelihood of leaks, which not only result in water losses but also raise the risk of water contamination. In addition, flood events can disrupt water supply services and reduce the reliability of distribution networks. Because water distribution systems are closely interconnected with other critical infrastructure, flood-induced failures may trigger cascading disruptions that extend beyond the affected area, highlighting the need for climate-resilient infrastructure and proactive flood risk management [42].

3.4.2 Threats of Pipe Failure

Climate change is expected to increase the risk of water pipeline failures by exposing buried infrastructure to more frequent and intense environmental stresses. Extreme rainfall and flooding can erode surrounding soils, reduce pipe support, and trigger ground movement, increasing the likelihood of pipe deformation, joint separation, and rupture. Conversely, prolonged drought and higher temperatures can cause soil shrinkage, differential settlement, and accelerated material aging, placing additional mechanical stress on buried pipelines [43]. These combined climate-related hazards reduce pipeline reliability, increase maintenance requirements, and raise the risk of water losses and service disruptions, highlighting the need for more climate-resilient water distribution networks.

3.4.3 Pressure Fluctuations

Climate change is expected to increase pressure fluctuations within water supply systems by increasing the frequency and intensity of extreme weather events that disrupt normal hydraulic conditions. Extreme climate events can alter water demand patterns, damage pipelines, and increase pipe leakage and bursts, leading to abnormal pressure variations throughout the distribution network. A field study of two severe cold waves demonstrated that extreme weather caused significant pressure fluctuations, with minimum average network pressure decreasing by 8.3–9.1%, while daily water demand increased by up to 14.8% compared with normal operating conditions [44]. The study further showed that pipe failures occurred more frequently during periods of rapid pressure and temperature changes, indicating that fluctuations in internal pressure generate additional mechanical stress on pipelines and increase the likelihood of structural failure. These findings highlight climate-driven extremes can compromise the hydraulic stability and reliability of water supply systems, emphasizing the need for resilient network design and adaptive pressure management strategies.

3.5 Wastewater Collection

3.5.1 Combined Sewer System

Urban water systems generally operate using one of two sewer configurations: separate sewer systems (SSSs) and combined sewer systems (CSSs). In an SSS, two independent pipeline networks are used, with one conveying municipal wastewater to a wastewater treatment plant and the other carrying stormwater runoff directly to a designated discharge point. In contrast, a CSS collects both municipal wastewater and stormwater within a single pipeline network, conveying the combined flow to a wastewater treatment plant or, during overflow events, to a designated discharge point.

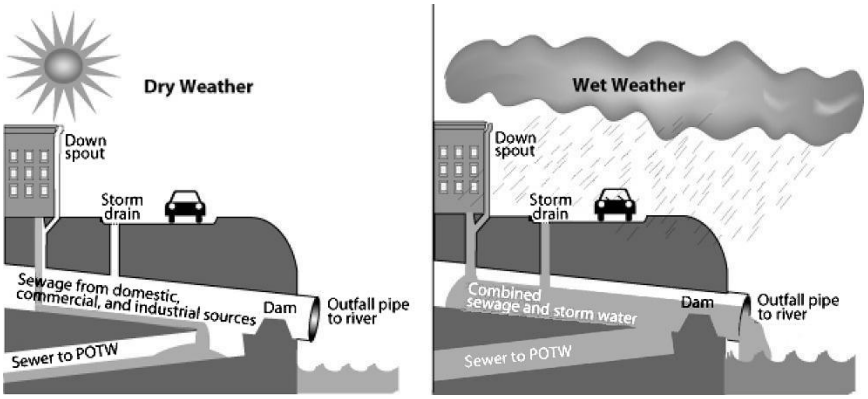


Figure 3-9: Comparison of the intended operation of a combined sewer system (CSS) and a combined sewer overflow (CSO) during a wet weather event. Source: U.S. Environmental Protection Agency (EPA).

3.5.2 The Issue with CSSs

Although separate sewer systems generally provide greater operational efficiency and reduce the risk of stormwater-related contamination, many Gulf countries continue to rely on combined sewer systems because of their lower infrastructure and construction costs. However, this dependence presents significant challenges for sustainable water management. Gastoldi, Gergawi, and Burt (2025) reported that only 73% of the municipal wastewater collected across the six Gulf Cooperation Council (GCC) countries was treated in 2020 [45]. In a region facing severe water scarcity, this represents a substantial loss of potentially reusable water resources and highlights the need to improve wastewater collection, treatment, and reuse infrastructure.

3.5.2.1 The Flooding Threats of CSSs

Climate change is expected to increase the frequency and intensity of extreme rainfall events, placing greater pressure on combined sewer systems. During heavy rainfall, stormwater runoff and domestic wastewater enter the same pipeline network, and when the combined flow exceeds the design capacity of the system, sewer nodes overflow, leading to urban flooding and untreated wastewater discharges. A SWMM-based modelling study demonstrated that increasing rainfall intensity substantially increased sewer flooding. As the rainfall return period increased from 2 years to 25 years, total runoff increased from 5,090 m^3 to 23,450 m^3, while the flooding volume rose from 3,817 m^3 to 13,434 m^3. Over the same range, the number of flooded sewer nodes increased from 36 (9%) to 138 (34%) of the total network nodes, illustrating how more intense rainfall can rapidly exceed the hydraulic capacity of combined sewer systems and increase the risk of sewer overflows and urban flooding [46].

3.5.2.2 The Economic Issue of CSSs

Although separate sewer systems require higher initial construction costs than combined sewer systems, they can provide substantial long-term economic and environmental benefits. By separating stormwater from municipal wastewater, stormwater can be safely discharged or reused while reducing the risk of combined sewer overflows during extreme rainfall events. Sušnik et al. (2014) evaluated this approach in Eindhoven and found that separating sewer and stormwater networks consistently reduced flood damage costs. Total flood damage decreased by approximately €136,000 during a 2-year rainfall event and by €780,000 during a 10-year event, while the expected annual damage (EAD) was reduced by approximately €130,500 [47]. These findings demonstrate that, despite higher upfront investment costs, separate sewer systems can generate significant long-term economic savings and enhance urban resilience to climate change.

3.6 Water Reuse

3.6.1 The Rule of Water Reuse in Enhancing Water Scarcity

Treated wastewater has become an increasingly important alternative water resource in Saudi Arabia, particularly for agricultural irrigation. By supplementing groundwater supplies, wastewater reuse helps reduce pressure on limited freshwater resources while providing a reliable, climate-independent water source. In the Al-Ahsa Oasis alone, approximately 200,000 m^3/day of treated wastewater is reused for irrigation [48]. In addition to conserving freshwater and reducing groundwater abstraction, treated wastewater contains nutrients that can improve agricultural productivity. Consequently, expanding wastewater reuse has become a key objective of Saudi Vision 2030 to strengthen national water security and reduce dependence on non-renewable groundwater.

3.6.2 Public Acceptance

Public acceptance is a key factor determining the successful implementation of wastewater reuse programmers. Although treated wastewater represents a sustainable alternative water source for water-scarce regions, public perception remains a significant barrier to its widespread adoption. Mu'azu et al. (2020) found that many people continue to associate treated wastewater with health risks regardless of the treatment technology employed, with concerns driven by perceived contamination, cultural beliefs, and limited public awareness. The study also reported that acceptance was generally higher for treated greywater than for mixed wastewater and was influenced by factors such as education level, age, gender, and place of residence. The authors concluded that achieving Saudi Arabia's wastewater reuse targets under Vision 2030 will require extensive public awareness campaigns, clear water quality standards, and improved communication regarding the safety and environmental benefits of treated wastewater reuse [49].

4 Solutions for Climate-Resilient Urban Water System

This chapter evaluates the climate vulnerabilities of major urban water sources and identifies measures that can strengthen their long-term resilience. The assessment focuses on desalination, groundwater, wastewater reuse, and rainwater harvesting, considering their exposure to climate-related stresses such as rising temperatures, changing precipitation, extreme events, and infrastructure failure. Based on these vulnerabilities, four main resilience strategies are evaluated: nature-based solutions, smart water systems, infrastructure resilience, and the circular water economy**,** which collectively aim to diversify water supplies, improve system reliability, and enhance adaptation to future climate conditions.

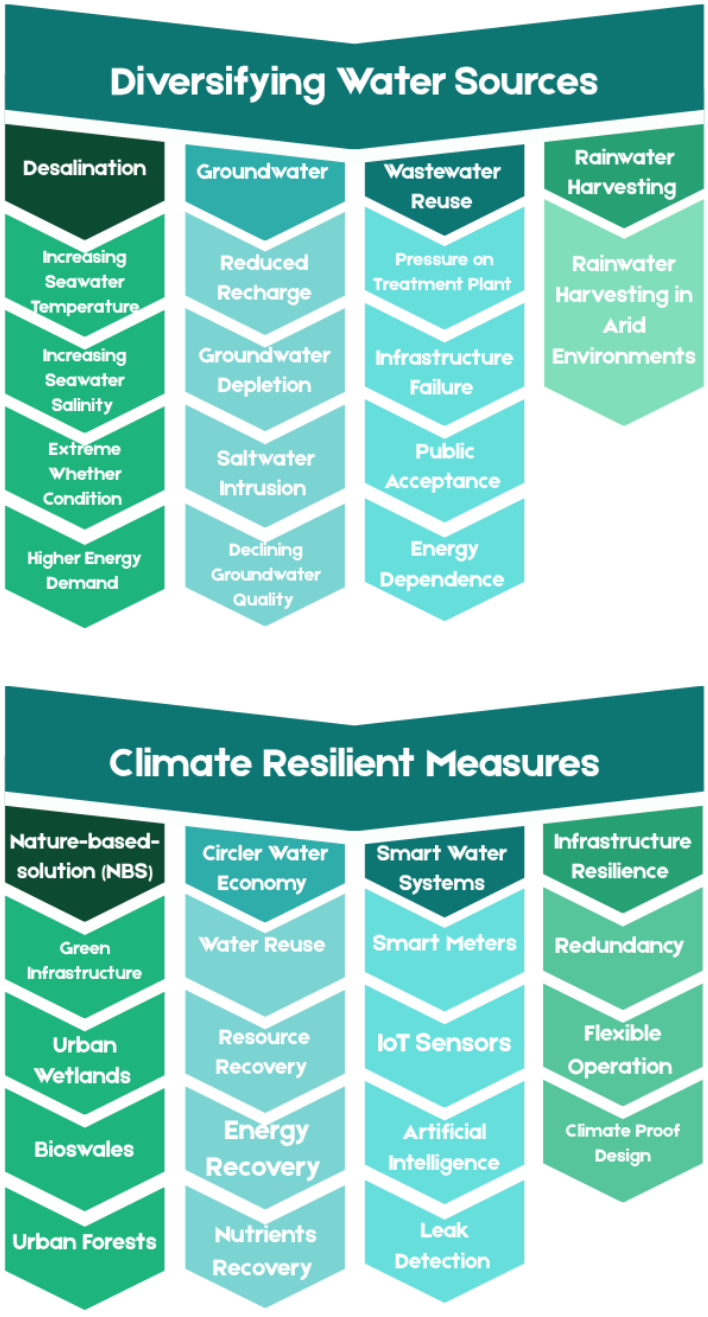


Figure 4-1: Summary of the proposed measures for enhancing climate resilience across urban water systems.

4.1 Diversifying Water Sources

4.1.1 Desalination

Desalination is the primary source of freshwater in the Gulf Cooperation Council (GCC) countries, where extremely limited rainfall, high evaporation rates, and scarce renewable freshwater resources make conventional water supplies insufficient to meet growing demand. As a result, desalination has become a critical component of regional water security. However, despite its importance, the sector remains vulnerable to climate change, highlighting the need to strengthen the resilience of desalination systems to ensure a reliable and sustainable water supply.

4.1.1.1 Increasing Seawater Temperature

Increasing seawater temperatures can reduce the climate resilience of seawater reverse osmosis (SWRO) desalination by affecting membrane separation performance and increasing the risk of fouling and scaling. Higher feedwater temperatures increase both water and salt permeability; however, salt permeability increases more rapidly, resulting in lower salt rejection and reduced permeate quality [50]. This is particularly relevant in the Arabian Gulf, where seawater already has high temperatures and salinity, making desalination systems more vulnerable to further warming [51]. Moreover, higher temperatures can intensify membrane scaling. Experimental results showed that increased temperatures enhanced calcium sulfate scaling, leading to greater crystal deposition, thicker scale layers, and more pronounced permeate flux decline [52]. Consequently, continued seawater warming may reduce SWRO performance, increase maintenance requirements, and challenge the long-term reliability and climate resilience of desalination systems.

4.1.1.2 Increasing Seawater Salinity

Increasing seawater salinity under climate change can further challenge the resilience and energy efficiency of seawater reverse osmosis (SWRO) desalination. Rising temperatures can intensify evaporation, contributing to higher seawater salinity and, consequently, greater feedwater osmotic pressure. This requires higher hydraulic pressure to overcome osmotic pressure and drive water through the RO membrane, thereby increasing energy consumption [53]. Chen and Yip (2018) demonstrated that osmotic pressure increases with total dissolved solids (TDS), while the energy requirements of conventional RO increase with feedwater salinity. Similarly, Koutsou et al. (2020) found that seawater osmotic pressure increases with temperature, reaching approximately 33.3 bar at 40°C compared with 30.6 bar at 15°C [25]. Therefore, climate-driven increases in seawater salinity and temperature may increase pumping pressure and specific energy consumption, placing additional pressure on the operational and energy requirements of SWRO systems.

4.1.1.3 Extreme Whether Condition

Extreme weather events can threaten the climate resilience of coastal desalination plants by disrupting seawater intake and treatment operations. Storm surges and coastal flooding can expose intake structures and other coastal infrastructure to physical damage, while strong winds and high waves can generate currents that resuspend organic and suspended materials around seawater intakes. During Storm Hans, for example, strong currents and waves stirred up organic material that clogged intake pipes and filters, causing pressure and pump performance issues and requiring manual cleaning and maintenance [54]. Strong winds can also increase turbidity and suspended solids, placing additional pressure on filtration systems [55]. Consequently, more frequent or intense coastal storms under climate change may reduce desalination reliability by damaging intake infrastructure, obstructing seawater intake, and causing temporary operational disruptions.

4.1.1.4 Higher Energy Demand

Climate change can increase the energy demand of desalination plants, particularly in hot and arid regions where rising temperatures increase cooling requirements. Higher ambient temperatures place additional demands on cooling systems, increasing the electricity required to maintain suitable operating conditions [56]. This is particularly significant because desalination is already an energy-intensive water supply technology. Moreover, increasing water scarcity may drive greater reliance on desalination, further increasing electricity consumption; Rosa et al. (2026) estimated that under a 3°C warming scenario, desalination used to address global water scarcity could require up to 1,669 TWh of electricity annually. Since energy is a major component of reverse osmosis desalination costs, increased electricity demand can also raise operational costs [57]. Consequently, rising temperatures may reduce desalination resilience by increasing cooling requirements, energy consumption, and the cost of maintaining reliable water production.

4.1.2 Groundwater Management

4.1.2.1 Reduced Recharge

Climate change can significantly reduce groundwater recharge by altering both precipitation patterns and evapotranspiration rates. Declining rainfall directly reduces the amount of water available to infiltrate through the soil and replenishes aquifers. Berghuijs et al. (2024) found that groundwater recharge is highly sensitive to changes in precipitation, with projected recharge changes generally being larger than the corresponding changes in rainfall; on average, a 1% change in precipitation was associated with approximately a 2.2% change in groundwater recharge. At the same time, rising temperatures increase potential evapotranspiration and evaporative demand, meaning a greater proportion of available water is returned to the atmosphere rather than recharged groundwater. Recharge therefore tends to decrease as potential evapotranspiration increases, particularly where potential evapotranspiration already exceeds precipitation [58]. Similarly, Condon et al. (2020) showed that warming increases evaporative demand and can shift the partitioning of precipitation toward evapotranspiration and away from subsurface recharge, ultimately contributing to declining groundwater storage [59]. Therefore, the combined effects of lower rainfall and higher evapotranspiration increase climatic aridity, reduce the fraction of precipitation reaching aquifers, and weaken the long-term replenishment of groundwater resources.

4.1.2.2 Groundwater Depletion

Climate change can accelerate groundwater depletion by increasing dependence on aquifers during droughts while contributing to long-term declines in groundwater levels. During prolonged dry periods, reduced precipitation and surface-water availability can force agricultural and municipal users to increase groundwater abstraction to compensate for shortages. Taylor et al. (2013) reported that during the 2006–2009 drought in California's Central Valley, irrigation shifted from surface water to predominantly groundwater, contributing to a groundwater-storage decline of approximately 24–31 km^3 [60]. This dependence is expected to become increasingly important under climate change, as longer droughts can increase irrigation-water demand and encourage further shifts toward groundwater supplies (Taylor et al., 2013). As abstraction increasingly exceeds aquifer replenishment, groundwater tables progressively fall. Jasechko et al. (2024), using measurements from approximately 170,000 monitoring wells across 1,693 aquifer systems, found that groundwater levels declined by more than 0.1 m yr^{-1} in 36% of the assessed aquifer systems and by more than 0.5 m yr^{-1} in 12% [61]. Moreover, groundwater-level declines accelerated in 30% of the aquifers with sufficient long-term records, and more than 80% of aquifers experiencing accelerating declines also experienced decreasing precipitation. These findings demonstrate how drought can create a reinforcing pressure on groundwater systems: less precipitation limits water availability and recharge, while greater abstraction during drought increases depletion, ultimately causing groundwater tables to fall and making groundwater resources increasingly difficult to access.

4.1.2.3 Saltwater Intrusion

Climate change increases the vulnerability of coastal groundwater resources to saltwater intrusion (SWI) through sea-level rise, intensified coastal storms, flooding, and changes in groundwater recharge. Cantelon et al. (2022) explain that SWI occurs when saltwater migrates into freshwater aquifers through both lateral and vertical pathways. Lateral saltwater intrusion can occur when rising sea levels, reduced aquifer recharge, or groundwater pumping decrease the hydraulic gradient between land and sea, allowing the freshwater–saltwater interface to move inland. In addition, climate-driven increases in coastal flooding can cause vertical saltwater intrusion, where seawater inundates the land surface and infiltrates downward into the aquifer, displacing and mixing with fresh groundwater [62]. This threat is expected to increase as rising sea levels and more intense coastal storms increase exposure to seawater flooding. The impacts can persist well beyond the initial flood event; although coastal flooding may last only hours or days, resulting groundwater salinization can persist for years or even decades before freshwater recharges fully flushes the saltwater from the aquifer. Consequently, saltwater intrusion can reduce groundwater quality, render freshwater unsuitable for human consumption, force the closure of agricultural, industrial, and domestic wells, and increase the cost of potable water, thereby reducing the long-term climate resilience of coastal groundwater supplies.

4.1.2.4 Declining Groundwater Quality

Climate change can contribute to declining groundwater quality by altering groundwater salinity, temperature, recharge, and contaminant concentrations. Changes in precipitation and rising temperatures affect groundwater recharge and hydrological conditions, while droughts can concentrate contaminants because less water is available for dilution [63]. Coastal aquifers face an additional threat from salinization, as sea-level rise and coastal flooding promote seawater intrusion and alter groundwater chemistry [64]. Extreme events can further accelerate this deterioration; Richardson et al. (2024) reported that groundwater salinity increased by more than tenfold following a tropical cyclone in the Northern Cook Islands and remained elevated for over two years, while chloride concentrations in coastal North Carolina increased from 40 to 280 mg/L following hurricane-related storm-surge flooding and remained elevated throughout a four-year monitoring period. More frequent storm surges under climate change can also repeatedly introduce salt into aquifers before they have sufficient time to recover, resulting in progressive salinization and making portions of coastal groundwater less suitable for freshwater extraction [65]. Therefore, climate change can reduce groundwater quality through the combined effects of increased salinity, contaminant concentration, altered groundwater chemistry, and repeated extreme events, ultimately reducing its suitability as a reliable freshwater source.

4.1.3 Wastewater Reuse

4.1.3.1 Pressure on Treatment Plant

Increasing urban water demand can reduce the climate resilience of wastewater reuse systems by generating larger wastewater volumes that place additional pressure on treatment plants. As influent volumes approach or exceed treatment capacity, hydraulic overloading can reduce treatment efficiency and compromise effluent quality, limiting the amount of wastewater that can be safely reused [66]. This vulnerability becomes increasingly important under climate change, as reliable wastewater reuse depends on treatment facilities maintaining sufficient capacity and water quality despite growing urban demand and changing operating conditions.

4.1.3.2 Infrastructure Failure

Infrastructure failure can reduce the climate resilience of wastewater treatment systems by disrupting wastewater collection and limiting the reliable production of reclaimed water. Sewer pipelines are particularly vulnerable to microbially induced concrete corrosion (MICC), where microbial activity produces hydrogen sulfide and acids that progressively deteriorate concrete. Yuan et al. (2022) found serious corrosion in sewer pipes of different service ages, with several locations requiring immediate rehabilitation [67]. Such deterioration can lead to sewage leakage, structural failure, higher maintenance requirements, and interruptions to wastewater treatment and reuse.

4.1.3.3 Public Acceptance

Public acceptance is an important factor influencing the climate resilience of treated wastewater reuse because the availability of reclaimed water does not guarantee its effective utilization. In the GCC, only 39% of treated wastewater is reused, partly due to social, health, and religious concerns, particularly regarding its use for food production [68]. Consumers may avoid products irrigated with treated wastewater, which can discourage farmers from adopting it and limit its ability to substitute freshwater and groundwater supplies. Increasing public awareness, trust in treatment processes, and understanding of water-scarcity benefits is therefore essential for wastewater reuse to function as a reliable climate-resilient water source.

4.1.3.4 Energy Dependence

Energy dependence reduces the climate resilience of wastewater treatment because treatment plants rely heavily on a continuous electricity supply for essential processes such as pumping, aeration, and filtration. Wastewater treatment plants typically consume around 0.85 kWh/m³, while facilities operating under stricter effluent-quality requirements can exceed 1.18–1.35 kWh/m³; despite the energy contained within wastewater, only a small proportion of plants currently achieve energy self-sufficiency [69] [70]. This dependence creates an important climate vulnerability because extreme events such as flooding can damage electricity networks and cause cascading failures that interrupt wastewater treatment services. Improving energy efficiency, recovering energy through biogas, and increasing renewable-energy integration can therefore reduce dependence on external power supplies and strengthen the climate resilience of wastewater treatment systems.

4.1.4 Rainwater Harvesting

4.1.4.1 Rainwater Harvesting in Arid Environments

Rainfall is not a major source of freshwater in Saudi Arabia due to its hyper-arid climate, with a country-average annual rainfall of only 92.5 mm during the period 1978–2019. However, climate change is altering precipitation patterns, making rainfall events less frequent but considerably more intense. Almazroui (2020) reported that the frequency of heavy rainfall events (≥30 mm/day) has increased, while light-to-moderate rainfall events have declined, increasing the likelihood of flash floods [71]. Similarly, Giorgi, Raffaele, and Coppola (2019) demonstrated that global warming leads to a higher-intensity, lower-frequency precipitation regime, characterized by fewer rainfall events but more extreme downpours [72]. Despite this emerging trend, Saudi Arabia has limited infrastructure for rainwater harvesting and stormwater reuse, resulting in large volumes of runoff being lost and causing flood hazards instead of contributing to the country's freshwater supply. Given the country's severe water scarcity, developing infrastructure to capture and utilize intense rainfall events through rainwater harvesting and managed aquifer recharge could transform an increasing climate risk into a valuable alternative water resource.

4.2 Climate Resilient Measures

4.2.1 Nature-based-solution (NBS)

Nature-Based Solutions (NBSs) can improve the sustainability and climate resilience of urban water systems by using natural processes to manage rainfall, runoff, water quality, groundwater recharge, and urban temperature. Instead of relying only on conventional grey infrastructure, NBSs can retain and treat stormwater locally, increase infiltration, and create additional opportunities for groundwater replenishment and water reuse. Meney and Pantelic (2021) identify wetlands, living streams, biofilters, and other green infrastructure as systems that can support the capture and treatment of stormwater, groundwater, and recycled wastewater, allowing them to complement existing centralized water networks [73].

4.2.1.1 Green Infrastructure

Green infrastructure provides a broader framework for integrating natural and decentralized systems into conventional urban water networks. It can include wetlands, greenways, living streams, rain gardens, green roofs, and infiltration systems that manage water closer to where rainfall occurs. Meney and Pantelic (2021) highlight that these systems can supplement conventional water infrastructure while supporting stormwater capture, groundwater replenishment, wastewater treatment, and urban heat mitigation [65]. The performance can be strengthened further when several NBSs are connected; for example, Dutta et al. (2021) found that a network combining vegetative swales and porous pavement removed approximately 33% of total suspended solids (TSS), 42% of total nitrogen (TN), and 38% of total phosphorus (TP) during a two-year rainfall event [74].

4.2.1.2 Urban Wetlands

Urban and constructed wetlands improve water-resource sustainability by storing stormwater, reducing flood peaks, naturally treating runoff, and potentially supporting groundwater recharge and water reuse. Barman et al. (2024) reported that constructed wetlands can reduce peak stormwater flows by up to 60% and remove approximately 90% of suspended solids from runoff [75]. Wetlands also filter nutrients and contaminants through sedimentation, vegetation uptake, and microbial processes, improving the quality of water available for subsequent infiltration or reuse. Consequently, wetlands can simultaneously improve the quantity and quality of locally retained water while reducing pressure on conventional drainage infrastructure.

4.2.1.3 Bioswales

Bioswales are shallow vegetated channels that collect stormwater from roads, parking areas, and other impermeable surfaces while slowing runoff and encouraging infiltration and natural treatment. Their effect can be substantial: Dutta et al. (2021) found that vegetative swales reduced peak flow by 46% during a two-year rainfall event while removing 43% of TSS, 56% of TN, and 62% of TP. Under a more intense five-year rainfall event, they still reduced both peak flow and runoff volume by 23%, with removal efficiencies of 40% TSS, 45% TN, and 41% TP [74]. These improvements increase the amount and quality of stormwater retained within the urban water cycle rather than rapidly discharging it from the city.

4.2.1.4 Urban Forests

Urban forests and street trees contribute to water-system resilience by intercepting rainfall, increasing permeable land cover, reducing surface runoff, and lowering urban temperatures through shading and evapotranspiration. Meney and Pantelic (2021) identify urban heat mitigation as one of the multiple benefits generated by green infrastructure [65]. The cooling effect can also be quantitatively significant: Zaerpour, Papalexiou, and Pietroniro (2025) found that increasing tree canopy by 10%, 20%, and 30% reduced average air temperatures in urban heat hotspots by approximately 0.8°C, 1.1°C, and 1.5°C, respectively [3]. This cooling can reduce heat stress on urban infrastructure and energy systems while vegetation simultaneously assists with rainfall interception and runoff management. However, the magnitude of cooling is site-specific and should not be interpreted as an equivalent reduction in seawater or desalination-feed temperature.

4.2.2 Smart Water Systems

Smart Water Systems can strengthen climate resilience by continuously monitoring water demand, water quality, storage levels, and distribution-network performance. This allows utilities to shift from reactive management to real-time and predictive operation, which is particularly important during droughts, extreme rainfall, and periods of high-water demand. Digital technologies can also reduce physical water losses and improve the allocation of limited resources, increasing the amount of existing supply that remains available during climate-related shortages. Pietrucha-Urbanik and Rak (2026) identify the integration of real-time monitoring, AI-enabled analytics, and intelligent leak detection as an important direction for improving the reliability and resilience of future water utilities [76].

4.2.2.1 Smart Meters

Smart meters provide continuous information on household and network water consumption, allowing utilities to identify abnormal consumption, improve demand management, and detect potential losses much earlier than conventional meter-reading systems. This is particularly valuable during droughts, when reducing unnecessary demand can preserve limited water supplies without constructing additional supply infrastructure. In a smart-meter pilot study, Einyu et al. (2025) reported a 23% reduction in non-revenue water, while the time required to repair detected leaks was reduced by 64% [77]. Smart meters can therefore increase climate resilience by reducing avoidable demand and maintaining more water within the distribution system during periods of scarcity.

4.2.2.2 IoT Sensors

Internet of Things (IoT) sensors can continuously monitor variables such as water level, pH, turbidity, temperature, dissolved oxygen, flow, and pressure, transmitting information directly to utilities for real-time decision-making. This enables operators to respond rapidly to abnormal conditions caused by floods, droughts, contamination events, or sudden changes in water availability. Chen et al. (2023) developed an IoT-based water monitoring system in which multiple sensors and dynamic controls improved water-level measurement accuracy by more than 15%, while the dynamic management system had the potential to conserve more than 15% of water resources; the proposed monitoring approach also reduced system costs by over 60% compared with existing technologies. Such systems can therefore help utilities balance storage and distribution dynamically as climate conditions change.

4.2.2.3 Artificial Intelligence

Artificial Intelligence can improve resilience by converting large amounts of sensor, climate, demand, reservoir, and groundwater data into forecasts that support anticipatory water allocation. Rather than waiting for a drought or shortage to occur, AI models can forecast reservoir inflows, groundwater levels, and future supply-demand imbalances and allow utilities to adjust operations beforehand. Moghaddam et al. (2025) used RNN and LSTM models to forecast the performance of five reservoirs and the Tehran aquifer under future climate scenarios [77]. Their optimized RNN models produced R^2 values of approximately 0.84–0.89 for reservoir inflow prediction, while detailed groundwater simulations achieved R^2 values of 0.88–0.99. The models also identified a projected 8–11% decline in dam inflows under future climate scenarios, demonstrating how AI can provide an early warning of future supply stress and support more resilient allocation decisions.

4.2.2.4 Leak Detection

Smart leak-detection systems use pressure, flow, acoustic, and other sensor data together with machine-learning algorithms to identify pipe failures rapidly and determine their location. Reducing leakage is especially important under climate change because every cubic metre lost from the distribution network increases the amount that must be extracted, treated, or desalinated to satisfy demand. Jiang et al.

(2025) developed an AI-based convolutional gated recurrent-unit system with an attention mechanism that achieved 98.75% leak-recognition accuracy under different leakage conditions [63]. Another transfer-learning approach reported by Cheng et al. (2025) achieved approximately 91.86% leak-detection accuracy [78]. Earlier and more accurate identification allows repairs to be initiated before leaks become major failures, reducing both water losses and the risk of supply interruption.

4.2.3 Infrastructure Resilience

Infrastructure resilience increases the ability of water-supply systems to maintain service during climate disturbances, recover rapidly after failures, and adapt their capacity and operation as climate conditions change. The main engineering principles include redundancy, flexible operation, and climate-proof design. Bhatta and Devkota (2026) identify robustness, redundancy, flexibility, and adaptive capacity as complementary characteristics of climate-resilient water infrastructure and emphasize that water infrastructure must increasingly be designed for non-stationary climatic conditions rather than historical conditions alone [79].

4.2.3.1 Redundancy

Redundancy involves providing alternative sources, treatment facilities, pipelines, or storage capacity so that failure of one component does not interrupt the entire water supply. Bhushan and Ng (2016) demonstrated this by integrating reservoirs with wastewater recycling and seawater desalination as backup supplies [43]. Under their optimized system, water-supply risk and vulnerability could be reduced to zero, although achieving this required additional investment. For the India case study, zero risk and vulnerability could be achieved with a 20–120% budget increase under the current climate and 30–150% under future climate conditions; for California, the corresponding ranges were 20–80% and 30–140%. This demonstrates how additional supply capacity can essentially provide insurance against climate-sensitive reservoir shortages.

A real-world example is Surat's interconnected GRID water distribution system, which allows distribution stations to receive water from alternative treatment plants if one facility fails. During the severe 2006 flood, approximately 80% of Surat was inundated, yet this redundancy helped the municipality restore the water supply within approximately 36 hours.

4.2.3.2 Flexible Operation

Flexible operation allows reservoir releases, treatment capacity, pumping, and water allocation rules to be adjusted as rainfall, storage, demand, and climate conditions change rather than relying on fixed historical operating rules. Willebrand et al. (2024) found flexible operation to be the most effective form of flexibility for reducing climate-related water shortage costs, particularly under dry climate scenarios [80]. Their Mwache Dam analysis showed that flexible operation could achieve optimized performance with an initial reservoir capacity of 110 MCM instead of 120 MCM, representing about an 8% reduction in required initial storage capacity, while also reducing initial infrastructure costs by approximately US$5 million. Flexible operating rules were particularly valuable as conditions became drier because they reduced water-shortage costs and allowed available storage to be used more efficiently.

4.2.3.3 Climate Proof Design

Climate-proof design incorporates expected future floods, droughts, temperature increases, changing precipitation, and other climate hazards directly into the design and maintenance of infrastructure. Measures can include elevated or protected electrical equipment, interconnected pipelines, additional storage, updated drainage capacity, modular infrastructure, updated rainfall design standards, and infrastructure that can be expanded or retrofitted later. Bhatta and Devkota (2026) note that without

deliberate adaptation, climate change could produce up to a tenfold increase in infrastructure damage from extreme weather by the end of the century, emphasizing the value of designing infrastructure for future rather than historical climate conditions [79].

Surat provides a useful practical example of the resulting recovery capacity. Despite the 2006 flood inundating approximately 80% of the city and disrupting electricity for nearly three days, climate-proofing measures—including interconnected water infrastructure, standardized maintenance, improved drainage, and emergency management—allowed water and electricity services to be restored within roughly 36 hours. The city subsequently developed an early-warning system capable of providing at least four days of advance notice before major releases from the upstream Ukai Dam reached the city, further improving preparedness.

4.2.4 Circler Water Economy

A Circular Water Economy (CWE) improves climate resilience by changing wastewater from an end-of-pipe waste stream into a source of water, energy, nutrients, and other recoverable resources. This reduces dependence on climate-sensitive freshwater supplies and external energy and material inputs. Tortajada et al. (2025) describe this transition from a linear water system toward one in which wastewater and stormwater are treated as resources, while Garrido-Baserba et al. (2024) show that decentralized circular systems can simultaneously recover water, energy, and nutrients and reduce pressure on centralized infrastructure [78].

4.2.4.1 Water Reuse

Reusing treated wastewater provides a reliable, locally generated water source that is considerably less dependent on rainfall than conventional surface-water supplies. It can substitute freshwater for irrigation, industry, groundwater recharge, and, with appropriate treatment, potable supply, leaving scarce freshwater available for higher value uses. During the severe 2015–2017 drought in Windhoek, Namibia, reused water supplied approximately 30% of the city's total water demand at the peak of the crisis, demonstrating its direct contribution to drought resilience. Similarly, California produced approximately 3.5 billion m^3 of reused water between 2019 and 2022, enough to cover the annual water requirements of an estimated 3–6 million households. Drechsel et al. (2022) further demonstrate that wastewater–freshwater swaps can improve water availability across sectors; in Mashhad, Iran, farmers exchanged 21 million m^3/year of freshwater for 25 million m^3/year of reclaimed wastewater, receiving a more reliable and approximately 1.2-times larger water allocation.

4.2.4.2 Resource Recovery

Circular systems can recover resources directly from wastewater instead of consuming additional freshwater and raw materials. Source separation is particularly useful because different wastewater streams contain very different concentrations of reusable materials. Garrido-Baserba et al. (2024) found that black water represents only about 20% of household wastewater volume but contains approximately 90% of its carbon and nitrogen and 80% of its phosphorus, making it a concentrated resource stream rather than simply waste [81]. Their decentralized city-block model showed that recycling household water streams could reduce freshwater demand by approximately 80–85%, while expanded potable reuse could potentially reduce dependence on centralized water supply by 90–95%. Such decentralized recovery also reduces the volume of water that must be transported through climate-vulnerable centralized sewer and supply networks.

4.2.4.3 Energy Recovery

Wastewater contains chemical, thermal, and hydraulic energy that can be recovered to decrease the energy dependency of water treatment systems. Anaerobic digestion can convert wastewater organic matter into biogas, which can then provide electricity and heat for treatment processes. In the decentralized system evaluated by Garrido-Baserba et al. (2024), anaerobic digestion and co-digestion recovered more than 50% of the wastewater treatment system's energy requirements through biogas [81]. At a larger operational scale, Sydney Water obtains approximately 21% of its total electricity requirements from 11 cogeneration plants located at eight wastewater-treatment facilities, while its North Head plant includes a 4.5 MW hydropower facility that recovers energy from treated wastewater discharge. Energy recovery therefore improves resilience by making water treatment less dependent on external electricity supplies while reducing operating emissions and costs.

4.2.4.4 Nutrients Recovery

Wastewater also contains valuable nitrogen, phosphorus, potassium and other nutrients that can be recovered instead of being discharged to the environment. This reduces nutrient pollution while decreasing dependence on externally manufactured fertilizers, whose availability and production can themselves be affected by energy and climate pressures. In the system modelled by Garrido-Baserba et al. (2024), separating urine allowed recovered nutrients to provide approximately 45% of the nitrogen and 7% of the phosphorus required by an associated vertical farm. Treatment of the brown-water stream through anaerobic digestion and struvite precipitation could recover approximately 90% of the phosphorus required by the vertical farm [81]. Anaerobic digestion also produces nutrient-rich digestate that can be reused as organic fertilizer, further closing the material cycle.

5 Policy Gaps

5.1 Existing Policy Framework for Water Resilience

Saudi Arabia has progressively strengthened its institutional and regulatory framework for water security. The National Water Strategy 2030 (NWS 2030) establishes continuous access to adequate quantities of safe water during both normal and emergency conditions as a strategic objective and includes a dedicated Sector Resilience Program intended to ensure preparedness for disruptions throughout the water and wastewater supply chain [82]. More recently, the Saudi Code for Water Sources and Their Uses, issued in 2025, introduced several provisions directly relevant to climate resilience, including drought classification, monitoring of climatic variability, groundwater abstraction control, flood-risk mapping, early-warning systems, and the reassessment of existing structures according to changing climatic conditions.

These developments indicate that climate resilience is increasingly recognized within Saudi water governance. Therefore, the principal policy gap is no longer the absence of climate considerations. Rather, the reviewed regulatory framework shows a remaining gap between strategic recognition of climate risks and their translation into standardized, measurable, and enforceable resilience requirements at the infrastructure and utility level. Existing penalties largely address conventional violations such as unauthorized abstraction, pollution, inefficient water use, and failure to comply with licensing requirements. The Water Law, for example, permits penalties including license revocation and fines of up to SAR 20 million per violation. However, equivalent regulatory mechanisms specifically linked to failure to assess, prepare for, or adapt infrastructure to projected climate conditions are less explicit in the reviewed instruments.



Figure 5-1: Summary of the main gaps in existing policy frameworks for addressing the climate resilience of urban water systems.

5.2 Gaps Related to Addressing Climate Resilience in the Water Sector

5.2.1 Gap 1: Limited Enforceable Climate-Resilience Performance Standards

Saudi Arabia's water policy framework recognizes preparedness, emergency supply, resource sustainability, and climate risk; however, resilience is generally expressed through planning requirements rather than a standardized set of performance indicators that utilities must achieve. This distinction is important because climate resilience extends beyond preventing failure. A resilient water system should be capable of resisting disturbances, maintaining essential services, recovering rapidly, and adapting to changing conditions. Tahir et al. (2026) similarly emphasize the importance of threshold, coping, recovery, and adaptive capacities for Gulf water infrastructure and recommend the integration of climate-risk assessments and adaptation measures into desalination policies and operations.

5.2.2 Gap 2: Climate-Resilience Requirements for Desalination Infrastructure

Desalination represents a particularly important regulatory gap because of the Gulf region's dependence on coastal desalination infrastructure. Climate change can affect desalination through rising seawater temperature, changes in salinity, harmful algal blooms, extreme heat, coastal flooding, and other environmental disturbances. Tahir et al. (2026) identify these factors as significant vulnerabilities and demonstrate that changes in seawater temperature, salinity, and ambient conditions can reduce SWRO freshwater productivity. The study therefore explicitly recommends integrating climate-risk assessment into desalination planning and operation.

5.2.3 Gap 3: Groundwater Regulation Requires Stronger Long-Term Climate Integration

Groundwater regulation in Saudi Arabia has developed considerably and already contains several adaptive management mechanisms. The Saudi Water Sources Code defines the concept of the safe yield of a water source, allows withdrawal quantities to be reduced where water scarcity becomes critical, requires monitoring of groundwater levels and changes in groundwater storage, and permits restrictions or suspension of water-use licences where scarcity indicators or water-security conditions justify intervention. It also requires annual identification of critical groundwater-management zones and a three-year plan for reducing groundwater-level decline.

5.2.4 Gap 4: Wastewater Reuse Should Be Treated as a Strategic Resilience Resource

Wastewater reuse is already recognized within Saudi Arabia's water strategy as an important alternative source. The National Water Strategy identifies treated sewage effluent (TSE) as a resource whose utilization should be increased and identifies infrastructure limitations, regulatory oversight, and economic incentives among factors affecting its wider use. Saudi Arabia is also strengthening direct regulatory incentives for alternative water use. The updated Executive Regulation for Monitoring and Compliance with Water Efficiency and Conservation Standards, published in August 2026, classifies the use of drinking water where treated wastewater or another approved alternative source is available as a serious violation, with a first penalty of SAR 25,000 and repeat penalties reaching SAR 200,000. The regulation enters into force on 21 March 2027.

5.2.5 Gap 5: Flood Management Requires Clearer Infrastructure Accountability

The 2025 Saudi Water Sources Code contains several progressive requirements related to flood resilience. The Ministry is required to develop and annually update flood-risk maps, prepare flood-management strategies, update detailed basin studies every five years, strengthen monitoring and early-warning systems, and use current climatic and hydrological data in flood assessment. Importantly, the Code also requires reconsideration of existing infrastructure designs in response to extreme climatic

events and changing climatic conditions. It further encourages the conservation of vegetation, wetlands, and other natural features capable of absorbing water and reducing flood risk.

5.3 Regional Policy Gaps Across the GCC

The gap between strategic water security and operational climate adaptation is not unique to Saudi Arabia. Similar challenges can be identified across other GCC countries.

5.3.1 United Arab Emirates

The UAE Water Security Strategy 2036 explicitly aims to ensure sustainable access to water under both normal and emergency conditions, demonstrating strong recognition of water-system resilience at the national strategic level. The UAE also maintains environmental legislation that imposes penalties for pollution of drinking and groundwater resources. Nevertheless, previous analysis of the UAE water-energy nexus identified a shortage of detailed climate-change adaptation planning and limited cross-sector integration between water, energy, and climate policies. The study specifically recommends stronger adaptation frameworks capable of considering future changes in temperature, humidity, and seawater salinity. It additionally identifies limited climate-risk analysis of vulnerable water-energy network components and emphasizes the need for improved regional data availability.

The UAE therefore illustrates a broader GCC challenge: national water-security objectives may be ambitious, but climate adaptation must be further converted into asset-level planning requirements, regional targets, and measurable performance criteria.

5.3.2 Qatar

Qatar regulates groundwater abstraction through its legislation on groundwater-well drilling, which establishes licensing requirements and gives authorities powers to control groundwater extraction. However, the underlying groundwater legislation originates from 1988. While subsequent regulatory measures may supplement this framework, its original structure primarily addresses well licensing and abstraction control rather than contemporary climate-resilience concepts.

A future-oriented groundwater framework could therefore more explicitly incorporate climate projections, aquifer recovery thresholds, drought indicators, remote-sensing observations, and adaptive abstraction limits. This is particularly relevant for GCC states where groundwater recharge is naturally limited and may become increasingly variable under climate change.

5.3.3 Oman

Oman provides an example of relatively detailed environmental regulation of coastal discharges. Its marine-discharge regulations establish requirements for discharge temperature, salinity, monitoring, and marine environmental protection. For instance, discharged liquid waste must not exceed surrounding seawater temperature by more than 10°C, and salinity variation within the initial mixing zone is regulated. Oman also applies coastal setback requirements of approximately 50, 150, or 300 m depending on coastal characteristics.

However, fixed environmental setbacks and discharge limits are not necessarily equivalent to climate-adaptive infrastructure planning. Coastal desalination and water facilities operate over several decades, during which sea level, coastal erosion, storm surge, and extreme-wave conditions may change. Future regulatory development could therefore convert static coastal requirements into **dynamic climate-risk zones** that incorporate projected changes over the expected lifetime of infrastructure.

6 Policy Roadmaps for Water Security

The following policy roadmap is therefore proposed to bridge the identified gaps and strengthen the long-term resilience of Saudi Arabia's water resources. The recommendations are organized under eight interconnected policy pillars. Rather than treating desalination, groundwater, wastewater reuse, and rainwater harvesting independently, the roadmap promotes an integrated water-resource portfolio in which vulnerabilities are continuously assessed, alternative sources provide redundancy, infrastructure is designed for future climatic conditions, and regulatory decisions respond dynamically to changing environmental conditions. This approach is consistent with resilience frameworks that emphasize absorptive, adaptive, and transformative capacities and the ability of water systems to maintain and recover their essential functions following disturbances.



Figure 6-1: Summary of the key policy pillars that should be considered when addressing the climate resilience of urban water systems.

6.1 Climate Resilience Policy Integration Pillars

6.1.1 Pillar 1: Climate-Informed Water Planning

The first policy priority is to incorporate climate projections systematically into water-resource planning. Although existing Saudi regulations increasingly recognize climate variability, emergencies, droughts, and future water availability, the identified policy gap lies in translating this recognition into consistent quantitative planning requirements for each water resource.

Climate-informed planning should evaluate how the performance and availability of each resource may change under future climatic conditions rather than assuming that historical environmental conditions will remain representative throughout the lifetime of water infrastructure. This is particularly important in Saudi Arabia, where groundwater depletion, increasing evapotranspiration, changing rainfall characteristics, rising temperatures, and changing marine conditions may simultaneously affect different components of the water portfolio. Recent national-scale studies demonstrate that future water stress is expected to increase under multiple socioeconomic and climate scenarios, emphasizing the importance of anticipatory rather than reactive management.

6.1.2 Pillar 2: Diversified and Secure Water Sources

A resilient water system should not depend excessively on a single source or technology. Diversification provides redundancy by allowing alternative sources to compensate when one source experiences reduced performance or temporary failure. This is particularly important in the Gulf, where desalination provides dependable freshwater production but remains exposed to marine and energy-related climate risks, while groundwater provides strategic flexibility but is constrained by depletion and limited recharge.

Accordingly, Saudi water-security policy should treat desalination, groundwater, treated wastewater and harvested rainwater as an **interconnected portfolio**, rather than as independent resources. Tahir et al. (2026) similarly emphasize diversification, water storage, wastewater recycling, renewable-energy integration and technological adaptation as essential components of resilient Gulf water systems.

6.1.3 Pillar 3: Resilient Infrastructure

The policy-gap assessment indicated that one of the most important remaining challenges is the translation of general resilience objectives into measurable infrastructure-performance requirements. Water infrastructure is generally designed for several decades of operation, meaning that infrastructure constructed today will operate under substantially different climatic conditions later in its service life.

The resilience of water sources therefore depends not only on resource availability but also on the ability of physical infrastructure to continue extracting, treating, storing and transporting water during climate disturbances.

6.1.4 Pillar 4: Digital Transformation

Effective climate resilience requires the ability to identify deteriorating conditions before they develop into water-supply emergencies. This requires transitioning from periodic resource assessment toward continuous monitoring, forecasting and early warning.

Saudi Arabia is already expanding digital transformation within the water sector, with current initiatives emphasizing artificial intelligence, data-based decision-making, operational efficiency and reduction of water losses. The proposed roadmap should extend this transformation specifically toward climate resilience.

6.1.5 Pillar 5: Circular Water Economy

The linear model of extracting, treating, consuming and disposing of water places unnecessary pressure on scarce natural resources. Climate resilience requires maximizing the productive value of every unit of water before it leaves the urban water cycle.

Wastewater is particularly important because it provides a comparatively dependable resource whose availability increases with urban water consumption. Previous Saudi research has demonstrated that greater wastewater treatment and reuse can simultaneously reduce demand for desalination, groundwater and associated energy consumption. Decentralized and circular systems can additionally improve resilience by diversifying supply and reducing reliance on large centralized networks.

6.1.6 Pillar 6: Governance and Institutional Coordination

Climate change affects the entire water cycle and therefore cannot be managed effectively by individual institutions acting independently. A coastal flood affecting a desalination plant, for example, may simultaneously involve water-resource management, desalination regulation, electricity supply, coastal planning, municipal emergency management and environmental protection.

The National Water Strategy already establishes an integrated national framework for water-sector management, while the Saudi Water Authority currently performs regulatory and management functions within the national water sector. The remaining opportunity is to establish a stronger cross-institutional climate-resilience governance mechanism.

6.1.7 Pillar 7: Financing Mechanisms

The transition toward climate-resilient water systems requires investment not only in new production capacity but also in adaptation, redundancy, monitoring, rehabilitation, water reuse and nature-based infrastructure. These investments can be difficult to prioritize when conventional project appraisal focuses primarily on initial capital cost and normal operating conditions.

Financing mechanisms should therefore recognize the economic value of avoided water shortages, avoided infrastructure damage, increased resource lifetime and faster recovery after disturbances.

7 Monitoring and Evaluation

7.1 Climate-Resilient Performance Assessment

To evaluate the effectiveness of the proposed climate-resilience measures, this study aims to determine a Climate Resilience Indicator (CRI) for each water source under three scenarios. The baseline scenario represents current system performance under normal climatic conditions. The climate change scenario evaluates the same system without additional adaptation measures but under the projected extreme climate conditions of 2050, allowing the impact of future climate stressors on performance to be quantified. Finally, the adaptation scenario applies the proposed long-term climate-resilience measures under the same 2050 climate conditions. Comparing the three scenarios enables the study to quantify both the expected loss in performance due to climate change and the extent to which the proposed adaptation measures can reduce or recover this loss.

This approach is consistent with the broader concept of water-resource resilience, which describes a system's capacity to resist disturbances, limit functional losses, recover from disruption, and adapt toward a stable operating state [83]. Similarly, resilience assessments can be structured around absorptive, adaptive, and transformative capacities, representing the ability to withstand an initial disturbance, adjust while maintaining functionality, and implement more fundamental changes when existing system configurations are no longer sufficient [84].

$$R_{Climate} = \frac{P_{Climate}}{P_{Baseline}}$$

Equation 7-1: Climate Resilience Indicator (CRI) equation used to quantify and compare the resilience performance of each water source under baseline and climate-adaptation scenarios [84].

7.1.1 Climate-Resilience Performance

The first step in calculating the CRI is to establish the baseline climate-resilience performance ($P_{baseline}$) of each water source, which provides the reference condition against which the climate change and adaptation scenarios will later be compared. At this stage, the analysis therefore focuses specifically on baseline performance under normal climatic conditions, representing the ability of each source to deliver its required water-resource function before the additional stresses associated with the 2050 climate scenario are introduced. Because groundwater, desalination, wastewater reuse, and rainwater harvesting operate through fundamentally different hydrological and technological processes, a single performance equation cannot adequately represent all sources. Instead, is defined using source-specific measurable variables that represent the principal function and performance of each system. The parameters for calculating the baseline performance of each water source are presented in ***Table 7-1***.

Table 7-1: Parameters required for evaluating the baseline performance () of each water source.

Water source	Performance (P)	Influence parameters
Desalination	Freshwater production (m^3/day)	1- Seawater temperature 2- Salt concentration at the membrane interface 3- Membrane water permeability 4- Applied pressure in bar
Groundwater	Sustainable available groundwater (m^3/yr)	1- Precipitation 2- Quick/surface runoff 3- Evapotranspiration
Wastewater reuse	Usable treated-water output (m^3/day)	1- Treated wastewater volume 2- Reuse fraction 3- Usable wastewater output
Rainwater harvesting	Captured usable runoff (m^3/yr)	1- Effective rainfall 2- Catchment area 3- Runoff-loss coefficient 4- Potentially harvested rainwater

7.1.1.1 Desalination Climate-Resilience Performance

To establish the baseline performance of desalination, this study evaluates the water flux of a seawater reverse osmosis (SWRO) plant in Al-Jubail, Saudi Arabia, using representative local operating conditions. Water flux was selected because it reflects the membrane's freshwater production performance under specific pressure, temperature, and salinity conditions. The adopted equation is based on the solution-friction model presented by Biesheuvel et al. (2023), which relates water flux to membrane permeability, applied hydraulic pressure, and osmotic pressure while accounting for the non-ideal behaviour of high-salinity seawater [85].

Table 7-2: Specific parameters and corresponding units used to calculate the desalination performance.

Parameter	Unit
Seawater temperature **(T)**	Kelvin
Membrane water permeability **(A)**	LMH/bar
Applied pressure in bar **(ΔP_h)**	bar
Universal gas constant **(R)**	-
Salt concentration at the membrane interface **(C_{int})**	mM

Table 7-2 defines the parameters required to calculate desalination performance. The equation considers seawater temperature (T), membrane water permeability (A), applied hydraulic pressure (ΔP_h), universal gas constant (R), salt concentration at the membrane interface (C_{int}), and the parameters used to correct the osmotic-pressure term. These variables are important because RO productivity is controlled by the balance between the applied pressure driving water through the membrane and the osmotic pressure opposing this transport. Biesheuvel et al. (2023) similarly describe water permeability, pressure, temperature, and membrane-interface salt concentration as key parameters governing RO water flux [85].

$$P = A\left[\Delta P_h - 2RTc_{int}\left(1 - \gamma\sqrt[3]{\frac{c_{int}}{c_{ref}}}\right)\right]$$

Equation 7-2: SWRO desalination performance equation based on membrane water flux (adapted from Biesheuvel et al., 2023).

7.1.1.1.1.1 Baseline Desalination Performance

Table 7-3: Parameter values used to calculate the baseline desalination performance for an SWRO plant in Al-Jubail, Saudi Arabia.

Parameter	Value used	Sources
T	300.45 K	Actual mean RO-feed temperature = 27.3°C at Al-Jubail [85]
A	1.56 LMH/bar	The Al-Jubail pilot used the Toray TM820V-400 membrane. [86]
ΔP_h	46 bar	Pressure after stabilization the feed [87]
c_f	778.3 mM	The salt concentration immediately outside the membrane on the upstream side [27]
c_{int}	889 mM	Using the equation $c_{int} = c_f e^{\left(\frac{v_w}{k_{dbl}}\right)}$ [27]
c_{ref}	1 mM	-
γ	0.0154	-
R	8.314 J mol−1K−1	-

Table 7-3 presents the values selected to represent the baseline operating conditions. A seawater temperature of 300.45 K (27.3°C) was adopted based on the reported mean RO-feed temperature at Al-Jubail, while a membrane water permeability of 1.56 LMH/bar was used for the Toray TM820V-400 membrane tested at the Al-Jubail pilot plant [86]. An applied pressure of 46.37 bar was selected to represent the stabilized feed pressure [88]. The membrane-interface concentration was estimated as 889 mM from an upstream concentration of 778.3 mM using the concentration-polarization relationship. Accounting for the interface rather than only the bulk feed concentration is important because salt accumulation near the membrane increases the local osmotic pressure that must be overcome during RO operation; Biesheuvel et al. (2023) specifically distinguish the membrane-interface concentration from bulk feed concentration when modelling RO performance.

$$P_{baseline} = 1.56\left[46 - \frac{2 \times 8.314 \times 300.45 \times 889}{100000} \times \left(1 - 0.0154\sqrt[3]{\frac{889}{1}}\right)\right] = \mathbf{13.31\ LMH}$$

7.1.1.1.2 Climate-Change Adjusted Desalination Performance

To evaluate the impact of 2050 climate conditions on desalination performance, the baseline SWRO model was recalculated using projected changes in seawater temperature and salinity. The seawater temperature was increased to 304.35 K, representing the expected seawater temperature in 2050, while seawater salinity was assumed to increase by 2%, resulting in a bulk salt concentration of 817.2 mM [7]. The corresponding membrane-interface concentration was estimated as 933.5 mM using the concentration-polarization relationship described by D. et al. (2007) [27]. Membrane permeability was maintained at 1.56 LMH/bar for the Toray TM820V-400 membrane used at the Al-Jubail pilot plant [86], while an applied pressure of 46 bar was adopted based on Bashitialshaaer, Persson, and Aljaradin (2011) [89].

Table 7-4: Parameter values used to evaluate climate change–adjusted SWRO desalination performance under projected 2050 seawater conditions.

Parameter	Value used	Sources
T_{2050}	304.35 K	Expected seawater temperature in 2050 [7]
A	1.56 LMH/bar	The Al-Jubail pilot used the Toray TM820V-400 membrane. [86]
ΔP_h	46 bar	[89]
$c_{f,\ 2050}$	817.2 mM	An expected increase by 2% to 5% in seawater salinity [7]
$c_{int,\ 2050}$	933.5 mM	Using the equation $c_{int} = c_f e^{\left(\frac{v_w}{k_{abl}}\right)}$ [27]
c_{ref}	1 mM	-
γ	0.0154	-
R	8.314 J mol−1K−1	-

$$P_{2050} = 1.56\left[46 - \frac{2 \times 8.314 \times 304.35 \times 933.5}{100000} \times \left(1 - 0.0154\sqrt[3]{\frac{933.5}{1}}\right)\right] = \mathbf{9.15\ LMH}$$

The same performance equation used for the baseline scenario was then applied using the adjusted 2050 parameters. The combined increase in seawater temperature and salt concentration increases the osmotic-pressure contribution opposing water transport across the membrane. Consequently, the calculated SWRO performance decreases to 9.15 LMH, compared with the baseline performance of 13.31 LMH. This represents an approximate 32.6% reduction in water flux, demonstrating the potential deterioration in desalination performance under the selected 2050 climate conditions.

7.1.1.1.3 2050 Climate-Resilience Desalination Performance

To evaluate desalination performance after implementing climate-resilience measures, the SWRO model was recalculated under the same projected 2050 seawater conditions while modifying operational and membrane parameters that can be controlled through adaptation. The seawater temperature and salinity therefore remain at 304.35 K and 817.2 mM, respectively, representing the 2050 climate stress projected by Tahir, Al-Ghamdi, and Al-Ansari (2026) [7]. However, membrane water permeability was increased from 1.56 to 1.70 LMH/bar to represent the use of improved high-permeability RO membranes, consistent with membrane-performance enhancement approaches discussed by Okamoto and Lienhard (2019) [90]. The operating pressure was also adjusted to 48.64 bar to maintain sufficient driving force under the higher osmotic pressure associated with future seawater conditions.

Table 7-5: Parameter values used to evaluate 2050 climate-resilient SWRO desalination performance following the implementation of adaptation measures.

Parameter	Value used	Sources
T_{2050}	304.35 K	Expected seawater temperature in 2050 [7]
A	1.7 LMH/bar	By enhancing membrane permeability [90]
ΔP_h	46 bar	
$c_{f,\,2050}$	817.2 mM	An expected increase by 2% to 5% in seawater salinity [7]
$c_{int,\,2050}$	933.5 mM	Using the equation $c_{int} = c_f e^{\left(\frac{v_w}{k_{dbl}}\right)}$ [27]
c_{ref}	1 mM	-
γ	0.0154	-
R	8.314 J mol−1K−1	-

$$P_{2050,\ resilience} = 1.7\left[46 - \frac{2 \times 8.314 \times 304.35 \times 933.5}{100000} \times \left(1 - 0.0154\sqrt[3]{\frac{933.5}{1}}\right)\right] = \mathbf{9.98\ LMH}$$

The climate-resilient parameters were substituted into the same SWRO performance equation to determine how much performance could be recovered despite the projected 2050 climate stress. The resulting water flux was approximately 9.98 LMH, compared with 8.97 LMH in the 2050 climate-change scenario. This corresponds to an improvement of approximately 9.0% relative to the unadopted 2050 system, indicating that enhanced membrane permeability and operational pressure adjustment can partially compensate for the performance losses associated with increasing seawater temperature and salinity.

7.1.1.2 Groundwater Climate-Resilience Performance

To establish the baseline performance of groundwater, this study evaluates the groundwater recharge rate under representative climatic conditions in Qatar. Groundwater recharge was selected as the performance parameter because it represents the amount of water replenishing the aquifer and therefore its capacity to maintain groundwater availability. The baseline performance is estimated using a simplified water-balance approach, where recharge is determined from precipitation after accounting for water losses through surface runoff, actual evapotranspiration, and interception. The mean annual precipitation of 76.6 mm/year was adopted from observations across six Qatar Meteorological Department stations for 1976–2005 [91].

Table 7-6: Specific parameters and corresponding units used to calculate the baseline groundwater recharge performance.

Parameter	Unit
Precipitation (**p**)	mm/year
Surface runoff ($\mathbf{Q_{runoff}}$)	
Transpiration (**T**)	
Interception (**I**)	
Groundwater recharge (**GR**)	

Table 7-6 defines the parameters required to calculate groundwater performance. Precipitation (p) represents the primary water input, while surface runoff (Q_{runoff}), actual evapotranspiration (ET), and interception (I) represent losses that reduce the fraction of rainfall potentially available for groundwater recharge. Accordingly, the baseline groundwater performance is expressed through the following water-balance relationship:

$$P = GR = P_r - S - T - I$$

Equation 7-3: Water-balance equation used to estimate baseline groundwater recharge performance.

7.1.1.2.1 Baseline Desalination Performance

Table 7-7: Specific parameters and corresponding units used to calculate the baseline groundwater recharge performance.

Parameter	Value used	
A	11,650 km^2	Area of Qatar
P_r	76.6 mm/year	Observed Qatar mean, 1976–2005 from six QMD stations [92]
S	2.13 mm/year	Converted from modeled historical runoff of 24.8 Mm^3/year [93]
GR	2.66 mm/year	By converting the groundwater recharge rate reported by Ajjur and Al-Ghamdi (2024) from 31 Mm^3/year to an equivalent mm/year value based on the corresponding recharge area
AET	71.81 mm/year	By applying the equation: $AET = P_r - S - GR$

Table 7-7 presents the values adopted for the baseline groundwater conditions in Qatar. A total area of 11,650 km² and precipitation of 76.6 mm/year were used. Historical surface runoff reported by Ajjur and Al-Ghamdi (2024) as 24.8 Mm³/year was converted to an equivalent depth of 2.13 mm/year. Similarly, their reported groundwater recharge of 31 Mm³/year corresponds to approximately 2.66 mm/year over the study area [93]. Using the water balance, the remaining 71.81 mm/year was attributed to actual evapotranspiration and other atmospheric losses for the baseline calculation.

$$P_{baseline} = 76.6 - 2.13 - 71.81 = \mathbf{2.66\ mm/year}$$

Converting this recharge depth back to volumetric groundwater recharge gives:

$$P_{baseline} = \frac{2.66}{1000} \times 11{,}650 = \mathbf{31\ Mm^3/year}$$

7.1.1.2.2 Climate-Change Adjusted Groundwater Performance

To evaluate the impact of 2050 climate conditions on groundwater performance, the baseline groundwater recharge calculation was recalculated using projected changes in precipitation. For Qatar, precipitation was reduced from the baseline value to 62.8 mm/year, based on the Ministry of Environment and Climate Change projection of an approximately 18% decrease by 2050. Using the same water-balance framework, surface runoff was adjusted to 1.75 mm/year, while groundwater recharge decreased to 2.18 mm/year. The corresponding actual evapotranspiration was estimated as 58.87 mm/year using the water-balance relationship.

Table 7-8: Parameter values used to evaluate climate change–adjusted groundwater recharge performance in Qatar under projected 2050 conditions.

Parameter	Value used	
A	11,650 km²	Area of Qatar
$P_{r,\ 2050}$	62.8 mm/year	According to the Ministry of Environment and Climate Change, precipitation is projected to decrease by approximately 18% by 2050 under future climate conditions.
S_{2050}	1.75 mm/year	
GR_{2050}	2.18 mm/year	
AET_{2050}	58.87 mm/year	By applying the equation: $AET = P_r - S - GR$

$$P_{2050} = 62.8 - 1.75 - 58.87 = \mathbf{2.18\ mm/year}$$

Converting this recharge depth back to volumetric groundwater recharge gives:

$$P_{2050} = \frac{2.18}{1000} \times 11{,}650 = \mathbf{25.4\ Mm^3/year}$$

Therefore, groundwater recharge is projected to decline from the baseline value of 31 Mm³/year to approximately 25.4 Mm³/year by 2050, representing a reduction of about 18%. This illustrates the direct effect of reduced precipitation on groundwater replenishment and the resulting decline in climate-adjusted groundwater performance.

7.1.1.2.3 2050 Climate-Resilience Groundwater Performance

To evaluate groundwater performance after implementing climate-resilience measures, the groundwater recharge model was recalculated under the 2050 climate scenario while incorporating measures that enhance precipitation capture and reduce runoff losses. Precipitation was increased to 74.54 mm/year to represent the expected contribution of Qatar's cloud-seeding program, for which a 20% increase in precipitation was adopted based on Al Hosari et al. (2021) [94]. In addition, nature-based stormwater management was incorporated through vegetative swales. Dutta et al. (2021) reported a 23% reduction in runoff volume under a five-year rainfall event, resulting in an adjusted runoff value of 1.35 mm/year [74].

Table 7-9: Parameter values used to evaluate 2050 climate-resilient groundwater recharge performance in Qatar following the implementation of adaptation measures.

Parameter	Value used	
A	11,650 km^2	Area of Qatar
$P_{r,\ 2050,\ resilience}$	74.54 mm/year	By adopting Qatar's cloud seeding program, 20% increase in precipitation is expected [94]
$S_{2050,\ resilience}$	1.35 mm/year	Dutta et al. (2021) found that vegetative swales reduced both peak flow and total runoff volume by 23% under a 5-year rainfall event [74]
$GR_{2050,\ resilience}$	2.32 mm/year	When adopting the increase in precipitation and runoff [28]
$AET_{2050,\ resilience}$	70.87 mm/year	By applying the equation: $AET = P_r - S - GR$

$$P_{2050,\ resilience} = 74.54 - 1.35 - 70.87 = \mathbf{2.32\ mm/year}$$

Converting this recharge depth back to volumetric groundwater recharge gives:

$$P_{2050,\ resilience} = \frac{2.32}{1000} \times 11{,}650 = \mathbf{27.03\ Mm^3/year}$$

7.1.1.3 Treated Wastewater Climate-Resilience Performance

To establish the baseline performance of treated wastewater reuse, this study evaluates the volume of treated wastewater that is successfully reused in Saudi Arabia under current conditions. Reused wastewater volume was selected as the performance parameter because it directly represents the contribution of treated wastewater to the available water supply. The baseline performance is calculated from the total volume of treated wastewater (Q_T) and the fraction of that water that is reused (f_R).

Table 7-10: Specific parameters and corresponding units used to calculate the baseline treated wastewater reuse performance.

Parameter	Unit
Treated wastewater volume (**Q_T**)	Mm^3/year
Reuse fraction (**f_R**)	-

Table 7-10 defines the parameters required to calculate treated wastewater performance. The total treated wastewater volume represents the amount of wastewater available after treatment, while the reuse fraction represents the proportion that is successfully recovered and utilized rather than discharged.

$$P = Q_T \times f_R$$

Equation 7-4: Treated wastewater reuse performance equation based on the volume of treated wastewater and reuse fraction.

7.1.1.3.1 Baseline Wastewater Performance

Table 7-11: Specific parameters and corresponding units used to calculate the baseline treated wastewater reuse performance.

Parameter	Value used	Source
Q_T	2,859.65 Mm³/year	SWA reported a total sewage treated in Saudi Arabia in 2025
f_R	0.33	SWA reported 33% of treated wastewater was reused

Table 7-11 The second table presents the values adopted for current conditions in Saudi Arabia. According to Saudi Water Authority (SWA) data, approximately 2,859.65 Mm³/year of sewage was treated in 2025, while approximately 33% of treated wastewater was reused. Applying these values provides an estimate of the volume effectively contributing to the water supply through reuse.

$$P = 2859.65 \times 0.33 = 944\ Mm^3/year$$

7.1.1.3.2 Climate-Change Adjusted Wastewater Performance

To evaluate the impact of 2050 climate conditions on wastewater treatment and reuse performance, the baseline calculation was adjusted to account for the expected increase in wastewater generation. The total treated wastewater volume (Q_{2050}) is projected to reach approximately 3,850 Mm³/year, reflecting increasing wastewater generation associated with future population growth and water demand [95]. However, the treated wastewater reuse fraction was maintained at the current value of 0.33 (33%), as reported by the Saudi Water Authority (SWA), representing a future scenario in which reuse practices are not further improved.

Table 7-12: Parameter values used to evaluate climate change–adjusted treated wastewater reuse performance under projected 2050 conditions.

Parameter	Value used	Source
$Q_{T,2050}$	3850 Mm³/year	Expected increase in wastewater generation [95]
$f_{R,\ 2050}$	0.33	SWA reported 33% of treated wastewater was reused

$$P_{2050} = 3850 \times 0.33 = \mathbf{1270.5\ Mm^3/year}$$

Therefore, the calculated wastewater reuse performance increases from the baseline 944 Mm³/year to approximately 1,270.5 Mm³/year in 2050. Importantly, this increase does not necessarily indicate improved climate resilience; it primarily results from the larger volume of wastewater expected to be generated, while the reuse efficiency remains unchanged at 33%. This distinction is important when comparing this scenario with the subsequent 2050 climate-resilient adaptation scenario.

7.1.1.3.3 2050 Climate-Resilience Wastewater Performance

To evaluate wastewater reuse performance after implementing climate-resilience measures, the 2050 wastewater generation volume was maintained at 3,850 Mm^3/year, based on the projected increase in wastewater generation reported by Dawoud, Ewea, and Alaswad (2022) [95]. Unlike the unadapted 2050 scenario, however, the reuse fraction was increased from 33% to 70%, representing Saudi Arabia's future wastewater reuse target reported by Mu'azu, Abubakar, and Blaisi (2020) [49]. Increasing the reuse fraction allows a substantially greater proportion of the wastewater already being treated to contribute to the water supply rather than being discharged.

Table 7-13: Parameter values used to evaluate 2050 climate-resilient treated wastewater reuse performance following the implementation of adaptation measures.

Parameter	Value used	Source
$Q_{T,\ 2050,\ resilience}$	3850 Mm^3/year	Expected increase in wastewater generation [95]
$f_{R,\ 2050,\ resilience}$	0.7	Saudi target 70% of wastewater reuse in 2050 [49]

$$P_{2050,\ resilience} = 3850 \times 0.7 = 2695\ Mm^3/year$$

Therefore, implementing the proposed reuse target increases the effective wastewater reuse performance from 1,270.5 Mm^3/year in the unadapted 2050 scenario to 2,695 Mm^3/year under the climate-resilient scenario. This represents an approximately 112% increase in reusable water output, demonstrating the significant potential of expanded wastewater reuse to strengthen water-supply resilience and reduce pressure on conventional freshwater resources.

7.1.1.4 Rainwater Harvesting Climate-Resilience Performance

To establish the baseline performance of rainwater harvesting, this study estimates the annual volume of rainwater that can be collected from a typical residential catchment in Dhahran, Saudi Arabia. Harvestable rainwater volume was selected as the performance parameter because it represents the contribution that rainfall could make to an alternative household water supply. A mean annual rainfall of 84 mm/year in Dhahran was adopted based on Pradipta et al. (2024) [96].

Table 7-14: Specific parameters and corresponding units used to calculate the baseline rainwater harvesting performance.

Parameter	Unit
Effective rainfall (**R_e**)	mm/year
Catchment area (**A**)	m^2
Runoff-loss coefficient (**k**)	-

Table 7-14 defines the parameters required to calculate rainwater harvesting performance. The calculation considers effective rainfall (R_e), catchment area (A), and the runoff-loss coefficient (k), which accounts for the fraction of rainfall that can be effectively collected from the catchment surface.

$$P = \frac{kAR_e}{1000}$$

Equation 7-5: Rainwater harvesting performance equation based on effective rainfall, catchment area, and runoff-loss coefficient.

7.1.1.4.1 Baseline Rainwater Harvesting Performance

Table 7-15: Specific parameters and corresponding units used to calculate baseline rainwater harvesting performance.

Parameter	Value used	Source
R	98.4 mm/year	Mean annual rainfall in Dhahran according to Japan Meteorological Agency (JMA) website
R_e	85.2 mm/year	Effective harvestable rainfall after applying the 2-mm threshold
A	400 m^2	Typical Saudi catchment area (house area)
k	0.8	Runoff-loss coefficient for concrete roofs

Table 7-15 presents the values adopted for a representative household in Dhahran. A mean annual rainfall of 84 mm/year was used based on Pradipta et al. (2024), together with a 400 m² residential catchment area based on Guizani (2016) and a runoff-loss coefficient of 0.8 for concrete roof surfaces.

$$P_{baseline} = \frac{0.8 \times 400 \times 85.2}{1000} = 27\ m^3/household$$

7.1.1.4.2 Climate-Change Adjusted Rainwater Performance

To evaluate the impact of 2050 climate conditions on rainwater harvesting performance, the baseline calculation was adjusted using projected changes in precipitation for eastern Saudi Arabia. Annual rainfall was increased to 118.4 mm/year, based on the projected precipitation change reported by Chowdhury and Al-Zahrani (2013) [97]. After applying the 2-mm rainfall threshold, the effective harvestable rainfall (R_{2050}) was estimated at 102.5 mm/year. The catchment area and runoff-loss coefficient were maintained at their baseline values of 400 m² and 0.8, respectively, allowing the effect of future rainfall conditions on harvestable water to be evaluated independently.

Table 7-16: Parameter values used to evaluate climate change–adjusted rainwater harvesting performance under projected 2050 conditions in eastern Saudi Arabia.

Parameter	Value used	
R_{2050}	118.4 mm/year	Chowdhury & Al-Zahrani (2013) expect +20 mm/year precipitation change by 2050 for eastern Saudi Arabia
$R_{e,\ 2050}$	102.5 mm/year	Effective harvestable rainfall after applying the 2-mm threshold
A	400 m^2	Typical Saudi catchment area (house area)
k	0.8	Runoff-loss coefficient for concrete roofs

$$P_{2050} = \frac{0.8 \times 400 \times 102.5}{1000} = \mathbf{32.8\ m^3/household}$$

Therefore, the estimated rainwater harvesting performance increases from the baseline value of 26.88 m³/household/year to 32.8 m³/household/year under the selected 2050 climate scenario, corresponding to an increase of approximately 22%. This increase reflects greater potential harvestable rainfall;

however, realizing this additional water resource depends on sufficient collection and storage capacity, particularly as future rainfall may occur through more intense and variable events.

7.1.1.4.3 2050 Climate-Resilience Groundwater Performance

To evaluate rainwater harvesting performance after implementing climate-resilience measures, the 2050 rainfall conditions were adjusted to represent the potential contribution of cloud seeding. A 20% rainfall enhancement was applied to the projected 2050 precipitation, based on Gulf-region cloud-seeding evidence reported by Al Hosari et al. (2021) [94]. This increases annual rainfall from 118.4 mm/year to 142.1 mm/year, with an effective harvestable rainfall ($R_{2050,\ resilience}$) of 123.0 mm/year after applying the 2-mm threshold. The catchment area and runoff-loss coefficient remain unchanged at 400 m² and 0.8, respectively.

Table 7-17: Parameter values used to evaluate 2050 climate-resilient rainwater harvesting performance following the implementation of rainfall-enhancement measures.

Parameter	Value used	
$R_{2050,\ resilience}$	142.1 mm/year	Assumed 20% rainfall enhancement based on Gulf cloud-seeding evidence; Al Hosari et al. (2021)
$R_{e,\ 2050,\ resilience}$	123.0 mm/year	Effective harvestable rainfall after applying the 2-mm threshold
A	400 m^2	Typical Saudi catchment area (house area)
k	0.8	Runoff-loss coefficient for concrete roofs

$$P_{2050,\ resilience} = \frac{0.8 \times 400 \times 123}{1000} = 39{,}36\ m^3/household$$

Therefore, the proposed measure increases rainwater harvesting performance from 32.8 m³/household/year in the unadopted 2050 scenario to 39.36 m³/household/year, representing a 20% increase in harvestable water. Compared with the baseline performance of 26.88 m³/household/year, the adapted system provides approximately 46.4% more harvestable rainwater, demonstrating the potential contribution of rainfall enhancement when combined with adequate collection and storage infrastructure.

7.2 Climate-Resilience Indicator ($R_{climate}$)

After calculating the baseline, projected 2050, and climate-resilient performance of each water supply source, the climate resilience indicator ($R_{climate}$) can be determined to evaluate the effectiveness and importance of integrating resilience measures into water supply systems. The indicator compares future system performance with baseline conditions and provides a normalized measure of how well each water source can maintain or improve its functionality under projected climate change. By comparing the 2050 scenario before and after resilience interventions, the indicator helps quantify the contribution of resilience measures in reducing climate-related performance losses and enhancing the long-term reliability of desalination, groundwater, wastewater reuse, and rainwater harvesting systems.

Table 7-18: Comparison of the 2050 climate resilience indicator ($R_{climate}$) for desalination, groundwater, wastewater reuse, and rainwater harvesting under climate-change and climate-resilience scenarios relative to baseline performance.

Water Sources	R_{2050}	$R_{2050,\ resilience}$
Desalination	$R_{Climate} = \left(\frac{9.15}{13.31}\right) = \mathbf{0.69}$	$R_{Climate} = \left(\frac{9.98}{13.31}\right) = \mathbf{0.75}$
Groundwater	$R_{Climate} = \left(\frac{25.4}{31}\right) = \mathbf{0.82}$	$R_{Climate} = \left(\frac{27.03}{31}\right) = \mathbf{0.87}$
Wastewater reuse	$R_{Climate} = \left(\frac{1270.5}{944}\right) = \mathbf{1.35}$	$R_{Climate} = \left(\frac{2695}{944}\right) = \mathbf{2.85}$
Rainwater harvesting	$R_{Climate} = \left(\frac{32.8}{27}\right) = 1.21$	$R_{Climate} = \left(\frac{39.36}{27}\right) = 1.46$

Table 7-18 compares the projected 2050 climate resilience indicators ($R_{climate}$) for the four water supply sources before and after implementing resilience measures. Overall, the resilience scenario improves the performance of all water sources. Desalination increases from 0.69 to 0.75, while groundwater increases from 0.82 to 0.87, indicating partial recovery but continued performance below the baseline level. In contrast, wastewater reuse and rainwater harvesting show stronger responses to the proposed measures. Wastewater reuse increases substantially from 1.35 to 2.85, representing the greatest improvement among the evaluated sources, while rainwater harvesting rises from 1.21 to 1.46. These results indicate that resilience interventions are particularly effective for alternative water resources such as wastewater reuse and rainwater harvesting, whereas desalination and groundwater remain comparatively more constrained by projected climate conditions.

8 Conclusion

Climate change is increasing the pressure on urban water systems in arid environments, where limited renewable freshwater resources, rapid urban development, and dependence on energy-intensive water supply technologies already create significant water-security challenges. This study demonstrated that climate resilience must therefore be addressed across the entire urban water cycle rather than through isolated improvements to individual water sources. The assessment of climate hazards, water-resource vulnerabilities, adaptation measures, policy gaps, and future performance provides an integrated framework for strengthening long-term water security in Saudi Arabia and the wider Gulf region.

The geospatial assessment conducted using Google Earth Engine, including NASA GRACE MASCON, TerraClimate, and ERA5-Land datasets, demonstrated changes in terrestrial water storage, evapotranspiration, and surface runoff across the Gulf region. These trends reinforce the increasing exposure of urban water systems to drought, rising temperatures, groundwater depletion, extreme rainfall, flooding, and other climate-related disturbances. The vulnerability assessment further showed that these impacts extend beyond water availability, affecting desalination plants, groundwater systems, transmission pipelines, pumping stations, distribution networks, wastewater collection, and water reuse. Consequently, climate resilience requires consideration of both water resources and the infrastructure through which water is produced, transported, treated, and reused.

The quantitative performance assessment further demonstrates the value of adaptation. Under projected 2050 conditions, the Climate Resilience Indicator (Rclimate) for desalination, groundwater, wastewater reuse, and rainwater harvesting was estimated at 0.69, 0.82, 1.35, and 1.21**,** respectively. Following the implementation of resilience measures, these values improved to 0.75, 0.87, 2.85, and 1.46. The results indicate that resilience interventions improve the performance of all evaluated water sources; however, their effectiveness differs considerably between systems. Desalination and groundwater remain below their baseline performance, demonstrating their continuing sensitivity to future climatic conditions. In contrast, wastewater reuse shows the greatest improvement, while rainwater harvesting also benefits substantially from adaptation measures. These findings emphasize the importance of expanding alternative and circular water resources rather than increasing dependence on conventional sources alone.

Accordingly, future water-security strategies should prioritize an integrated portfolio of climate-informed planning, water-source diversification, resilient infrastructure, digital monitoring, circular water management, coordinated governance, appropriate financing mechanisms, and capacity building. Technological adaptation alone is insufficient without regulatory standards, institutional coordination, continuous monitoring, investment mechanisms, and clear implementation responsibilities. The proposed policy roadmap therefore supports a transition from reactive water management toward proactive climate-resilience planning**,** in which risks are anticipated, system performance is continuously evaluated, and adaptation measures are implemented before critical thresholds are reached. Ultimately, strengthening urban water resilience in arid environments will depend not on a single technology or water source, but on the coordinated integration of diversified resources, adaptive infrastructure, effective governance, and evidence-based decision-making. Such an approach can reduce vulnerability to future climatic uncertainty while supporting a more secure, sustainable, and resilient water future for Saudi Arabia and the Gulf region.

9 References

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