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Hydrological Assessment Under Climatic and Socioeconomic Scenarios Using Remote Sensing, QGIS, and Climate Models: A Case Study of the Tuban Delta, Yemen

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Abstract: (1) Background: Water scarcity is a pressing global issue, impacting food security, health, and economic stability in many regions. In Yemen, the challenges related to water resources are particularly acute, exacerbated by climate change, overuse, and a lack of sustainable management strategies. (2) Objective: this paper assesses water resources and demands under two shared socioeconomic pathways, SSP3 and SSP5. (3) Methods: remote sensing, the MRI-ESM2-0 climate model, and QGIS 3.28 are used for spatial analysis and climate projections. (4) Results: The 2022 estimation of water supplies comprising renewable surface water, renewable groundwater, and non-conventional water resources are estimated at 208 million m^3 (MCM). In contrast, water demands are estimated at 244 MCM, resulting in a total water deficit of 36 MCM. For future projections, two scenarios are assessed: business as usual and the improved scenario considering two climate change scenarios, SSP3 and SSP5. The improved scenario considers using drip irrigation, decreasing population growth rates, and constructing seawater desalination plant. Findings indicate that maintaining land and irrigation practices will exacerbate groundwater depletion and threaten water security, while the improved scenario effectively narrows the supply–demand gap. (5) Conclusions: All scenarios predict severe water shortages in the Lower Region, underscoring the urgent need for additional water resources, including a proposed 50 MCM seawater desalination plant. This study provides critical insights into sustainable water management strategies for Yemen, highlighting the necessity for immediate action.

Keywords: Tuban Delta; shared socioeconomic pathways; QGIS; MRI-ESM2-0 climate model; desalination plant

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1. Introduction

Climate change and water scarcity significantly impact sustainability in semi-arid areas, necessitating climate change adaptation, appropriate long-term planning, and the implementation of appropriate socioeconomic policies to enhance the sustainability of these regions [1].

In Yemen, the most water-scarce nation in the world, every drop of water matters, as current groundwater extraction surpasses the yearly recharge [2]. Moreover, water security is crucial for mitigating the impacts of human-induced and climate change-related effects on water resources, as climate change and variability significantly affect vital sectors such as agriculture and the economy [3,4]. Recently, a substantial portion of the population experiences acute water shortages. Approximately 90% of the available water resources are primarily allocated for irrigation, predominantly through traditional methods [5]. In addition to these conventional irrigation practices, Yemen's water resources encounter several challenges, including climate change, inadequate water management strategies, overexploitation of resources, and population growth. These factors contribute to socioeconomic instability and have precipitated water-related conflicts, which are sadly not monitored and are frequently too complex to be resolved by sheikhs or the legal system alone in Yemen [6].

Conversely, a decade of conflict has exacerbated water scarcity and groundwater depletion, resulting in saltwater intrusion that threatens food and water security. In this context, the Tuban Delta (TD), which includes the major port city of Aden, faces severe water scarcity, making it one of Yemen's most water-stressed regions.

The increasing population, overexploitation of groundwater, and climate change have impacted the area and highlighted the needs for studying these challenges [2,7]. Thus, hydrological research is required to evaluate the hydrological conditions and potential climatic risks facing the Tuban Delta to help address these challenges and the research progress of surface water in other water basins and communities in Yemen.

Most surface water resources in Yemen are utilized in the Upper and Middle Regions. These resources are impacted by agriculture-related pollution from fertilizers, chemical products, and untreated wastewater discharged directly into streams and canals. Conversely, the quality of groundwater has not been thoroughly studied regarding its suitability for irrigation or drinking purposes.

The primary sources of groundwater pollution include the following:

1. Natural radioactivity: Groundwater in Aden, similar to many regions globally, may contain naturally occurring radionuclides such as radium, uranium, and thorium, which can leach from geological formations. Harb et al. [8] collected and analyzed 37 groundwater samples from 4 areas in the Aden governorate—Beer Ahmed, Beer Fadle, Daar Saad, and Al-Masabian. The findings indicated that the annual dose received was approximately 5–10 times higher than the WHO-recommended limit of 0.1 mSv/year for drinking water. Additionally, another study [9] assessed the radioactivity of groundwater in the Juban District, revealing that high concentrations of radionuclides were primarily found in water from wells in the basement aquifer. This study determined that the mean annual effective dose for infants was nearly twenty times the WHO guideline level for drinking water. Thus, it is imperative to address the issue of groundwater quality through collaboration among local authorities, environmental agencies, health departments, and scientific institutions. This effort is essential to ensure the provision of safe and potable groundwater while minimizing health risks associated with radioactivity.
2. Salinity: According to Yemeni drinking water standards, the preferred electrical conductivity (EC) for drinking water is less than 1000 µS/cm, with a maximum allowable limit of up to 2500 µS/cm [10]. However, testing of numerous samples from the lower region revealed elevated EC values, exceeding 3000 µS/cm in some wells. This salinity can be attributed to both the natural characteristics of the aquifer and the effects of saltwater intrusion, particularly in coastal areas. After analyzing available data from 2007 and 2021, there has been an increase in average EC mainly in LR, which exceeds the Yemeni standards for drinking water—5526.42 µS/cm and 4629 µS/cm—but it can still be used for other uses. The wells in the Middle and Upper Regions continue to provide drinkable water, with electrical conductivity (EC) concentrations around 2110 µS/cm as of 2021.

3. Nitrate: The concentrations of nitrate in Bir Ahmed and Bir Naser are approximately 75 mg/L and 58 mg/L, respectively, both exceeding the Yemeni standard of 50 mg/L. Regarding wastewater, cities and industries discharge untreated domestic and industrial wastewater into peri-urban areas. While the pollution risks from urban wastewater are more apparent, untreated wastewater from rural settlements also poses a significant threat to aquifers. To evaluate groundwater pollution in the Bir Nasser and Bir Ahmed water fields in TD, ref. [11] collected 20 groundwater samples from February to July 2021. The results indicated that most physical, chemical, and biological parameters were above the permissible limits set by WHO. The primary causes of this pollution include the use of cesspits, the proximity of wells to agricultural lands that utilize chemical and animal fertilizers, random well drilling, and excessive pumping rates [11].

Moreover, no specific estimates of water resource availability in TD have been made thus far. However, some estimates exist for Yemen as a whole or for specific governorates. For example, one assessment indicated that Lahj's potential water resources amount to 130 million cubic meters (MCM) per year [12]. TD is situated downstream of the Tuban Wadi Basin. Consequently, the total renewable water resources in TD will be the sum of inflows from the highlands of Tuban Wadi, rainfall and runoff from the three regions, and groundwater flow from the highlands.

Based on this brief introduction, the following are the main research gaps in Yemen in general, and in TD in particular, which have also been recognized by [1,3,13]:

1. Groundwater quality: limited studies on groundwater radioactivity, salinity, and nitrate levels, and their impacts on water scarcity and pollution.
2. Impact of water scarcity: insufficient analysis of how water scarcity influences social conflicts.
3. Hydrological assessments: need for detailed hydrological studies to evaluate current and future conditions under climate and socioeconomic changes.
4. Wastewater management: lack of strategies for managing untreated wastewater and agricultural runoff.

These gaps need actual contributions from scientific people and international organization to mitigate potential risk and ensure water sustainability in the region. The following are some proposed contributions:

- Propose integrated strategies for efficient water use.
- Recommend frameworks for pollution control and safe drinking to mitigate risks from water pollution.
- Predict the impacts of climate change and growth on the limited water resources.
- Develop frameworks combining traditional and modern agricultural and managerial methods.

Based on the Un-Habitat mission in Yemen [14], this paper contributes to water resource management in Yemen by assessing the current resources, both renewable and non-conventional. Then, it quantifies the gap in water supply and demand under current and future water conditions considering different socioeconomic and climate scenarios. It offers recommendations for sustainable solutions such as introducing drip irrigation and desalination of seawater to improve the security of water.

2. Materials and Methods

Figure 1 outlines the steps involved in conducting the hydrological assessment aimed at estimating the unmet water demand. Notably, each step actively engages stakeholders in various processes, including data collection, verification, addressing information gaps, discussing the current situation, proposing future scenarios, and selecting potential adaptation measures. This collaborative approach ensures a comprehensive understanding of the challenges and opportunities in water resource management.

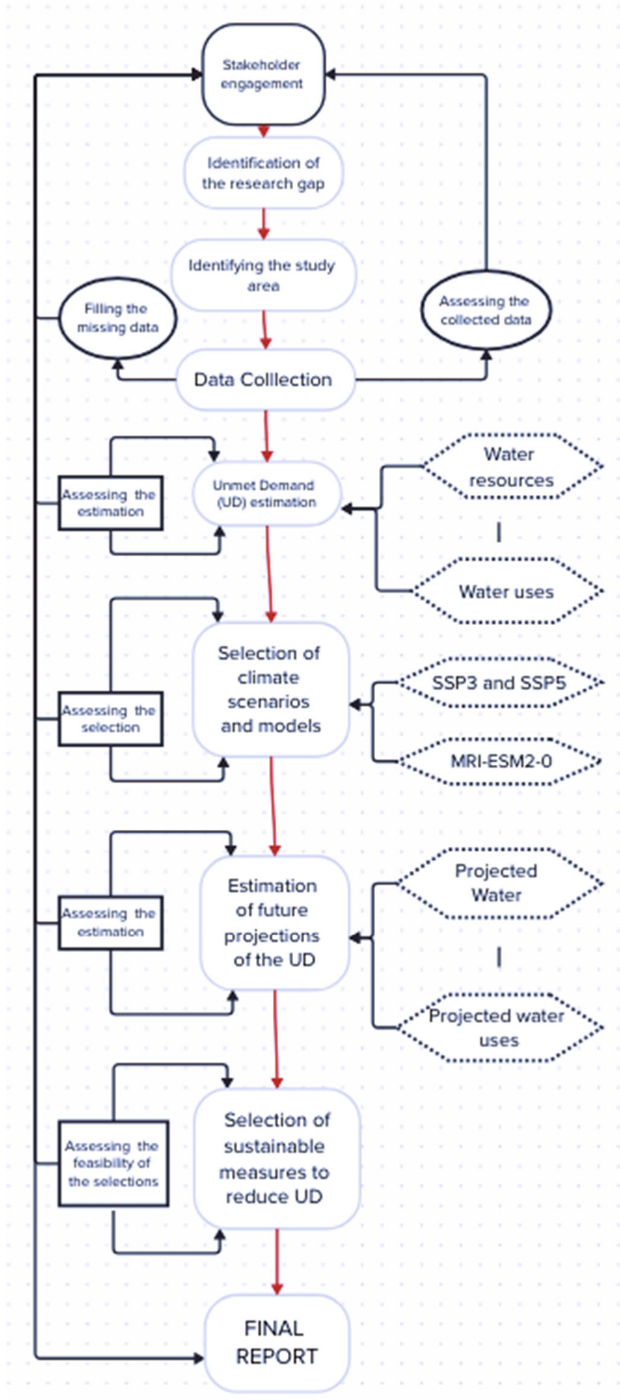

Figure 1. A flowchart of the performed methods in assessing the unmet demand.

2.1. Study Area

TD is situated downstream of the Wadi Tuban basin, which covers a total area of 7360 km^2 and consists of seven sub-basins: Maytem, Saelah Qataba, Worzan, As-Sodan, Tuban, Al Enteshari, and Agreen [10].

Geographically, the Tuban Delta is located between 44.65–45.1° E and 12.7–13.3° N, with topography ranging from 10 m below to about 800 m above mean sea level. Administratively, TD is divided into three regions: the Upper Region (UR), the Middle Region (MR), and the Lower Region (LR).

To delineate the watershed of TD, QGIS and the HEC-HMS model were utilized.

The digital elevation model for the study area was obtained from the Shuttle Radar Topography Mission (SRTM) of the United States Geological Survey. Ten break points (outlets) were established, leading to the creation of several sub-basins that were subsequently merged into one administrative watershed, as shown in Figure 2. The Tuban Delta is divided into three regions: UR with an area of 450 km^2 and a population of 36,900 people; MR with an area of 570 km^2 and a population of 85,950 people; and LR with an area of 1030 km^2 and a population of 1,133,000 people.

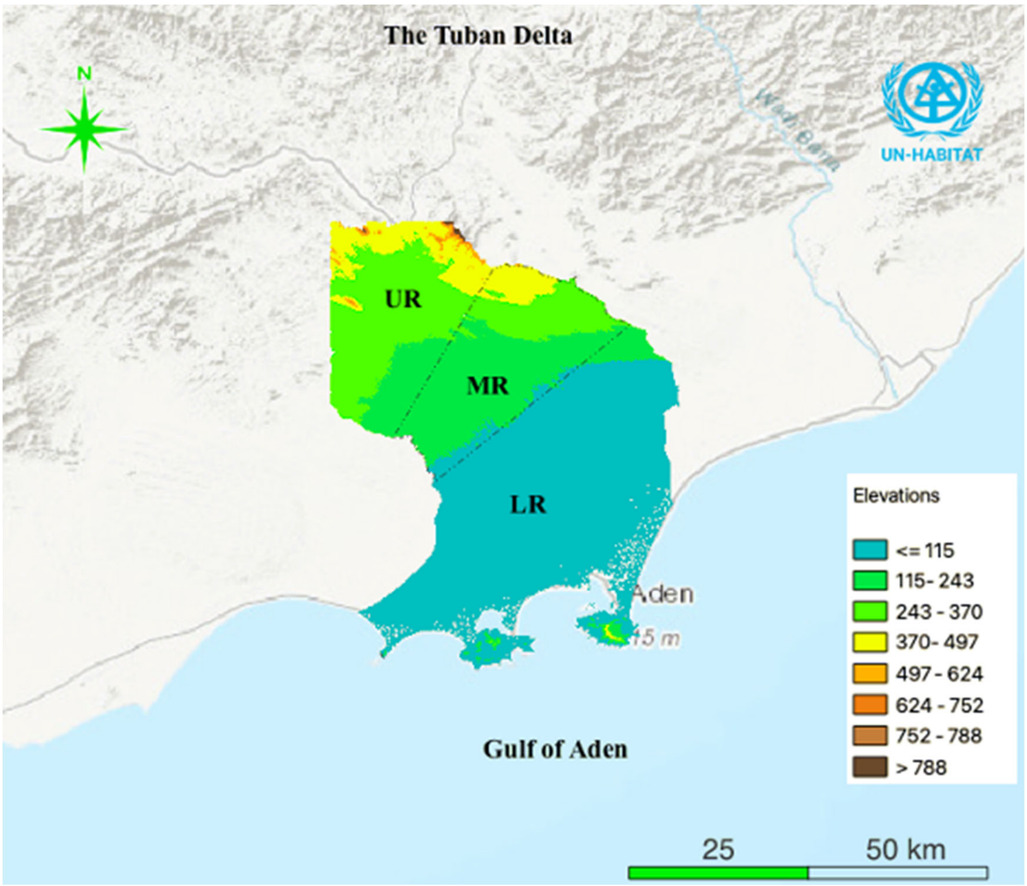

Figure 2. The three regions of TD (administrative map).

2.2. Data Collection

Different sorts of data were required, namely hydrological data, land and water uses, demographic and socioeconomic data, and climatic projections, to carry out the hydrology study and to carry out the related analysis. Therefore, data were collected from four main sources as follows:

1. Desk review: some of the required information was gathered from open-access websites and earlier studies.

   Consultation: Due to the war in Yemen, most data were outdated. Consequently, after 2015, it was difficult to obtain reliable data. As a result, numerous consultation meetings were arranged to correct the data that were gathered. The following national organizations contributed to the gathering and validation of the data: Environmental Protection Agency (EPA), National Water Resources Authority (NWRA), Ministry of Agriculture and Irrigation and Fish Wealth (MAIFW), Ministry of Water and Environment (MWE), and Local Water and Sanitation Corporation (LWSC).

It is worth mentioning that consultations were conducted in four national workshops in Aden, and in meetings with some decision makers. In addition to validating the data, these consultations continued until the end of the project to confirm the results of this research.

2. Remote sensing: Due to the war, there have been no rainfall records available since 2015. To address this gap, monthly rainfall rates were obtained from the Multi-Source Weighted-Ensemble Precipitation (MSWEP), a global precipitation product that provides a 3-hourly resolution at 0.1°. This product integrates gauge, satellite, and reanalysis data to deliver high-quality precipitation estimates. The monthly rainfall rates were then processed in QGIS to calculate the annual precipitation for 2022. In general, QGIS 3.28 is good software to use; however, it has some limitations including the following:
    - Combining QGIS with other software for simulations and modeling can be difficult.
    - The interface may be less intuitive for hydrological analyses compared with specialized software.
    - QGIS is not designed for real-time data processing, which can hinder dynamic studies.
    - Creating custom visuals may require extra effort or external tools.
    - As an open-source platform, QGIS does not offer the same level of customer support as commercial alternatives.
3. Field visits: In February 2023, local government officials and representatives from the water user associations (WUAs) were interviewed. Subsequently, three field trips were conducted to the Upper, Middle, and Lower Regions of TD, during which, three focus group discussions (FGDs) were held at each location, involving farmers, men, and women. The following subjects were discussed during the focus group discussions:
    a. Local issues and demographic trends.
    b. Institutional structures.
    c. Socioeconomic activities (agriculture, water consumption, and land use).
    d. Climate-related risks (including sea level rise, drought, saltwater intrusion, and flooding).

Additionally, to estimate groundwater abstraction and assess the quality of water discharged from wells, local team members conducted several field visits to collect data on agricultural and domestic wells. The collected data included water levels, average abstraction rates, temperature, and electrical conductivity (EC), which were then compared with data from 2007.

2.3. Climate Scenarios

The climate modeling community under the Coupled Model Intercomparison Project (CMIP) utilizes two main frameworks to predict climate change impacts: CMIP5 and CMIP6. CMIP5 focuses on representative concentration pathways (RCPs), and CMIP6 projects socioeconomic trends through shared socioeconomic pathways (SSPs).

Examining the performance of CMIP5 and CMIP6, global climate models (GCMs) across various countries revealed that CMIP6 GCMs significantly improved the reproduction of temperature and rainfall patterns. While CMIP5 models excelled in replicating geographical distributions, they were less effective at simulating spatial variability for most climatic variables, except for minimum temperatures at different timeframes [15].

Consequently, the Meteorological Research Institute Earth System Model Version 2.0 (MRI-ESM 2.0) was selected under CMIP6, with expectations that it would perform better in many experiments scheduled for CMIP6 compared with earlier models from

CMIP5 [16]. The CMIP6 data archives make MRI-ESM2-0 outputs readily accessible for research purposes. Moreover, MRI-ESM2-0 has shown improvements in simulating atmospheric circulation, ocean currents, and sea ice [17]. These improvements are relevant for understanding large-scale climate drivers that influence Yemen's climate. In general, the model is based on prediction; therefore, it will not be 100% accurate. However, the main aim is to highlight the possible related risks and the affected areas.

It is worth mentioning that, despite their effectiveness in forecasting future climate conditions, climate models are susceptible to uncertainties pertaining to data inputs, model parameterization, and future emission assumptions. Therefore, in order to guarantee trustworthiness, model outputs must be verified using empirical data or stakeholder consultation, which is a vital pillar of this work.

Future projections in this report, based on CMIP6 and aligned with the Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report [18], are conducted under climatic scenarios SSP3 and SSP5. These scenarios are influenced by increasing global conflicts and traditional socioeconomic activities:

- SSP3 is linked to RCP7, indicating significant challenges in adaptation and mitigation due to conflicts and instability.
- SSP5 is associated with RCP8.5, suggesting substantial obstacles in mitigation, leading to increased fossil fuel consumption.

Overall, both SSP3 and SSP5 represent high-emission high-impact scenarios. However, the rate of emission reduction over the past 13 years is not optimistic enough to consider lower emission scenarios like SSP2.

Some climate projections extending to 2100 are supported by the United Nations Economic and Social Commission for Western Asia (UNESCWA). Additional projections were sourced from various climate service platforms, including the Climate Change Knowledge Portal (CCKP), developed by the World Bank (WB) to meet the needs of development practitioners and policymakers.

https://climateknowledgeportal.worldbank.org (accessed on 20 January 2023).

Moreover, the timeframes for the extreme events scenarios have been modified from 2010–2039, 2035–2060, 2060–2089, and 2070–2099 to 2023–2040, 2041–2060, 2061–2080, and 2081–2100.

2.4. Water Availability

Water availability in a specific area or watershed is determined by the sum of incoming water and direct runoff within that study area. Previous estimates have been utilized to assess the incoming water.

Runoff water availability can be calculated by subtracting evaporation and infiltration from the total rainfall [19]. The main methods for estimating runoff and water availability include the following:

- Rational method.
- Cook's method.
- Curve number method.

These methods provide a framework for evaluating runoff and understanding water availability in a given watershed [20]. The rational method is utilized in this paper to estimate water availability using the following equations [20]:

$$\mathrm{C} = \Sigma(\mathrm{Ci} \times \mathrm{Ai})/\Sigma\mathrm{Ai} \quad (1)$$

$$\mathrm{R} = \Sigma\mathrm{Ri}/\mathrm{m} \quad (2)$$

$$\mathrm{WA} = \mathrm{C} \times \mathrm{R} \times \mathrm{A} \quad (3)$$

where WA = water availability (MCM/year), C = weighted runoff coefficient, Ci = land use coefficient, Ai = land area (km^2), R = average yearly rainfall data (m/year), Ri = rainfall at station i, and m = number of rainfall stations.

In this research, the rational method is only used to estimate available water in TD. Regarding its accuracy, the rational method is helpful for small urbanized areas since it offers a straightforward method for estimating peak runoff based on rainfall intensity and watershed features. However, in intricate large watersheds where terrain and fluctuating land use play important roles, its accuracy may decrease, which is not the case in TD. Moreover, the rational method may not give accurate estimates for extreme events of heavy rainfall or droughts.

2.5. Future Projections

Future projections of unmet demand have been conducted based on water demand and resource projections, considering different scenarios that cover domestic demand, agricultural demand, and water resources.

2.5.1. Water Demand Projection

Recently, environmental flow has not been incorporated into national water plans in Yemen. However, it is recommended to include this demand in future water management strategies. An average environmental flow of 10–30 L/s at the basin outlet could significantly contribute to water sustainability in TD. Thus, the total demand projections in the three regions have been estimated based on the current domestic water use (DWU) and agricultural water use (AWU) as follows:

1. DWU projections up to 2100 have been estimated based on average water consumption per capita assuming that the non-revenue water (NRW) will be eliminated by 2040. Thus, domestic water consumption starting from 2040 will be 90, 99, and 96 L/day in LR, MR, and UR, respectively.

On the other hand, the domestic water demand projection depends on population growth. Thus, future population and DWU projections up to 2100 can be estimated based on the following two scenarios:

(a) DWUn: normal increase, which means the rate of growth of 3% will stay the same up to 2100 using the following equation:

$$PF = PP \times (1 + R)n \tag{4}$$

where PF is the future population at time T, PP is the present population, R is the growth rate (3%), and n is the number of years.

(b) DWUr: Reduction in the population growth rate, which means a growth rate of 3% until 2040, 2.5% from 2040 to 2060, 2% from 2060 to 2080, then 1.5% from 2080 to 2100. In this case, Equation (5) is used.

$$PF = PP\ (1 + r_1)^{n1}(1 + r_2)^{n2} \tag{5}$$

where

- r1, r1 are the growth rates in the specific period.
- n1, n2 are the number of years for each period.

2. For agricultural water use (AWU) projections: the following two scenarios have been assessed, as shown in Table 1:
   (a) AWUa: constant land and irrigation practices.
   (b) AWUb: constant land, modern irrigation starts with 50% in 2040, 70% in 2060, and 100% in 2080.

Table 1. Agricultural water uses projections (MCMs).

Year	Lower Region		Middle Region		Upper Region		Total	
	AWUa	AWUb	AWUa	AWUb	AWUa	AWUb	AWUa	AWUb
2022	92	92	74	74	28	28	194	194
2040	92	92	74	74	28	28	194	194
2060	92	66	74	53	28	20	194	139
2080	92	51	74	41	28	16	194	108
2100	92	42	74	34	28	13	194	88

2.5.2. Water Supply Projections

For the water supply scenarios, the following two have been considered based on the use of non-conventional water resources (NCWRs):

- Reference NCWR (NCWRr): no increase in current NCWR.
- Improved NCWR (NCWRi): In this scenario, treated wastewater (TWW) is estimated to meet 33% of domestic water demand. The same percentage will be applied for future projections, with all TWW being reused.

3. Results and Discussions

3.1. Water Resources Availability

3.1.1. Water Availability from the Highlands

Between 1955 and 1983, the average annual flow at the top of TD was estimated to be 125 million cubic meters (MCM). The highest inflow occurred in 1982, with an annual inflow of 350 MCM, leading to catastrophic flooding in March 1982.

Due to a lack of recent estimates for inflow from the highlands, and after consultations with local authorities, the annual inflow from the northern highlands in 2022 was estimated at 125 MCM based on water use. This inflow is typically utilized before reaching the ocean, with distributions as follows: 35% (43.75 MCM) in the Upper Region, 50% (62.5 MCM) in the Middle Region, and 15% (18.75 MCM) in the Lower Region (before the city of Aden).

This limited flow to the city of Aden has negatively impacted soil quality, exacerbated desertification, and compelled people to overuse groundwater for agricultural and domestic purposes, thereby increasing saltwater intrusion.

3.1.2. Water Availability from Runoff

Specific estimates of water resource availability in TD have so far not been made to assess water availability from local runoff. The rational method was used, considering the rainfall of 2022. Runoff coefficient Ci depends on soil type, land slope, and land cover. According to [10], the soil types in TD are clay loam, silt clay, loam, and silty clay loam. However, because silty clay loam and clay loam are the most common soil textures, the average values of silty clay loam and tight clay were chosen. Tuban Delta's slope was calculated in the HEC-HMS model to be about 5%, indicating that the basin is represented by a gentle slope (rolling) [21]. Considering the tabulated runoff coefficients for the rational method (see: https://codelibrary.amlegal.com/codes/tatamyborpa/latest/tatamy_pa/0-0-0-4853, accessed on 20 January 2023), the average runoff coefficients for different land uses in TD based on soil texture and slope were estimated as 0.65, 0.45, and 0.6 for agricultural areas, pastureland, and populated areas, respectively. Then, the weighted runoff coefficients for each region and the various land uses were estimated using recent data from Google Maps, QGIS, and national documents. Based on this analysis, the weighted runoff coefficients were determined. The acquired monthly rainfall data from the Multi-Source Weighted-Ensemble Precipitation (MSWEP) were processed in QGIS to calculate the annual precipitation for 2022, as illustrated in Figure 3.

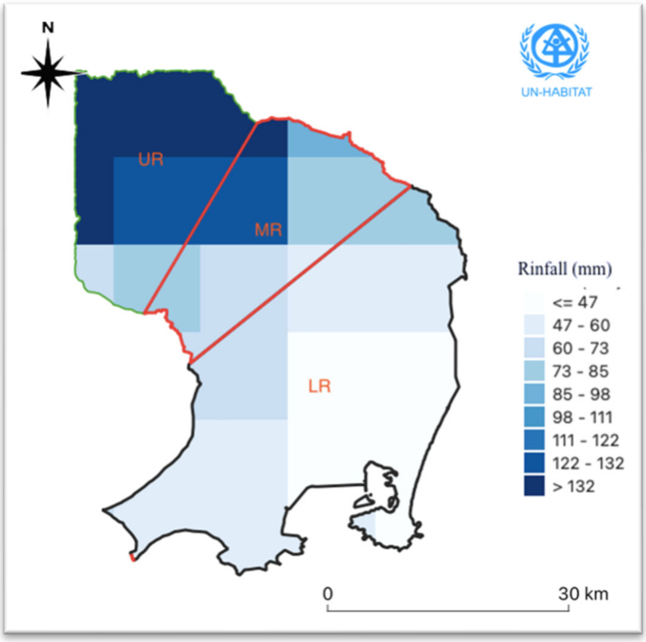

Figure 3. Precipitation in 2022 in Tuban regions based on MSWEP data.

Water availability in the three regions was estimated using the rational method, as shown in Table 2.

Table 2. Water availability in TD based on runoff estimations.

Regions	UR	MR	LR	Total
Rainfall (m)	0.118	0.084	0.051	
Weighted C	0.466	0.476	0.485	
Area (km^2)	450	570	1030	
Runoff MCM	25	23	25	73

3.1.3. Total Renewable Water

Groundwater aquifers provide limited flows from the northern aquifers, so groundwater recharge in TD mainly occurs due to local rainfall, check dams, and inflows from the highlands into streams and canals. According to [22], 70% of the available water (including runoff and inflow from the highlands) contributes to groundwater supplies. Consequently, the total renewable surface water will consist of the remainder, as detailed in Table 3.

Table 3. Renewable water resources in TD (MCM).

Regions	UR	MR	LR	Total
Renewable GW	47.9	59.7	31.0	138.6
Renewable SW	20.5	25.6	13.3	59.4
Total	68.5	85.3	44.2	198

Based on field visits, TD currently has around 3600 wells, a significant increase from 350 wells in 1966. However, over 1200 of these wells have dried up due to climate change and overuse. The visits revealed that there are 2200 functioning wells for agricultural purposes, while 107 wells are used for domestic needs in Aden.

Comparing the average water levels and discharge rates of 120 wells from 2007 to 2023 indicates a decrease in average water level from 37.1 m in 2007 to 49.5 m in 2023, signifying a groundwater depletion of 12.4 m over these 16 years, which averages to an annual depletion rate of 80 cm. The estimated annual discharge rates are 147.4 million cubic meters (MCM) for agricultural use and 50.1 MCM for domestic use.

The distribution of wells in TD is approximately 10.2% in UR, 37.5% in MR, and 52.3% in LR. Consequently, groundwater extractions for agriculture are estimated at 15 MCM from UR, 55 MCM from MR, and 77 MCM from LR. For domestic uses, extractions are estimated at 1.3 MCM from UR, 3.2 MCM from MR, and 45.5 MCM from LR.

In this context, ref. [23] suggests reducing the extraction rate in LR to 36.4 MCM to mitigate saltwater intrusion. Additionally, data from NASA's Gravity Recovery and Climate Experiment (GRCE) indicate that solar power usage is contributing to the depletion of Yemen's groundwater, as shown in Figure 4.

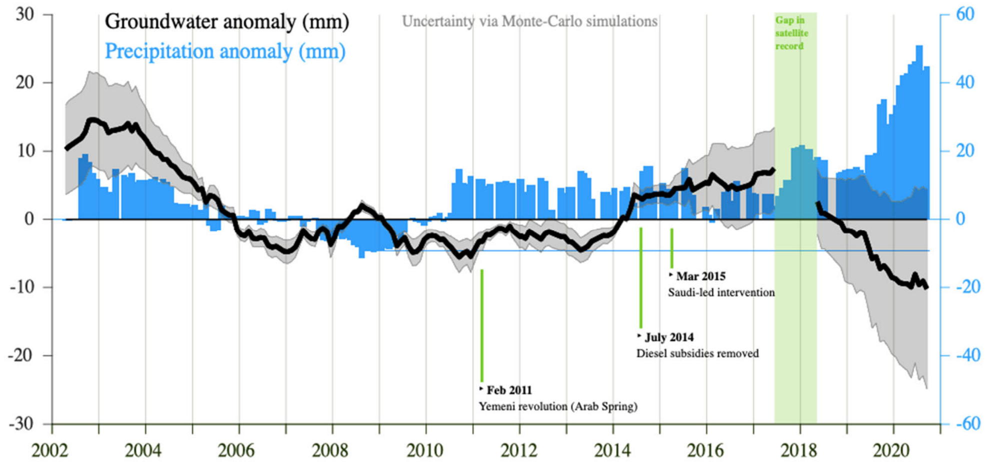

Figure 4. Groundwater depletion in Yemen [24].

3.1.4. Non-Conventional Water Resources

Non-conventional water resources primarily include greywater reuse and treated wastewater.

Greywater Reuse

Greywater reuse is an effective practice that can potentially save up to 30% of domestic water demand when used for toilet flushing [25]. However, in Yemen, greywater reuse is limited and primarily implemented in some mosques, where greywater is utilized to irrigate the gardens.

Treated Wastewater

The availability of treated wastewater is contingent on the presence of sewage networks and wastewater treatment plants (WWTPs). In TD, there are seven WWTPs employing oxidation pond treatment methods. Three are located in the Tuban district (Saber WWTP, Al-Waht WWTP, and Al-Hamra WWTP), two in Al-Hwtah District (Tahror WWTP and Al-Fashlah WWTP), and two in Aden (Al-Areesh and Al-Mansorah WWTPs).

In the Lower Region, 9 MCM of treated wastewater is utilized in wetlands, while the remainder is discharged directly into the ocean. A study assessing secondary effluents and biosolids from four sewage treatment plants in Yemen found that concentrations of fecal coliforms (FCs) were higher than those recommended by the World Health Organization (WHO) [26].

In MR, there is only one WWTP treating approximately 1.0 MCM per year, while wastewater in the Upper Region is neither treated nor reused.

3.2. Water Demand

Water demands in TD encompass agricultural, domestic, and industrial needs. Industrial demand is limited, and environmental demands remain unmet due to the lack of water flow in the streams leading to the ocean. Municipal water networks supply a portion of the community, including commercial and government buildings. However, the remaining water needs are satisfied by privately owned wells.

3.2.1. Domestic Demand

Domestic water use (DWU) in TD is primarily met through municipal water supplies provided by the Local Water and Sanitation Corporation (LWSC) or through private suppliers for those not connected to the public system. Approximately 25% of the population in the Lower Region lacks access to public water, while this figure is around 40% in the Upper and Middle Regions.

According to Aden's Water Corporation, half of the produced water is classified as non-revenue water (NRW). In the Middle Region, the Lahij Water Corporation reports that 40% of the population is not connected to the public water supply, with NRW estimated at about 30%.

Based on available data, domestic water use is approximately 110, 103, and 100 L per capita per day (including NRW) in the Lower Region (LR), Middle Region (MR), and Upper Region (UR), respectively. Consequently, the total DWUs are estimated at 45.5 MCM for LR, 3.2 MCM for MR, and 1.3 MCM for UR.

3.2.2. Agriculture Demand

Agriculture land in TD measures about 18,356 ha in total. However, due to water shortage, the cultivated areas are about 60% of the total cultivated area.

There are three types of irrigation in TD as follows:

a. Spate irrigation: this method utilizes traditional intakes and canals to divert water flow from valleys, rivers, and wadis into farmlands that are situated at lower elevations (approximately 40% lower than the valley).
b. Check basin irrigation: this technique involves constructing soil bunds around the field to create a boundary, allowing the field to be inundated with water (about 55%).
c. Drip irrigation: about 5%.

The total agricultural water use (AWU) for each region is calculated as the sum of groundwater extraction from agricultural wells, non-conventional water resources (NCWR), and 30% of the inflow water from the highlands. The estimated total agricultural water uses are as follows:

- Upper Region (UR): 28.1 MCM/year.
- Middle Region (MR): 74 MCM/year.
- Lower Region (LR): 91.8 MCM/year.

3.3. Unmet Demand Assessment

In general, the unmet demand in a catchment area can be estimated by subtracting the total water supply from the total water demand. Current estimates indicate that the Lower Region is experiencing a severe water shortage, reaching up to 84.3 MCM. This shortage is attributed to limited water availability due to climate change, over-extraction of depleting groundwater, and inadequate operation and maintenance of water and wastewater systems.

3.4. Future Projections

3.4.1. Water Demand Projection

Table 4 presents future domestic water projections considering the two scenarios of normal population growth (DWUn) and reduction in population growth rate (DWUr).

Table 4. Domestic water projections (MCMs).

Year	Lower Region		Middle Region		Upper Region		Total DWU	
	DWU_n	DWU_r	DWU_n	DWU_r	DWU_n	DWU_r	Normal	Decline
2022	45.5	45.5	3.2	3.2	1.3	1.3	50.1	50.1
2040	77.4	77.4	5.5	5.5	2.3	2.3	85.2	85.2
2060	139.9	126.9	9.9	9.0	4.1	3.8	154.0	139.7
2080	252.6	170.9	17.9	13.4	7.5	5.6	278.1	189.9
2100	456.3	254.0	32.4	18.0	13.5	7.5	502.2	279.5

Table 1 illustrates agricultural water uses (AWUs) based on the two proposed scenarios: constant land and irrigation practice (AWUa); and constant land and modern irrigation, starting with 50% in 2040, 70% in 2060, and 100% in 2080 (AWUb).

Based on the above-mentioned scenarios, two demand scenarios have been considered as follows (see Figure 5):

- Reference demand scenario: constant cultivated lands, constant population growth rates, and the same agricultural practices.
- Improved demand scenario: modern irrigation and decreased population growth.

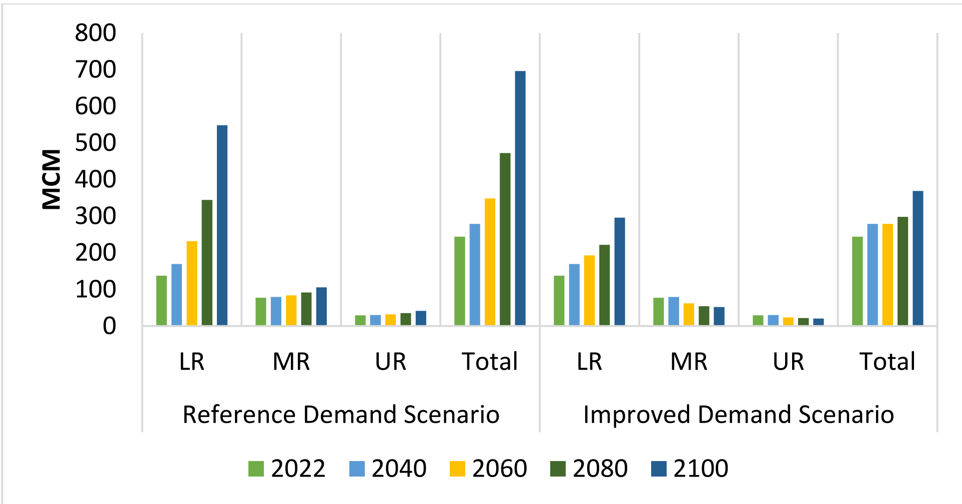

Figure 5. Total water demand projections (MCMs).

Figure 5 illustrates that the improved scenario could help alleviate water shortages, with potential water savings of 20%, 37%, and 47% projected for the years 2060, 2080, and 2100, respectively. By fostering fruitful cooperation and actively engaging all relevant stakeholders, new demand scenarios can be developed to enhance water management strategies. However, the developed scenarios should be concrete and based on what can be carried out in TD to save water resources. For example, reusing greywater in toilet flushing needs social acceptance and involves some private costs.

3.4.2. Water Supply Projection

The average annual rainfall projections under SSP3 show an increase in rainfall rates after 2040 and they will reach the highest between 2061 and 2080 in the Lower Region (with

50% certainty), while the annual rainfall rates will start to increase after 2060 in the Middle and Upper Regions. On the other hand, the low rainfall rates projected before 2040 may result in more dry years. However, forecasts indicate an increase in wet years after 2040, as shown in Table 5.

Table 5. Average annual rainfall projections (mm) under SSP3 and SSP5.

Years		SSP3			SSP5	
Regions	**LR**	**MR**	**UR**	**LR**	**MR**	**UR**
2022	51	84	118	51	84	118
2023–2040	69.8	69.4	76.3	82.3	79.9	87.8
2041–2060	76.4	68.3	75.1	89.6	90.0	99.0
2061–2080	110.4	106.2	116.8	77.7	74.8	82.3
2081–2100	100.5	94.9	104.4	97.2	84.3	92.7

From Table 6, the average change in water availability from runoff compared with 2022 is estimated and presented under SSP3 and SSP5, as illustrated in Table 6.

Table 6. Average change factors in water availability under SSP3 and SSP5 compared with 2022.

Climate		SSP3			SSP5	
Regions	**LR**	**MR**	**UR**	**LR**	**MR**	**UR**
2023–2040	1.37	0.83	0.65	1.61	0.95	0.74
2041–2060	1.50	0.81	0.64	1.76	1.07	0.84
2061–2080	2.16	1.26	0.99	1.52	0.89	0.70
2081–2100	1.97	1.13	0.88	1.91	1.00	0.79

UR and the highlands are assumed to have the same average change factors in water availability. Using the same methodology as outlined in Section 3.2 for estimating water availability from runoff, projections under SSP3 indicate that the Lower Region (LR) will experience increased water scarcity due to consecutive dry years lasting two to four years, particularly between 2040 and 2060. There might be some wet years after 2060 that cause flooding in UR and MR, which will be combined with wetter years in UR and MR, which might bring some floods.

NCWR: Non-conventional water resources (NCWR) include treated water (TWW) and desalinated water. Two scenarios are presented here as follows:

(a) Reference NCWR (NCWRr): no increase on the current NCWR;
(b) Improved NCWR (NCWRi): In this scenario, treated wastewater (TWW) is estimated to meet 33% of the domestic water demand. This percentage will be applied to future projections, with the expectation that all TWW will be reused. Additionally, a new water supply option—a solar-powered desalination plant with a production capacity of 10 MCM/year—can be introduced every 20 years in the Lower Region, starting in 2040.

In this regard, the high solar irradiance and access to seawater make the option of a solar-powered seawater desalination feasible. However, due to financial shortage, Yemen may depend on adaptation funds (AF) and green climate funds (GCF) to install and run the plant.

Tables 7 and 8 present water supply projections in the three regions considering NCWRr and NCWRi under SSP3 and SSP5, respectively.

Table 7. Water supply projections under SSP3.

Year	UR		MR		LR		Total	
	$NCWR_r$	$NCWR_i$	$NCWR_r$	$NCWR_i$	$NCWR_r$	$NCWR_i$	$NCWR_r$	$NCWR_i$
2022	68.8	68.8	86.5	86.5	52.8	52.8	208.1	208.1
2040	63.0	63.0	60.4	60.7	37.3	46.5	160.7	170.2
2060	66.2	66.2	59.5	60.9	36.8	60.7	162.5	187.8
2080	99.1	99.1	92.0	95.3	52.3	102.6	243.4	297
2100	90.8	90.8	82.0	88.8	47.6	145.7	220.4	325.3

Table 8. Water supply projections under SSP5.

Year	UR		MR		LR		Total	
	$NCWR_r$	$NCWR_i$	$NCWR_r$	$NCWR_i$	$NCWR_r$	$NCWR_i$	$NCWR_r$	$NCWR_i$
2022	68.8	68.8	86.5	86.5	52.8	52.8	208.1	208.1
2040	51	62.5	91	91.3	103.6	112.7	245.6	266.5
2060	57.7	65.3	102.8	104.2	112.6	136.4	273.1	305.9
2080	48.1	97.4	85.7	89	98.3	148.6	232.1	335
2100	54.2	87.8	96.5	103.4	119.1	217.2	269.8	408.4

3.4.3. Unmet Demand Projection

Based on the water supply projections under SSP3 and SSP5 and water use scenarios, two scenarios for each SSP are assessed as follows:

- Reference scenario: reference demand scenario and NCWR
- Improved scenario: improved demand scenario and NCWRi

Figure 6 presents the projections under SSP3, considering both the reference and improved scenarios. The data indicate that MR and LR will face water shortages under the reference scenario, projected to reach 24 MCM in MR and 501 MCM in LR by 2100. In contrast, projections based on the improved scenario suggest a more favorable situation in TD after 2060. However, LR is still expected to experience a water shortage of around 150 MCM in 2100, highlighting the need for more substantial water desalination solutions in that region.

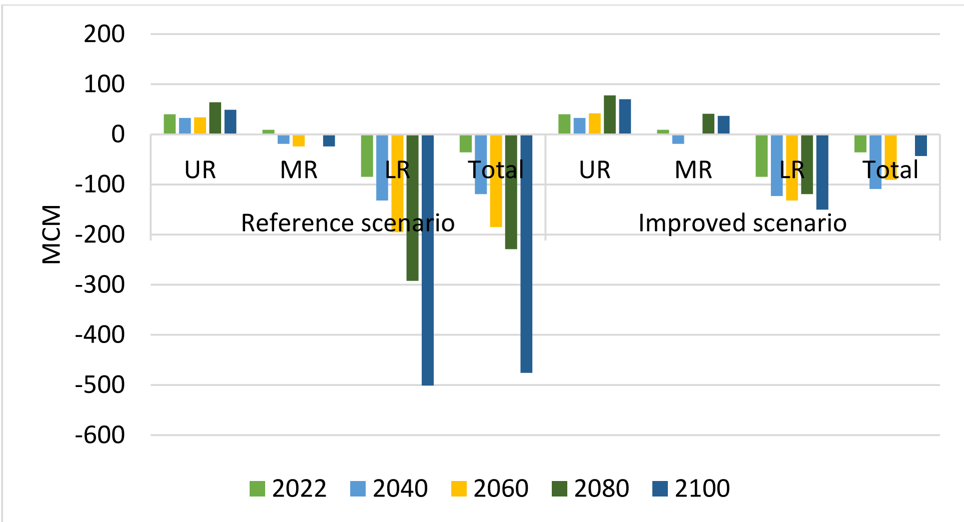

Figure 6. Unmet demand projections under SSP3.

Figure 7 presents the projections under SSP5, comparing the reference and improved scenarios. The data indicate that the Lower Region (LR) will continue to face severe water shortages under the reference scenario. In contrast, the improved scenario may enhance conditions in TD by 2060. However, effective water management and allocation plans are essential to address the challenges in the LR.

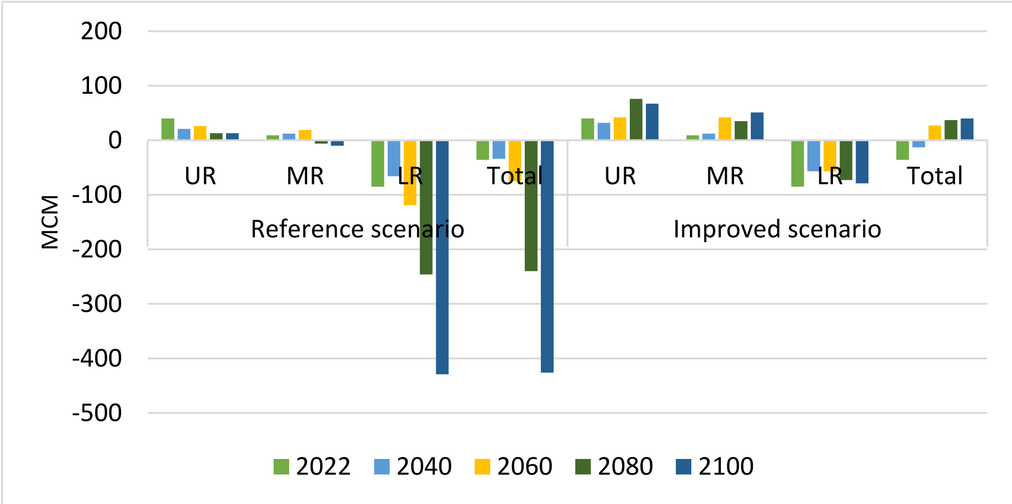

Figure 7. Unmet demand projections under SSP5.

4. Conclusions

Water scarcity, over-exploitation, and climate change are the primary threats facing the Tuban Delta. Therefore, an advanced hydrological assessment is essential to propose potential adaptation measures and provide policy recommendations. This assessment takes into account the hydrological year of 2022 for analysis and the development of future scenarios.

The 2022 estimations of water supplies and demand indicate a total water deficit of 36 MCM. Additionally, the development of various dams and rainwater harvesting techniques, along with the overuse of surface water in the upper section of the Tuban watershed (upstream), has reduced flood risks but diminished surface water availability in TD downstream. As a result, limited water reaches the Lower Region, and no water flows to the ocean, compelling communities and farmers to rely primarily on groundwater with renewable energy, leading to an increased water deficit of 84 MCM in LR, which might keep increasing due to internal migration, population expansion, and climate change.

The MRI-ESM2-0 climate model has been employed to project future conditions under SSP3 and SSP5. The results indicate a significant variation in water availability estimates across the three regions up to 2100. Under the reference scenario, the water deficit could exceed 400 MCM in 2100 for both climatic pathways. However, examining the improved scenarios shows a better situation in TD. To conclude, all these scenarios predict severe water shortages in LR, which might range from 60 to 80 MCM under the improved scenarios. Therefore, LR requires additional water resources, such as a 50 MCM seawater desalination plant, to address the ongoing water scarcity.

5. Recommendations for Policy Makers

I. Draw up preliminary plans for setting up a 50 MCM seawater desalination plant in LR, considering the following steps:
   - Feasibility study and environmental impact assessment.
   - Budget allocations through foreign aid such as adaptation funds (AFs) and green climate funds (GCFs).
   - Consultations with system providers offering solar-powered desalination.

II. Enhance infrastructure and approaches toward adaptation to climatic variability according to the following:
   - Enhance existing dams and rainwater harvesting facilities to increase storage and reduce evaporation losses.
   - Promote climate adaptation at the community level through education.
   - Run future projected climates to model and monitor them for proactive decisions in response.

III. Adopt and implement integrated IWRM strategies considering the following steps:
   - Set up a multi-sectoral committee tasked with undertaking the management of TD.
   - Implement and enforce controls on the abstraction of groundwater, ensuring that overexploitation of this resource is avoided.
   - Encourage farmers through incentives to capture rainwater and employ better irrigation techniques.

IV. Engage in teamwork between the local communities, farmers, and authorities through the following:
   - Workshops and forums regarding problems and solutions in water management.
   - Institutional involvement of local participation in decision-making processes in terms of water resource allocation.
   - Creating incentives for communities to be motivated in conserving water.

V. Establish an effective water resource and demand monitoring system by conducting the following:
   - Deploying technologies in monitoring water levels in both surface and groundwater sources.
   - Periodically assessing water supply and demand for readjusting policies when necessary.
   - Base decisions on data regarding future infrastructure and management.

VI. Climate models, in general, have uncertainties; therefore, for future studies, it is recommended to use MRI-ESM2-0 with other models like EC-Earth3 or NorESM2 to reduce uncertainties. Moreover, there is a need to study other hydrological basins that suffer from climate change and water scarcity.

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