# Study of the Hydrology of the Tuban Delta Yemen and the Impacts of Climate Change

## Disclaimer



This report has been reviewed by:
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- The Ministry of Agriculture, Irrigation, and Fish Wealth,
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# Background

This study is part of the Green Climate Fund (GCF) Readiness project 'Strengthen the capacities of sub-national authorities and key actors in the water sector to adapt to climate change in Tuban Delta'. The project is implemented by the United Nations Human Settlements Program (UN-Habitat) in coordination with the Environmental Protection Authority (EPA) of Yemen, through Mr. Abdulwahid Arman and some national and international stakeholders.

The goal of the project is to enable the Government of Yemen and sub-national authorities to respond to climate change in the highly vulnerable Tuban Delta. This goal is achieved through the preparation of a hydrology study and Climate Change Vulnerability Assessment (CCVA) focused on Tuban Delta water system, and based on that, identifying adaptation measures which will allow the government to identify strategic and investment priorities, responding to the most urgent water-related climate change challenges.

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# List of acronyms

| | |
|---|---|
| AWUa | Agricultural Water Uses (current irrigation methods) |
| AWUb | Agricultural Water Uses (modern irrigation) |
| CCCM | Camp Coordination and Camp Management Cluster |
| CCUS | Carbon capture, utilization, and storage |
| CCVA | Climate Change Vulnerability Assessment |
| CGWD | Commercial & Governmental Water Demand |
| CMIPs | Coupled Model Inter-comparison Projects |
| CWD | Consecutive Wet Days |
| CWR | Crops Water Requirements |
| DEM | Digital Elevation Model |
| DWUn | Drinking Water Uses (normal scenario) |
| DWUr | Drinking Water Uses (reduced scenario) |
| E | Electric Conductivity |
| ESCWA | Economic and Social Commission for Western Asia |
| GRCE | Gravity Recovery and Climate Experiment |
| EPA-Aden | Environmental Protection Agency- Aden |
| EWD | Environmental Water Demand |
| FGDs | Focus Group Discussions |
| HEC-HMS | Hydrologic Engineering Center -Hydrologic Modeling System |
| IDP | Internally Displaced People |
| IMSC | Inter-Ministerial Steering Committee |
| IPCC | Intergovernmental Panel on Climate Change |
| IWRM | Integrated Water Resources Management |
| GCMs | Global Climate Models |
| LWSC | Local Water and Sanitation Corporation |
| LR | Lower Region |
| LWSC | Local Water and Sanitation Corporation |
| MAIFW | Ministry of Agriculture and Irrigation and Fish Wealth |
| MPIC | Ministry of Planning and International Cooperation |
| MR | Middle Region |
| MRI-ESM 02 | Meteorological Research Institute Earth System Model Version 2.0 |
| MSWEP | Multi-Source Weighted-Ensemble Precipitation |
| MWE | Ministry of Water and Environment |
| NASA | National Aeronautics and Space Administration |
| NCWR | non-conventional water resources |
| NRW | Non-Revenue Water |
| NWRA | National Water Resources Authority |
| NWSSIP | National Water Sector Strategy and Investment Program |
| NWSSIP II | National Water Sector Strategy and Investment Program Update |
| PET | Potential Evapotranspiration |
| QGIS | Quantum Geographical Information System |
| RCMs | Regional Climate Models |
| RCPs | Representative Concentration Pathways |
| RO | Reverse Osmosis |
| SPEI | Standardized Precipitation-Evapotranspiration Index (SPEI) |
| SPI | Standardized Precipitation Index (SPI) |
| SSPs | Shared Socioeconomic Pathways |
| TD | Tuban Delta |
| TDS | Total Dissolved Solids |
| TWW | Treated Wastewater |
| UNESCWA | United Nation Economic and Social Commission for Western Asia |
| UNDP | United Nation Development Program |
| UNHCR | United Nations High Commissioner for Refugees |
| UNIDO | United Nations Industrial Development Organization |
| UR | Upper Region |
| WUAs | Water use Associations |
| WWTP | Wastewater Treatment Plant |
| WB | World Bank |

# EXECUTIVE SUMMARY

**i. Overall goal and objectives:**

Climate change, population growth, poor water management practices, overexploitation of water resources and the war have contributed to water scarcity, groundwater depletion and saltwater intrusion to many Yemeni aquifers, including Tuban Delta. Therefore, the purpose of this study is to assess present and future water supplies, water demands, the impact of climate change and its risks under different socioeconomic and climatic scenarios. To achieve this goal, this report has the following objectives:

1. Analyze collected data to determine current water supplies and demands,

2. Using remote sensing data, climate models and hydrological models, assess future water supplies and demands and balance projections under different climatic and socioeconomic scenarios,

3. Using climate models, Quantum Geographical Information System (QGIS) and field observations, assess and map potential climate risks,

4. Propose sustainable solutions to meet the increasing water demand and to reduce climate related risks in Tuban Delta.

**ii. ii. Contribution to the Discourse and Target Audiences:**

Based on collaboration between different stakeholders, including local communities, the research that comprises this report was conducted using a combined method including field visits to the various regions of Tuban Delta, remote sensing to fill gaps in data, assessing hydrological conditions and mapping potential climatic risks using climate models HEC-HMS and QGIS.

The results of this report come in the context of an ongoing conflict that has severely affected the water sector, including both physical infrastructure and government capacity to implement legislation and policy. Field research is supported by extensive communication and engagement with various national and international stakeholders, via workshops, meetings and focus group discussions (FGDs). The findings of this study will also serve as the foundation for a Climate Change Vulnerability Assessment (CCVA) and recommendations of possible climate adaptation measures/strategies for Tuban Delta. Moreover, this study includes significant findings and data that can be used by a variety of actors, including the Environmental Protection Agency-Yemen (EPA), GIS units, Ministry of Water & Environment (MWE), Ministry of Agriculture, Irrigation and Food Wealth (MAIFW), Ministry of Education, Local Water and Sanitation Corporation (LWSC), National Water Resources Authority (NWRA), Water User Associations (WUAs), University of Aden, farmers, local communities and international partners.

**iii. Main outcomes:**

**Present status:** Water resources in Tuban Delta face many challenges, including climate change, overuse and a lack of a sustainable water management strategy. Climate change impacts on water resources include:

1) Reduced water availability due to the reduction of annual rainfall rates in recent decades, which have depleted groundwater levels by approximately 1 m/year, increased saltwater intrusion and the resulting land and soil degradation,

2) Increased drought periods have dried out many streams in the Lower Region, which has encouraged illegal housing near the streams, thus exposing housing to the risk of inundation during intense flooding events,
3) Increased extreme weather events that increase the risk of catastrophic floods.

These issues have impacted population growth, land use, water quality, water quantity and agricultural systems. The 2022 estimation of water supplies includes renewable surface water, renewable groundwater water and non-conventional water resources, which have been estimated at 59, 139, and 10 Million Cubic Metres (MCM) respectively. Whilst total water demand includes 194 MCM for agricultural uses and 50 MCM for domestic uses, which means agricultural water represents 80% of the total water use. This results in a total water deficit of 36 MCM. Furthermore, the development of several dams and other rainwater harvesting techniques and the overuse of surface water in the upper section of Tuban watershed (upstream) have decreased the risk of floods but also decreased the availability of surface water in Tuban Delta (downstream). As a result, limited water reaches the lower region and no water reaches the ocean, which has forced the general population and farmers to depend mainly on groundwater pumped using renewable energy, contributing to a significant water deficit. These factors coupled with climate change have increased saltwater intrusion to groundwater aquifers, desertification, increased groundwater depletion, led many wells to run dry and deteriorated the fertile soils in the Lower Region of Tuban Delta.

Possible options to reduce the water deficit include:

1. Shifting from traditional surface irrigation to drip irrigation (if all agricultural lands use drip irrigation, 45-50% of the deficit will be covered),

2. Wastewater treatment and reuse: The majority of the population in Tuban Delta use septic tanks. The available wastewater that can be treated can cover approximately about 10% of the deficit,

3. Greywater treatment and reuse: can be used in the nearby areas, however if it is used in toilet flushing, it can cover 5% of the deficit, which is not applicable at this time,

4. Groundwater recharge from flood water and from the treated wastewater can cover 5% of the deficit,

5. Monitoring groundwater resources and preventing unauthorized extraction activities. This option should be used to reduce illegal groundwater recharge, thus reducing groundwater depletion and saltwater intrusion.

The above-mentioned options however will be insufficient to satisfy the growing water demand in Aden, especially considering future climate change impacts and population growth. Therefore, with the current dependence on depleting groundwater resources, sea-water desalination has become a crucial alternative for providing fresh water and forms part of a strategy to diversify water supply and use renewable water resources.

**Future projections:** The MRI-ESM2-0 climate model and QGIS have been used to analyze future water availability under two Shared Socioeconomic Pathways (SSP3: RCP 7) and (SSP5: RCP 8.5).

Two main scenarios have been assessed, the first is the reference scenario where all activities and population growth remains the same, while the second one is the improved scenario, which considers modern irrigation, decreased population growth rates and increased use of treated wastewater.

The results reveal a wide divergence in the water availability estimates by the year 2100 in the three regions. Under the reference scenario, the water deficit is forecasted to be more than 400 MCM in 2100 under both climatic pathways (SSP3 and SSP5). Under the improved scenario however, the water shortage is forecasted to be not more than 43 and 10 MCM in 2100 under SSP3 and SSP5 respectively. On the other hand, assessing the three regions of Tuban Delta individually, the Upper Region (UR), the Middle Region (MR) and the Lower Region (LR), shows that severe water shortages in the LR are predicted under all scenarios, potentially ranging from 60 to 80 MCM under the improved scenario. Findings therefore suggest that the extent of the LR's additional needs will require an intervention such as a 50 MCM solar pumped sea-water desalination plant as soon as possible, followed by additional 10 MCM plants every 5-10 years.

Regarding groundwater resources, the assessment of 2023 shows that there are 3,600 wells, 1,200 of which have gone dry, and the average annual drop of groundwater levels has reached one meter due to the imbalance between the discharge and recharge rate. If this imbalance continues at the rate at which it was in 2022, the projections show that most of the wells will go dry or become brackish in the LR by 2060.

**Future climate risks:** The three regions have an elevated risk of being affected by drought and flooding in the future. For instance, under SSP3 and SSP5, extremely high rainfall rates have the potential to cause flooding between 2060 and 2063, and between 2074 and 2076 respectively, while drought might occur between 2029 and 2034 and between 2069 and 2072. The LR on the other hand is the most susceptible to the effects of climate change since it is impacted by four main climate hazards; flooding, drought, sea-level rise and saltwater intrusion. All these hazards will have an impact on water supply systems and coastal infrastructure. Moreover, the LR faced severe meteorological and socioeconomic droughts in 2022, and unfortunately the socioeconomic drought will persist in the coming years unless a new water resource is secured.

**Management and climate adaptation options:** The study reveals management shortcomings and the requirement for a sustainable water management strategy to distribute the existing water resources under climatic and socioeconomic challenges. The study reveals a need for new sustainable solutions to meet the rising water demand in the LR and to reduce saltwater intrusion. Different adaptation options have been discussed and ranked with national stakeholders through consultation and workshops. Prioritized options include:

- Rehabilitating irrigation canals and upgrading the current irrigation system to drip irrigation,
- Rehabilitating some of the wastewater treatment plants to reuse treated wastewater and sludge to improve agricultural productivity,
- Groundwater recharge and floodwater harvesting,
- Installing solar-powered seawater desalination plants to meet the rising demand in Aden,
- Disaster management planning coupled with an early warning system at the head of Tuban Delta to alert residents of flooding dangers if water flow surpasses 150 m3/sec, combined with a proper disaster management plan to reduce the risk of flooding .[1]

[1] For context it is important to note that a devastating flood in Tuban Delta in 1982 was brought on by a water flow of 225 MCM from the top of the Delta (Wadi Tuban upstream).

The regulatory framework in Yemen includes both a water law and a water policy, however both are currently not being implemented and are thus not contributing to improving the current situation. To conserve natural resources, particularly groundwater and to enhance human welfare, updated legislation and policy instruments are required that address climate-related hazards and water management methods, whilst being cognizant of the challenges of the current institutional context. However, these might take a long time to be adapted and approved. Therefore, an Integrated Water Resources Management strategy for Tuban Delta is urgently needed.

# 1. INTRODUCTION

## 1.1. Study Purpose and Problem Statement

YYemen has sufficient water resources to meet its drinking water needs, but a significant portion of the population suffers from acute water shortages, and 90% of those resources are primarily used for irrigation using traditional methods (UNDP 2021).

In addition to sub-optimal irrigation methods, water resources in Yemen face other challenges including climate change, lack of water management practices, overexploitation and population growth.

These factors have contributed to socioeconomic instability and water related conflicts, many of which are too complex for local systems of dispute resolution to address (Huntjens et al., 2014). Furthermore, ten years of war has undermined water management, increased water scarcity and groundwater depletion leading to saltwater intrusion and increased food and water insecurity.

Tuban Delta is at once one of the most water scarce areas of Yemen and-containing the city of Aden-is also one of the most population dense. The convergence of challenges highlights the need for hydrological research to evaluate the conditions and potential climatic risks. This research forms an evidence base on which interventions to address these as well as challenges further afield in Yemen can be based. Therefore, this study has been carried out by the UN-Habitat Yemen team in collaboration with the Environmental Protection Agency (EPA) of Yemen and funded by the Green Climate Fund (GCF). The study uses local data, remote sensing data, Global Climate Models (GCMs) and QGIS to assess water resources and climatic risks under different scenarios.

TIn exploring the current and potential future environmental and socioeconomic situation in Tuban Delta, the study has the following foci:

- Assessment and predictions of water resources,
- Assessment and predictions of water demands,
- Mapping climate threats (drought, sea-level rise, saltwater intrusion and flooding),
- Potential adaptation options/measures.

The findings of this study will contribute to the creation of the Climate Change Vulnerability Assessment (CCVA) report and the form the basis of potential climate adaption strategies.

## 1.2. Climate Scenarios

The climate modeling field of study contains two major tools to model the impacts of climate change: known as Coupled Model Inter-Comparison Projects CMIP 5 and CMIP6. CMIP 5 uses a Representative Concentration Pathway (RCP) to attempt to capture future trends in how concentrations of greenhouse gases in the atmosphere will change as a result of human activities. The RCP ranges from very low to very high, including warming of 2.6, 4.5, 6 or 8.5 watt/m2 under the following scenarios:

- RCP 2.6: CO2 emissions start to decline by 2020 and reach zero by 2100.
- RCP 4.5; CO2 emissions start to decline by 2040.
- RCP 6: CO2 emissions start to decline by 2060.
- RCP 8.5: CO2 emissions will increase throughout the 21st century (the worst-case scenario).

On the other hand, CMIP6 projects global socioeconomic trends via the Shared Socioeconomic Pathways (SSPs) up to 2100. The SSPs are built on five scenarios that describe various rates and trajectories of socioeconomic processes. They include: sustainable development (SSP1), regional rivalry (SSP3), inequality (SSP4), fossil-fueled development (SSP5) and middle-of-the-road development (SSP2) as shown in Figure 1 (Riahi et al., 2017).

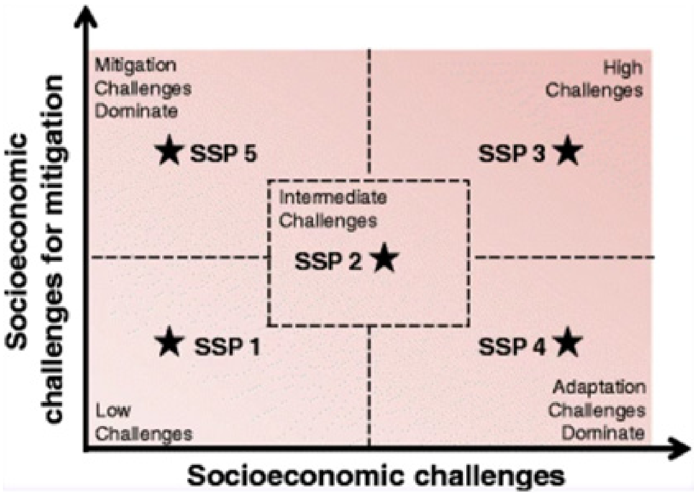

***Figure 1.*** *Combinations of Challenges to Mitigation and Adaptation in SSPs.*

SSP1 and SSP5 are indicators of effective institutions, wise investments in health and education and quick economic expansion. SSP1 is based on sustainable practices, whereas SSP5 is based on a fossil fuel-driven economy SSP3 and SSP4 show low investments in health and education in developing nations, a rapidly expanding population and rising inequality (Bassetti, 2022).

SSP based scenarios further refine the RCPs. Thus, coupling SSPs and RCPs is used to describe possible alternative conditions of human society and the environment at the macro scale that could shape future society (Hausfather, 2018; Frame et al., 2018). Scenarios include the following:
SSP1: A world where development is based on the Sustainable Development Goals (SDGs) (RCP 1.9 and RCP 2.6),
SSP2: 'Middle of the road' (RCP 4.5),
SSP3: A fragmented world of regional rivalry and resurgent nationalism (RCP7),
SSP4: A world of ever-increasing inequality (RCP6),
SSP5: A world of rapid and unconstrained growth using fossil fuel driven development (RCP 8.5).

# 2. METHODOLOGY/DATA

## 2.1. Data Collection

### 2.1.1. Consultations

The hydrology study and related analysis require a variety of data, including hydrological data, land and water uses, demographic and socioeconomic data and climatic projections.
A portion of the required information was obtainable from open-access websites and earlier studies. However the majority of available secondary sources of data were collected before the outbreak of the war and were thus outdated. Therefore additional data has been gathered from national authorities. The following national organizations have contributed to the gathering and validating the data: EPA, National Water Resources Authority (NWRA), Ministry of Agriculture, Irrigation and Food Wealth (MAIFW), and Ministry of Water & Environment (MWE).

In this context, it is important to note that many hydrological measurements have ceased because of the war, whilst some equipment has either been stolen or destroyed. Consequently, after 2015 it was difficult to obtain reliable data. As a result, numerous consultation meetings were arranged to verify and update existing data.

### 2.1.2. Field data

In February 2023, local government officials and representatives of the Water User Associations (WUAs) were interviewed. Three field trips were then conducted to the top, middle, and lower parts of Tuban Delta, with three Focus Group Discussions (FGDs) held during each visit, with farmers, men and women. The following subjects were discussed:

- Local issues and demographic trends,
- Institutional structures,
- Socioeconomic activities (agriculture, water consumption and use of the land),
- Climate-related risk (including sea level rise, drought, saltwater intrusion and flooding),

To estimate groundwater abstraction and the quality of the discharged water from wells, the local team members conducted several field visits to collect data about agricultural and domestic wells. The data collected included the water level, average abstraction rates, temperature and the Electric Conductivity (EC) to compare the collected data with the data of 2007.

### 2.1.3. Remote sensing data

Due to the disruption caused by the war, no rainfall records were measured after 2015. Monthly rainfall rates were thus acquired from Multi-Source Weighted-Ensemble Precipitation (MSWEP), a worldwide precipitation product with a 3 hourly 0.1° resolution that combines gauge, satellite, and reanalysis data to produce the highest quality precipitation estimates. Subsequently, the monthly rainfall rates were processed in QGIS to calculate the annual precipitation in 2022.

## 2.2. Climate Scenarios

Examining how well CMIP5 and CMIP6 Global Climate Models (GCMs) performed in various nations revealed that CMIP6 GCMs are significantly improved at reproducing temperature and rainfall. With the exception of  minimum temperatures at various timeframes, CMIP5 GCMs perform better at replicating geographical distribution but less well at simulating spatial variability of most climatic variables (Kamruzzaman et al. 2021). As a result, the Meteorological Research Institute Earth System Model Version 2.0 (MRI-ESM 2.0) will be considered under CMIP6. It is anticipated that MRI-ESM 2.0 will perform better in many of the experiments scheduled for CMIP6 than earlier models that took part in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Yukimoto et al., 2019a).

Based on the Coupled Model Inter-comparison Project 6 (CMIP6), which supports the Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report, the future projections in this report have been performed under climatic scenarios SSP3 and SSP5, due to the increase of conflicts and the traditional socioeconomic activities all over the world:

- SSP3 is coupled to RCP7, which suggests high obstacles in adaptation and mitigation due to conflicts and instabilities, and

- SSP5 is coupled to RCP8.5, which indicates high challenges in mitigation leading to an increase in fossil fuel consumption.

In general, SSP3 and SSP5 represent high emission, high impact scenarios, as the rate of emission reduction during the last 13 years is not significant enough to render lower emission scenarios such as SSP2 realistic.

Some climate projections up to 2100 were obtained with the support of United Nation Economic and Social Commission for Western Asia (UNESCWA).

Other climate projections were obtained from different climate services platforms such as Climate Change Knowledge Portal (CCKP)[2], which was created by the World Bank (WB) for use by development practitioners and policy makers. Moreover, the time frames for the extreme events scenarios have been modified from 2010-2039, 2035-2060, 2060-2089 and 2070-2099 to be 2023-2040, 2041-2060, 2061-2080, and 2081-2100 respectively.

## 2.3. Runoff

Runoff water availability can be calculated by subtracting evaporation and infiltration from total rainfall (Dingman 2015). The Rational Method, Cook's method or Curve Number are three basic runoff estimation methods that can be used to estimate water availability (Juniati et al., 2021). This study utilized the Rational Method using the following equations (Juniati et al. 2021):

$$C = \Sigma\ (ci \times Ai) / \Sigma Ai \quad (1)$$
$$R = \Sigma\ Ri / m \quad (2)$$
$$WA = C \times R \times A \quad (3)$$

where, WA = water availability (MCM/year), C = weighted runoff coefficient, Ci = Land-use coefficient, Ai = Land Area (Km2), R = average yearly rainfall data (m/year), Ri = Rainfall in station i, m = number of rainfall stations, A = Total Area (ha), 10 = conversion factor.

## 2.4. Assessment, Mapping, and Projections

The collected datasets were then analyzed to assess present and projected unmet demand (Eq. 4):
Unmet demand = water supply – water demand. (4)

Water supply includes available water from runoff, renewable groundwater, reclaimed water and available water from the northern highlands of Tuban Wadi. While water demands include domestic, agricultural, commercial, industrial and environmental demands.

The collected data, future projections, saltwater intrusion, sea-level rise, drought and flooding have been mapped using QGIS.

## 2.5. Study Area and Watershed Delineation

Tuban Delta is the downstream of Wadi Tuban basin. Wadi Tuban has a total area of 7360 Km2 and consists of seven sub-basins (Saleh et al., 2012), see Table 1.

| **Sub-basin** | Maytem | Saelah Qataba | Worzan | As-Sodan | Tuban | Al Enteshari | Agreen |
|---|---|---|---|---|---|---|---|
| **Area Km2** | 1068 | 765 | 1295 | 862 | 1448 | 1415 | 507 |

***Table 1.*** *The Sub-Basins in Tuban Watershed*

Tuban Delta is located between 44.65o - 45.1o E and 12.7o -13.3o N, its topography ranges from 10m below sea level to approximately 800m above sea level. Administratively, Tuban Delta can be divided into three regions the Upper Region (UR), the Middle Region (MR) and the Lower Region (LR), Figure 2. The area and population of each region are presented in Table 2.

[2] https://climateknowledgeportal.worldbank.org.

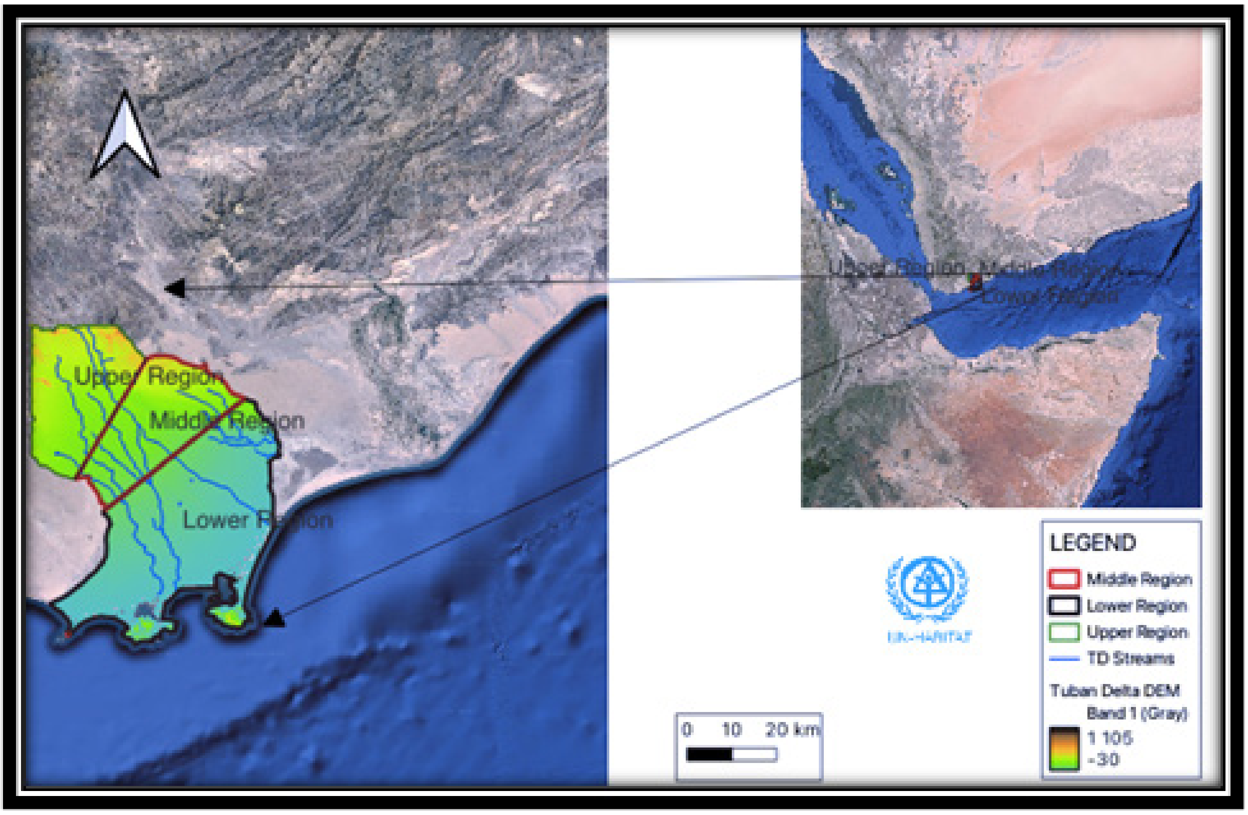


***Figure 2.*** *Tuban Delta location (administrative map).*

| **Sub-basin** | Area (Km2) | PopulationAgreen |
|---|---|---|
| **Lower Region** | 1030 | 1 133 013 |
| **Middle Region** | 570 | 85 954 |
| **Upper Region** | 450 | 36 921 |

***Table 2.*** *The Area and population of the Three Regions of Tuban Delta*

To delineate the watershed of Tuban Delta, QGIS and HEC-HMS models have been used. The Digital Elevation model for the study area was downloaded from the Shuttle Radar Topography Mission (SRTM) of the United States Geological Survey (USGS). Ten break points (outlets) formed, which led to many sub-basins, which have subsequently merged in one watershed. Then the shapefile was processed in QGIS to create a better visualization of the study area, the three regions and the streams (see Figure 3).

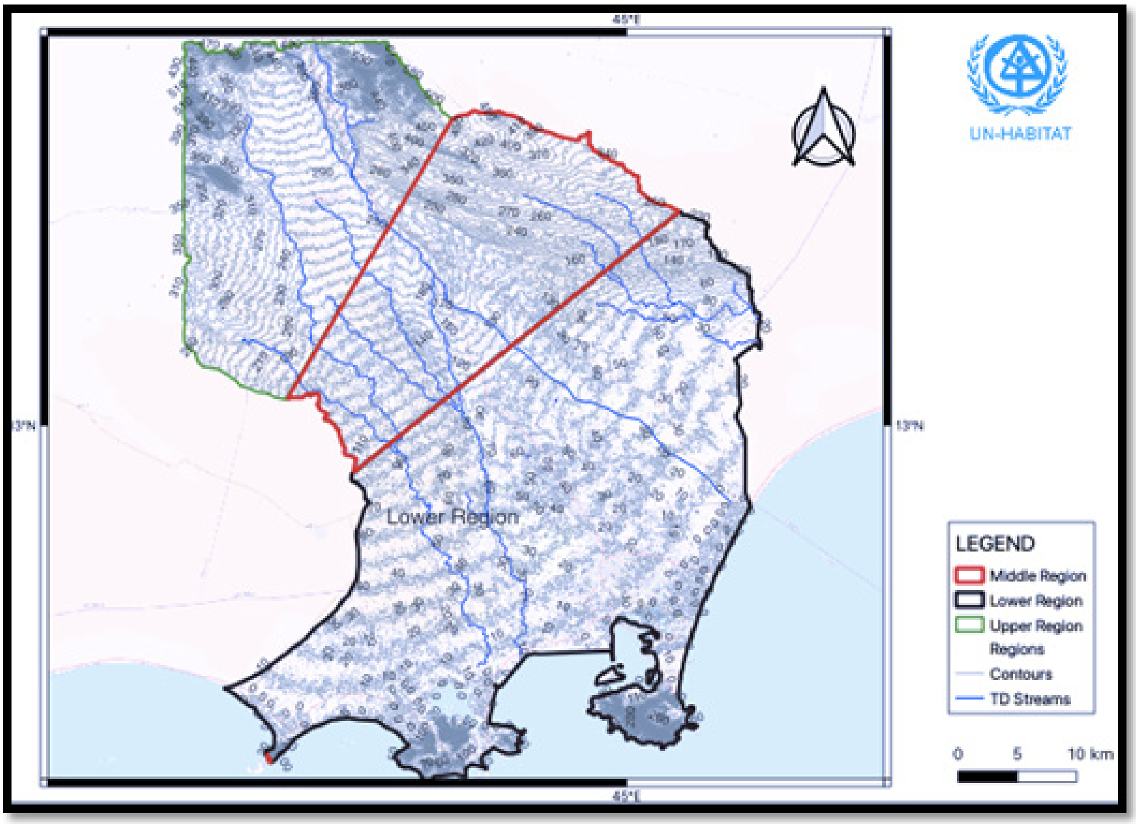


***Figure 3.*** *Contours, and Streams at Tuban Delta.*

## 2.6. Hazard Assessment

Hazard assessment values are determined by multiplying the scores for severity values and the probability of occurrence for each recognized risk. Severity is the amount of damage or harm a hazard could create and is ranked on a four-point scale; 4- Catastrophic, 3- Critical, 2- Marginal and 1- Negligible. Probability is the likelihood of the hazard occurring and is ranked on a five-point scale; 5- Frequent, 4- Probable, 3-Occasional, 2-Remote and 1- Improbable. Hazard values are then grouped into four categories; Low: II, Medium-Low: III, Medium: IV, Medium-High and V High (see Figure 4).

| Probability | Severity 1 | Severity 2 | Severity 3 | Severity 4 |
|---|---|---|---|---|
| 5 | 5 | 10 | 15 | 20 |
| 4 | 4 | 8 | 12 | 16 |
| 3 | 3 | 6 | 9 | 12 |
| 2 | 2 | 4 | 6 | 8 |
| 1 | 1 | 2 | 3 | 4 |

| I | II | III | IV | V |
|---|---|---|---|---|
| Low | Medium/low | Medium | Medium/High | High |

***Figure 4.*** *Risk Assessment Values and Categories.*

# 3. WATER RESOURCES AVAILABILITY

No specific estimates of water resource availability in Tuban Delta have been made so far. However, there are some estimates for Yemen as a whole or for specific governorates; for example, Haidera and Noaman (2008) assessed Lahj's potential water resources to be 130 MCM/ year.

Tuban Delta is not a separate watershed. It is considered the downstream of Tuban Wadi Basin. As a result, the total renewable water resources in Tuban Delta will be the sum of inflow from Tuban Wadi's highlands, rainfall/runoff from the three regions and groundwater flow from the northern highlands.

## 3.1. Water Availability from the Highlands

Between 1955 and 1983, the average annual flow at the top of Tuban Delta was estimated to be 125 MCM. The highest inflow occurred in 1982 with an annual inflow of 350 MCM, which led to a catastrophic flood in March of that year.

Due to the lack of recent estimations of the inflow from the highlands and after consultation with the local authorities, the annual inflow from the northern highlands in 2022 is estimated at 125 MCM. This inflow is usually totally utilized before reaching the ocean with 35% (43.75 MCM) deposited in the UR, 50% (62.5 MCM) in the MR and 15% (18.75 MCM) at the top of the LR(before the city of Aden). This limited flow to the city of Aden has altered soil qualities, enhanced desertification and driven the population to overuse groundwater for agricultural and domestic uses, thus increasing saltwater intrusion.

## 3.2. Water Availability from Runoff

To estimate water availability from local runoff, the Rational Method was used (Equations 1, 2 and 3), considering the rainfall of 2022. Runoff coefficient Ci depends on soil type, land slope and land cover (See Table 3).

***Table 3:*** *Runoff Coefficient for Different Land Cover, Slope, and Soil Types.*

| Land Use/ Topography | Sub-basin | | |
|---|---|---|---|
| | Sandy loam | Clay and silt loam | Tight clay |
| **Cultivated land** | | | |
| Flat | 0.3 | 0.5 | 0.6 |
| Rolling | 0.4 | 0.6 | 0.7 |
| Hilly | 0.52 | 0.72 | 0.82 |
| **Pasture** | | | |
| Flat | 0.1 | 0.3 | 0.4 |
| Rolling | 0.16 | 0.36 | 0.55 |
| Hilly | 0.22 | 0.42 | 0.6 |
| **Forest land** | | | |
| Flat | 0.1 | 0.3 | 0.4 |
| Rolling | 0.25 | 0.35 | 0.6 |
| Hilly | 0.3 | 0.5 | 0.6 |
| **Populated land** | | | |
| Flat | 0.4 | 0.5 | 0.65 |
| Rolling | 0.5 | 0.65 | 0.8 |

Sources: (Suresh 1997 and Shrestha et al. 2012).

According to Saleh et al. (2017), the soil types in Tuban delta 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 these two soil types were chosen for modelling. Tuban Delta's slope was calculated in the HEC-HMS model to be about 5%, indicating that the basin's topography could be described as a rolling gentle slope (Marifa et al. 2021). Table 4 illustrates the average runoff coefficients for different land uses in Tuban Delta based on soil texture and slope.

***Table 4:*** *Ruoff Coefficient for the Different Land Uses in Tuban Delta*

| Land use | Ruoff coefficient |
|---|---|
| Agricultural land | 0.65 |
| Pastureland | 0.45 |
| Populated land | 0.6 |

To estimate the weighted runoff coefficient for each region, the different land uses were estimated using recent Google Map, QGIS and various national documents (see Table 5).

***Table 5:*** *Land Uses in Tuban Delta.*

| Land cover/use | Lower region | Middle Region | Upper Region |
|---|---|---|---|
| Agricultural land (%) | 8.6 | 11.1 | 7.1 |
| Pastureland (%) | 79.6 | 86.6 | 91.4 |
| Populated land (%) | 11.8 | 2.3 | 1.6 |

Subsequently, the weighted runoff coefficients were estimated using Equation (1) as shown in Table 6.

***Table 6:*** *Weighted Runoff Coefficient in the Three Regions of Tuban Delta.*

| Tuban Delta | Lower Region | Middle Region | Upper Region |
|---|---|---|---|
| Weighted C | 0.485 | 0.476 | 0.466 |

The acquired monthly rainfall MSWEP were processed in QGIS to calculate the annual precipitation for 2022, see Figure 5.

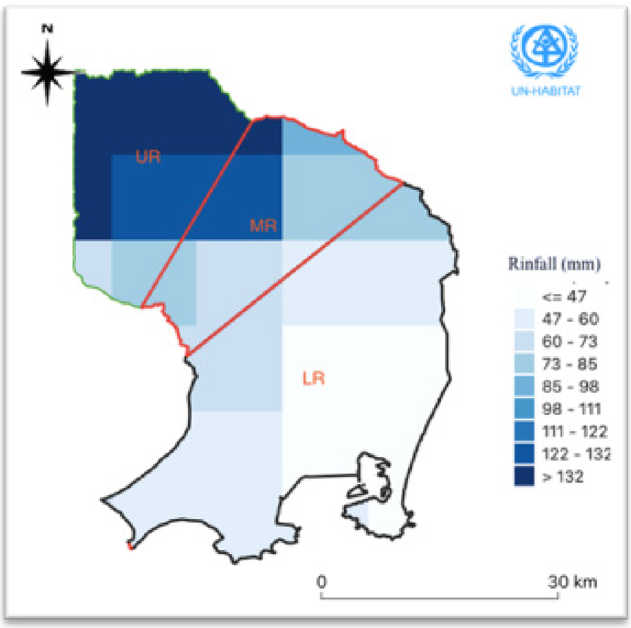


***Figure 5.*** *Precipitation in 2022 in Tuban Regions Based on MSWEP Data.*

Then, water availability in the three regions have been estimated using the Rational Method as shown in Table 7.

***Table 7:*** *Water Availability in Tuban Delta 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 (Km2) | 450 | 570 | 1030 | |
| Runoff MCM | 25 | 23 | 25 | 73 |

## 3.3. Total Renewable Water

Based on the map of groundwater aquifers (Figure 6), limited groundwater flows come from the northern aquifers. Therefore, the groundwater recharge in Tuban Delta will occur mainly due to local rainfall, check dams and the inflow from the highlands to the streams and canals. According to Girgirah et al., (2007), 70% of the available water (runoff and inflow from the high lands) supplies groundwater. Thus, the total renewable surface water will be the remainder (30%) as illustrated in Table 8.

***Table 8:*** *Renewable Water Resources in Tuban Delta (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 |

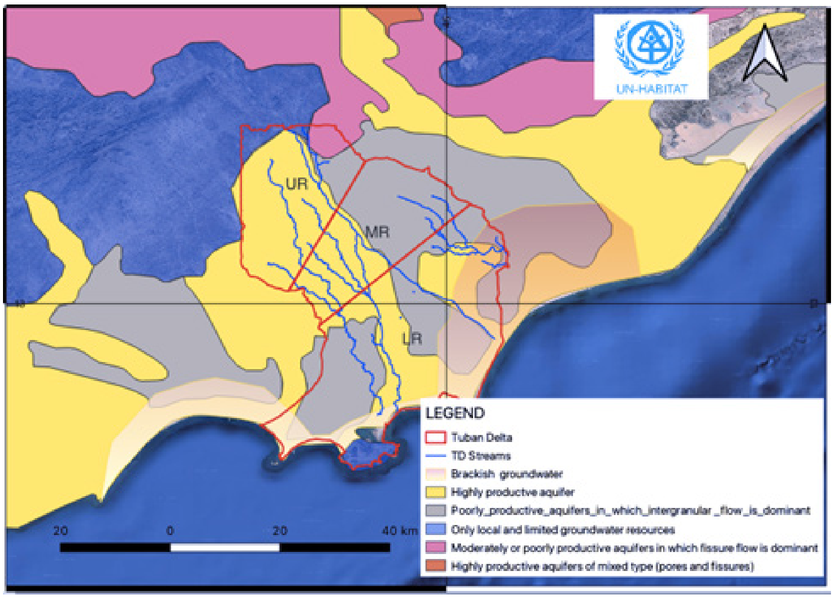


***Figure 6.*** *Groundwater Aquifers in Tuban Delta*

Based the FGDs, Tuban Delta currently has approximately 3,600 wells compared to 350 wells in 1966. Of these wells, more than 1,200 are dried out due to climate change and overuse. Field visits showed that there are 2,200 working wells for agricultural uses, while for domestic uses in Aden there are 107 wells. Comparing the average water level and discharge of 120 wells in 2007 with 2023 shows a decrease in the average water level from 37.1 m to 49.5 m.

This decrease indicates that the depletion in groundwater has reached 12.4 m during these 16 years (annual groundwater depletion reaches 80 cm). The annual discharge rates for agriculture and domestic uses are estimated at 147.4 and 50.1 MCM respectively. No change in water quality or Electric Conductivity (EC) was found during the observation period. The distribution of wells in Tuban Delta was estimated to be 10.2%, 37.5% and 52.3%, respectively, at the UR, MR and LR. As a result, groundwater extractions for agriculture are estimated at 15, 55 and 77 MCM from the UR, MR and LR respectively. While groundwater extractions for domestic uses are estimated at 1.3, 3.2 and 45.5 MCM from the UR, MR and LR respectively. In this regard, Komex (2001) suggested reducing the extraction rate in the LR to 36.4 MCM to stop saltwater intrusion.

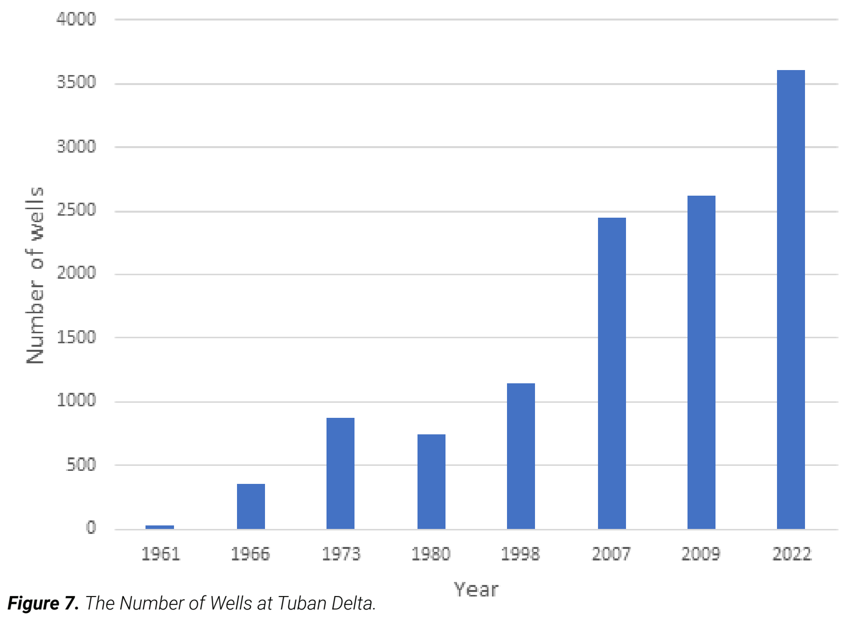


***Figure 7.*** *The Number of Wells at Tuban Delta.*

Data from the National Aeronautics and Space Administration (NASA) Gravity Recovery and Climate Experiment (GRCE) published in 2021 argued that the use of solar power in pumping water is draining Yemen's groundwater as it is a free source (CEOBS, 2021), (see Figure 8), which has been confirmed in the conducted field visits in March 2023 as some farmers pump 12 hours while others have batteries and pump even at night.

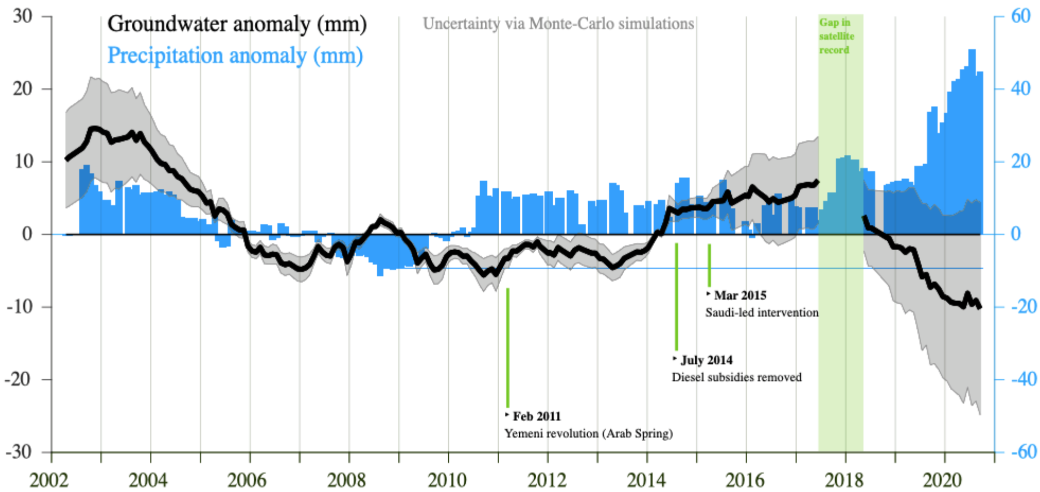


***Figure 8.*** *Groundwater Depletion in Yemen Based on (NASA) and (GRCE).*

## 3.4. Non-Conventional Water Resources

The non-conventional water resources (NCWR) include mainly greywater reuse and treated wastewater.

**1. Greywater reuse:** The reuse of greywater is a good practice that can save up to 30% of the domestic demand if it is used in toilet flushing (Mourad et al., 2011). However in Yemen, greywater reuse is limited and mainly applied in some mosques, where greywater is used to irrigate the gardens.

**2. Treated wastewater:** The availability of sewage networks and wastewater treatment plants (WWTPs) determines the availability of treated wastewater. There are seven WWTPs in Tuban Delta utilizing the treatment method of oxidation ponds, three are located in Tuban district (Saber WWTP, Al-Waht WWTP, 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 LR, nine MCM of the treated wastewater is used in the wetlands, while the remainder is discharged directly to the ocean. This implies that the reclaimed water is not being properly reused/managed, but due to an overload and a need for rehabilitation of most WWTPs, treated wastewater is polluting the ocean and surrounding environment. In this regard, a study evaluated secondary effluents and biosolids generated from four sewage treatment plants in Yemen, which revealed that concentrations of faecal coliforms (FCs) were higher than those recommended by the World Health Organization (WHO) guidelines in all wastewater samples (Al-Gheethi et al., 2014). There is only one WWTP in the MR that treats about 1.0 MCM per year. While the UR's wastewater is not treated or reused. Thus, the total annual non-conventional water resources are estimated at 10 MCM as shown in Table 9.

***Table 9:*** *Non-Conventional Water Resources (MCM/year).*

| Regions | UR | MR | LR | Total NCWR (MCM) |
|---|---|---|---|---|
| Produced wastewater (MCM) | 0.06 | 1.15 | 12.9 | |
| Reused | 0 | 1 | 9 | 10 |

# 4. WATER DEMANDS

Water demand can be classified as either agricultural, domestic, industrial or environmental. Industrial demand in Tuban Delta is limited, and environmental demand is unmet because no water flows via the streams towards the ocean. Municipal water networks serve a portion of the community, including commercial and government buildings. While the needs of the remainder are met by privately owned wells.

## 4.1. Domestic Water Uses

The majority of Domestic Water Use (DWU) is met by municipal water supply provided by the Local Water and Sanitation Corporation (LWSC) or by private supply for individuals who are not connected to a public supply. Around 25% of people in the LR are not connected to the public water system, compared to 40% of people in the UR and MR .

Based on the data of the LWSC, drinking water in the LR is supplied by several well fields that have around 107 working wells (see Table 10).

***Table 10:*** *Wellfields and Pumping Rates in the LR in 2023.*

| Wellfields | Nr of working wells | m3/day |
|---|---|---|
| Maghras Nagi (Lahj) | 16 | 8990.6 |
| Bir Naser (Aden) | 46 | 56716.73 |
| Manaserah (Aden) | 16 | 21259.23 |
| Bir Ahmed (Aden) | 29 | 48000 |
| Total | 107 | |

According to Aden's water corporation, half of the produced water is non-revenue water (NRW), which is the difference between the amount of water that is produced by a water utility for consumption/use, and the amount of water that is billed to customers due to losses or illegal connections. According Lahij water corporation, 40% of the MR's population is not linked to the public water supply system, compared to approximately 30% in the NRW. The available data indicates that the domestic water uses are approximately 110, 103and 100 L/capita/day (including the NRW) in the LR, MR and UR respectively. Table 11 presents the total domestic use for each region including the NRW.

***Table 11:*** *Domestic Water Uses in Tuban Delta (2022).*

| Regions | UR | MR | LR | Total |
|---|---|---|---|---|
| Population | 36921 | 85954 | 1133013 | 1255888 |
| Daily (L/capita/day) | 100 | 103 | 110 | |
| Total DWU (MCM)1.3 | 3.2 | 45.5 | 50.1 | |

## 4.2. Agriculture Water Uses

The total agricultural land in Tuban delta is approximately 18,356 ha. However, due to water shortages, the cultivated land areas are only approximately 40-60% of the total agricultural area, (see Table 12).

***Table 12:*** *Cultivated Areas/Crops in Tuban Delta (ha).*

| Crops | Sub-basin | | | | | |
|---|---|---|---|---|---|---|
| | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 |
| **Sesame** | 279 | 276 | 282 | 285 | 279 | 276 |
| **Sorghum Millet** | 4181 | 4139 | 3725 | 1308 | 3557 | 1252 |
| **Cotton** | 331 | 328 | 337 | 331 | 336 | 309 |
| **Vegetables** | 518 | 505 | 499 | 506 | 504 | 511 |
| **Watermelon** | 119 | 117 | 117 | 119 | 127 | 132 |
| **Muskmelon** | 34 | 34 | 35 | 37 | 39 | 36 |
| **Fodder** | 4 477 | 4 519 | 4 301 | 4 507 | 4 491 | 4 467 |
| **Total area** | **10 739** | **10 715** | **10 118** | **7 923** | **10 175** | **7 840** |

There are three types of irrigation as illustrated in Table 13:

1. Spate irrigation: This approach uses traditional intakes and canals to shift water flow from valleys, rivers, and wadies into farmlands that are lower in elevation than the valley.
2. Check basin irrigation: In this approach, soil bunds are built all around the field as a boundary, the field is inundated with water.
3. Modern irrigation: Drip irrigation, which is the most efficient water and nutrient deliery system for growing crops, involves placing tubing with emitters on the ground alongside the plants.

***Table 13:*** *Irrigation Methods in Tuban Delta.*

| Regions | Spate Irrigation | Check basin Irrigation | Modern irrigation |
|---|---|---|---|
| UR | 40% | 50% | 10% |
| MR | 40% | 55% | 5% |
| LR | 20% | 75% | 5% |

Table 14 presents crop water requirements in Yemen.

***Table 14:*** *Crop Water Requirements in Tuban Delta in 2022.*

| Crops | Water Use (m3/ha) | |
|---|---|---|
| | Surface irrigation | Drip irrigation |
| §Sesame | 8960 | 5282 |
| Sorghum | 6802 | 5328 |
| Millet | 6367 | 5222 |
| Tobacco | 7000 | 5000 |
| Cotton | 11143 | 8750 |
| Vegetables | 10000 | 4706 |
| Watermelon | 8571 | 5241 |
| Muskmelon | 7785 | 4752 |
| Fodder | 7500 | 5500 |

Table 14 presents crop water requirements in Yemen, farmers however frequently choose not to follow these requirements. Therefore the total Agricultural Water Use (AWU) for each region has been estimated as the sum of groundwater extraction from agricultural wells, the NCWR and surface water (the 30% of the inflow water from the highlands). The total agricultural water uses in the UR, MR and the LR are 28.1, 74 and 91.8 MCM/year respectively as shown in Table 15.

***Table 15:*** *Agricultural Water Use (MCM).*

| AWU | UR | MR | LR | Total (MCM) |
|---|---|---|---|---|
| Groundwater (MCM) | 15 | 55.2 | 77.2 | 147.4 |
| Surface water (MCM) | 13.1 | 18.8 | 5.6 | 37.5 |
| Treated WW (MCM) | 0 | 0 | 9 | 9 |

## 4.3. Environmental Flow

Environmental flow refers to the quantity and timing of water flows required to maintain the components, functions, processes and resilience of aquatic ecosystems, as well as the products and services they give to people. Furthermore, a minimum flow in a river is essential to ensure pollutant dilution and the preservation of biodiversity.

In general, rapid population increase, urbanization, poverty and a lack of adaptation capacity have posed a danger to river deltas in most Asian and African countries (Kazem, 2015). Furthermore, reducing river discharge in delta rivers increases saltwater intrusion (Bellafiore et al., 2021). By preventing saltwater intrusion, sustaining environmental flows in the wadies can safeguard freshwater resources.

Construction of dams and the use of surface water for irrigation upstream on the other hand, have restricted natural water flow and reduced groundwater recharge downstream. As a result, water flow in streams has never reached the ocean in the last 30 years, implying that environmental flow is also neglected.  However, sustaining environmental flow can reduce the impact of saltwater intrusion and desertification.

Comparing agricultural and domestic water uses for the three regions shows that agriculture consumes almost 82% of the water resources in Tuban Delta as shown in Figure 9 .

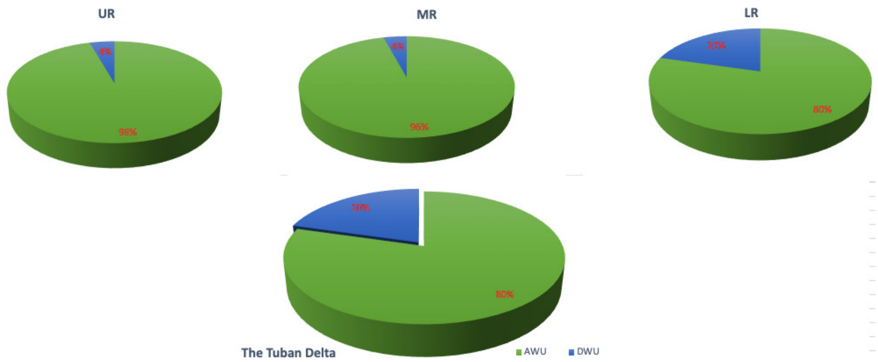


***Figure 9.*** *Water Uses in Tuban Delta (%).*

## 5. UNMET DEMAND ASSESSMENT

In general, the unmet demand in a catchment can be estimated by subtracting total water demands (domestic demands + agriculture demand + industrial demand + commercial and governmental + environmental demand) from the total water supply (surface water + renewable groundwater + non-conventional water).

The current estimations based on the collected data are presented in Table 16. The table shows that Tuban Delta is facing a water shortage, mainly in the LR due to the limited water availability (linked to climate change), over-abstraction of the depleting groundwater and lack of or insufficient operation and maintenance of water and wastewater systems.

***Table 16.*** *Unmet Demand (MCM) in Tuban Delta in 2022.*

| Regions | UR | MR | LR | Total |
|---|---|---|---|---|
| Domestic demand | 1.3 | 3.2 | 45.5 | 50.1 |
| Agriculture demand | 28.1 | 74 | 91.8 | 193.9 |
| Water supply | 68 | 86 | 53 | 208 |
| Unmet demand | 38.6 | 8.8 | -84.3 | -36 |

## 6. WATER RESOURCES QUALITY

### 6.1. Surface Water Quality

Most of the surface waters are used in the UR and MR. These resources suffer from agriculture-based pollution (contamination with fertilizers and chemical products) and untreated wastewater that is discharged directly to the streams and canals.

### 6.2. Groundwater Quality

Groundwater quality has not been studied in detail in terms of its suitability as irrigation or drinking water. Here are the most important sources of groundwater pollution:

**1. Natural radioactivity:** Groundwater in Aden, like many areas globally, may contain naturally occurring radionuclides such as radium, uranium and thorium. These substances can enter groundwater from geological formations and rocks. Harb et al. (2013) collected and tested a total of 37 groundwater samples from four areas in Aden governorate: namely Beer Ahmed, Beer Fadle, Daar-saad and Al-Masabian. The results showed that the annual average obtained dose of radioactivity was approximately 5-10 times higher than the recommended value of (0.1 mSv/year) for drinking water as stipulated by WHO. Moreover, Abdurabu et al. (2016) tested the radioactivity of groundwater in Juban District and found that the high radionuclide concentrations were found mainly in water from wells in the basement aquifer. The study found that the mean annual effective dose of radiation for infants is almost 20 times the WHO guideline level for drinking water. Therefore, it is recommended to investigate this issue in collaboration with local authorities, environmental agencies, health departments and scientific institutions to ensure the provision of safe and potable groundwater to the community. while minimizing health risks associated with radioactivity.

**2. Salinity:** According to Yemeni drinking water standards, EC for drinking water is recommended to be less than 1,000 μS/cm, and the maximum permissible limit is 2,500 μS/cm (Saleh et. al. 2017). However, testing many samples in the LR indicated high EC values (more than 2,000 μS/cm and in some wells more the 5,000 μS/cm. Some of this salinity is based on aquifer characteristics (natural salinity), while the rest is due to saltwater intrusion, especially in the coastal areas.

The wells in the MR and the UR still have drinkable water with EC concentrations of approximately 2113.28 μS /cm in 2021.

**3. Nitrate:** The concentrations of nitrate in Bir Ahmed and Bir Naser were 75 and 58 mg/l, which exceed the Yemeni standard of 50 mg/l.

**4. Wastewater:** Cities and industries discharge untreated domestic and industrial wastewater in peri-urban areas. While the dangers of pollution produced by urban wastewater are more visible, there is also a potential pollution hazard to aquifers from untreated wastewater from rural settlements.

To assess groundwater pollution in Bir Nasser and Bir Ahmed waters fields in Tuban Delta, Saleh and Al-Sallami (2022) collected 20 groundwater samples in the period from February-to July 2021. The results showed that most of the physical, chemical and biological parameters are higher than the permissible limits stipulated by the WHO. The main reasons for this pollution are the use of cesspits, the proximity of wells to agricultural lands that use chemical and animal fertilizers, the unplanned drilling of wells and excessive pumping rates (Saleh and Al-Sallami, 2022).

# 7. FUTURE PROJECTIONS

## 7.1. Water Demand Projection

In recent years, environmental flow has not been considered in Yemen's national water management plans. Thus, the total demand projections in the three regions have been estimated based on the cumulative total of domestic water demand and agricultural water demand.

**1. DWU projection:** Domestic water demand projections up to 2100 have been estimated based on average water consumption per capita, assuming that NRW will be eliminated by 2040. Thus, domestic water consumption starting from 2040 is forecasted to be 90, 99 and 96 L/day in the LR, MR and UR respectively.

Population growth is a determining factor of the domestic water demand projection. Future population and DWU projections up to 2100 can be estimated based on two scenarios:

a) $DWU^n$: Normal increase, which assumes a rate of growth that remains stable at 3% until 2100 as presented in Table 17 using the following equation:

PF = Pp x (1+R)n (5)

where :

- PF : future population at time T,
- PP: present population,
- R: growth rate (3%),
- n: number of years.

b) DWUr : Reduction in population growth rate, which assumes 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 the Equation 6 is used and the results are presented in Table 18:

PF = Pp (1+r1)n1(1+r2)n2..... (6)

were:

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

***Table 17:*** *Future Population and DWUn Projections under Constant Growth Rate.*

| Year | Lower region | | Middle Region | | Upper Region | | Total DWU (MCM) |
|---|---|---|---|---|---|---|---|
| | Population | DWUn | Population | DWUn | Population | DWUn | |
| 2022 | 1133013 | 45.5 | 85954 | 3.2 | 36921 | 1.3 | 50.1 |
| 2040 | 1928879 | 77.4 | 146331 | 5.5 | 62856 | 2.3 | 85.2 |
| 2060 | 3483770 | 139.9 | 264290 | 9.9 | 113524 | 4.1 | 154.0 |
| 2080 | 6292076 | 252.6 | 477337 | 17.9 | 205037 | 7.5 | 278.1 |
| 2100 | 11364188 | 456.3 | 862124 | 32.4 | 370320 | 13.5 | 502.2 |

***Table 18:*** *Future Population and DWUr Projections under Declining Growth Rates.*

| Year | Lower region | | Middle Region | | Upper Region | | Total DWU (MCM) |
|---|---|---|---|---|---|---|---|
| | Population | DWUn | Population | DWUn | Population | DWUn | |
| 2022 | 1133013 | 45.5 | 85954 | 3.2 | 36921 | 1.3 | 50.1 |
| 2040 | 1928879 | 77.4 | 146331 | 5.5 | 62856 | 2.3 | 85.2 |
| 2060 | 3160692 | 126.9 | 239780 | 9.0 | 102997 | 3.8 | 139.7 |
| 2080 | 4256995 | 170.9 | 356301 | 13.4 | 153048 | 5.6 | 189.9 |
| 2100 | 6325670 | 254.0 | 479886 | 18.0 | 206133 | 7.5 | 279.5 |

**2. AWU projections:** Two scenarios have been assessed as shown in Table 19

**a) $AWU_a$:** Constant land and irrigation practices.
**b) $AWU_b$:** Constant land, modern irrigation practices on 50% of land in 2040, 70% in 2060 and 100% in 2080.

***Table 19:*** *Agricultural Water Uses Projections under Two Scenarios (MCM).*

| 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 |

Based on the above-mentioned options, two demand scenarios have been considered (see Table 20):
<u>- Reference Scenario:</u> Constant cultivated lands, constant population growth rates, consistent agricultural practices.
~~- Improved Scenario:~~ Modern irrigation and decreased population growth.

***Table 20:*** *. Total Water Uses Projections (MCM).*

| Year | Reference scenario | | | | Reference scenario | | | |
|---|---|---|---|---|---|---|---|---|
| | LR | MR | UR | Total | LR | MR | UR | Total |
| 2022 | 137.5 | 77.2 | 29.3 | 244.1 | 137.5 | 77.2 | 29.3 | 244.1 |
| 2040 | 169.4 | 79.5 | 30.3 | 279.2 | 169.4 | 79.5 | 30.3 | 279.2 |
| 2060 | 231.9 | 83.9 | 32.1 | 348.0 | 192.9 | 62.0 | 23.8 | 278.7 |
| 2080 | 344.6 | 91.9 | 35.5 | 472.1 | 221.9 | 54.4 | 21.6 | 297.9 |
| 2100 | 548.3 | 106.4 | 41.5 | 696.2 | 296.0 | 52.0 | 20.5 | 368.5 |

Table 20 shows that the improved irrigation and reduced population growth scenario can contribute to solving the water shortage, as water savings can reach 20%, 37% and 47% in 2060, 2080 and 2100 respectively. Through fruitful cooperation and active involvement with all concerned stakeholders, new demand scenarios can be developed. However, the developed scenarios should be evidence based and cognizant of the contextual realities of Tuban Delta. For example, reusing greywater in toilet flushing has the potential to save 35% of the domestic water needs (Mourad et al., 2011). However, this scenario assumes a level of social acceptance of the practice and involves some private costs.

## 7.2. Water Supply Projections

**1. Runoff:** Figures 10 and 11 show various projected annual rates of precipitation according to the climate model MRI-ESM2-0for Aden and Lahij. Projections are based on a reference period of 1995-2014.The figures show an increase in rainfall extremes especially between 2060 and 2065 under SSP3 and SSP5.

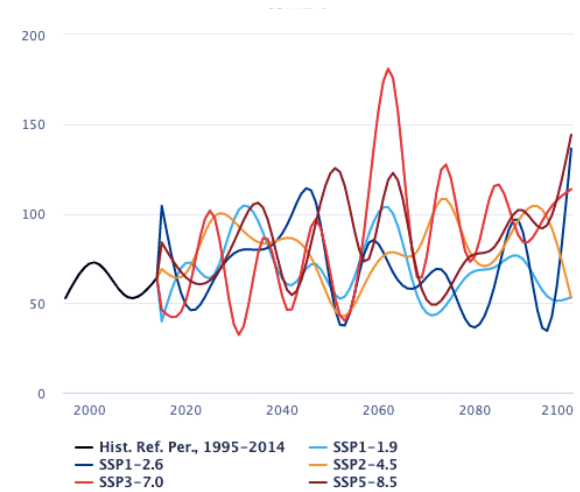


***Figure 10.*** *Projected Annual Precipitation in Aden (mm).*

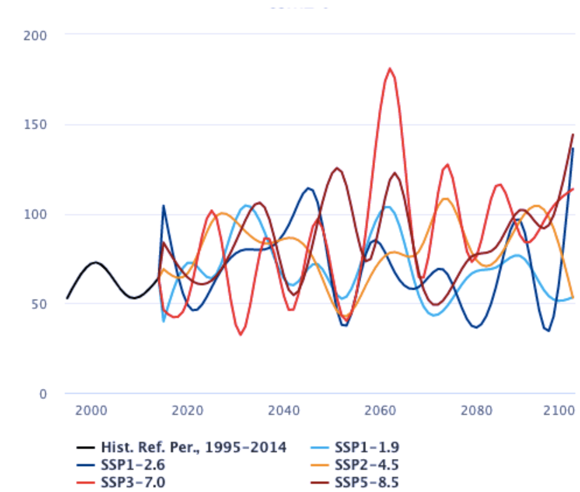


***Figure 11.*** *Projected Annual Precipitation in Lahij (mm)*

The average annual rainfall projections under SSP3 show an increase in rainfall rates after 2040, reaching the highest rate between 2061 and 2080 in the LR (with 50% certainty). Whilst in the MR and UR, the annual rainfall rates are projected to increase after 2060. While projected low rainfall rates before 2040 might lead to more dry years, projections show an increase in wet years after 2040 (See Table 21).

***Table 21:*** *Average Annual Rainfall Projections (mm) under SSP3 and SSP5.*

| Year | 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 |

Using the annual rainfall projections from Table 21, the percentage of changes in annual rainfall compared to 2022 are estimated, which can be the percentage of the average predicted change in water availability from runoff as illustrated in Table 22.

***Table 22:*** *Average Change Factors in Water Availability under SSP3 and SSP5 Compared to 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 |

The UR and the highland are assumed to have the same average change factors in water availability. Then, using the same procedure that was used in section 3.2 in estimating water availability from runoff, Figure 12 and Figure 13 show future projections for water availability under SSP3 and SSP5 respectively. Under SSP3, the water scarcity in the LR is projected to increase, due to consecutive dry years lasting for periods of two to four years, especially between 2040 and 2060. Whilst in the UR and MR, wet years after 2060 have the potential to cause flooding events.

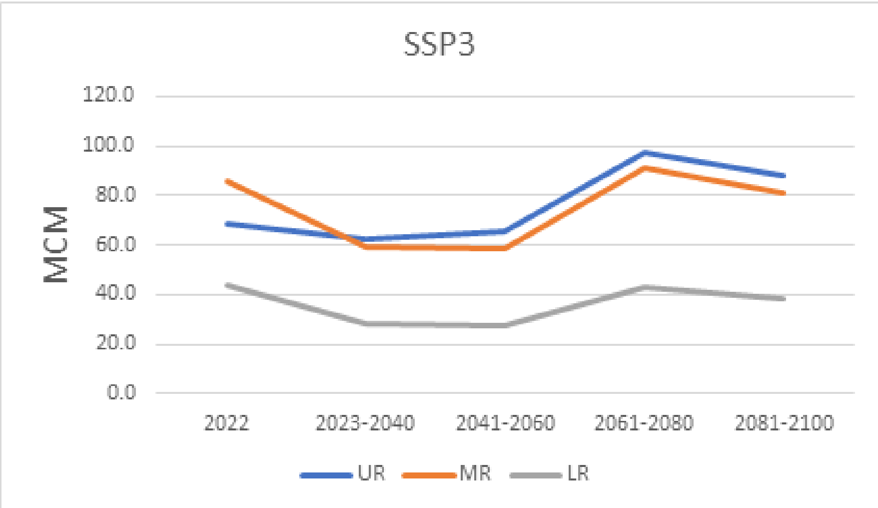


***Figure 12.*** *Total Water Availability under SSP3.*

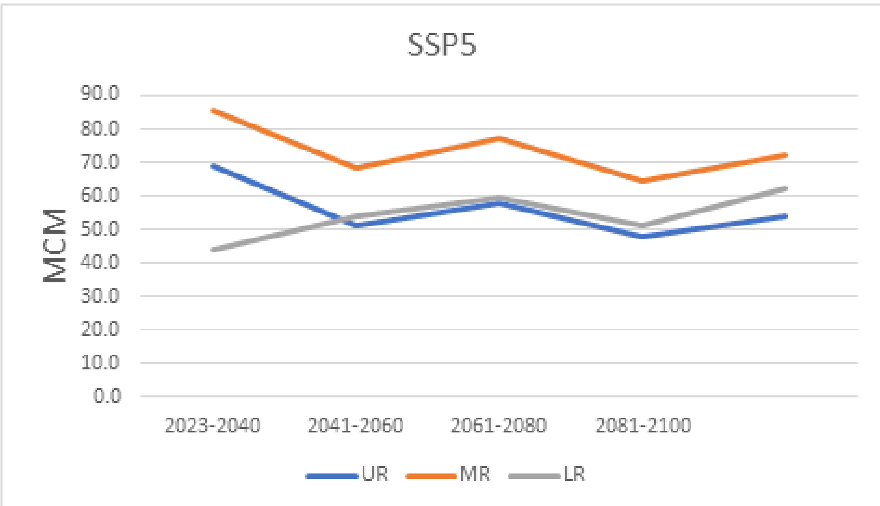


***Figure 13.*** *Total Water Availability under SSP5.*

NCWR: NCWR include treated wastewater (TWW) and desalinated water. Two scenarios are presented here:

**a) Reference NCWR (NCWRr):** no increase on the current NCWR,
**b) Improved NCWR (NCWRi):** The TWW is estimated at 33% of the domestic water demand. Thus, the same percentages will be applied for future projections (all TWW will be reused). Moreover, a new water supply, a solar-powered desalination plant with a production capacity of 10 MCM/year can be added every 20 years to the LR starting from 2040.

Table 23 and Table 24 present water supply projections in the three regions considering NCWRr and NCWRi under SSP3 and SSP5, respectively.

***Table 23:*** *Water Supply Projections under SSP3*

| Year | UR | | MR | | LR | | Total | |
|---|---|---|---|---|---|---|---|---|
| | NCWRr | NCWRi | NCWRr | NCWRi | NCWRr | NCWRi | NCWRr | NCWRi |
| 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 24:*** *. Water Supply Projections under SSP5.*

| Year | UR | | MR | | LR | | Total | |
|---|---|---|---|---|---|---|---|---|
| | NCWRr | NCWRi | NCWRr | NCWRi | NCWRr | NCWRi | NCWRr | NCWRi |
| 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 |

## 7.3. Unmet Demands Projections

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

- **Reference Scenario:** Reference Demand scenario and NCWR
- **Improved Scenario:** Improved irrigation and reduced population growth scenario and NCWRi

Under SSP3

Table 25 presents the projections under SSP3 considering the reference and the improved scenarios. The table shows that the ML and LR will be facing water shortages under the reference scenario up to 2100, which will reach 24 and 501 MCM in 2100 in the MR and the LR respectively. The projections based on the Improved Scenario on the other hand show a better situation in Tuban Delta in general after 2060.However, the water shortage in the LR will be approximately 150 MCM in 2100, which highlights the need for more than small water desalination plants in the LR.

***Table 25:*** *The Projections of the Unmet Demands under SSP3.*

| Scenario | Reference scenario | | | | Improved scenario | | | |
|---|---|---|---|---|---|---|---|---|
| Region | LR | MR | UR | Total | LR | MR | UR | Total |
| 2022 | 40 | 9 | -85 | -36 | 40 | 9 | -85 | -36 |
| 2040 | 33 | -19 | -132 | -119 | 33 | -19 | -123 | -109 |
| 2060 | 34 | -24 | -195 | -185 | 42 | -1 | -132 | -91 |
| 2080 | 64 | 0 | -292 | -229 | 78 | 41 | -119 | -1 |
| 2100 | 49 | -24 | -501 | -476 | 70 | 37 | -150 | -43 |

<u>Under SSP5</u>

Table 26 presents the projections under SSP5 considering the reference and improved scenarios. The table shows that the LR will still have a severe water shortage under the refence scenario, while the improved scenario might improve the situation in Tuban Delta by 2060. However, a proper water management and allocation plan are needed to improve the situation in the LR.

***Table 26:*** *The Projections of the Unmet Demands (MCM) under SSP5.*

| Scenario | The Reference scenario | | | | The improved scenario | | | |
|---|---|---|---|---|---|---|---|---|
| Region | LR | MR | UR | Total | LR | MR | UR | Total |
| 2022 | 40 | 9 | -85 | -36 | 40 | 9 | -85 | -36 |
| 2040 | 21 | 12 | -66 | -34 | 32 | 12 | -57 | -13 |
| 2060 | 26 | 19 | -199 | -75 | 42 | -42 | -57 | 27 |
| 2080 | 13 | -6 | -246 | -240 | 76 | 35 | -73 | 37 |
| 2100 | 13 | -10 | -429 | -426 | 67 | 51 | -79 | 40 |

# 8. CLIMATE IMPACTS/RISKS

## 8.1. Heat Waves

According to the climate model MRI-ESM2-0, the number of hot days per year is forecasted to increase starting from 2050 to reach 40 days/ year under SSP3, and 70 days/year under SSP5 in 2100 (see Figure 14). This increase of temperature will increase evapotranspiration rates and water scarcity thus reducing agricultural production (food security) and the domestic water supply.

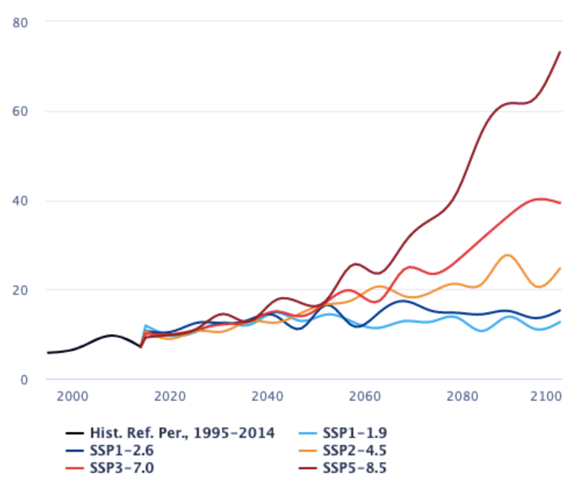


***Figure 14.*** *The Number of Hot Days > 40 oC in Lahj.*

Moreover, the temperature increase will have adverse health impacts on vulnerable populations such as the elderly and women (Extreme heat can exacerbate menstrual discomfort for some women. Moreover, pregnant women are more vulnerable to heat-related complications, as heat stress can contribute to preterm birth and low birth weight).

The severity levels of heat waves, measured on a scale of in 1 to 4 scale, whereby 1- Negligible, 2- Marginal, 3- Critical, and 4- Catastrophic, are shown in Table 27. The table shows that the LR will have the highest heatwave severity followed by the MR.

***Table 27:*** *The Severity of Heat Wave Risks.*

| Years/regions | SSP3 (RCP 7) | | | SSP5 (RCP 8.5) | | |
|---|---|---|---|---|---|---|
| | LR | MR | UR | LR | MR | UR |
| 2023-2040 | 1 | 1 | 2 | 1 | 1 | 2 |
| 2041-2060 | 2 | 2 | 3 | 2 | 2 | 3 |
| 2061-2080 | 3 | 3 | 4 | 3 | 4 | 4 |
| 2081-2100 | 3 | 4 | 4 | 3 | 4 | 4 |

## 8.2. Saltwater Intrusion

The salinity of groundwater in Tuban Delta was estimated based on the Electric Conductivity (EC). In general, EC concentrations in Tuban Delta have increased in the LR near the coast due to overexploitation and saltwater intrusion. Moreover, the aquifer type near the coast is semi-confined[3], which allows saltwater intrusion and the movement of the salty water from the brackish aquifer.

Elsewhere in the MR and UR there are medium salinity levels due to the characteristics of the rocks. Figure 15 shows the variety of salinity levels in the three regions.

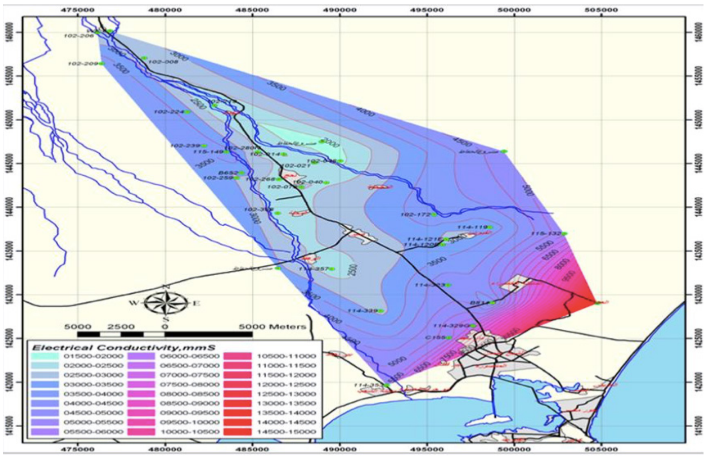

***Figure 15:*** *EC Concentration Lines in Tuban Delta*

According to the Yemeni drinking water standards, EC for drinking water is recommended to be less than 1,000 µS/cm and the maximum allowed limit can reach 2,500 µS/cm (Saleh et. Al. 2017). WHO recommends EC in drinking water to be about 400-800 µS/cm, while water with EC from 800 to 2,500 µS/cm can be used for irrigation and livestock (Al-Khashman, 2014). Figure 16 shows EC concentrations in some wells in Tuban Delta, demonstrating that all wells located near the coast have high EC concentrations, especially those located at a brackish aquifer.

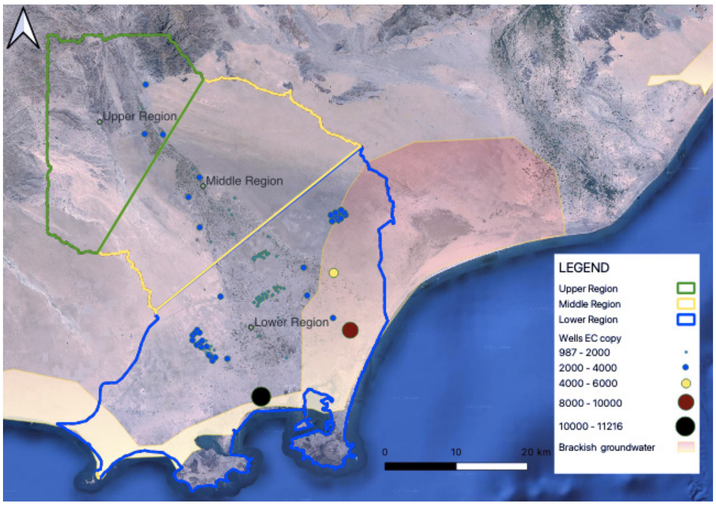


***Figure 16:*** *EC Concentrations (µS/cm) in Some Well in Tuban Delta.*

**<u>In 2023</u>**, based on NWSA data of 2019, many wells of the Dar Almanasira well field located 15 km northern the eastern costal line have high EC concentration (more than 2,500 µS/cm), which means brackish water is about 20 m below sea level.

[3]https://static1.squarespace.com/static/5eb18d627d53aa0e85b60c65/t/5ef47844acde830a0b6e7b51/1593079895175/Aquifer-System-in-Yemen.pdf

. Taking an average annual drop in water table of 1 m, all wells of Dar Almanasira well field will become brackish after 2040. Thus, discharged water won't be drinkable without a proper purification/treatment via Reverse Osmosis system (RO) for example. However, water in this condition can be used to irrigate salinity tolerant crops. In this regard, bio-saline agriculture, which is the production and growth of plants in saline rich groundwater and/or soils, is important because it allows using low quality of water to irrigate some species and to adapt to local climatic conditions (Oumara and  El Youssfi 2022). For example, in Morocco, some crop species were tested and showed very high tolerance to salinity, such as Quinoa, Pearl millet, Barley, and Panicum Blue (Hirich et al., 2021).

Only a small number of wells outside of the Bir Ahmed well field located 8-14 Km from the coast, have EC less than 2,000 µS/cm. These wells are located at the level of a low productive aquifer (about 65-70 m below the surface) and above the brackish water, which means these wells are vulnerable to drought and to sea-level rise. The well field is located at 40 m above sea level. Thus, in case of drought, people might resort to increasing the depth of these wells ignoring the possibility of reaching the brackish aquifer. Thus, in case of drought and continuous over abstraction, these well are forecasted to become brackish after 2080.  Abubaker (2012) argued that wells that have a depth of 65 m or more will be contaminated by brackish water.

**Bir Naser well field** that is located about 16 km from the coast has fair water quality, based on the Yemeni standards, EC range 1,500 to 1,800 µS/cm. However, these wells are vulnerable to sea-level rise and overexploitation. Thus, EC concentrations are very likely to increase in future. The statistic water levels (SWL) of the wells are about 20-30 m below sea level. These wells will become brackish when SWL reaches 80 m below sea level. Thus, in case of drought and continuous over abstraction, these wells might become brackish by 2080.

If these well fields, which are the main drinking water resource in the LR Figure 17, become brackish, people in the LR, mainly Aden, will face water scarcity.  Moreover, other legal and illegal wells used for irrigation at the coastal area will be affected as well. Therefore, new allocation strategies will be needed and the identification of new domestic water resources will be essential. The National Authority of Water and Sanitation in Aden suggested drilling new wells with a depth of 300-350m to cover the increasing demand.

However, it is not recommended to increase the depth of wells in the coastal area, as this may reach the brackish water, thus, this might not be a sustainable solution.

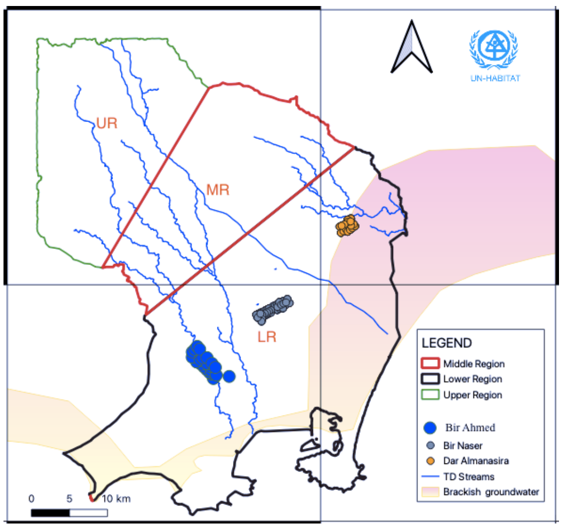


***Figure 17:*** *Main Well Fields in the LR.*

Constructing solar-powered desalination plants however does have potential to be a sustainable option to address the increasing demand in Aden.

Saltwater intrusion is forecasted to keep increasing due to increasing water demand and drought in the years between 2023 and 2040.

After 2040, the probability for the years to be wetter is high, however population increase and unmonitored pumping might undermine/negate potential positive impacts. Table 28 shows saltwater intrusion risks at the main water supply well fields in Aden taking into consideration the continuous illegal and unmonitored groundwater withdrawal.

***Table 28:*** *The Risk of Saltwater Intrusion in the Coastal Area.*

| Years/Well fields | Saltwater intrusion | | |
|---|---|---|---|
| | Dar Almanasira | Bir Ahmed | Bir Naser |
| 2023-2040 | High risk | Low risk | Low risk |
| 2041-2060 | Brackish | Medium risk | Medium risk |
| 2061-2080 | Brackish | High risk | High risk |
| 2081-2100 | Brackish | Brackish | Brackish |

After 2040, the probability for the years to be wetter is high, however population increase and unmonitored pumping might undermine/negate potential positive impacts. Table 28 shows saltwater intrusion risks at the main water supply well fields in Aden taking into consideration the continuous illegal and unmonitored groundwater withdrawal.

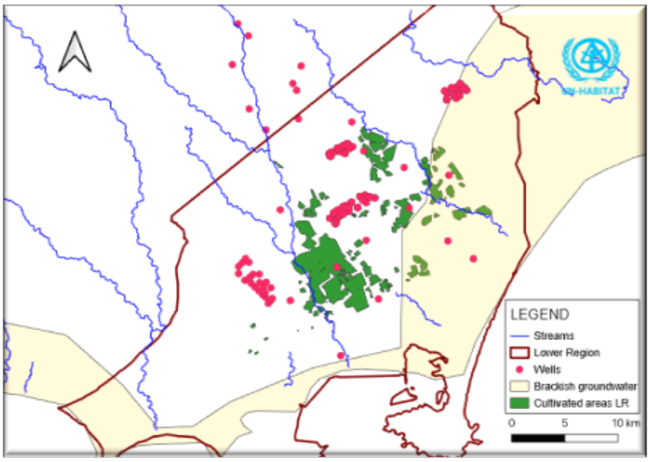


***Figure 18.*** *The Impact of Saltwater Intrusion on Agriculture Area in the LR.*

## 8.3. SEA-LEVEL RISE

### 8.3.1. Mapping Sea Level Rise

QGIS has been used to map the affected areas if sea-level rises by 1 meter. Figure 19 shows that most of the coastal areas in Aden might be impacted, especially the airport.

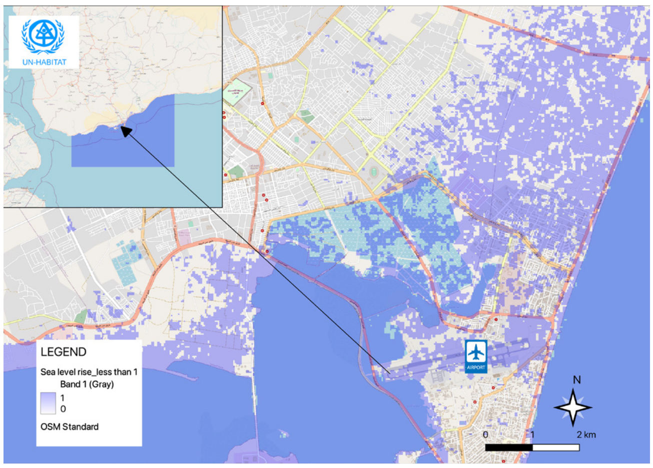


***Figure 19:*** *The Impacts of Sea-Level Rise in the Coastal Areas of Aden.*

Regarding rising sea levels, the Climate Change Knowledge Portal (CCKP), shows a sea-level rise from 2008 to 2100 under RCP2.6, RCP4.5 and RCP8.5 respectively (see Figure 2. While based on the CMIP6, Table 29 shows projected sea-level rise under SSP5 and SSP4 (Climate Central 2023).

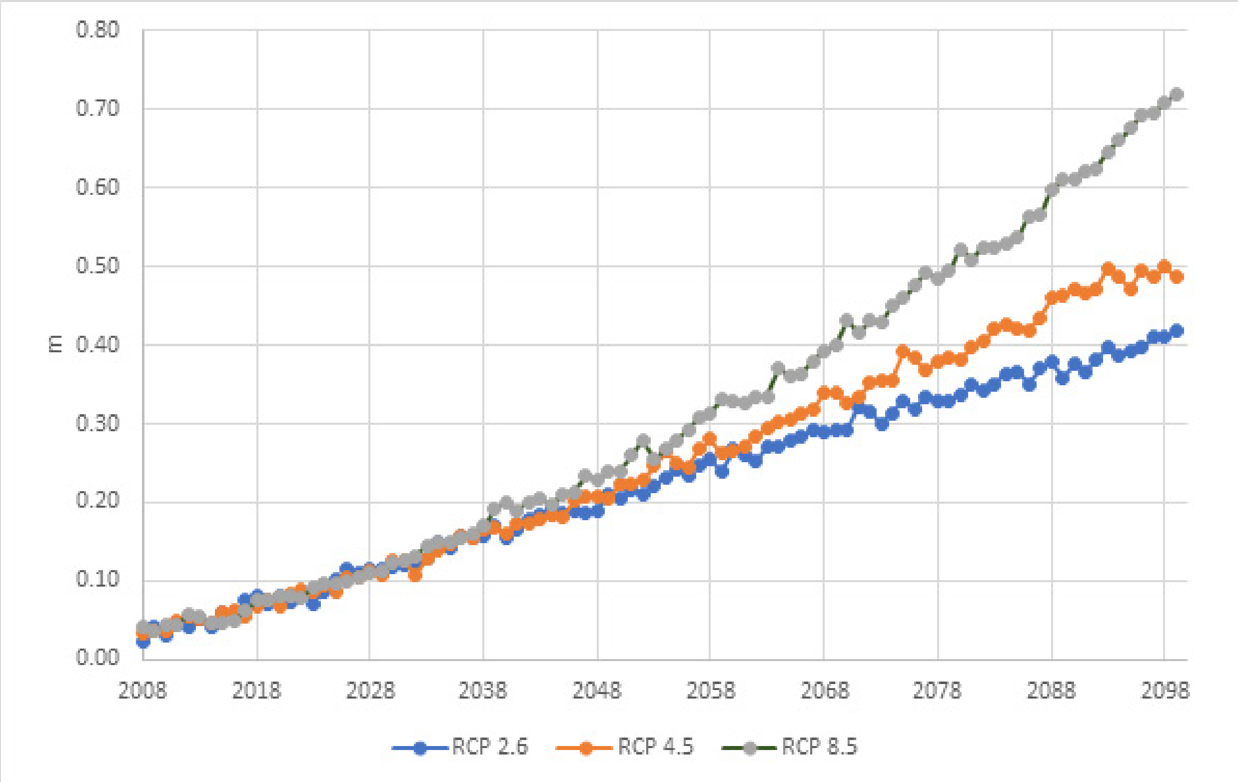


***Figure 20:*** *Future Projections of Sea-Level of Coastal Yemen.*

| YEAR | SSP5 (RCP 8.5) | SSP3 (RCP 7) |
|---|---|---|
| 2020 | 0.05 | 0.05 |
| 2040 | 0.16 | 0.16 |
| 2060 | 0.31 | 0.28 |
| 2080 | 0.51 | 0.46 |
| 2100 | 0.77 | 0.67 |

***Table 29:*** *Projected sea-level rise (m) under CMIP6.*

### 8.3.2. The Impacts of Sea-Level Rise

Sea-level rise has the potential to affect the majority of the structures near the coast that have an elevation of zero or below sea level. Mapping sea-level rise under RCP 8.5 shows that the risk will be low in 2040 in the coastal area compared with 2100, by which time the airport is likely to be affected if no measures are taken (see Figure 21, flooded area indicated in red).

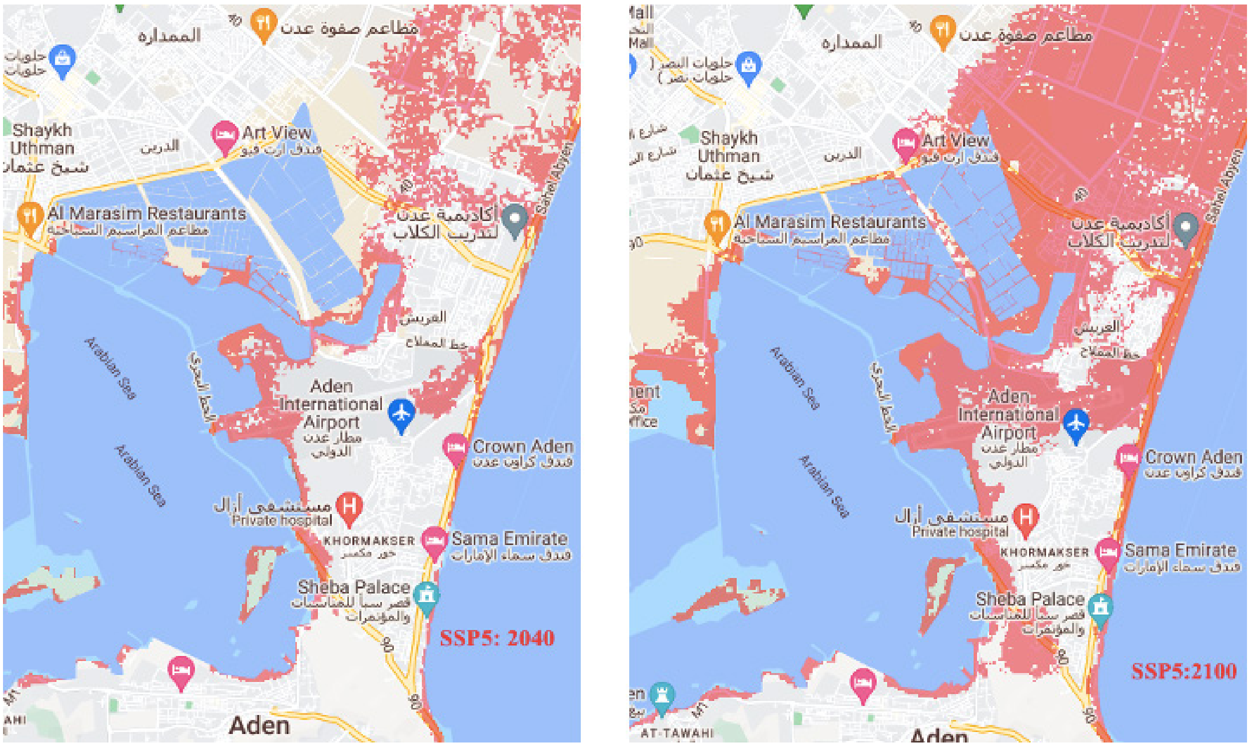


*Figure 21:* Sea-Level Rise in 2040 and 2100 under SSP5.

The following significant facilities forecasted to be impacted by seal-level rise if there are no appropriate protection measures implemented: Sahel Abyan highway, Sama Emirate hotel, Crown Aden Hotel, Aden Academy, Al Marasem restaurants and the Art View Hotel. Moreover, the airport is located at an elevation range between 0 and -10 m below sea level as shown in Figure 22, the airport will thus be under significant threat by 2100, especially from the west. Visiting the Eastern side of the airport area shows that the infrastructure of Sahel Abyan highway has a higher elevation, which will act as a barrier to rising seawater up to 60 cm from the eastern side only.

Furthermore, sea-level rise will increase saltwater intrusion into many wells in Aden, especially Dar Almanasira well field and Bir Naser, which will affect domestic water supply.

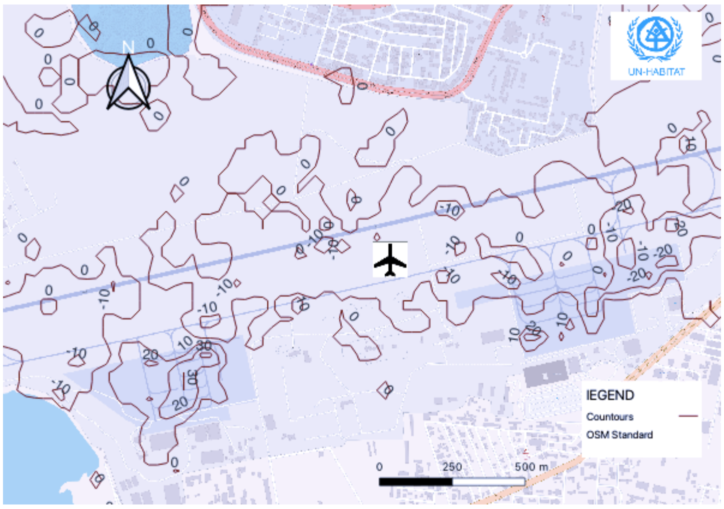


*Figure 22:* The Area of Aden Airport.

## 8.4. Flooding

Flooding is likely to increase due to the increase in heavy rainfall/rainstorms. Using the MRI-ESM2.0 climate model (Yukimoto et al. 2019b), the projections show extreme rainfall in some months that may reach 80-100 mm, which might occur in both SSPs resulting in flooding as shown in Figure 23 and Figure 24. The figures show the monthly rainfall in mm starting from January 2015 (month 0), meaning month 600 represents January 2065.

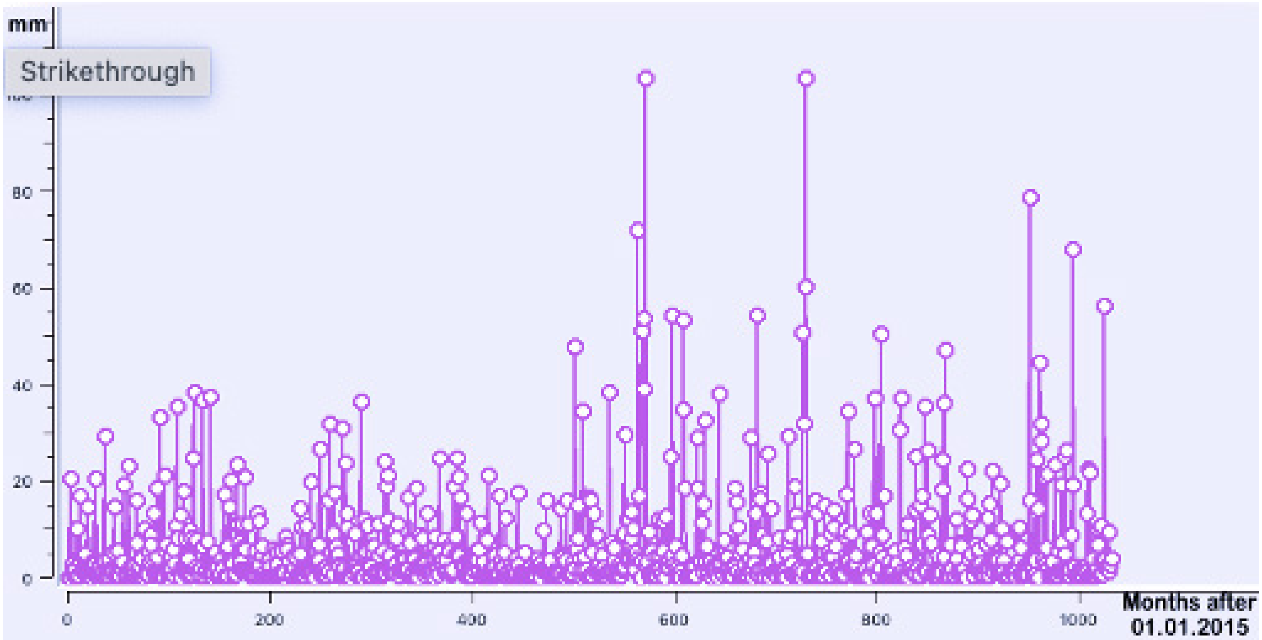


***Figure 23:*** *Monthly Rainfall in Tuban Delta between 2015 and 2100, SSP3.*

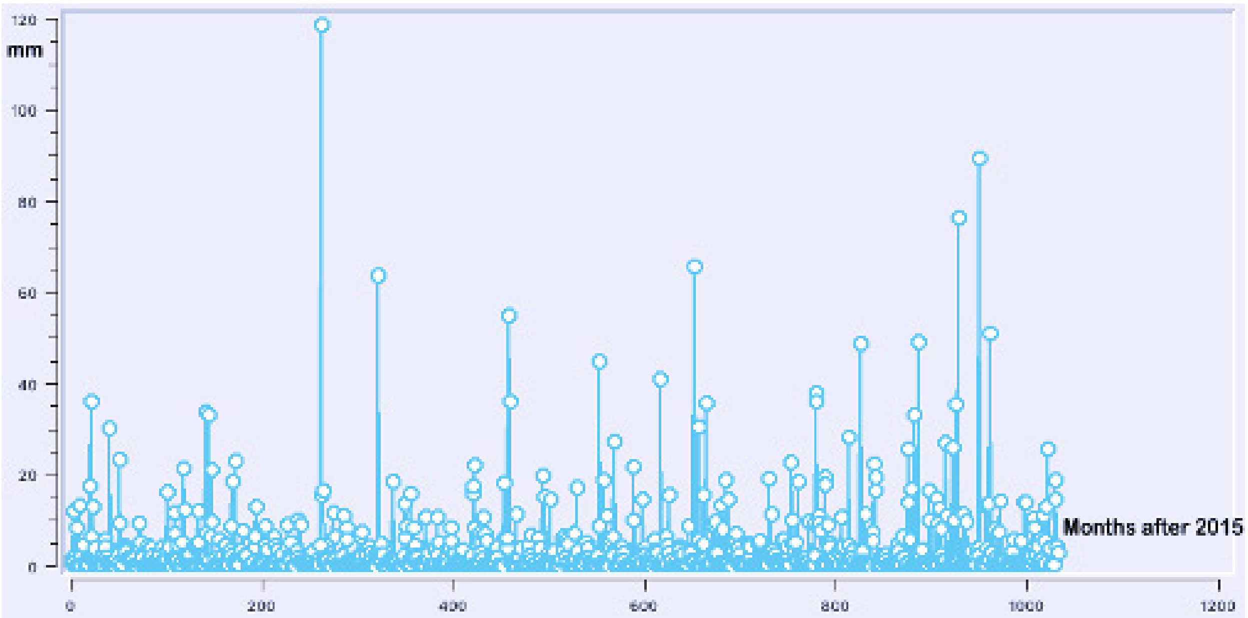


***Figure 24:*** *Monthly Rainfall in Tuban from 2015 to 2100 under SSP5.*

### 8.4.1. Quantifying the Runoff

Quantifying runoff from the largest one-day precipitation gives an idea about the significance of a flood event. However, in order to estimate the risk of the flash flood, the main Tuban watershed will be considered. As shown in Figure 25, the water runoff will come first from 1,730 km$^2$, 990 km$^2$, and 1,550 Km$^2$ of Al Dhali, Ibb and Ta'izz, respectively, through 1,400 km2 from Lahj to Dukeim at the top of Tuban Delta. Runoff will then pass through 392 Km2 of the UR, 136 Km$^2$ of the MR, and 84 Km$^2$ of the LR, finally passing to the ocean in Aden.

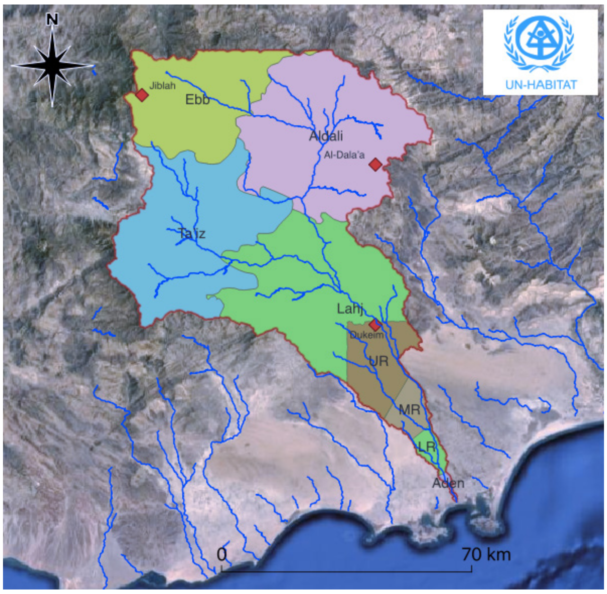


***Figure 25:*** *The Boundaries of Tuban Watershed that Contributes to Flash Flood in Tuban Delta.*

Table 30 shows the largest one-day rainfall rates in each area.

***Table 30:*** *Largest One-Day Precipitation (mm).*

| | SSP3 (RCP 7) | | | | | | | SSP3 (RCP 8.5) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Regions** | Ta'iz | Ebb | Aldali | Lahj | UR | MR | LR | Ta'iz | Ebb | Aldali | Lahj | UR | MR | LR |
| 2023-2040 | 9 | 11 | 10 | 8 | 8 | 8 | 1.5 | 1 | 7 | 6 | 2 | 2 | 2 | 2 |
| 2041-2060 | 13 | 14 | 16 | 10 | 10 | 10 | 4 | 9 | 14 | 15 | 11 | 11 | 11 | 5 |
| 2061-2080 | 23 | 19 | 16 | 19 | 19 | 19 | 24 | 27 | 28 | 24 | 20 | 20 | 20 | 20 |
| 2081-2100 | 30 | 39 | 29 | 23 | 23 | 23 | 18 | 33 | 30 | 26 | 30 | 30 | 30 | 41 |

The resulting runoff is then estimated using the rational method as illustrated in Table 31 .

| | SSP3 | | | SSP5 | | |
|---|---|---|---|---|---|---|
| **Years** | Dukein/UR | MR | LR/Aden | Dukein/UR | MR | LR/Aden |
| 2023-2040 | 310 | 329 | 336 | 126 | 131 | 133 |
| 2041-2060 | 441 | 463 | 473 | 403 | 428 | 439 |
| 2061-2080 | 632 | 675 | 702 | 809 | 854 | 880 |
| 2081-2100 | 974 | 1026 | 1053 | 976 | 1044 | 1087 |

***Table 31:*** *Runoff Peak Flow due to the Largest One-Day Precipitation (m3/sec).*

### 8.4.2. Urban Flood Assessment

In general, the LR faces four main climate hazards: flooding, drought, sea-level rise and saltwater intrusion. While the MR faces mainly flooding and drought.

Table 32 shows a comparison of actual average annual rainfall rates (45, 54 and 62mm in the LR, MR, and UR, respectively), with the projected rainfall rates and the forecasted percentage changes between the two. The table shows a general increase in annual rainfall patterns after 2040.

| Years/regions | Annual change (%) /RCP 7 | | | Annual change (%) 7 RCP 8.5 | | |
|---|---|---|---|---|---|---|
| | LR | MR | UR | LR | MR | UR |
| 2023-2040 | 56 | 29 | 23 | 84 | 49 | 42 |
| 2041-2060 | 441 | 463 | 473 | 403 | 428 | 439 |
| 2061-2080 | 632 | 675 | 702 | 809 | 854 | 880 |
| 2081-2100 | 974 | 1026 | 1053 | 976 | 1044 | 1087 |

***Table 32:*** *Future Change in Rainfall Rates in Tuban Delta.*

The severity of urban floods in combination with sea-level rise can be divided into four categories based on the increased percentages of the annual rainfall compared to the average values as below:

0. **Negligible:** Low severity when the increase in rainfall patterns is less than 51%,
1. **Marginal:** Medium severity when the increase in rainfall patterns is between 51 and 99%,
2. **Critical:** Serious severity when the increase in rainfall patterns is between 100 and 200 %,
3. **Catastrophic:** High severity when the increase in rainfall patterns is more than 200%.

Table 33 illustrates urban floods severity in Tuban Delta.

| Years/regions | SSP3 | | | SSP5 | | |
|---|---|---|---|---|---|---|
| | UR | MR | LR | UR | MR | LR |
| 2023-2040 | 1 | 1 | 2 | 1 | 1 | 2 |
| 2041-2060 | 1 | 1 | 2 | 2 | 2 | 3 |
| 2061-2080 | 2 | 2 | 3 | 1 | 1 | 2 |
| 2081-2100 | 2 | 2 | 3 | 2 | 2 | 3 |

***Table 33:*** *Urban Flood Severity for Tuban Delta.*

The probability of urban flood occurrence has been estimated based on the probability of the largest one-day rainfall that generates serious or high severity in each region as illustrated in Table 34.

1- Improbable (less than 20%),
2- Remote (between 20 and 39%),
3- Occasional (between 40 and 59%),
4- Probable (between 60 and 80%),
5- Frequent: more than 80%

| Years/regions | SSP3 | | | SSP5 | | |
|---|---|---|---|---|---|---|
| | UR | MR | LR | UR | MR | LR |
| 2023-2040 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2041-2060 | 2 | 1 | 1 | 2 | 2 | 2 |
| 2061-2080 | 4 | 3 | 3 | 1 | 1 | 1 |
| 2081-2100 | 3 | 2 | 3 | 3 | 3 | 3 |

***Table 34:*** *The Probability of Urban Flood Occurrence.*

Urban flood hazard assessment values can be estimated and categorized into five categories (from I to V); low, low/medium, medium, medium/high, or high, (see Table 35).

| Years/regions | SSP3 (RCP 7) | | | SSP5 (RCP 8.5) | | |
|---|---|---|---|---|---|---|
| | UR | MR | LR | UR | MR | LR |
| 2023-2040 | I | I | I | I | I | I |
| 2041-2060 | I | I | I | II | II | II |
| 2061-2080 | III | II | III | I | I | I |
| 2081-2100 | II | II | III | II | II | III |

***Table 35:*** *Urban Flood Hazard Assessment under SSP3 and SSP5.*

### 8.4.3. Flash Flood Assessment

Flash floods occur as a result of the excess runoff flow that comes from the highland before Tuban Delta (at Dukeim). The average annual water flow at Dukeim was 110 MCM between 1980 and 2014. Typically the largest monthly flow was approximately 31 MCM in September while the lowest was 0.25 MCM in March. However, in March 1982 the flow reached 225 MCM resulting in a catastrophic flood. Considering that the flood is the result of five days of rainfall, the average flow at Dukeim would be approximately 521 m3/s. Thus, the severity of flash floods can be assessed based on the peak flow at Dukiem and Aden as the following:

1. Low severity when the peak flow less than 200 m3/s,
2. Medium severity when the peak flow is between 200 and 350 m3/sec,
3. Serious severity when the 350 and 500 m3/sec,
4. High severity peak flow in more than 500 m3/s.

Table 36 presents flash flood severity projections up to 2100 in the three regions.

***Table 36:*** *Flash Flood Severity in Tuban Delta.*

| Years | SSP3 | | | SSP5 | | |
|---|---|---|---|---|---|---|
| | Dukein/UR | MR | LR/Aden | Dukein/UR | MR | LR/Aden |
| 2023-2040 | 2 | 2 | 2 | 1 | 1 | 1 |
| 2041-2060 | 3 | 3 | 3 | 3 | 3 | 3 |
| 2061-2080 | 4 | 4 | 4 | 4 | 4 | 4 |
| 2081-2100 | 4 | 4 | 4 | 4 | 4 | 4 |

Flash flood severity then informs the flash flood hazard assessment (Table 37). Hazard assessments can be categorized based on severity and considering a low probability, (less than 20%).

***Table 37:*** *Flash Flood Hazard Assessment.*

| Years | SSP3 | | | SSP5 | | |
|---|---|---|---|---|---|---|
| | Dukein/UR | MR | LR/Aden | Dukein/UR | MR | LR/Aden |
| 2023-2040 | I | I | I | I | I | I |
| 2041-2060 | I | I | I | I | I | I |
| 2061-2080 | II | II | II | II | II | II |
| 2081-2100 | II | II | II | II | II | II |

### 8.4.4. The Impacts of Flooding

There are more than 200 dams and water barriers in Tuban basin mainly in the UR, which in total have a cumulative capacity of approximately 5 MCM. These dams are 70% full. Thus, they can absorb only 1.5 MCM. Therefore, in the event of an extreme rainfall event (see Table 34), large amounts of flood water will flow downstream in the streams and may pose significant risks to nearby infrastructure and agriculture lands. For example in the UR, two villages (Al shqa'ah and Zaedah) and some agricultural lands near the streams have the potential to be affected by flooding from the Wadi Tuban, see Figure 26.

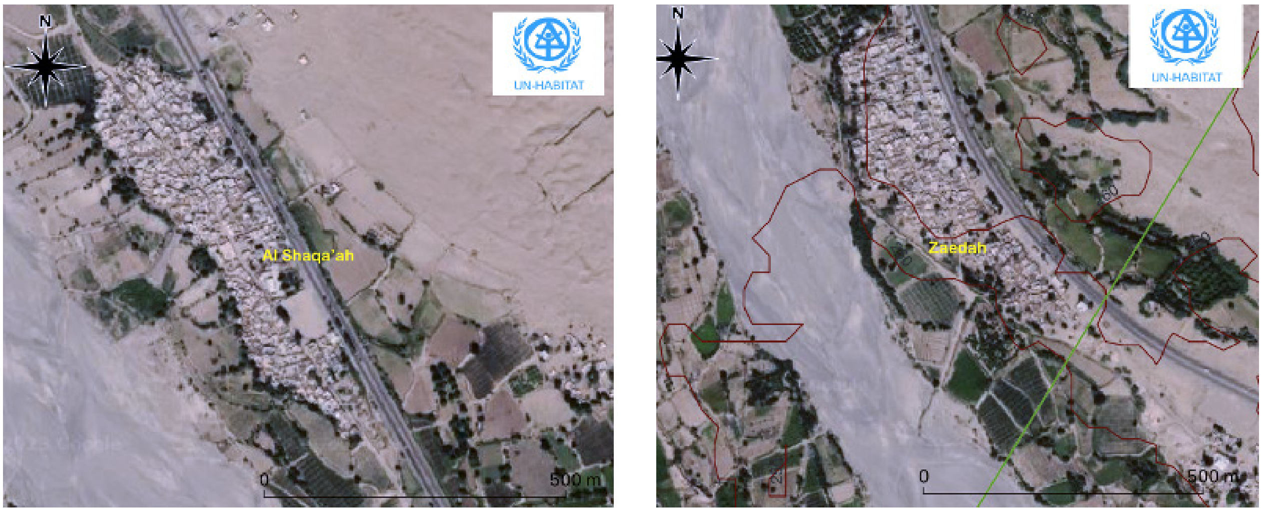


***Figure 26:*** *Two Villages (AlShaqa'ah and Zaedah) in the UR might be Affected by Flash Floods.*

Taking into consideration the risk of sea-level rise after 2080, flood risk that might occur after 2060 and the location (distance to the streams/ocean) (see Figure 27), Table 38 presents the main infrastructure in Tuban delta and their associated climate risks based on their locations.


***Figure 27:*** *Main Streams and Infrastructure in Tuban Delta.*

***Table 38:*** *Main Assets and Infrastructure and their Associated Risks in Tuban Delta.*

| Name | Region | Climate risks |
|---|---|---|
| Aden Airport | LR | High flood risks |
| **Biodiversity** | | |
| The natural channel from Byzag Weir to Al-Hadarm Weir | MR | Medium flood risk |
| Nature reserve of the Swans | LR | High sea-level rise risk |
| Al-Heswah Wetlands | LR | Medium Sea-level rise risk |
| **Heritage** | | |
| Aden National Museum | LR | Low risk |
| Dar Al-Araes Palace | UR | High flood risk |
| Al-Rawda Palace | MR | Low flood risk |
| Al-Qomondan Palace | MR | Low risk |
| **Hospitals** | | |
| Ibn Khldoon Hospital | MR | Low risk |
| Al-Waht Hospital | LR | Medium flood risk |
| Aden Hospital | LR | Medium flood risk |
| Al-Gamhoria Hospital | LR | Low risk |
| Al-Sadakh Hospital | LR | Low risk |
| Refinary Hospital | LR | Low risk |
| 22 May Hospital | LR | Low risk |
| **Power stations** | | |
| Abass Power Station | MR | Low flood risk |
| Al-Haswah Termoelctric Plant | LR | Low risk |
| Al-Mansorah Power station | LR | Low risk |
| Khormksr Power station | LR | Low risk |
| Hugaif Power station | LR | Low risk |
| Chihnaz Power station | LR | Medium flood risk |
| **Water Supply and WWTps** | | |
| Al-Anad Water Supply station | UR | High flood risk |
| Al-Hawtah Water supply station | MR | Low flood risk |
| Al-Hawtah Wastewater treatment plant | MR | Low flood risk |
| Bir Naser Water Supply station | LR | Low flood risk |
| Al-Barzakh water supply station | LR | Medium flood risk |
| Bir Ahmed Water Supply station | LR | Low flood risk |
| Saber Wastewater treatment plant | LR | Low flood risk |
| Al-Mansorah Wastewater treatment plant | LR | Low flood risk |
| Al-Areesh Wastewater treatment plant | LR | Low flood risk |
| Salah Addin Wastewater treatment plant | LR | High flood risk |
| **Landfills (waste management)** | | |
| Al-Fashlah waste landfills | LR | Low flood risk |
| Al-Haswah waste landfills | LR | Medium sea-level rise risk |

| | | |
|---|---|---|
| **IDP camps** | | |
| Al-Khudad IDP Camp | MR | Low flood risk |
| Al-Feuosh IDP Camp | LR | High flood risk |
| Al-Rugaa IDP Camp | LR | Low risk |
| Al-Rubat IDP Camp | LR | High flood risk |
| Madinat Al-Shaab IDP Camp 1 | LR | Low risk |
| Madinat Al-Shaab IDP Camp 2 | LR | Low risk |
| **Roads** | | |
| Al-What Al-Rugaa Road | LR | High flood risk |
| Al-What Al-Rugaa Road | LR | رHigh flood risk |

Based on the Camp Coordination and Camp Management Cluster (CCCM) National Flood Hazard Analysis for the Internally Displaced People (IDP) sites in Yemen (REACH 2023), Table 39 presents some of these sites that will be impacted by flooding after 2060.

***Table 39:*** *IDP under Flood Risk in Tuban Delta.*

| Governorates | District Name | Site Name (English) | Site Name (Arabic) | Regions | Flood risk |
|---|---|---|---|---|---|
| Aden | Al Burayqah | Al Burayqah | رأس عباس | LR | High risk |
| Aden | Dar Sad | Dar Sad | حوش درهم | LR | High risk |
| Aden | Dar Sad | Dar Sad | موقع عمار بن ياسر | LR | High risk |
| Aden | Dar Sad | Dar Sad | حوش عثمان | LR | High risk |
| Aden | Dar Sad | Dar Sad | المعهد السعودي | LR | High risk |
| Lahj | Tuban | Al Hawtah - Tuban | الرباط الغربي | LR | High risk |
| Lahj | Tuban | Al Hawtah - Tuban | المخشابة | MR | High risk |
| Lahj | Tuban | Al Hawtah - Tuban | سد فالح | MR | High risk |
| Lahj | Tuban | Al Hawtah - Tuban | مخيم عطيرة | LR | High risk |
| Lahj | Radfan | al Habilin | المحوى الأعلى | LR | High risk |
| Lahj | Radfan | al Habilin | محوى الكهرباء | UR | High risk |
| Lahj | Al Malah | Al Malah | سيلة بله | LR | High risk |
| Lahj | Radfan | al Habilin | المحوى الاسفل | LR | High risk |

In addition, long periods of droughts and lack of maintenance of canals (see Figure 28) contribute to a high flood risk in many areas in Tuban Delta.

***Figure 28:*** *Plants and sediments in the canals in Tuban Delta.*

## 8.5. Drought

Drought events are characterized by the degree of dryness and the duration of the dry period. Droughts typically have four categories:

1. Meteorological drought, which represents the change in meteorological measurement in the meteorological stations (rainfall, temperature, humidity, etc.),
2. Agricultural drought, which occurs due to a decrease of soil humidity that affects agriculture production, which can be estimated in the field by measuring soil humidity,
3. Hydrological drought due to low rainfall rates that may affect runoff and water storage,
4. Socioeconomic drought due to excessive imbalances in between supply and demand. This category is influenced mainly by population increases and a lack of local water supply management.

Drought indices have been developed in recent decades to assimilate data on precipitation, streamflow and other water supply indicators into a comprehensible big picture. These indices include the Standardized Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), Standardized Runoff Index (SRI), rainfall anomaly index (RAI), the Deciles Index (DI), drought area index (DAI), standardized precipitation evaporation index (SPEI), surface humidity index and streamflow drought index (SDI) (Eslamian et al., 2017).

Analyzing precipitation data is the most common method to study drought in each area because precipitation is the most common variable which directly impacts the level of soil moisture content, steam flows and groundwater resources (Eslamian et al., 2017). Therefore in this report, SPI and SPEI are favored as options to assess the temporal variability of rainfall in Tuban Delta.
In this report two drought categories will be considered in the assessment: the meteorological drought and the socioeconomic drought.

### 8.5.1. Meteorological Drought

Meteorological drought can be assessed by SPI and SPEI. SPI is mainly caused by a deficiency of precipitation. A long-term precipitation record is needed to calculate SPI. After the statistical fitting and transformation of the long-term precipitation data, region-specific deviations are mostly minimized. SPI is a probability-based index, so the heaviness or lowness of a precipitation event in the SPI is relative to the rainfall characteristics of that area. SPEI is an extension of the SPI. It considers both precipitation and potential evapotranspiration (PET) in determining drought. Thus, it uses the monthly (or weekly) difference between precipitation and PET. SPI and SPEI classify different drought severities from extremely dry to extremely wet as shown in Table 40.

***Table 40:*** *Drought Classification based on SPI and SPEI Indices.*

| SPI classification | Condition |
|---|---|
| +2.0 | Extremely wet |
| 1.5 to 1.99 | Very wet |
| 1.0 to 1.49 | Moderately wet |
| - 0.99 to 0.99 | Near normal |
| - 1 to -1.49 | Moderately dry |
| - 1.5 to – 1.99 | Severely dry |
| - 2 and less | Extremely dry |

To assess drought conditions based on SPI in 2022, monthly SPI maps have been obtained from the Emergency Management Service. The maps show that the SPI for the upper and the middle regions is near normal (0), while it is extremely dry (-2) in the Lower Region, see Figure 29.

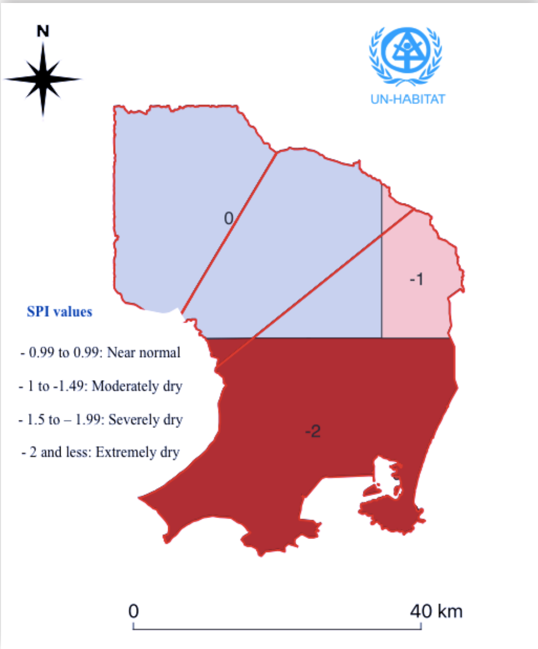


***Figure 29:*** *SPI Drought Index in Tuban Delta in 2022.*

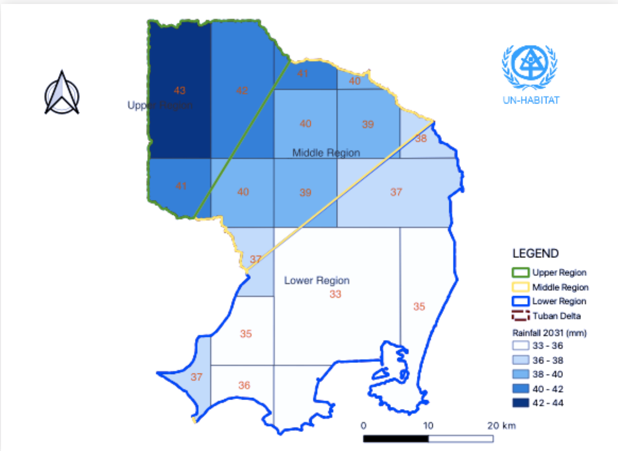


***Figure 31:*** *Annual Rainfall Distribution (2030-2033) under SSP3.*

For future projections under SSP3, high annual rainfall is forecast to occur in Aden and Lahij between 2060 and 2065 (see Figure 30). However, there is a likelihood of drought occurring on average for three years each decade due to limited rainfall (less than 50mm) in Aden and Lahij as shown in Figure 31.

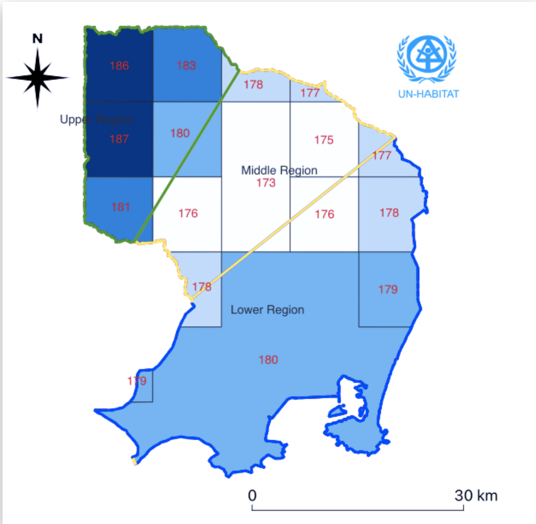


***Figure 30:*** *Annual Rainfall Distribution (2060-2063) under SSP3.*

Under RCP 8.5, there is the potential for drought to occur between 2070 and 2073, where annual precipitation will be less than 50 mm (see Figure 32). Whilst the model shows potential for high rainfall rates occurring between 2090 and 2100 (see Figure 33).

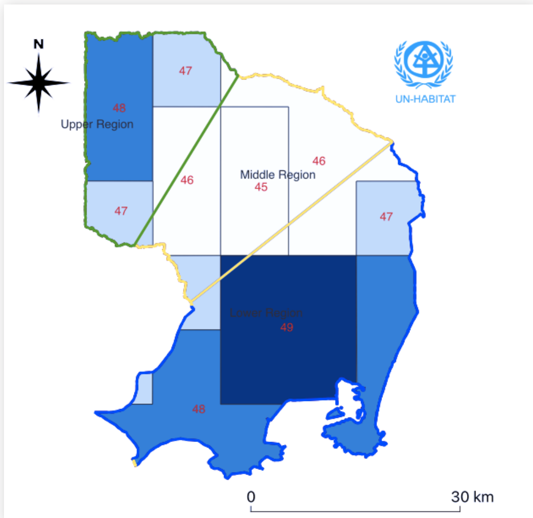


***Figure 32:*** *Average Annual Rainfall Distribution in (2070-2073) under SSP5.*

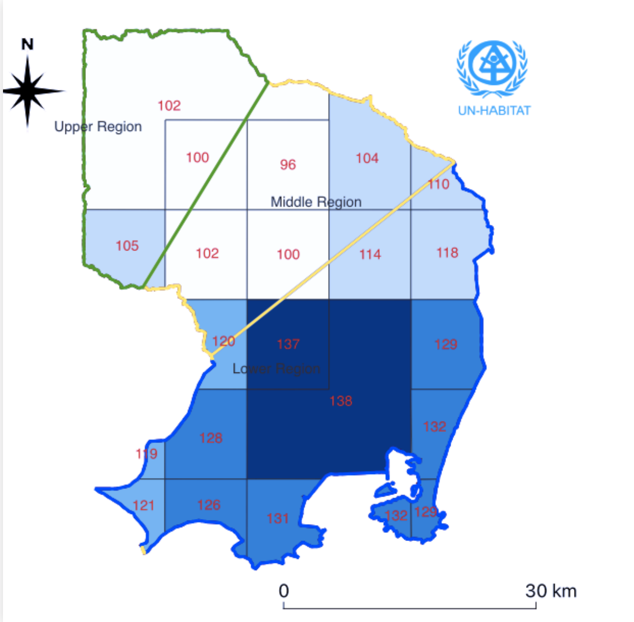

*Figure 33: Average Annual Rainfall Distribution (2095 -2100) under SSP5.*

The severity of drought can be divided into four categories based on the % decrease in the annual rainfall compared to the average values:

**1. Negligible: :** Low severity when the decrease in rainfall patterns is less than 25%,

**2. Marginal:** Medium severity when the decrease in rainfall patterns is between 25 and 50 %,

**3. Critical:** Serious severity when the decrease in rainfall patterns is between 51 and 75 %,

**4. Catastrophic:** High severity when the decrease in rainfall patterns is more than 75%.

The probability of drought occurrence has been estimated based on the probability of the low precipitation rates that generate serious or high severity droughts.

1- Improbable (less than 20%)
2- Remote (between 20 and 39%)
3- Occasional (between 40 and 59%)
4- Probable (between 60 and 80%)
5- Frequent: more than 80%

Following the same flooding risk assessment procedure, Table 41 presents drought risk assessment under SSP3 and SSP5. The table shows that the LR is forecasted to have more drought periods compared to the other regions.

| Years/regions | SSP3 (RCP 7) | | | SSP5 (RCP 8.5) | | |
|---|---|---|---|---|---|---|
| | UR | MR | LR | UR | MR | LR |
| 2023-2040 | II | II | III | II | II | III |
| 2041-2060 | I | II | II | I | I | II |
| 2061-2080 | I | I | I | III | III | III |
| 2081-2100 | I | I | I | I | I | I |

*Table 41: Drought Risk Assessment under SSP3 and SSP5.*

### 8.5.2. Socioeconomic Drought

For socioeconomic drought, future projections of the unmet demands show potential water shortages under the three demand scenarios especially in the LR.
The hazards of socioeconomic drought have been grouped into five categories under SSP3 and SSP 5,(see Table 42 and Table 43) based on the projected water shortages that have been estimated in section 7.5.3:

I. Low, if the annual water shortage is equal or less than 10 MCM,
II. Low/Medium, if annual water shortage is between 10.1 and 40 MCM,

III. Medium, if annual water shortage is between 41 and 100 MCM,
IV. Medium/High, if annual water shortage is between 101 and 150 MCM,
V. High, if annual water shortage is more than 150 MCM.

***Table 42:*** *Socioeconomic Drought Hazard Assessment under SSP3.*

| Scenario | The Reference scenario | | | The improved scenario | | |
|---|---|---|---|---|---|---|
| Region | UR | MR | LR | UR | MR | LR |
| 2022 | - | - | III | - | - | III |
| 2040 | - | II | IV | - | II | IV |
| 2060 | - | II | V | - | I | IV |
| 2080 | - | - | V | - | III | IV |
| 2100 | - | II | V | - | II | IV |

***Table 43:*** *Socioeconomic Drought Hazard Assessment under SSP5.*

| Scenario | The Reference scenario | | | The improved scenario | | |
|---|---|---|---|---|---|---|
| Region | UR | MR | LR | UR | MR | LR |
| 2022 | - | 9 | III | - | - | III |
| 2040 | - | 3 | III | - | - | III |
| 2060 | - | 9 | IV | - | - | III |
| 2080 | - | -14 | V | - | - | III |
| 2100 | - | -19 | V | - | - | III |

### 8.5.3. The Impacts of Drought

Drought will increase water insecurity in Tuban Delta, mainly in the LR leading to low recharge rates and overexploitation of groundwater resources, which will increase groundwater depletion and salt-water intrusion. Thus, many wells in the lower region are projected to go dry, especially the wells of Bir Ahmed well field affecting the main domestic water source of Aden.

The thickness of groundwater aquifers in Tuban Delta3 increases from 30m to 170m. Due to drought, groundwater recharge rates will be limited and are at risk of reaching zero. In the current conditions, ground water levels drop by about 3-7 m/year due to overexploitation (UNDP, 2021). However the field visits in March 2023 showed that groundwater levels drop approximately 1m/year. Assuming a 1m drop in groundwater levels and a thickness of 30-170 m for groundwater aquifers, fresh groundwater resources in the LR will start to go dry in 30 years if urgent actions are not taken. Thus, most of the wells will go dry by 2080 due to the increase in the annual water deficit.

## 9. ADAPTATION OPTIONS

This hydrology study highlights the main climate risks that are facing Tuban Delta as shown in Table 44.

| Climate risks | Upper Region | Middle Region | Lower Region |
|---|---|---|---|
| Water Security | Medium-High | High | High |
| Flooding | Medium | Medium-High | High |

***Table 44:*** *Climate Related Risks Facing Tuban Delta.*

To propose possible adaption options, stakeholders have been consulted through workshops and meetings to brainstorm climate related risks and possible responses. The outcomes of these workshops are summarized in Table 45 considering short-, medium- and long-term adaptation options.

***Table 45:*** *Possible Adaptation Measures.*

| Regions | Short-term options (1-3 years) | Medium-term options (4-6 years) | Long-term options (6+ years) |
|---|---|---|---|
| **Upper region** | **Urban:** Flood protection walls or gabions. Early Warning System. **Rural:** Raising awareness Improve irrigation efficiency | **Urban:** Disaster risk management plan, Early Warning system. Water conservation. **Rural:** Water Harvesting, irrigation technologies, Greywater reuse | **Urban:** Sustainable water use management . Flood risk management. Green Tree Planting **Rural:** Water barriers. Irrigation Technologies |
| **Lower region** | **Urban:** Greywater reuse Awareness-raising in water usage rationalization **Rural:** Raising awareness Improve irrigation efficiency | **Urban:** Rehabilitation of wetlands **Rural:** Drought-tolerant crops Salt-tolerant crops | **Urban:** Greywater reuse. Sustainable water use management. Rehabilitation of Al-Tawelah Tanks **Rural:** Sustainable water use management; Green Tree Planting Rural: Mangrove cultivation |
| **Lower region** | **Urban:** Greywater reuse Awareness-raising in water usage rationalization **Rural:** Raising awareness Improve irrigation efficiency | **Urban:** Rehabilitation of wetlands **Rural:** Drought-tolerant crops Salt-tolerant crops | **Urban:** Greywater reuse. Sustainable water use management. Rehabilitation of Al-Tawelah Tanks **Rural:** Sustainable water use management; Green Tree Planting Rural: Mangrove cultivation |

Based on Table 44 and Table 45 the following adaption measures are proposed:

1. New desalination plant to cover the increasing drinking water demands in Aden,
2. Greywater reuse from Mosques and schools in agriculture/creation areas,
3. Rehabilitate the existing wastewater treatment plants and reusing the treated wastewater in agriculture/creation areas,
4. Early warning Systems & Risk Management plans,
5. Re-utilization of desalinated water from Al-Hswah Thermal Power Plant by a) creating artificial ponds/lake for ground water recharge OR b) sending the water to the national water company,
6. Rehabilitation and protection of irrigation systems of Tuban Delta for effective water delivery and to reduce floods risks.

## 10. WATER MANAGEMENT AND INSTITUTIONAL FRAMEWORKS

According to the study's findings, there is an urgent need to address water management techniques and related frameworks based on Integrated Water Management (IWRM) principles to mitigate climatic risks, regulate socioeconomic activities and ensure environmental sustainability. The outcome of the FGDs revealed that the three regions face the following challenges: lack of water and climate related management plans, inactive agricultural plans, lack of a proper monitoring mechanism and inactive Water Use Associations (WUAs) in the agriculture sector or practices. All these challenges have led farmers to dig more illegal wells, which have depleted groundwater resources and reduced water quality (through increased salinity).

In terms of political frameworks, the water sector is governed by the Water Law and the National Water Sector Strategy and Investment Program (NWSSIP). The Water Law no. 33 of 2002 was modified by Law no. 41 in 2006, and the Executive Regulations were published in 2011 after the establishment of the MWE. This protracted process, combined with the conflict, insecurity and poverty have hampered the law's implementation and enforcement. Therefore, the legislation should be modified to include additional specifics concerning enforcement, operation, cooperation, roles and responsibilities considering the emerging challenges, which include climate change, groundwater depletion, conflicts and poverty.

The NWRSIP 2005-2009 was issued in 2004, followed by an updated version (2008-2015), the NWRSIP II. The strategy lacks specifics on climate change risks, adaptation measures, and the vulnerability of water resources. Groundwater depletion was highlighted in the strategy, but no activities were offered to prevent such, to reduce water usage or to cope with climate change threats. Therefore it is recommended that a new water plan be develop, including the following considerations:

1. Water governance, allocation, roles and responsibilities of different entities,
2. Monitoring (training and equipment) to protect natural resources, mainly groundwater,
3. Climate-related risks (flood, drought, sea-level rise etc.),
4. Information management: data collection and sharing,
5. Basin planning, management and community-based organizations to facilitate decentralized water management at the watershed level,
6. Climate risks, adaptation and mitigation measures,
7. Protecting groundwater by monitoring and law enforcement,
8. Water saving in agriculture: the implementation of modern irrigation systems and investigating the possibility of changing crop patterns,
9. Decentralized management: create and promote water users' associations to serve as the accountable bodies for sustainable water management among basin users, considering water shortages, water usage efficiency and sea water intrusion issues,
10. Raising public awareness and enlisting the collaboration and participation of stakeholders (including decision-makers and research institutes) to manage water supply and demand in an integrated and sustainable manner,
11. Increasing the water supply: Fundraising and international collaboration should be used to assist individual, national and international projects

A pervasive challenge is also the fact that most governmental agencies including water and environmental related institutions lack financial resources. This undermines capacity to perform core functions such as operations, maintenance and monitoring as well as the capacity to implement legislation and policy. Interventions to improve institutional capacity thus must include a consideration of financial resources.
Thus the financial viability of relevant institutions must be considered a core challenge to effective management, resource allocation, conservation, and protection of natural resources.

## 11. CONCLUSIONS

This hydrological assessment of Tuban Delta was carried out via a collaboration between UN-Habitat and EPA Yemen as well as a number of national and international stakeholders. Using climate models and QGIS, the current and future hydrological state and risks have been examined. The 2022 estimation of water supplies includes renewable surface water, renewable groundwater water and NCWR, which have been estimated at 59, 139, and 10 MCM respectively.

While the water uses include 194 MCM for agricultural uses and 50 MCM for domestic uses, which means agricultural water represents 82% of the total water use. This results in a total water deficit of 36 MCM. Furthermore, the development of several dams and other rainwater harvesting techniques and the overuse of surface water in the upper section of Tuban watershed (upstream) have decreased the risk of floods but decreased the availability of surface water in Tuban Delta (downstream). As a result, limited water reaches the lower region and no water reaches the ocean, which has forced the general public and farmers to depend mainly on groundwater using renewable energy, leading to 84 MCM of water deficit in the LR of Tuban Delta in 2022. In addition to all these, internal migration, population expansion and climate change have impacted groundwater levels and thus increased saltwater intrusion, changed soil qualities and enhanced desertification. If the imbalance between groundwater recharge and discharge persists, groundwater levels will fall further and saltwater intrusion will rise.

To project the future situation, the MRI-ESM2-0 climate model and QGIS have been used. under two climactic pathway models; SSP3 and SSP5. Two main scenarios have been assessed, the first is the reference scenario where all activities and population growth stay the same, while the second one is the improved scenario, which considers modern irrigation, decreasing population growth and increasing use of treated wastewater.

The results reveal a wide range in water availability estimates up to 2100 in the three regions. Under the reference scenario, the water deficit is forecasted to be more than 400 MCM in 2100 under both climatic pathways (SSP3 and SSP5). The improved scenario however shows a more favorable outlook, with the forecasted water deficit less than 43 and 10 MCM in 2100 under SSP3 and SSP5 respectively. In the LR however, both scenarios predict severe water shortages ranging from 60 to 80 MCM under the improved scenario. Thus under the modelling, the LR is forecasted to require additional water resources such as could be provided by a 50 MCM solar-powered seawater desalination plant as soon as possible, followed by an additional 10 MCM plant every subsequent 10 years.
The simultaneous depletion of groundwater resources presents an additional challenge. Tuban Delta is one of the critical basins in Yemen where most of the illegal rigs/wells are found. The assessment of 2023 shows that there are 3,600 wells, 1,200 of which have gone dry, and the average annual drop of groundwater levels reaches one meter due to the imbalance between discharge and recharge rate.

The LR is the most susceptible to the effects of climate change since it is impacted by four main climate hazards: flooding, drought, sea-level rise and saltwater intrusion, all of which impact water supply systems and coastal infrastructure. Furthermore, the model predicts an increase in the number of extreme hot days per year beginning in 2050, reaching 40 days per year under SSP3 and 70 days per year under SSP5 in 2100. This increase in extreme temperatures will have a negative impact on the population and socioeconomic activities. Moreover, modelling sea-level rise using QGIS showed that the majority of coastal areas, including the international airport will be affected by 2100. Finally, the lack of financial resources and insecurity have hindered national institutions from performing their core functions and from implementing relevant laws and strategies. Therefore, these is a need for an appropriate financial framework to ensure institutional capacity is sustainable.

## 12. RECOMMENDATIONS

To cope with climate change and water scarcity challenges in Tuban Delta, the following measures are recommended:

1. A solar-powered desalination plant should be constructed as soon as possible to meet the needs of the LR,
2. Wastewater treatment plants should be rehabilitated, and appropriate management plans to reuse treated water for irrigation or for groundwater recharge should be developed, including monitoring,
3. Irrigation channels should be maintained, applying modern irrigation methods,
4. Disaster management plans should be developed, coupled with an early warning system to mitigate the impacts of flooding and drought,
5. Groundwater discharge should be monitored to control groundwater depletion and saltwater intrusion in the LR,
6. Conducting capacity building programs to address hydrological modeling, water use efficiency, water allocation and climate change adaptation should be implemented,
7. Environmental flow has not been considered in Yemen's national water management plans, It is recommended that future plans rectify this as an average environmental flow of 10-30 l/s at the basin outlet can contribute to water sustainability in Tuban Delta,
8. Increasing creation and maintenance of green areas should be included in future urban plans to help mitigate the impacts of heatwaves,
9. Underpinning all of the above, an Integrated Water Resource Management (IWRM) plan/strategy for Tuban Delta should be developed.

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