Photo by Bernard Gagnon, 1986.

Hydrological study of Wadi Tuban catchment

Data collection, methodology and work plan

Final Report

ACACIA WATER

Data collection, methodology and work plan

Hydrological study of Wadi Tuban

Executive summary

Water management is a pressing issue in Yemen. A hydrological assessment of Wadi Tuban catchment and four target districts in Taiz and Lahj governorates is envisaged to support and inform sustainable water management. In this first phase of the assignment, a comprehensive data collection exercise was performed. The data collection focused on mapping and gathering available information and data (both primary and secondary) related to the hydro-meteorological characteristics of the Wadi Tuban catchment and sub-catchments representing the four target districts (Al-Mawaset and Al-Selw upstream and Al-Mosaymer and Tuban downstream). This data will be used to develop a reconnaissance-level hydrological model for the primary Wadi Tuban catchment and detailed (distributed/semi-distributed) models for the four sub-catchments, with a particular emphasis on land use/land cover characteristics and water usage in a subsequent phase. An evaluation of selected hydrological models was done and the SWAT hydrologic model has been selected as the primary option for this project, with the MIKE SHE model as an alternative. This report presents a methodology for the water balance assessment and a work plan for the next phase of the project.

Colophon

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List of acronyms

AREA	Agriculture Research Extension Authority
ASL	Above Sea Level
BGR	Federal Institute for Geosciences and Natural Resources (Germany)
FAO	Food and Agriculture Organization
KfW	German Development Bank
MoAIF	Ministry of Agriculture, Irrigation, and Fisheries
MoWE	Ministry of Water and Environment
NWRA	National Water Resources Authority
RVO	Rijksdienst voor Ondernemend Nederland (The Netherlands Enterprise Agency)
UNDP	United Nations Development Programme
WaPOR	WAter Productivity through Open-access of Remotely sensed derived data

1. Introduction

Yemen faces critical challenges in water availability. Even before the current conflict intensified the crisis, Yemen ranked among the most water-stressed countries globally, highlighting the urgent need for effective water resource management.

In response, the UNDP Yemen and the German Development Bank (KfW) have launched a series of initiatives aimed at improving water management and enhancing food security. These initiatives prioritize sustainable agriculture, support for small-scale farmers, and the strengthening of local food systems to combat hunger and poverty. Key components include the construction and rehabilitation of water infrastructure, improved market access, and the empowerment of women in agriculture. A crucial element of these efforts is conducting a comprehensive catchment water balance assessment.

The project will ultimately conduct a catchment water balance for Tuban. This includes hydrological assessments of water resources at reconnaissance level at catchment scale, and more detailed assessments for four target sub-catchments located in the target districts of Taiz and Lahj governorates. In the first step, the current assignment seeks to map and collect essential data to perform the respective hydrological assessments. Additionally, the study will establish a methodology for selecting an appropriate hydrological model for the second phase of the project. The current data collection phase is foundational to the upcoming "Hydrological Study for the Tuban Catchment in Yemen" project. The findings will inform the development of a work plan focused on analysing the hydrological characteristics and water availability in the Tuban catchment and its sub-catchments. Special emphasis will be placed on assessing the water balance of Wadi Tuban and evaluating the impact of upstream development on downstream flow patterns.

1.1 Objective

The main objective of this assignment is to conduct a comprehensive data collection effort, focusing on mapping and gathering available primary and secondary information on the hydro-meteorological, water use, and geographic/biophysical characteristics of Wadi Tuban and its four sub-catchments within the targeted districts.

The main focus areas of this assignment are:

1. Wadi Tuban primary catchment, at a reconnaissance level; and
2. Four sub catchments at a detailed level, located in the target districts:
    - Al-Mawaset and Al-Selw districts (upstream) in Taiz governorate, and
    - Al-Musaymir and Tuban districts (downstream) in Lahj governorate.

The secondary objectives of this assignment are to develop a methodology for selecting an appropriate hydrological model, including identifying its limitations and proposing a suitable water balance methodology for the targeted sub-catchments. Additionally, it aims to propose a work plan for the second phase of the project, which will focus on developing hydrological models based on the data collected in this phase.

The second phase of the project will include:

1. Water balance assessment for the whole Tuban catchment.
2. Reconnaissance level hydrological assessments for water resources of the Tuban catchment.
3. Detailed hydrological assessments for the four sub-catchments.

1.2 Outline report

This draft report outlines the main objectives (Chapter 1), the overview of water resources (Chapter 2), data inventory (Chapter 3), hydrological model selection (Chapter 4), proposed water balance methodology (Chapter 5), work-plan for hydrological study, and conclusions and recommendations (Chapter 6).

2. Overview of water resources

2.1 Extent of the Study Area

This study focuses on the Wadi Tuban catchment and four sub-catchments representing the four selected districts. With support and guidance from UNDP, the geographical delineation of the primary Wadi Tuban catchment and its sub-catchments across the four focus districts has been completed: 1) Al-Mawaset and 2) Al-Selw districts (upstream) in Taiz governorate, and 3) Al-Mosaymer and 4) Tuban districts (downstream) in Lahj governorate (Figure 1). These sub-catchments aim at covering as much of the part of the target district falling within Tuban catchment as possible, while limiting the area of the sub-catchment falling outside of the district. An overview of the area of the districts and subcatchments is provided in Table 1. A brief overview of the study area's location and geographical extent, based on our catchment delineation, is provided in this section.

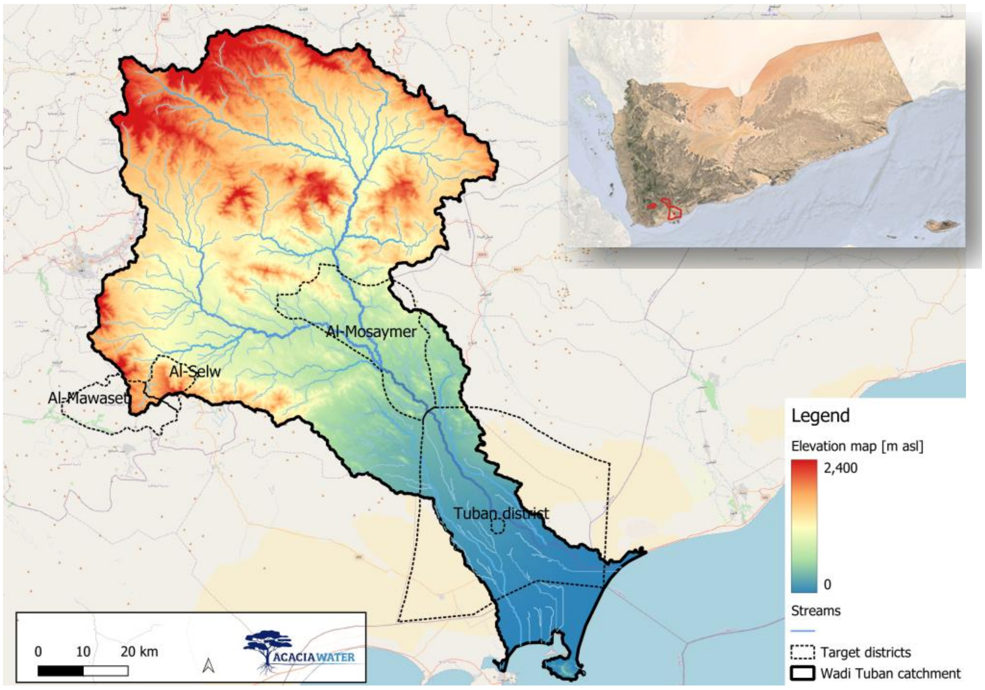


Figure 1. Map of Wadi Tuban catchment area with the four target districts.

Table 1. Overview of district and subcatchment areas, along with the area of the districts falling within the subcatchment and total Tuban catchment area.

District	Area subcatchment	Area district	Area district within subcatchment		Area district within Tuban catchment	
	km2	km2	km2	%	km2	%
Al-Mawaset	36.4	215.9	27.3	13	31.5	15
Al-Selw	238.4	83.2	58.5	70	73.2	88
Al-Mosaymer	5370.6	558.8	422.3	76	537.7	96
Tuban	7168.7	1626.3	804.3	49	804.3	49

2.1.1 Wadi Tuban Catchment

The Wadi Tuban catchment area is 7168.7 km^2, of which the delta area on the coast is about 700 km^2 (Comparison Between the main results of UN-Habitat & BGR Studies of Tuban Delta 2013, n.d.). Wadi Tuban lies between latitudes 13°59'54.459" N and 12°56'33.061" N and the longitudes between 44°5'57.797" E and 45°5'58.651" E. The elevation of Wadi Tuban ranges between 3209 m ASL down to sea level where the catchment reaches the Arabian Sea. The wadi length is about 156 km, stretching from the city Ibb in the north, Taizz in the west, and Abawil in the east. The wadi outlets into the Arabian sea near the city Aden.

2.1.2 Al-Mawaset District

Al-Mawaset district is situated in the highlands of the eastern part of Taiz Governorate. The elevated terrain causes the majority of the water to flow towards the southern and western regions of the district (Alfadali, A. & Social Fund for Development - Taiz Branch 2020). The district features diverse topographical formations, including plains, plateaus, and towering mountains. In the southern section, below a steep escarpment known as Mamsa Zubairah, the landscape transitions into lower elevations. The highest peak in the district is Mount Motran. The mountains are composed of various rock types, including igneous, metamorphic, and sedimentary formations. Spanning an area of 228 km^2, the district contains 149 valleys (Alshojaa, K. 2023) and has a population of approximately 169,704 residents, with a near-equal gender distribution (51% male and 49% female).

The hydrology of Al-Mawaset is characterized by water flow primarily directed southward and westward, but this runoff does not contribute to the Wadi Tuban catchment (Figure 2). In the current study, we focus on the northeastern section of Al-Mawaset that lies within the Wadi Tuban catchment to define the boundaries of the sub-catchments. The outlet point for this area is located at 44°9'41.21" E and 13°19'57.287" N, outside the administrative borders of Al-Mawaset, within the Al-Selw district. The highlands generate two principal streams that pass through the district, both of which are accounted for in the hydrological sub-catchment analysis through the defined outlet point (Figure 2). The area of the sub-catchment is approximately 36 km^2.

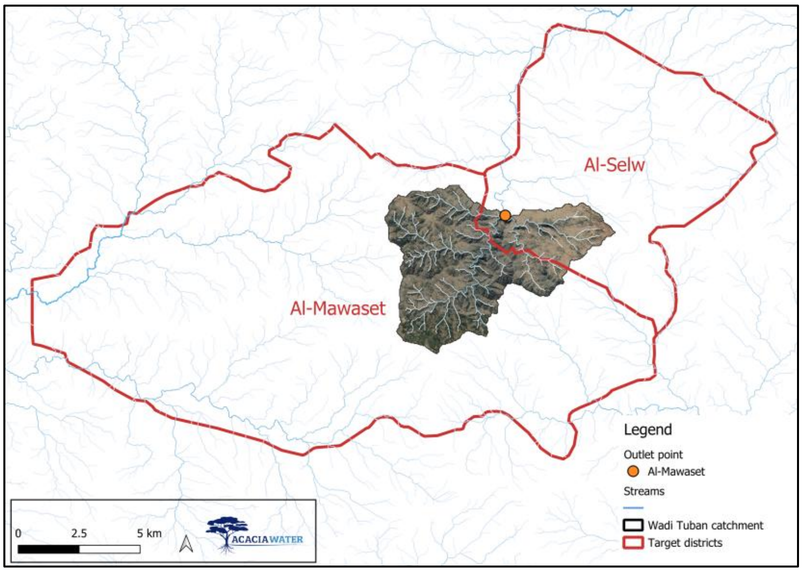


Figure 2. Detail map of the catchment delineation for Al-Mawaset.

2.1.3 Al-Selw District

Al-Selw district, part of the Taiz Governorate, shares a border with Al-Mawaset. The district rises to an elevation of 1,637 meters above sea level and spans an area of 89.3 km². Al-Selw is characterized by rugged, mountainous terrain, with steep slopes and a fractured mountain mass extending from north to south, covering approximately 95% of the district. The highest elevation, peaking at approximately 2,400 meters, is found in the southwestern highlands of Yemen (Alhamadi, A. J., & Social Fund for Development - Taiz Branch, 2024). The district has a population of around 71,914, with a gender distribution of 48% male and 52% female (Alhamadi, A. J., & Social Fund for Development - Taiz Branch, 2024).

The outlet point defined for the sub-catchment delineation is located at 44°14'4.557" E and 13°24'44.169" N. This point ensures that the largest streams within Al-Selw district are included in the sub-catchment analysis (Figure 3). The area of the sub-catchment is approximately 238 km².

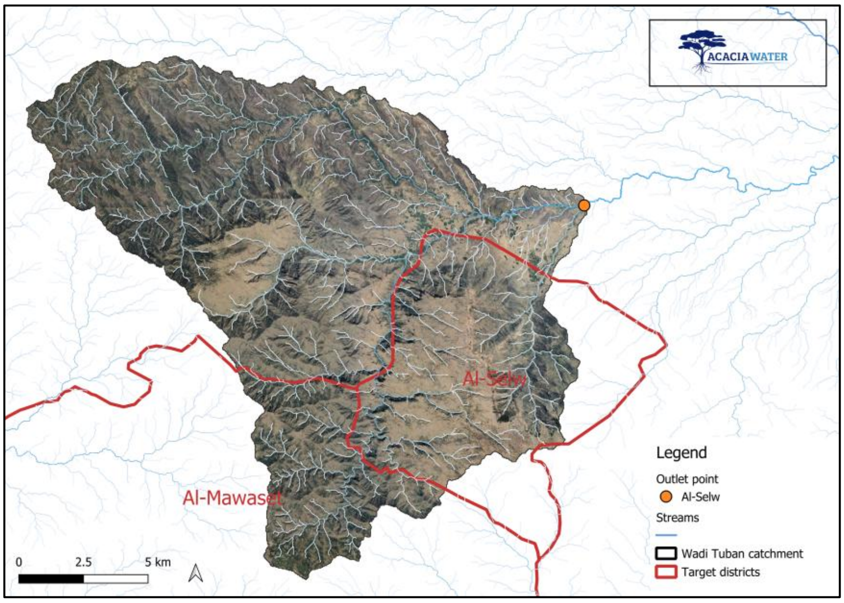


Figure 3. Detail map of the catchment delineation for Al-Selw.

2.1.4 Al-Mosaymer District

Al-Mosaymer district is located within Lahj governate. It receives inflow from the upper and lower highlands in Ad Dali, Ibb and Taiz governorates. The water comes together at the main Wadi Tuban, flowing through Al-Mosaymer. The outlet point is defined at the Wadi Tuban, bordering Al-Mosaymer from Tuban district, at 44°44'2.611" E and 13°17'29.521" N (Figure 4). Where its upstream area receives more rainfall ranging between 200 mm up to 600 mm in the mountainous regions, Al-Mosaymer is an arid area with 10 up to 200 mm of rainfall per year. The Wadi Tuban forms an important part of the district, as most of the people and agricultural plots are found along this stream. The area of the sub-catchment is approximately 5370 km² (Table 1).

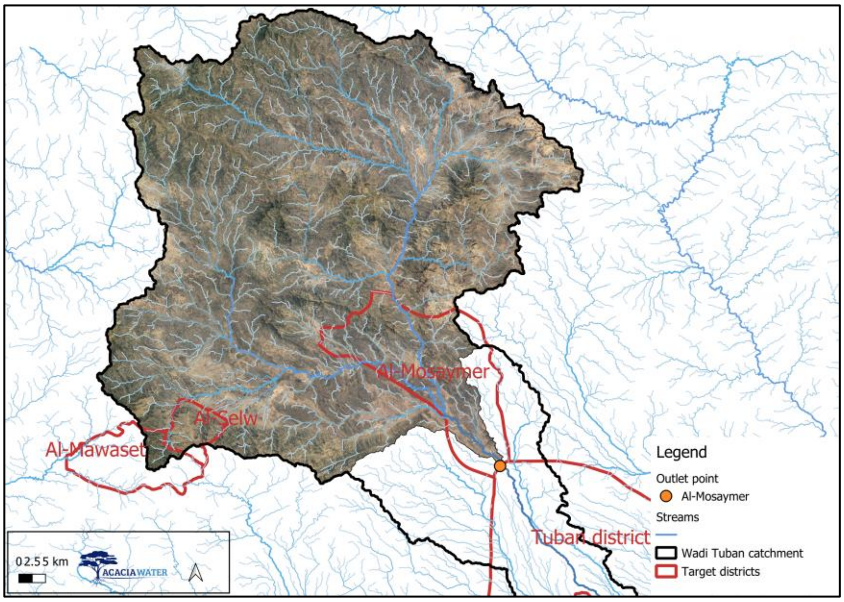


Figure 4. Detail map of the catchment delineation for Al-Mosaymer.

2.1.5 Tuban District

Located in Lahj governorate, Tuban district is part of the Gulf of Aden coastal plain. The Wadi Tuban flows from Al-Mosaymer further downstream into Tuban District, before it pours into the sea at the city Aden. Tuban District covers part of the lower region of the Tuban Delta, which is an important area in terms of population, economy, ecology and agriculture. The wetland in Tuban Delta includes lagoons, salt plains, mudflats and marshes, and are habitats for many bird species (UN-Habitat 2024). The main Wadi Tuban splits into two Wadis at 13° 9'25.79"N & 44°48'47.25"E. The left stream, known as Big Wadi, pours into the sea at 12°49'37.25"N & 44°56'36.34"E. The right stream is known as Small Wadi and usually ends at 12°59'9.08"N & 45° 2'15.63"E near the Bir Jabir Village. The final outlet point of the Small Wadi at the sea is not well defined (Figure 5).

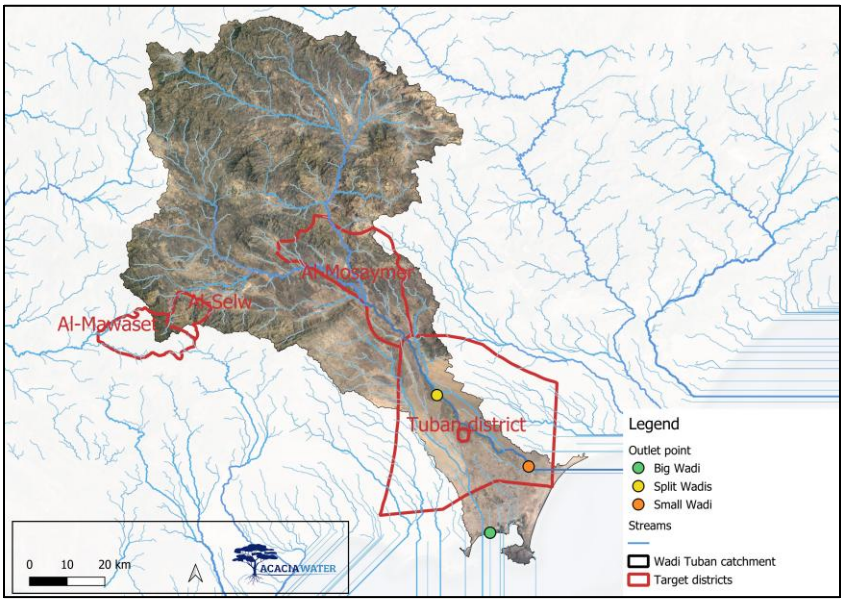


Figure 5. Catchment delineation Tuban district.

The Delta covers about 2000 km^2 of the fovernorates Aden and Lahj, and is divided into three sections according to the division of the Office of Agriculture and Irrigation in Lahj Governorate. Upper Delta Region: It extends from the village of Dukeim in Al-Anad subdistrict at the top of the valley in the Delta to the site of Ras Al-Wadi Dam and is located entirely in Lahj governorate in the district of Tuban; Central Delta Region: It extends from Ras Al-Wadi Dam to the borders of Mujahid Dam and is located within the districts of Tuban and Al-Houta in Lahj governorate; and Lower Delta Region: It extends from the borders of Mujahid dams to the coasts of Aden Governorate and the area is located in the district of Tuban and the end of the Delta is in the coast of Aden Governorate (MOA 2023). This means that more than 70% of the area of Tuban delta is located in the district of Tuban – Lahj governorate.

The Tuban Delta spans approximately 2,000 km^2 across two governorates and is divided into three sections, according to the classification by the Office of Agriculture and Irrigation in Lahj Governorate. More than 70% of the Tuban Delta lies within Tuban District in Lahj Governorate (MOA 2023).

1. **Upper Delta Region**: This section extends from the village of Dukeim at the head of the valley to the Ras Al-Wadi Dam, and is entirely located within Tuban District in Lahj Governorate.
2. **Central Delta Region**: Extending from Ras Al-Wadi Dam to the borders of Mujahid Dam, this region spans both Tuban and Al-Houta districts in Lahj Governorate.
3. **Lower Delta Region**: This section stretches from the borders of the Mujahid Dam to the coastal areas of Aden Governorate, encompassing parts of Tuban District and extending to the districts at the delta's end in Aden Governorate.

2.2 Biophysical context

2.2.1 Hydrogeology

The geology of the catchment as a whole is based on the 1:1M scale geological map of Yemen from the Yemen Geological Survey and Mineral Resources Board (YGSMRB), shown in Figure 6. According to this dataset, the upstream area of Tuban catchment is dominated by Tertiary volcanics. These also dominate the western part of **Al-Mawaset** district, largely falling outside of Tuban catchment. Most of the area of the district falling within the catchment area is covered by Tawilah sandstone. This formation extends into the western portion of **Al-Selw** district. Roughly the eastern part of this district is covered by Migmatites. Further downstream, the **Al-Mosaymer** target district is dominated by Tertiary volcanics, with some Taliwah sandstone in the south. In these areas, the Tawilah sandstone contains the main (exploitable) aquifers, which can be highly productive (Yemen Water 2024). Where these are overlain by basalts, the rocks may form two-layered aquifer systems. The Eocene Lower basalts have lower potential (NWRA Consultants 1997).

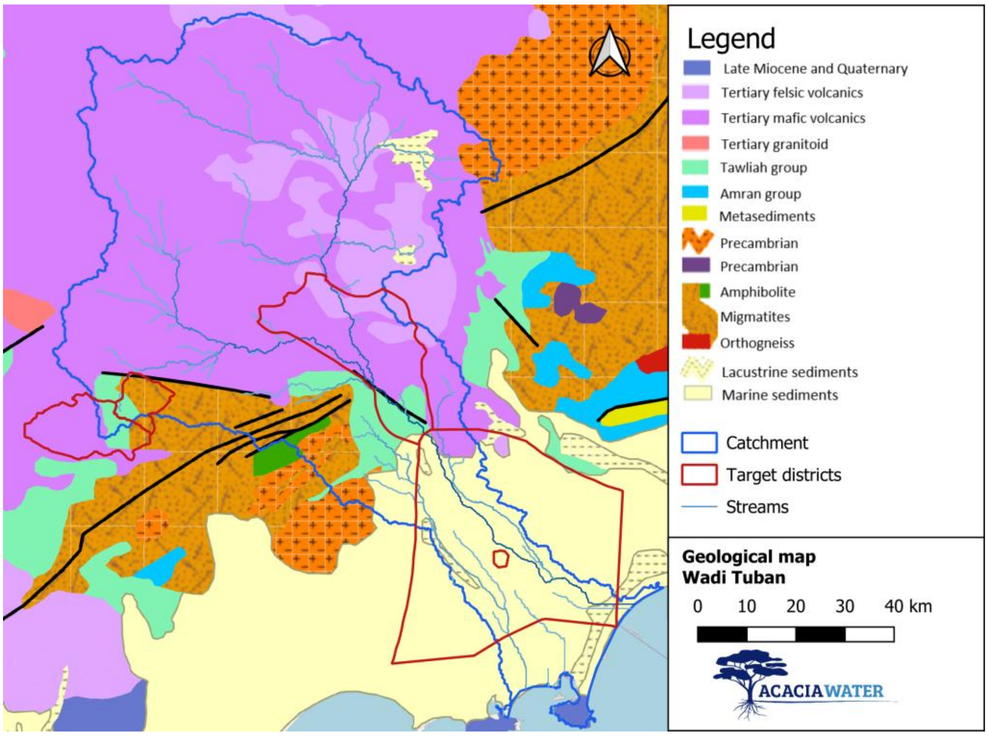


Figure 6. Geological map of Yemen (source: YGSMRB).

Further south, surface geology of **Tuban** target district is dominated by recent sediments. A detailed description of the geological setting of the Tuban Delta is provided by Al-Darwish (2023). Precambrian metamorphic rocks are overlain by Jurassic limestones, which are, in turn, topped by Cretaceous sandstone and basaltic volcanic rocks from the Tertiary period. These formations surround the delta on its northern and eastern sides. The main stratigraphic formations are summarized Table 1. In the upper part of the delta, sediment thickness ranges from 30 to 20 m, increasing to more than 400 m in the lower part (KOMEX 2002). Geological cross-sections of the delta area are shown in Figure 7. The layers above the bedrock are generally hydraulically connected, forming an unconfined aquifer (KOMEX 2002). Notably, the Quaternary alluvium has good water-bearing characteristics, even at significant distances from the current wadi channels, where sand and gravel lenses may represent paleo-wadi channels (KOMEX 2002).

Table 2. Major known stratigraphic formations from most recent to oldest in Tuban delta (from: KOMEX 2002)

Type	Description
Alluvial deposits	sand, silts and clays with some coarser grained material, Quaternary
Basement complex	crystalline and metamorphic rocks of the Aden Metamorphic Group, and granites with dikes
Aden volcanic series	recent volcanism, from Late or Early Miocene to present
Trap series	olivine basalts, rhyolites, tuffs and agglomerate, Upper Cretaceous to Lower Tertiary
Tawilah group	coarse grained sandstone and arkosic sandstone, Cretaceous
Amran group	calcareous materials, Upper Jurassic

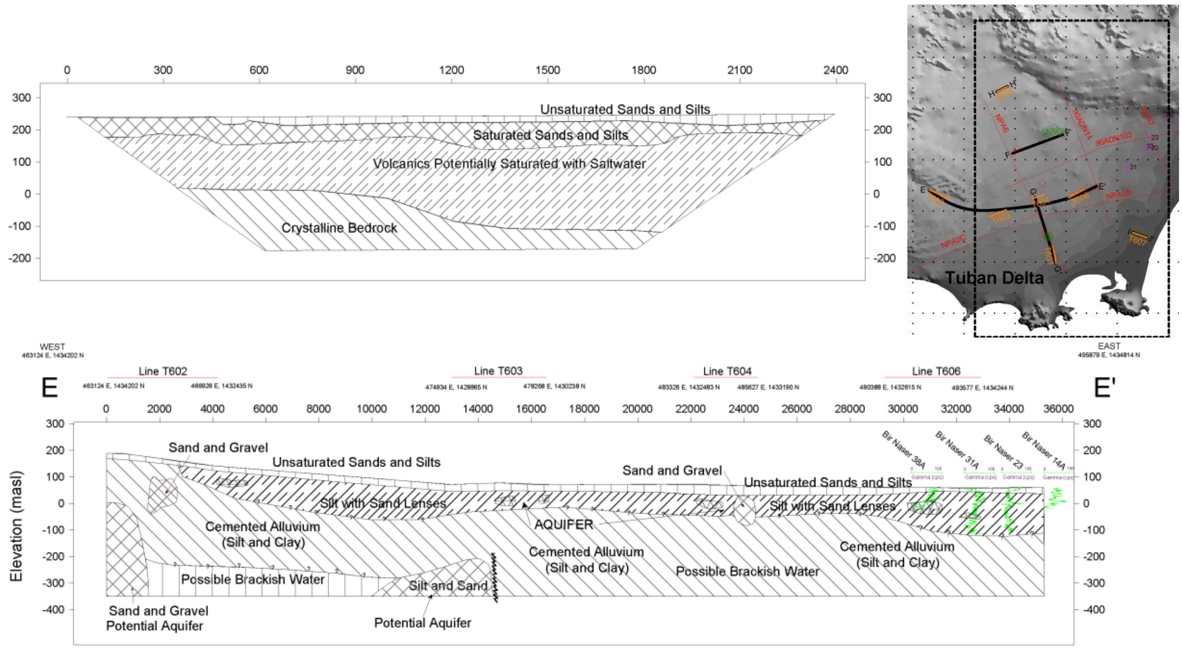


Figure 7. Interpreted geological cross-section running roughly east to west in the upper part of Tuban Delta (above, line H) and in the southern half of the delta (below, line E) (from: KOMEX 2002).

2.2.2 Soils

An overview of the most probable soil class in the catchment is presented in Figure 8. Based on this figure, the upper catchment is dominated by leptosols, which are typically stony and/or of limited depth. In the downstream area, fluvisols (recent alluvial deposits) are found, reflecting the importance of the wadi on soil formation. Around the stream channels in the upstream part of the catchment, cambisols, and to a lesser extent vertisols (clayey soils) and calcisols (soils with lime), are found. Regosols are mainly limited in the middle catchment area.

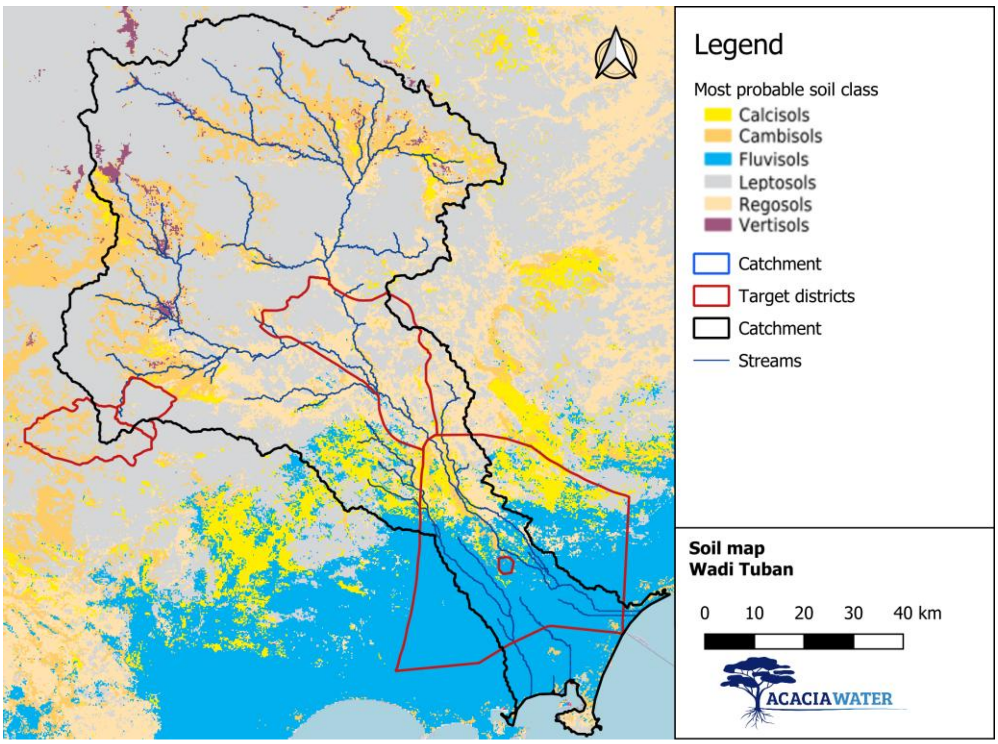


Figure 8. Most probable soil class in and around Tuban catchment (source: SoilGrids).

In the **Taiz area**, which includes the Al-Mawaset and Al-Selw focus districts, soils on the plateaus tend to be sandy loam and silt loam (Al-Ghory 1997). On volcanic slopes, soils are mainly loam and clay loam (Al-Ghory 1997). Terraces are common in this region, meaning that soil depths vary between tens of centimeters and several meters (Al-Ghory 1997).

In **Lahj area**, soil is characterized by great diversity due to the diversity of terrain and climate in the governorate. Fertile clay soil, is mainly found in Tuban Delta which is one of the most fertile agricultural lands in Yemen. This soil is the result of river sediments, and supports the cultivation of many crops such as cotton, vegetables and fruits. In surrounding areas, soils are typically sandy. These soils are less fertile, but it supports some crops such as fruit trees and palm trees.

Most of the detailed available literature on soil types and characteristics focuses on the **Tuban Delta** area, which is part of the catchment within the Tuban district. In the Tuban Delta area, soil texture is determined largely by wind and water erosion processes (بيانات هيدولوجية وزراعية لدلتا تبن , [Hydrological and agricultural data for Delta Tuban], n.d.). Soils in spate irrigation areas are characterized by deep deposits of silty material (loams, silt loams or silty clay loams) over the original sandy or gravelly soils (World Bank 1978). The bulk density of the topsoil varies between about 1.0 to 1.6 g/cm^3, and of the sandy subsoil between 1.2 and 1.8 g/cm^3, depending on their condition (MOA 2023). Bulk density tends to increase with depth (MOA 2023). Soils in perennial irrigated areas are typically sandy and occasionally gravelly alluvial deposits, as there has been little to no deposition of silty materials (World Bank 1978). Most of the soil is light brown when dry, and dark yellowish-brown when wet (بيانات هيدولوجية وزراعية لدلتا تبن , [Hydrological and agricultural data for Delta Tuban], n.d.). Effective soil depth is typically more than 2 meters [4]. Infiltration rates are reported to be moderate (4 cm/h) (Girgirah et al. 1987) to high (12-50 cm/h) (MOA 2023). A classification of soil area in the delta by water-holding capacity is presented in Table 3.

Table 3. Land distribution in Tuban delta in relation to water-holding capacity (from Girgirah et al. 1987, after Dar Al-Handasah 1973)

Capacity	Class	Area [ha]	Area [%]
Good	1	3980	23.8
Fair	2	3840	23.0
Poor	3	2700	16.0
Very Poor	4	-	-
Non arable	6	6210	37.1
Total classified area		**16730**	**100**

The soil's ability to retain moisture increases and the apparent density decreases. The soil's ability to retain water and its wilting point differ according to the soil's texture (Hydrometeorological data for TUBAN, n.d.). Below is the description of retention capacity and permanent wilting points for different types of soils in the Tuban delta. These data are relevant for hydrological modelling planned in the second phase, as they determine available water content of soils.

Table 4. Water retention capacity and wilting point of different soils (from: Hydrometeorological data for TUBAN, n.d.).

Textural Classes	Retention Capacity (% by weight) at pF*2.5	Permanent Wilting point (± 1% by weight) at pF 4.5
Loamy sand	7.3	1.8
Sandy loam	11.5	4.5
Loam	18.9	7.2
Silt loam	23.9	9.1
Clay loam	27.9	11.4
Silty clay loam	30.4	8.7

Soils in the Tuban delta area have a pH between 8.5 and 8.9. Salinity values are variable, between 1.6 and 13.0 microS/m (بيانات هيدولوجية وزراعية لدلتا تبن , [Hydrological and agricultural data for Delta Tuban], n.d.), where especially soils with heavier textures in the perennial irrigated areas being vulnerable to salinization (World Bank 1978). The soils are typically nitrogen-deficient (World Bank 1978), with values between 0.01 and 0.13 % (Girgirah et al. 1987). Available phosphorous tends to be low, less than 10%, while potassium is relatively high for agricultural crops (بيانات هيدولوجية وزراعية لدلتا تبن , [Hydrological and agricultural data for Delta Tuban], n.d.). The spate irrigation areas have more available phosphorous and potassium compared to the perennial irrigated areas (World Bank 1978). Organic matter content at the surface is usually low, less than 1%, and decreases with depth (بيانات هيدولوجية وزراعية لدلتا تبن , [Hydrological and agricultural data for Delta Tuban], n.d.).
Soil chemical characteristics are described in the Volume 6 of the Spate Irrigation Improvement Project (SIIP) reported by FAO, 2000. The image below provides the available information, which requires formatting improvements for better clarity, along with the inclusion of the coordinates for the described profiles. These data are detailed, though limited to the area around the wellfield, and therefore not representative of the Tuban Delta let alone the catchment as a whole.

Typical soil profile physical and chemical characteristics in Wadi Tuban around Bir Ahmed.

Profile No.	Soil Class	Soil Depth cm	Clay + Silt, %	CEC meq/100g Soil	Exchangeable Bases, meq/100g Soil: Ca	Mg	K	Na	ESP %	pH	TSS %	Water Soluble Cations: Na	K	Ca	Mg	Water Soluble Anions: Cl	SO4	HCO3	CO3
SP2	IV	0-25	15.0	10.0	6.2	2.6	0.3	1.0	10.8	7.6	0.33	3.75	0.14	0.58	0.57	2.42	2.25	0.32	0.00
		25-40	38.0	21.1	5.5	11.3	0.4	3.9	18.8		0.29	3.75	0.08	0.17	0.27	1.50	2.05	0.75	0.00
		40-75	78.0	29.6	14.5	10.1	0.4	4.6	15.5	8.2	0.42	5.25	0.06	0.32	0.47	2.75	2.65	0.66	0.00
		75-120	18.0	9.1	4.8	2.9	0.2	1.2	13.2	8.7	0.14	1.62	0.14	0.22	0.10	0.47	0.87	0.68	0.00
SP3	IV	0-30	72.0	23.8	10.6	8.1	0.8	4.3	18.1	8.2	0.41	5.75	0.09	0.17	0.25	2.12	3.30	0.87	0.00
		30-60	78.0	26.3	10.4	10.5	0.5	4.9	18.6	8.6	0.25	3.37	0.05	0.20	0.08	1.00	1.63	1.16	0.00
		60-115	76.0	27.3	13.6	8.5	0.4	4.8	17.6	8.5	0.27	3.75	0.04	0.17	0.10	1.00	1.95	1.08	0.00
		115-150	46.0	19.3	9.2	5.9	0.3	3.9	20.2	8.7	0.24	3.15	0.04	0.17	0.10	1.00	1.40	1.06	0.00
SP8	III	0-20	40.0	16.8	3.9	6.6		0.7	4.2	7.6	0.77	6.30	0.05	2.80	3.15	6.65	5.55	0.30	0.00
		20-125	42.0	16.3	6.8	7.3	0.3	1.3	8.0	8.0	0.44	5.10	0.05	0.62	1.00	3.60	2.75	0.42	0.00
		125-150	12.0	8.1	3.6	2.9	0.2	1.4	17.3	8.6	0.17	1.87	0.03	0.62	0.12	0.80	1.22	0.60	0.00
SP11	VI	0-25	8.0	7.6	3.9	2.0	0.2	0.9	11.8	7.8	0.22	2.36	0.08	0.50	0.35	1.30	1.55	0.44	0.00
		25-40	18.0	12.3	4.3	6.3	0.4	1.3	10.6	8.6	0.14	1.75	0.04	0.27	0.70	0.62	1.75	0.36	0.00
		40-50	48.0	21.2	9.6	8.5	0.4	2.7	12.7	8.7	0.30	3.25	0.04	0.23	0.70	1.27	1.00	0.60	0.00
		50-150	4.0	3.4	1.6	0.8	0.3	0.7	20.6	8.8	0.08	0.62	0.04	0.22	0.37	0.17	0.47	0.60	0.00
SP13	II	0-20	38.0	17.3	7.1	7.4	0.6	2.2	12.7	8.6	0.23	2.50	0.07	0.45	0.35	0.90	1.27	1.18	0.00
		20-50	42.0	17.9	10.9	3.5	0.6	2.9	16.2	8.5	0.25	2.87	0.05	0.50	0.30	1.25	1.63	0.84	0.00
		50-80	46.0	28.3	11.5	13.3	0.4	3.3	11.7	8.5	0.27	3.00	0.03	0.52	0.27	1.40	1.63	0.82	0.00
		80-130	70.0	31.4	14.9	12.1	0.4	3.9	12.4	8.6	0.24	2.50	0.04	0.52	0.27	1.12	1.09	1.14	0.00
SP17	IV	0-35	N/A	N/A	N/A	N/A	N/A	N/A	N/A*	9.0	0.14	1.75	0.06	0.35	0.27	0.45	0.85	1.12	0.00
		35-70	N/A	N/A	N/A	N/A	N/A	N/A	N/A	8.7	0.26	3.75	0.09	0.25	0.57	1.15	2.21	1.26	0.00
		70-100	N/A	N/A	N/A	N/A	N/A	N/A	N/A	8.7	0.31	4.00	0.03	0.37	0.46	1.60	2.15	1.14	0.00
		100-130	N/A	N/A	N/A	N/A	N/A	N/A	N/A	8.7	0.32	4.37	0.03	0.27	0.21	1.75	2.25	0.90	0.00

Source: The problems of Salinity and Treatment in Agricultural Soils in PDR Yemen. Prepared by Anwar Abdulkarim, Feruary 1989.

2.2.3 Land cover and land use

The European Space Agency (ESA) WorldCover 10 m 2021 product provides a global land cover map for 2021 at 10 m resolution based on Sentinel-1 and Sentinel-2 data. product features 11 land cover classes and was developed as part of the ESA WorldCover project, which is a component of the 5th Earth Observation Envelope Program (EOEP-5) by the European Space Agency (Zanaga, 2022). In the **Wadi Tuban catchment** area, the higher-elevation upstream regions are predominantly covered by grassland, shrubland, and cropland, with trees occasionally found along some tributaries. Moving further downstream, the landscape becomes more barren, with patches of cropland and shrubland mainly concentrated along the main tributaries (Figure 7).

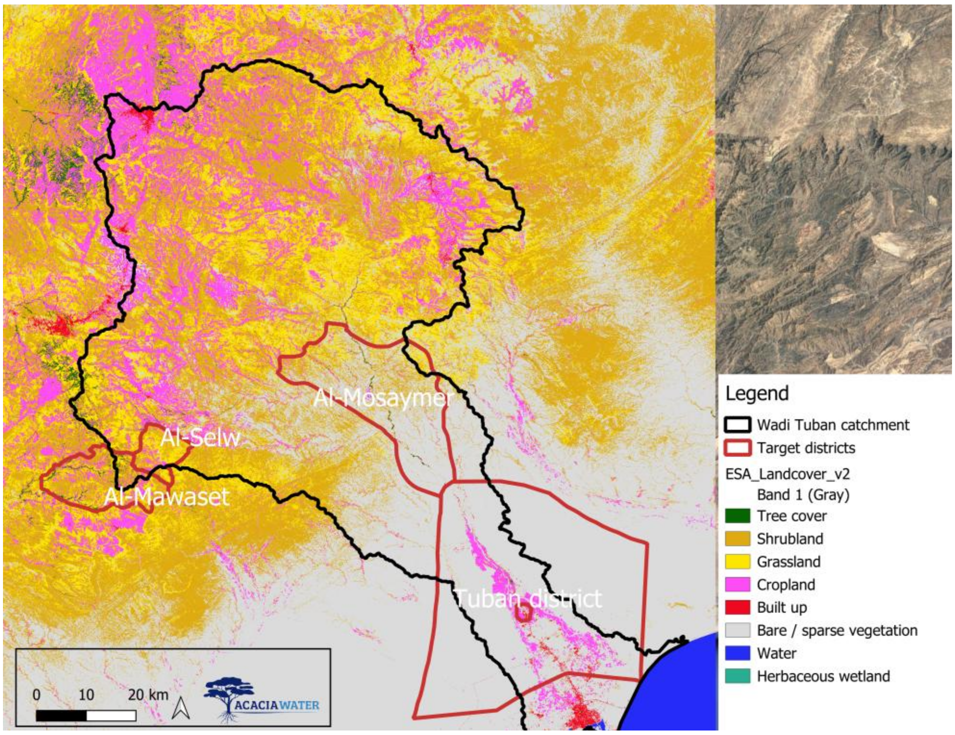


Figure 9. Landcover map (ESA, 2020).

An overview of the land cover distribution for the entire catchment and the four target districts is presented in Table 5. At the catchment scale, the most common land use types are shrubland and bare/sparse vegetation, followed by cropland and grassland.

Table 5. Land cover distribution percentages in the four target districts and the Tuban catchment according to the ESA WorldCover 10 m 2021 product.

ESA Landcover	Al-Selw	Al-Mawaset	Al-Mosaymer	Tuban	Total Catchment
Tree cover	<1	4	<1	<1	<1
Shrubland	44	55	25	1	32
Grassland	36	24	7	<1	17
Cropland	16	17	2	6	18
Built-up	<1	<1	<1	<1	1
Bare/sparse vegetation	3	1	66	93	32
Permanent water bodies	<1	<1	<1	<1	<1
Herbaceous wetland	<1	<1	<1	<1	<1

In the four target districts, however, different land use patterns emerge. In the upstream districts (**Al-Selw and Al-Mawaset**), shrubland dominates, followed by grassland and cropland. Al-Selw district is notable for its cultivation of cereal crops in summer, as well as peanuts, and in winter, vegetables such as potatoes, onions, garlic, green beans, watercress, radishes, cabbage, leeks, and more. The valleys of Ozlet Alsharaf are known for producing fruit crops, including guava and Persian trees in Wadi Al-Jamar and Wadi Al-Aqar (Alhamadi, A. J., & Social Fund for Development - Taiz Branch 2024). In **Al-Mawaset district**, the vegetation varies among different types of trees such as prickly pear, tamarind, ficus, panicum turgidum; while the Jujube trees in the valleys and Ghaf trees in the mountains covers more than 50% of the land (20% and 30% respectively). A variety of fruit trees such as mango, palms, and coffee trees are grown, alongside various types of vegetables. The total agricultural land area is estimated at 10,544 ha, though only approximately 78% is currently used for agriculture. The table below shows the types of crops and the land allocated to each (Alfadali, A. & Social Fund for Development - Taiz Branch 2020). Water use for irrigation for selected crops is described in the section on water demand, specifically section 2.4.1.

Table 6. Type of crops and area in the Al-Mawaset district (from: Alfadali, A. & Social Fund for Development - Taiz Branch 2020).

Crop type	Area (ha)
Vegetables	533
Coffee	551
Fruits	839
Qat	2476
Beans	4015
Total used area	**8414**

In the downstream districts (**Al-Mosaymer and Tuban**), the predominant land cover is bare/sparse vegetation. Al-Mosaymer also has a significant amount of shrubland, while in Tuban, cropland is the second most prominent land use, although it accounts for only 6% of the district's area.

2.3 Water availability

2.3.1 Meteorology

Precipitation

The climate of Wadi Tuban catchment is arid to semi-arid, with rainfall divided over two main rainy seasons: March-April and July-September (Al-Ghory 2004). Precipitation is linked to elevation, with higher values in the headwaters and low values in the Tuban Delta (Figure 10). In the Ta'iz area, including the upstream target districts Al-Mawaset and Al-Selw, where annual rainfall is reported to be between 300 and 500 mm on average (Al-Ghory 2004), with values over 600 mm per year at higher elevations (NWRA Consultants 1997). In the Tuban delta, rainfall is low and erratic, with an annual average of less than 100 mm (World Bank 1978).

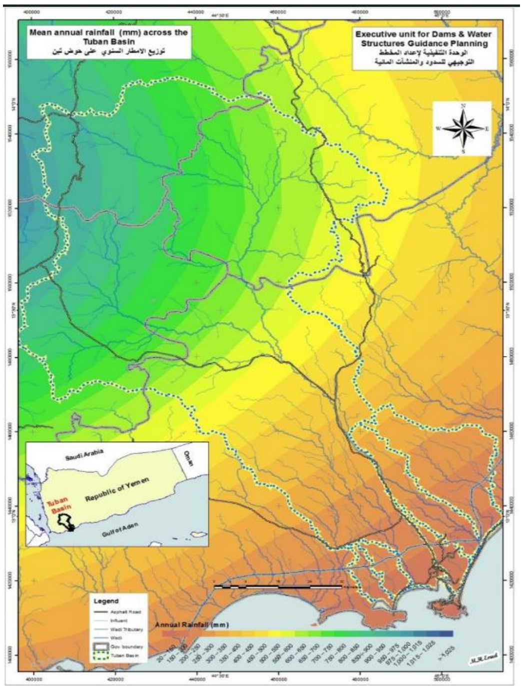


Figure 10. Annual average precipitation map for Wadi Tuban (from: Al-Mahab, A. A. 2016).

Daily precipitation data were obtained from NWRA for 13 meteorological stations spread throughout Tuban catchment or the immediate surroundings (Figure 11). The data for stations with at least one year of data are summarized in Table 7. Over most stations, data is available for the period 1981 – 2008, with a gap between 1995 and 1998. However, no individual station covers this entire period. On average, data coverage per station is about 7 years, with the most common period being around 1998–2005. A few stations started data collection between 2022 and 2024.

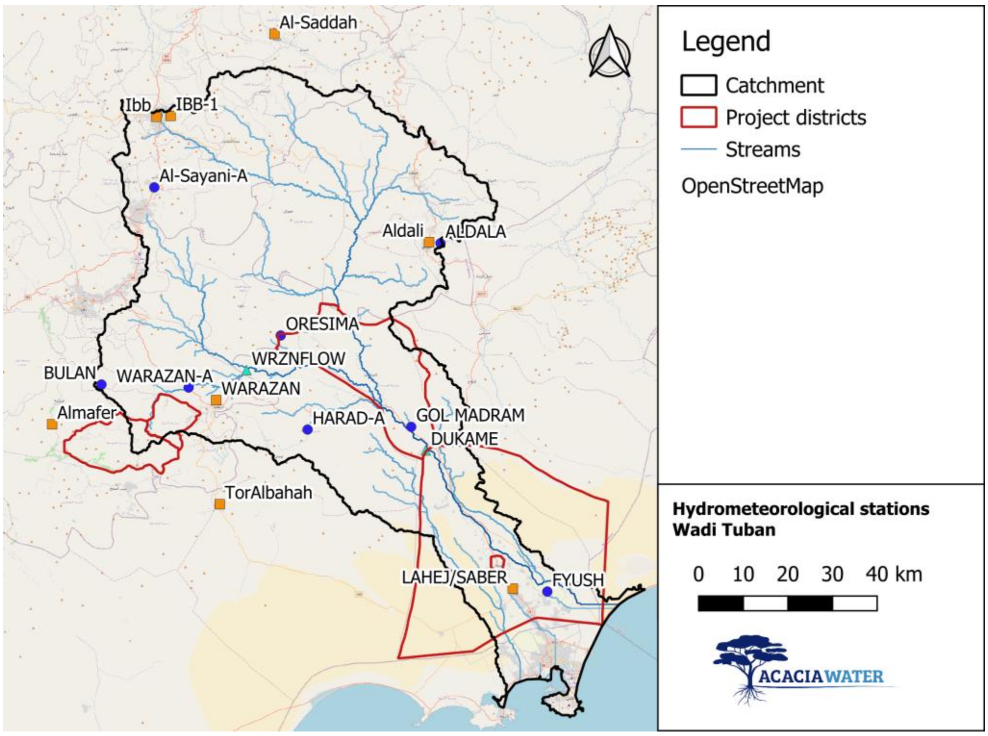


Figure 11. Locations of hydrometeorological stations from NWRA.

Based on the sites with at least five years of data between 1998 and 2005, precipitation is relatively high in the upper reaches of the catchment, with annual averages of about 420 and 530 mm at stations within 8 km of the upstream target districts. Annual precipitation decreases at lower elevations, to an annual average of 30 mm/y or lower stations in the delta area near the sea.

Table 7. Monthly average precipitation based on data from NWRA with at least one year of data

Station	Elev.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total	Period
ALDALA	1588	5	5	2	30	29	23	91	73	33	15	5	8	319	1997-2005
Al-Sayani-A	1826	1	2	5	0	20	38	4	8	7	130	48	9	272	2004-2006
BULAN	1654	1	1	16	65	45	54	82	122	89	52	2	0	529	1998-2006
FYUSH	56	23	38	27	14	7	5	18	6	2	14	0	14	166	2002-2007
GOL MADRAM	510	1	0	1	13	7	7	12	17	31	4	0	4	98	2002-2008
HARAD-A	750	6	0	19	5	19	11	39	50	45	24	18	6	242	1997-2002
IBB-1	1760	8	8	42	79	116	128	163	163	104	20	12	2	842	1981-1991
LAHEJ/SABER	84*	4	1	1	5	0	0	0	0	6	13	1	1	31	1998-2007
ORESIMA	832	3	1	3	16	47	11	60	86	52	28	12	14	332	1997-2003
WARAZAN	1200	2	18	0	24	27	56	26	70	39	10	0	2	274	1987-1992
Al-Dali	1427	3	0	64	56	107	82	166	256	132	35	0	2	903	2021-2024
Saddah	1885	3	1	16	27	49	6	54	87	8	11	2	2	265	2022-2024

* Elevation based on ALOS

Average annual precipitation based on Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (Funk et al. 2015) between 1994 and 2023 ranges between 20 mm near the catchment outlet in the southeast and 340 mm in the northwest (Figure 12). These values are in slightly lower than the data based on weather stations and found in literature. According to CHIRPS, the first of the two rainy seasons lasts somewhat longer than in literature and based on the weather station data, with relatively high rainfall in May (Figure 13).

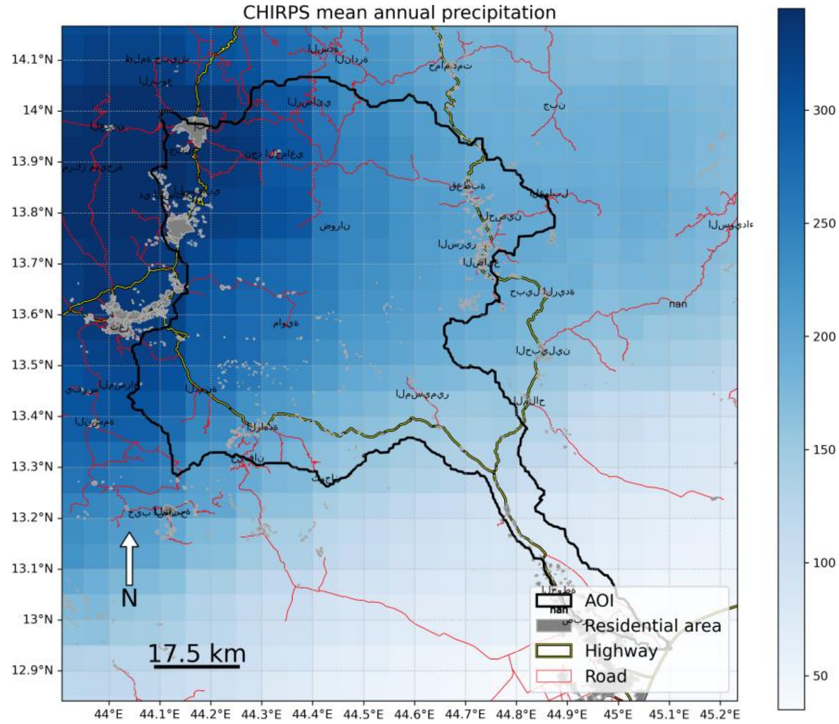


Figure 12. Annual average precipitation [mm] in and around Tuban catchment based on CHIRPS (Funk et al. 2015) over the period 1994 – 2023.

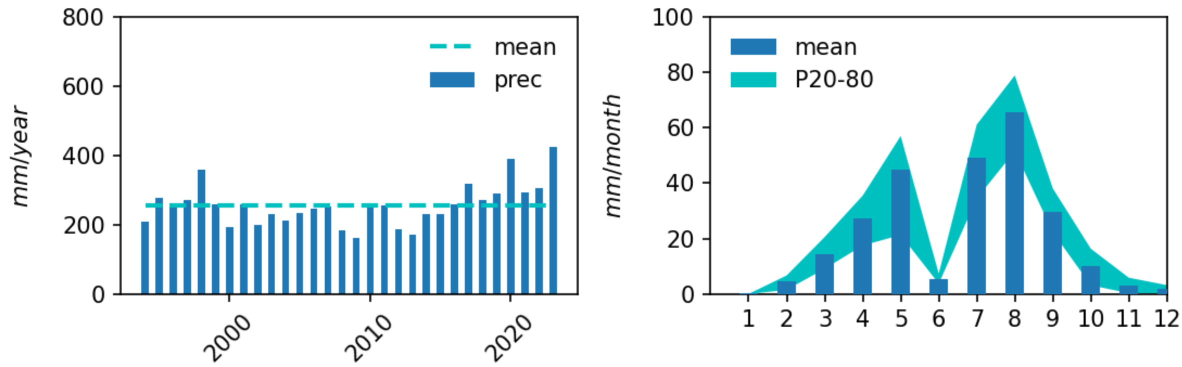


Figure 13. Interannual variability in annual (left) and monthly (right) precipitation based on CHIRPS over the period 1994 – 2023.

Temperature

In the Tuban Delta, temperatures average about 24°C winter and 33°C summer (World Bank 1978). In the upstream districts, temperatures are somewhat lower than at the lower elevations downstream, with the average temperature for Ta'iz governorate reported to be about 21°C winter and 27°C summer (Table 8).

Table 8. Average temperature in Lahj and Taz governorates (from: بيانات هيدولوجية وزراعية لدلتا تبن , [Hydrological and agricultural data for Delta Tuban], n.d.)

Governorate	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Average
Lahj	24.6	24.8	26.2	28.3	30.3	32.4	32.2	32.1	30.8	27.7	25.8	24.3	28.3
Taz	21.3	22.1	24.1	25.3	26.6	27.2	26.5	26.1	26.5	24.6	23.3	22	24.6

Weather data from five ground stations in the Tuban catchment obtained from NWRA are presented in Table 9. Locations of the stations are presented in Figure 11. The values for the Tuban delta (LAHEJ/SABER) station are in agreement with the range found in literature, despite the data being more recent. Temperatures in Warazan, a few kilometers east of the eastern border of Al-Selw, are typically 3–5° lower throughout the year. And at the IBB-1 station in the far north of the catchment, average monthly temperature varies between 15°C winter and 20°C summer.

Table 9. Monthly mean of average temperature in Celsius based on data from NWRA

Station	Elev.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Period
IBB-1	1760	15.3	16.4	18.1	18.4	19.8	20.4	20.2	20.0	18.8	16.7	15.4	14.9	1981-1991
LAHEJ/ SABER	84	24.3	24.5	26.0	28.4	31.1	32.8	32.6	32.0	31.5	28.5	26.1	25.0	1998-2008
WARAZAN	1200	20.3	21.6	23.3	24.4	28.3	28.5	28.8	28.4	26.7	24.6	21.5	20.5	1987-1991
Al-Dali	1427	17.6	18.6	20.4	22.7	24.7	25.9	24.9	24.4	24.0	22.3	20.3	17.8	2021-2024
Saddah	1885	15.9	18.2	19.4	19.8	22.2	25.9	24.7	23.7	24.2	20.4	18.3	15.0	2022-2024

* Elevation based on ALOS

Figure 14 shows minimum and maximum temperature in Wadi Tuban by month based on the on the daily 1-km temperature dataset based on a combination of remote sensing datasets and station measurements (Zhang 2022). The values are similar to the weather station data and values reported in literature.

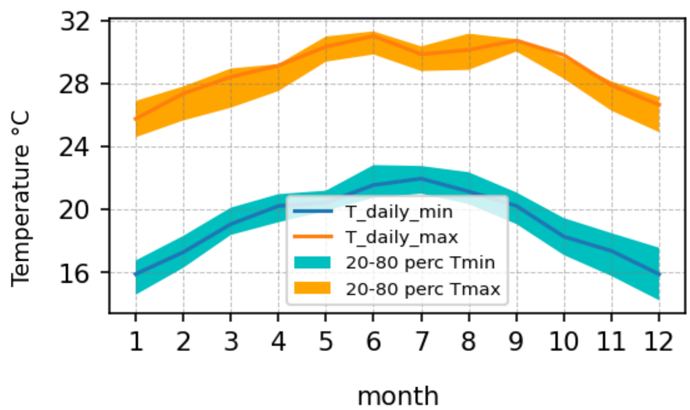


Figure 14. Minimum and maximum temperature in Wadi Tuban by month.

Evaporation

There is limited data available in the literature regarding evaporation rates. Reportedly, evaporation in the Lahj Governorate is about 106 mm/year, while in Taiz it is 146 mm/year (Iskander, A. W. 2023). According to the World Bank (1978), evaporation in the Tuban Delta averages 6.6 mm/day but may exceed 9 mm/day in summer or drop to as low as 2.8 mm/day in winter. Presumably, this refers to the irrigated areas in the delta.

The Water Productivity through Open-access of Remotely Sensed Derived Data (WaPOR) portal provides, among other products, actual evapotranspiration information (FAO, 2020). Based on the version 2 dataset, average annual evaporation from 2009 to the present ranges from about 20 mm in the bare areas of the Tuban Delta to 430 mm along stream channels in the northern reaches of the catchment.

Other meteorological data

In the Tuban Delta area, winds are typically diurnal, with speeds ranging from 10 to 20 km/h (World Bank, 1978). Data from the Taiz Governorate report wind speeds of approximately 9 km/h (NWRA Consultants, 1997), which is close to the lower range of values observed in the delta. Average solar radiation is around 8.5 kWh/m²/day, with slightly higher values in the Lahj Governorate compared to Taiz (Table 10). The relative humidity in the Lahj Governorate ranges from 59.4% to 68.2% (Iskander, A. W. 2023), while in the Taiz Governorate, it is somewhat lower, between 53.7% and 55.2% (Table 11).

Table 10. Average radiation [h/d] for Lahj and Taz governorates (from: بيانات هيدولوجية وزراعية لدلتا تبن , [Hydrological and agricultural data for Delta Tuban], n.d.).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Average
Governorate Lahj	7	7.5	7.8	8.9	9.5	8.6	7.4	7.8	8	8.7	9.1	7.8	8.2
Governorate Taz	8.3	10	7.9	7.9	8.5	8	7.1	7	7.8	8.9	9.1	9	8.3

Table 11. Average humidity [%] for Lahj and Taz governorates (from: بيانات هيدولوجية وزراعية لدلتا تبن , [Hydrological and agricultural data for Delta Tuban], n.d.).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Average
Governorate Lahj	73	75	74	70	67	62	62	63	69	67	66	70	68.2
Governorate Taz	61.3	60.9	54.6	51.9	51.8	52.8	56.3	58.5	55.5	49.7	51.2	57.6	55.2

On the NWRA website, the meteorological stations in Figure 11 also provide other meteorological variables at daily resolution. The period of collection is listed in Table 9, except for stations where the data record is less than one year. Parameters include relative humidity (min, max, and average), radiation, barometric pressure, wind speed (max and average), and wind direction.

2.3.2 Surface water

Quantity

The annual water flow in Wadi Tuban is approximately 125 million cubic meters, with most of the flow is reported to be diverted in Tuban Delta for irrigation of seasonal crops (Girgirah et al. 1987). However, up to 70% of the flow is reported to be lost to groundwater before it reaches the fields (GCD 1981). There are over 200 km of canals, around 51 barriers and 22 harvesting tanks within the catchment (MOA 2023, Girgirah et al. 1987), though some may require maintenance or rehabilitation.

In the upstream area, there is a large number of springs serving as sources for upper tributaries of the wadi. In Al-Mawaset, there are 190 springs, some of which seasonal and others perennial. A map with locations of some of these springs is included in Figure 15. Flooding is reported to be a hazard in the catchment, see for example Figure 16.

Figure 15. Location of springs and tributaries in Muwaset district (from: Alfadali, A. & Social Fund for Development - Taiz Branch 2020).

Figure 16. Damages due to flooding in Al Muwaset in 2023.

Annual flow data between 1955 and 2000 at Dukeim gauging station (Figure 11), near the outlet of the catchment for Al-Mosaymer district and just upstream of the delta area, is shown in Figure 17 (Hydrometeorological data for TUBAN, n.d.). Stakeholders in the area have stated that the flow in 1982, which is not include in the dataset shown in the figure, was extremely high, and that the peak flow at the Arayes Dam reportedly reached 1950 m/s. The figure shows that the annual volume can vary considerably. The notably high values in the last two years of measurement could be related to the use of the stage-discharge relationship of 1998, and are not included in calculation of the average annual flow of 123 MCM/y. Monthly data for the period 1973 – 1983 are presented in Table 12. The monthly average shows two peaks, the first in March and the second in August and September. These correspond to the rainy seasons in the catchment area (Table 12). Note that the available flow data, especially at monthly scale, is outdated and may not reflect the current situation. Both climate change and land use changes in the past 20 years may have caused flow rates to have changed from the available historical data.

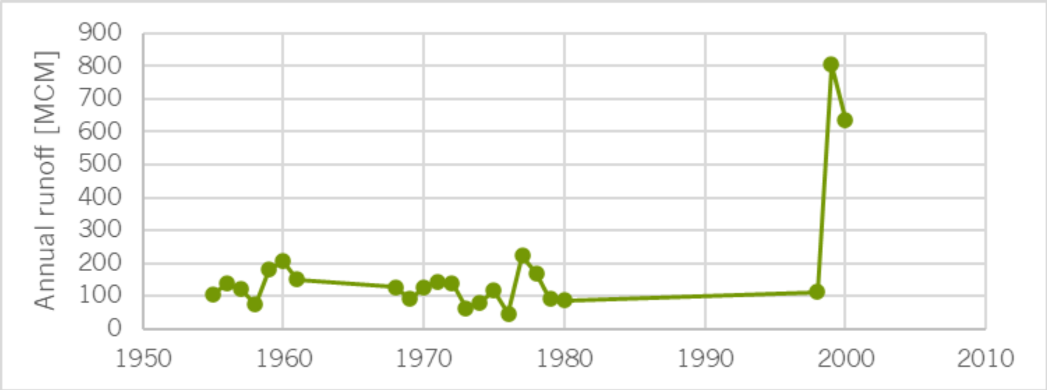


Figure 17. Annual flow data for Wadi Tuban at Dukeim (from: Hydrometeorological data for TUBAN, n.d.). Note that the discharges of 1998–2000 are calculated from the stage-discharge relationship for 1998.

Table 12. Monthly flow data for Wadi Tuban at Dukeim (from: Hydrometeorological data for TUBAN, n.d.).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1973	0.46	0.32	0.21	0.19	0.42	7.99	8.20	26.00	18.00	0.58	0.34	0.20	62.80
1974	0.19	0.08	0.09	0.75	9.58	13.40	13.40	21.10	18.10	2.85	1.18	0.56	81.20
1975	0.33	0.52	0.29	19.70	3.09	3.79	8.80	16.10	52.90	6.97	1.85	1.25	116.00
1976	0.80	0.51	0.35	5.55	5.13	4.58	6.77	7.28	6.79	3.91	2.99	1.16	45.80
1977	0.65	0.15	0.07	1.69	27.60	26.50	33.60	58.90	42.70	19.10	7.76	3.77	222.00
1978	1.91	1.65	0.52	0.55	13.10	3.04	4.67	48.70	57.10	30.70	5.92	2.13	170.00
1979	1.38	0.27	0.12	4.00	4.89	1.58	11.80	19.40	34.80	7.32	3.53	2.75	91.80
1980	1.40	0.65	0.35	4.18	6.93	10.20	11.70	23.90	17.60	4.83	2.31	1.68	85.70
1981	0.19	1.10	23.64	9.01	9.30	1.33	21.26	31.26	26.24	9.58	0.86	0.64	134.41
1982	1.96	1.19	225.19	23.70	19.66	5.84	11.39	37.32	10.08	2.40	0.95	0.19	339.87
1983	0.05	7.93	1.99	5.64	4.24	2.09	6.92	17.02	4.30	1.49	0.18	0.18	52.03
Mean	**0.85**	**1.31**	**22.98**	**6.81**	**9.45**	**7.30**	**12.59**	**27.91**	**26.24**	**8.16**	**2.53**	**1.32**	**127.42**

The Warazan stream level monitoring station lies further upstream, close to the outlet of the catchment representing Al-Selw district. Daily data obtained from the website of NWRA are shown in Figure 18. The data show considerable interannual variability, with relatively high levels in 1998 and low levels in 2001. The flow in 1998 was noticeably high compared to the other years, while the annual flow data at Dukeim show an opposite pattern. It is possible that this is caused by the local nature of the precipitation leading to a peak in Warazan in 1998. The short term variation in stream level is relatively high, changing with 2 m or more on consecutive days. This suggests a rapid response to precipitation. A rating curve is needed to translate stream levels into streamflow.

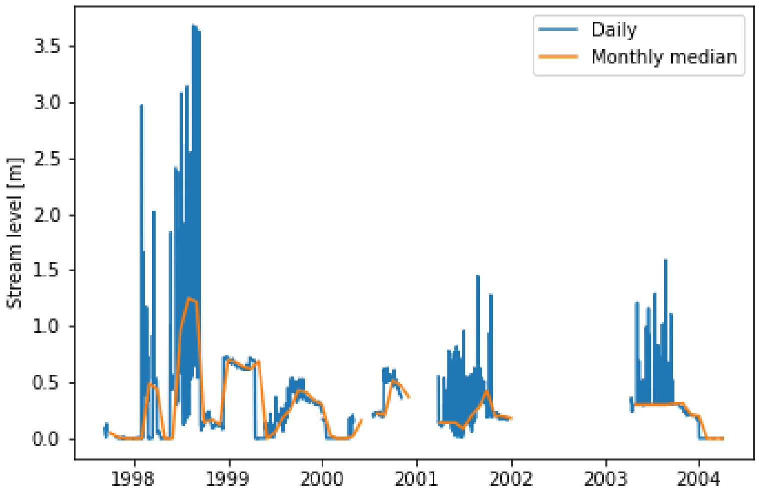


Figure 18. Daily stream level data for stream level station Warazan (from: NWRA).

Quality

There is little data available about surface water quality. Girgirah et al. (1987) reported that suspended solids reached 11.4-55.6g/L in 1973, and were possibly as high as 100g/L in 1981. The highest concentrations were found in the early phase of flood events, with grades up to and including gravel. The authors suggested an annual mean sediment transport of 25 g/L and a total of 3.5-4 Mt/y. The bed load was estimated to be 10-20% of the suspended solids load (Girgirah et al. 1987).

2.3.3 Groundwater

Quantity

Three aquifers are distinguished in the catchment of Wadi Warazan, which is in the upstream area of Wadi Tuban and overlaps with the catchments of the **Al-Selw** and **Al-Mawaset** target districts. These are the shallow alluvial aquifer, the deeper volcanic aquifer, and the combined aquifer, where the alluvial aquifer is in contact with the upper part of the volcanic rocks (NWRA Consultants, 1997). Groundwater recharge mechanisms in the upstream target areas include direct rainfall on the plains, indirect rainfall from runoff leaving the surrounding areas of higher relief, and lateral subsurface flow from adjacent, mainly volcanic, formations (NWRA Consultants, 1997). A groundwater level map for the catchment of Wadi Warazan was developed based on static water levels in 94 wells (Figure 19). According to the figure, groundwater flow is primarily towards the east or northeast, with a reported hydraulic gradient of approximately 0.02 (NWRA Consultants, 1997).

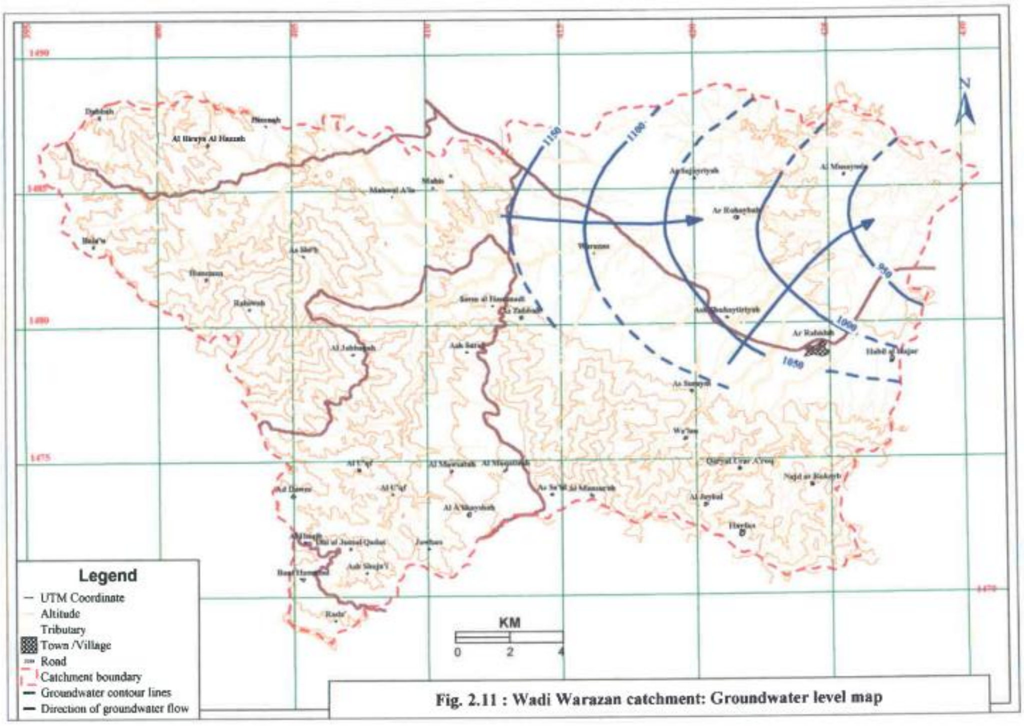


Figure 19. Wadi Warazan groundwater level map (from: NWRA Consultants 1997).

Further downstream, indirect recharge from infiltration along wadi channels becomes more important. Girgirah et al. (1987) state that the recharge to Tuban delta aquifer from the Wadi Tuban and its tributaries was about 60% of average annual recharge in 1981. The KOMEX (2002) study indicate that 25% of the applied volume of spate irrigation ends up as groundwater recharge, as well as 20% of applied volumes of groundwater irrigation and 40% of water use in towns. An explanation for the fact that the reported percentage for 1981 was higher than the KOMEX study is that in 1981 there was a relatively large flooding event, covering a longer period. As a result, groundwater recharge was higher than average in that year.

The aquifer in the Tuban Delta area, within the **Tuban** target district, has an area of 532 km^2 (BGR Consult 2013). KOMEX (2002) created a water balance for the Tuban Delta area for the year 2000, and a more recent groundwater balance is reported in MOA (2023). Both estimates are presented in Table 13. The studies report recharge estimates between 87 and 112 MCM/y. In comparison, GDC (1981) reported an annual recharge of 130 – 150 MCM/y. The more recent figure is also the lower value, though it is unclear whether this has to do with difference in the period under study, or differences in the methodology of the estimates. The difference in estimated abstraction, however, is much larger. The value reported by (MOA 2023) is more than two times higher than that of the earlier study and four times higher than annual recharge. As a result, the aquifer storage loss reported by the 2023 report is more than four times higher than in KOMEX (2002).

Table 13. Groundwater balance for Tuban Delta.

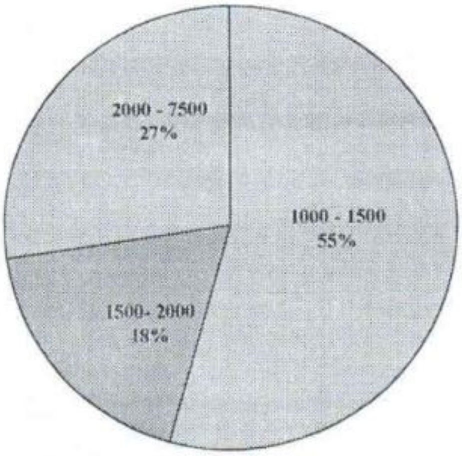
Year	Estimated recharge [MCM/y]	Estimated abstraction [MCM/y]	Aquifer storage loss [MCM/y]	Source
2000	112	162	50	KOMEX (2002)
unknown	87	360	225	MOA (2023)*

* values in table are as reported, though the groundwater balance does not close.

Changes in well levels support the aquifer depletion derived from the water balance estimates for the aquifer in Tuban Delta. On average, groundwater levels in wells between 2009 and 2010 dropped by an average of 1.5 m (Al-Darwish, K. A 2023, UN-Habitat & BGR Consult 2013). In addition, resting water levels in dip tubes at four (deep) wells at Bir Ahmed wellfield decreased with on average 3.6 m between 2013 and 2015 (The Bir Ahmed wellfield water quality 2016, n.d.). However, two wells with longer records, from 1997-2008 and 2000-2008, respectively, report a decline in groundwater levels of only 0.3 to 0.5 m/y, based on information gathered during an interview with Salim Bashuaib.

Quality

Groundwater quality data is available for the (north)eastern part of catchment of Wadi Warazan and for the Tuban Delta area. In the (north)eastern part of Wadi Warazan catchment, representative of conditions in Al-Selw and Al-Mawaset target districts, electrical conductivity (EC) ranges from 0.7 – 9.1 mS/cm (NWRA Consultants 1997). The distribution of EC values by source type is shown in Figure 20 and the location of measurements in Figure 21. For the boreholes, the three locations with EC values higher than 2 mS/cm are linked to the presence of acidic volcanic rocks in the direct vicinity. More than half of measured boreholes have EC values lower than 1.5 mS/cm. For the dugwells, about a third of measured EC values are lower than 1.5 mS/cm. The two springs where EC values were measured had EC values of 1.1 and 1.3 mS/cm (NWRA Consultants 1997).



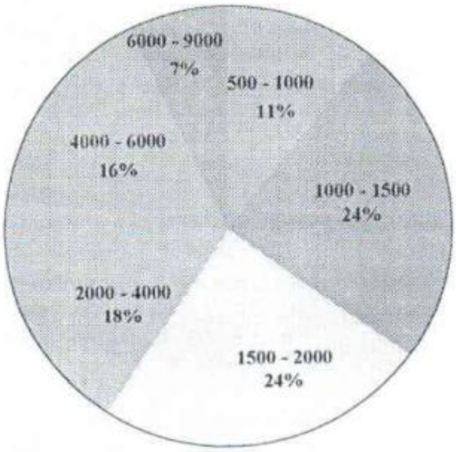


Figure 20. Distribution of EC values [µS/cm] for boreholes (left) and dugwells (right) in the catchment of Wadi Warazan (from: NWRA Consultants 1997).

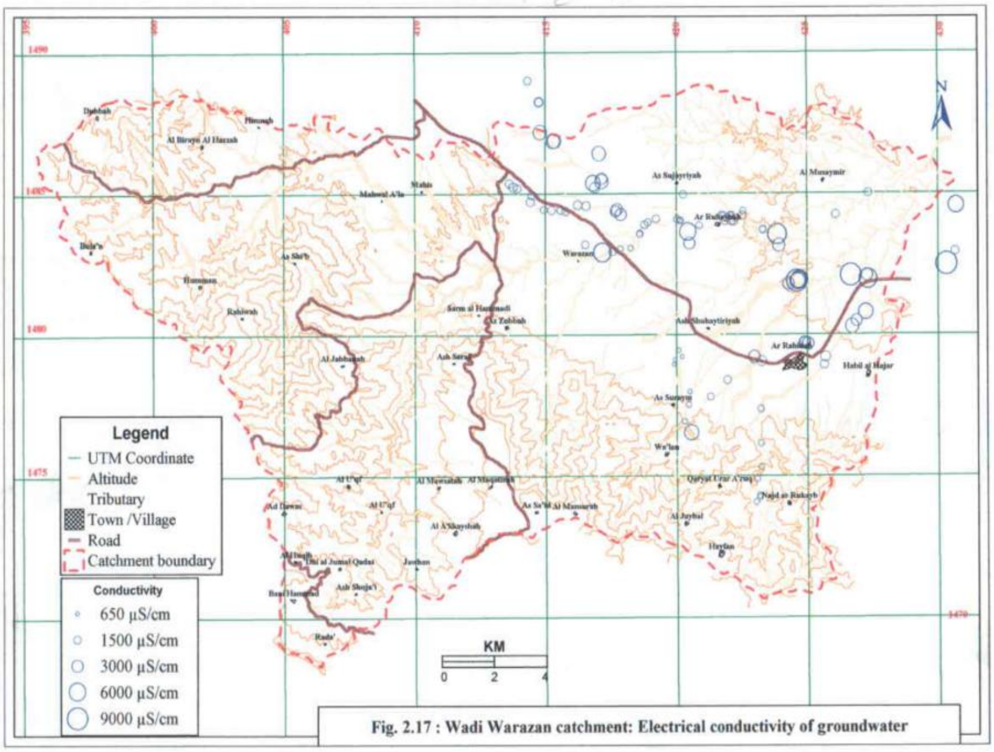


Figure 21. Electrical conductivity of groundwater in the catchment of Wadi Warazan (from: NWRA Consultants 1997).

Further downstream, in the Tuban delta within Tuban district, groundwater quality issues include brackish or saline conditions, and high nitrate concentrations. Figure 22 shows a Maucha diagram of average composition of groundwater in the Tuban region.

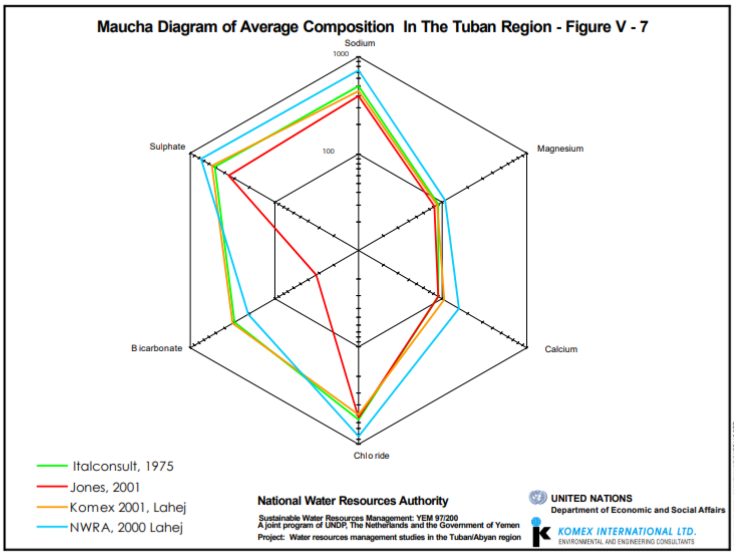


Figure 22. Maucha Diagram of average composition of groundwater in the Tuban Delta region (from: KOMEX 2002).

A previous study concluded that effects of sea water intrusion extend to approximately 10 km from the seashore (Comparison between the main results of UN-Habitat & BGR Studies of Tuban Delta 2013, n.d.), referencing BGR Consult 2013). Indeed, well quality data from wells in the delta area received from the MoAIF indicate that electrical conductivity

(EC) values within about 7 kilometers from the sea are relatively high, with values larger than 7 mS/cm and up to 18 mS/cm (Figure 23). This is indicative of brackish to saline groundwater. The same dataset shows that EC values in the upper central part of the Tuban Delta are relatively low (<2 mS/cm).

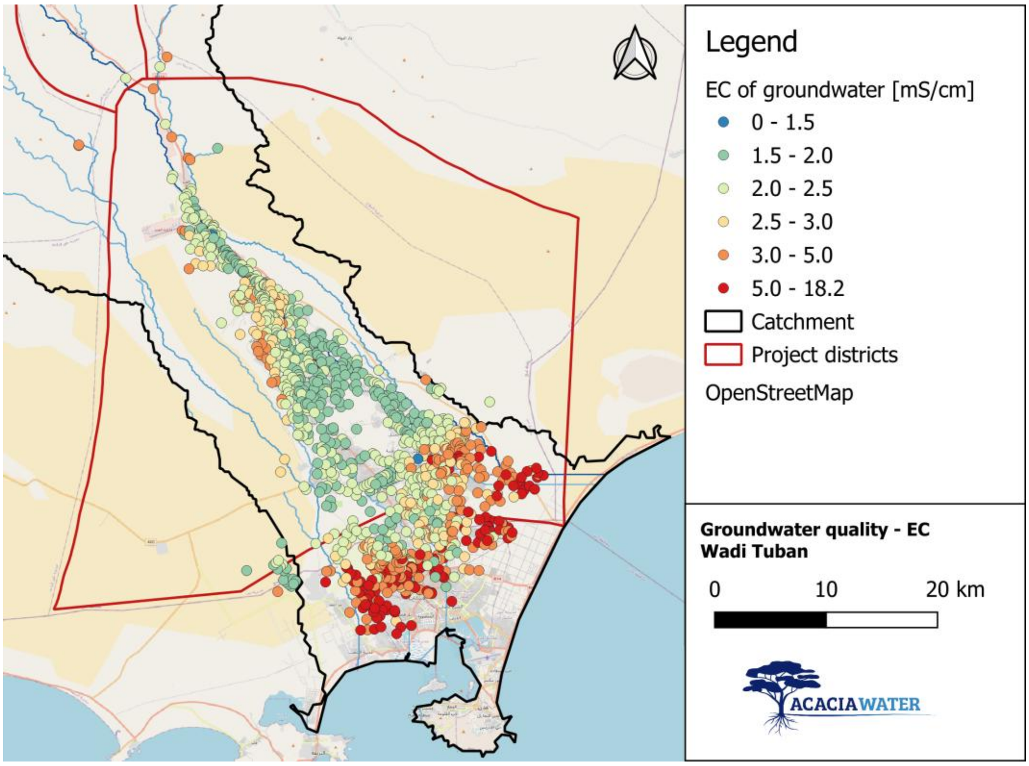


Figure 23. Electrical conductivity of groundwater in Tuban Delta (from: MoAIF).

Approximate nitrate concentration data are available for some of the wells in the well inventory received from the MoAIF. Overall, there is a similar pattern in water quality with relatively low values (<10 mg/l) in the upper central part of the delta, and relatively high values (up to 150 mg/l) near the coast. A little over one third of the wells where nitrate concentrations are available have values above 50 mg/l, the WHO limit for nitrate.

Additional tables containing water quality information can be found in **Annex 1** and in the Annex of KOMEX (2002), though coordinates of the wells are not always available and data tends to be decades old.

2.3.4 Climate change

Climate change is likely to affect water availability in the future. Monthly rainfall is projected to change by 2–6 mm per month in 2020–2039 compared to the current climate according to the RCP8.5 scenario (MOA 2023). Models do not agree on the sign of the change, as both increases and decreases in precipitation have been simulated. Temperatures are projected to increase by on average 0.5°C assuming the same period and climate scenario (MOA 2023).

2.4 Water use

2.4.1 Water demand

Population

According to Al-Ghory (2004), the total amount of water used in 1990 was 2899 million cubic meters in Yemen. Of this total amount of water, 6% was used by 15.8 million people. This means that each person on average used 10.6 m³ water per year, or 29 liters per day.

Table 2.1: Water demand throughout the period from 1990 to 2025 (MM^3/Year)

	1990	%*	2000	%*	2010	%*	2025	%*
Agriculture	2700	93.1	3149	88.2	3328	83.9	3661	79
Industrial	31	1.1	61	1.7	90	2.2	134	2.9
Municipal	168	5.8	360	10.1	552	13.9	840	18.1
Total	2899	100	3570	100	3970	100	4635	100

Source: World Bank report 1993 and Van der Gun el al., 1995 * calculated by author

A prediction was made for water demand throughout the period from 1990 to 2025. The expected demand for 2025 is 4,635 MCM. Of this total amount of water, 79% is expected to be used for agriculture, followed by 18.1% for municipal purposes and 2.9% for industry. According to the United Nations World Population Prospects, approximately 40.5 million people live in Yemen in 2024. Dividing this by the predicted water use for municipal purposes, each person in Yemen, on average, uses 20.7 m³ of water per year, or 56.8 liters per day.

Yemen's population is estimated to increase to 55.08 million people by 2080 (UN-DESA, 2019), with an average of 122 liters per capita per day (44.53 m³/year). This results in an estimated demand of 2,452.71 MCM per year for domestic purposes.

To calculate the domestic water demand within the Wadi Tuban catchment and sub-catchments, population data of each catchment is necessary. In literature, population data for El-Mawaset was found through a study received from NWRA (Alshojaa, K. 2023). The study mentions El-Mawaset has 41,230 inhabitants of which 60% live under the poverty line. Furthermore, a report from UN-Habitat (2020) provides information on the population and water use in Adan City. According to the study, 1.14 million people live in the city. The average water consumption in Aden governorate is 8.2 m³/month per household, for an average household of 6. This means that the average water consumption is 16.6 m³/person/year. This amount is much lower than the calculated demand based on the study done by Al-Ghory (2004). For the rest of the catchments, population data is missing.

To estimate the domestic water demand for the catchments, population numbers per governate can be used. First, the extent to which a sub-catchment overlaps with the area of a governorate was calculated in QGIS (Table 14). This area can be used to estimate how many people live in a catchment (Table 15). Note that this analysis is at catchment scale rather than district scale. For example, though Al-Mosaymer district does not lie in Ad-Dali governorate, its sub-catchment does. Based on the average water demand in Aden city (Al-Ghory 2004), the domestic water demand is calculated for each sub-catchment (Table 15).

Table 14. Population at governorate level, as well as the proportion of the area of the governorates covered by Wadi Tuban and each of the sub-catchments.

Governorate	Estimated population (Yemen, 2022)	Area covered (%) by subcatchment			
		Tuban	Al-Mawaset	Al-Selw	Al-Mosaymer
Ad Dali	818,507	43.3	-	-	43.3
Aden	1,053,455	37.3	-	-	-
Ibb	3,143,818	21.7	-	-	-
Lahj	1,076,450	19.3	-	-	7.3
Ta'iz	3,104,579	15.6	0.4	2.4	15.6

Table 15. Estimated water demand for the catchment areas.

Sub-catchment	Estimated population 2024	Water demand 2024 (MCM)
Whole Wadi Tuban catchment	2,122,424	22.05
Al-Mawaset	11,176	0.12
Al-Selw	73,578	0.80
Al-Mosaymer	917,713	10.03

The estimations show that the population for Al-Mawaset turns out to be much lower than numbers given in literature (Alshojaa, K. 2023). For more precise calculations, a population density map or local census data could be used.

Agricultural

The northern part of the Tuban catchment receives significant amounts of rainfall; therefore, vegetation on the slopes is semi-dense due to the poor thickness of the soil. However, some scattered areas near water springs exhibit denser vegetation. The soil's weakness is attributed to the erosion caused by water, which washes away and deposits soil at the bottom of the slopes.

In the valleys, plant density increases as it reaches the shallow groundwater level. Vegetation here takes the form of arcades, consisting of various plant types, including seasonal species with short life cycles and perennials. These plants have adapted to withstand harsh climatic conditions, and many are spiny.

Approximately 70% of irrigated land in the Tuban Delta is irrigated by spate flows, 5% from base flow, and 25% from groundwater. The irrigation scheme supports an estimated population of 75,000 across 13,000 households in 80 villages and 2 towns (Bahamis, A. A. 2004). The main crops include cotton, sesame, corn, tomatoes, melons, bananas, mangoes, and papaya. Among these, sesame, and melons are the primary crops irrigated by spate flows. Cotton was also listed as a primary crop irrigated by spate flows in the past, but is currently considered to be less important. Table 16 details the water requirements for the most important crops grown in the Tuban Delta under different irrigation systems. However, the reported water use of drip irrigation seems high compared to the older (surface) irrigation types. Table 17 outlines the requirements under floodwater conditions in the Wadi Al-Arais and the Delta Tuban regions.

Table 16. Seasonal water requirements for crops irrigated under irrigation systems (from: MOA 2023, Hydrological and agricultural data for Delta Tuban, n.d.).

Soil Type	Crop	Months	Quantity of water needed m3/h		Used irrigations system
			Spate irrigation	Drip irrigation	
Sand	corn	August	6802	5328	water network
Sand	corn (animal feed)	March	6367	5222	water network
Clay	Mango	October	24592	20858	water network
Clay	watermelon	February	8571	5241	drip system
Sand	melon	March	7785	4752	drip system
Clay	tomato	October	4627	3072	drip system
Clay	lemon - Orange	October	25,840	17054	water network
Mix	Mango	October	24592	16027	water network
Mix	Sesame	August	8960	5282	water network
Mix	Onion - winter	October	9360	5839	water network
Mix	Okra - winter	October	6786	3552	drip system
Mix	cotton	August	11143	8750	water network
Mix	eggplant	August	4627	2784	drip system
Mix	pepper	October	8460	3552	drip system

Table 17. Net water requirements for crops irrigated with floodwaters at wadi Al-Arais and Delta Tuban (from: MOA 2023).

Crop	Planting time	Harvesting time	Days	Water needed m³/ha
Cotton with long Staple	August	January -March	240	7850
	15-Sep	January -April	225	7150
Cotton with medium staple	August	December -February	212	5780
	September	December -February	195	5360
Corn	August	October	90	4350
	September	November	90	4200
Corn for animal feed	April	May	50-60	1350-1820
Sesame	August	October	90	4200
	October	December	90	4100
Watermelon & Melon	August	October	90	3550
	November	January	90	3450

Livestock

The available literature provides only livestock numbers for Al-Mawaset. According to data from the NWRA (Alfadali, A. & Social Fund for Development - Taiz Branch 2020), the total livestock population is 54,801, distributed as follows: 29,262 goats, 12,193 rams, 7,213 cows, 38 camels, 4,745 bees, and 1,350 classified as others.

2.4.2 Water infrastructure

Several types of water infrastructure impact the hydrological functioning of Wadi Tuban, including wells, dams and reservoirs, diversions, and water harvesting systems. Both spate and base flow irrigation rely on a combination of traditional and modern structures—primarily modern in the upper delta and traditional in the lower areas (Bahamis, A. A. 2004). Modern systems consist of permanent canals, branches, and gates, and do not use field-to-field irrigation. In contrast, traditional systems employ uqma (earthen dikes) and obar (canal intakes), and rely on field-to-field irrigation. For an example of traditional spate irrigation infrastructure, refer to **Annex 2**. This section provides an overview of the water infrastructure in Wadi Tuban.

Wells

Groundwater is abstracted from wells throughout Tuban catchment. In Ta'iz area, including Al-Mawaset and Al-Selw target districts, wells are dug to irrigate cash crops such as qat (Al-Ghory 1997). This reportedly has caused springs downstream to run dry (Al-Ghory 1997). In Wadi Warazan, overlapping the part of Tuban catchment in Al-Selw and Al-Mawaset, an inventory reported 21 boreholes, 98 dugwells, and 2 springs, the locations of which are shown in Figure 24 (NWRA Consultants 1997). The boreholes have reported total depths between 29 and 334 m, and the dug wells between 4 and 22 m (NWRA Consultants 1997). Reportedly, 36% of water points in the inventory obtain water from the alluvial aquifer, 14% from the volcanic aquifer, and the remaining 48% from the combined aquifer, with the remaining being unknown.

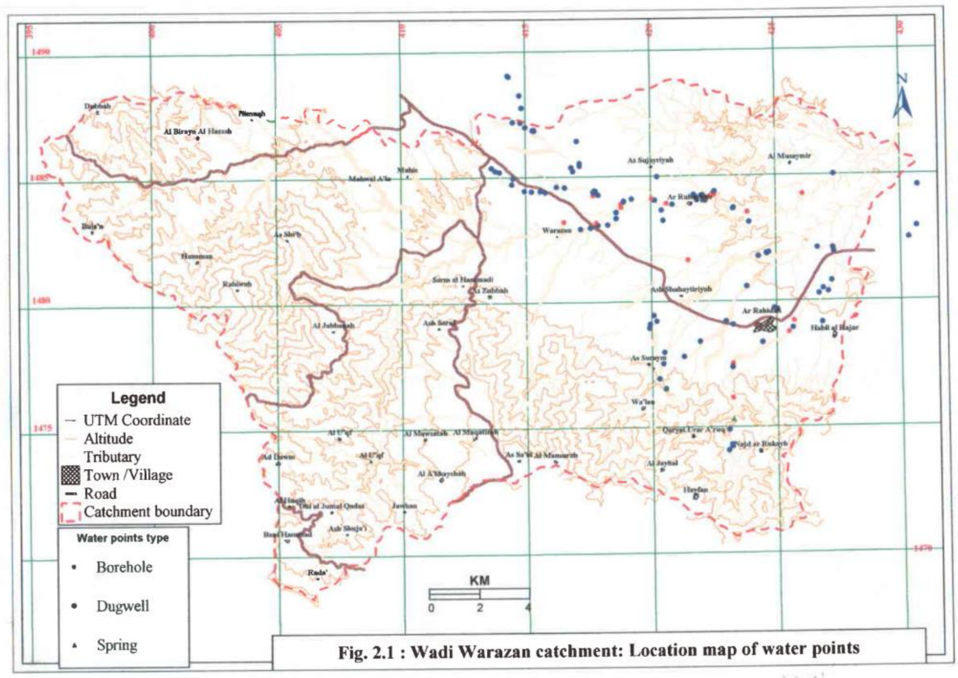


Figure 24. Locations of boreholes, dug wells, and springs in Wadi Warazan (from: NWRA Consultants 1997).

In the Tuban delta, groundwater is used for irrigation and water supply. The number of wells in Tuban delta increased from about 1150 in 1998 to 3600 in 2022 (MOA 2023). Groundwater is the most important source of water for Aden, with three main wellfields: El Manasra (29 wells), Bir Nasser (46 wells), and Bir Ahmed (40 wells) (UN Habitat 2020). The same report stated that about 20 to 40% of the wells are not functioning, depending on the wellfield.

In Bir Ahmed wellfield, wells installed in 2013 had an increased depth of 300 m compared to the 150 m for wells installed in the nineties up to 2005 (The Bir Ahmed wellfield water quality 2016, n.d.). The wellfields are supplemented by water from private wells (UN-Habitat 2020). In 2004 the actual pumping rate was 5.4 MCM for Aden water supply in the Bir Ahmed wellfield (The Bir Ahmed wellfield water quality 2016, n.d.).

Dams and reservoirs

Reportedly, there are 53 dams and barriers and 22 reservoirs in the Tuban catchment. The total storage capacity of these is reported to be 4.4 MCM (Hydrometeorological data for TUBAN, n.d.) to 4.8 MCM (Al-Mahab, A. A. 2016). These dams and reservoirs impact wadi flow downstream, as they affect the timing and magnitude of flow. The locations of these dams and their relation with groundwater is presented in Figure 25. An overview of dams and their area and storage capacity is shown in Figure 26. Most of the dams are used for agriculture, though a minority (8%) are used to recharge the aquifer (Al-Mahab, A. A. 2016). One report stated that about 75% of the dams are operational.

According to Figure 25 and Figure 26, none of the dams are located in the target districts of Al-Mawaset and Al-Selw. In contrast, nearly all dams are in the upstream area of Al-Mosaymer and Tuban target districts, meaning these could affect flow patterns in the districts. Indeed, hydrological studies suggest that the flow of floodwater has decreased in recent years due to the construction of a large number of small dams in the upper reaches of the catchment (Hydrometeorological data for TUBAN, n.d.).

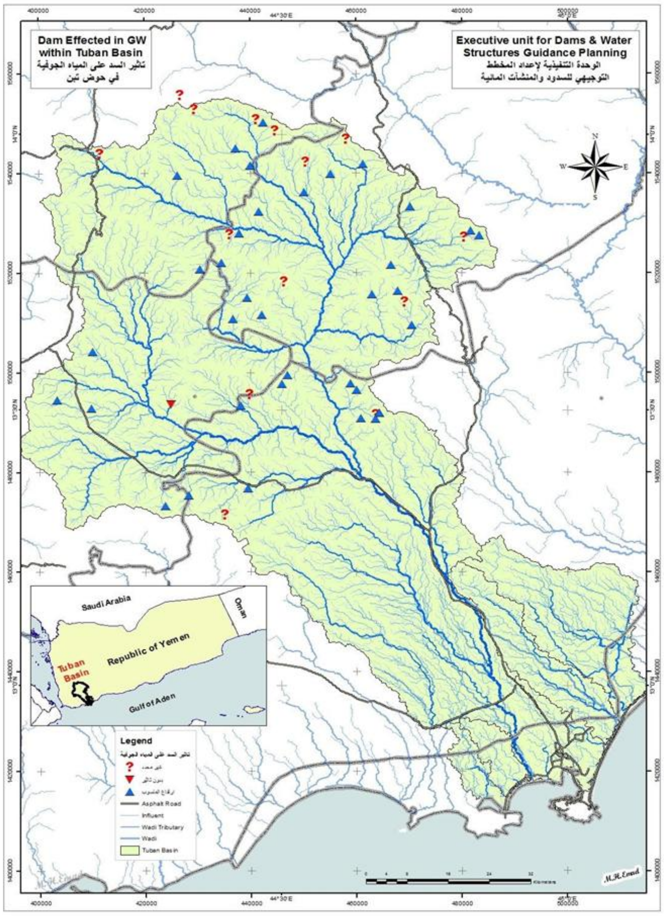
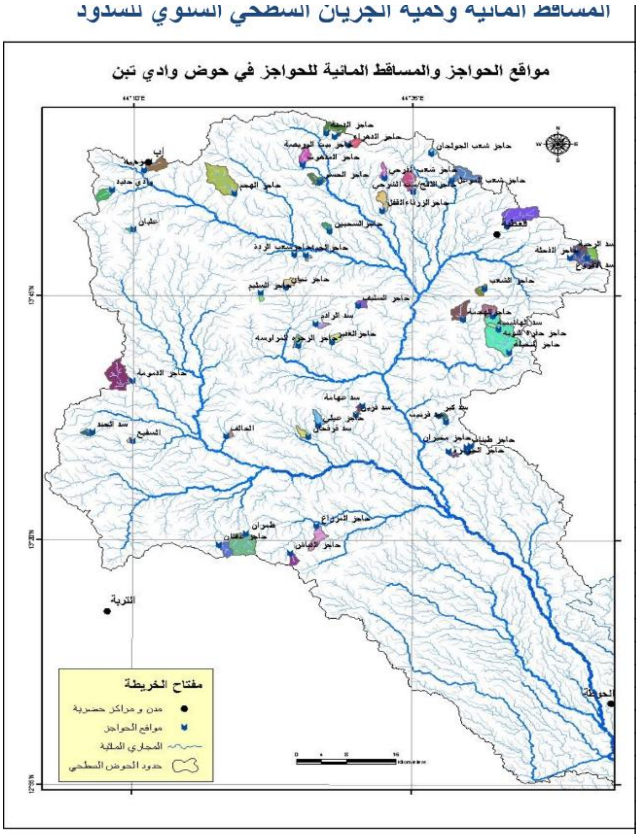


Figure 25. Location of dams in the Tuban catchment, where red triangle: no effect of dams on groundwater, blue triangle: high impact on groundwater, red question mark: undefined (from: MOA 2023).



اسم الحاجز أو السد	المحافظة	مساحة المسقط المائي، كم مربع	كمية المياه السطحية السنوية المتدفقة المتوقعة، متر مكعب
عليان	إب	0.69492	65,079
حاجز الدهراء	إب	2.32988	19,249
حاجز الدمنة	إب	5.06270	52,167
حاجز الهجم	إب	18.66917	845,628
حاجز الحسو	إب	3.33595	76,109
حاجز المذهوب	إب	4.85135	115,113
المزهمه	إب	5.88238	437,112
حاجز السليم	إب	0.89017	35,423
وادي حديد	إب	4.74117	328,568
حاجز بيت الوريصة	إب	0.44706	4,796
حاجز عفنان	تعز	3.98432	30,654
حاجز عيلي	تعز	3.19757	71,021
سد الجند	تعز	1.76094	82,516
الخالف	تعز	0.80367	38,862
حاجز الدمومة	تعز	15.22382	902,348
السقيع	تعز	0.87983	39,461
حاجزاللفج/بيت الشرجي	الضالع	5.93890	75,152
حاجز الذحلة	الضالع	10.55324	34,105
حاجز شعب الذرحي	الضالع	1.93429	21,407
حاجزالغدير	الضالع	2.47848	59,018
حاجزالهجمة	الضالع	6.71941	45,397
حاجزالجبه	الضالع	0.68884	11,020
حاجز شعب الجولجان	الضالع	1.18112	12,816
حاجزالخلفة	الضالع	14.72306	115,169
حاجز الزحره المراوسه	الضالع	2.54115	76,711
حاجز شعب الموعل	الضالع	8.47287	76,111
حاجز نمان	الضالع	3.52521	66,980
حاجز حذرة النوبه	الضالع	1.42767	6,234
حاجز النخيلة	الضالع	26.26749	227,370
سد الرادم	الضالع	1.56620	39,906
سد الرحبة	الضالع	0.71143	2,063
حاجزشعب الردة	الضالع	0.14442	3,965
حاجزالسحبين	الضالع	1.81036	39,962
حاجز السليف	الضالع	2.02781	16,289
حاجز الشعب	الضالع	2.44731	17,661
حاجزالزرقاءالقفل	الضالع	4.08379	64,975

Figure 26. Locations of dams, along with their area and storage capacity (from: Al-Mahab, A. A. 2016).

Weirs

In the Tuban delta area, corresponding to the part of Tuban catchment within the Tuban target district, a system of weirs are used to divert flows to irrigation areas in the delta. A total of 11000 ha of agricultural land is irrigated by these weirs in the delta (Bahamis, A. A. 2004). A schematic view of the delta area is presented in Figure 27. The Al-Arais and Ras Al-Widi weirs are in the main channel of Wadi Tuban and serve an area of 2083 and 1171 hectares, respectively, serving respectively 1113 and 757 farmers (بيانات هيدولوجية وزراعية لدلتا تبن , [Hydrological and agricultural data for Delta Tuban], n.d.). In Al-Kabir valley there are reported to be six weirs constructed over an area of 4420 ha, and serving more than 2123 farmers. In the small valley there are 8 weirs constructed over an area of 7,928 ha and serving more than 3,884 farmers (بيانات هيدولوجية وزراعية لدلتا تبن , [Hydrological and agricultural data for Delta Tuban], n.d.). Table 18 presents the total area and number of farmers using water from the Water User Association (2008) at the main weirs constructed along the primary branches of the Tuban Valley (بيانات هيدولوجية وزراعية لدلتا تبن , [Hydrological and agricultural data for Delta Tuban], n.d.).

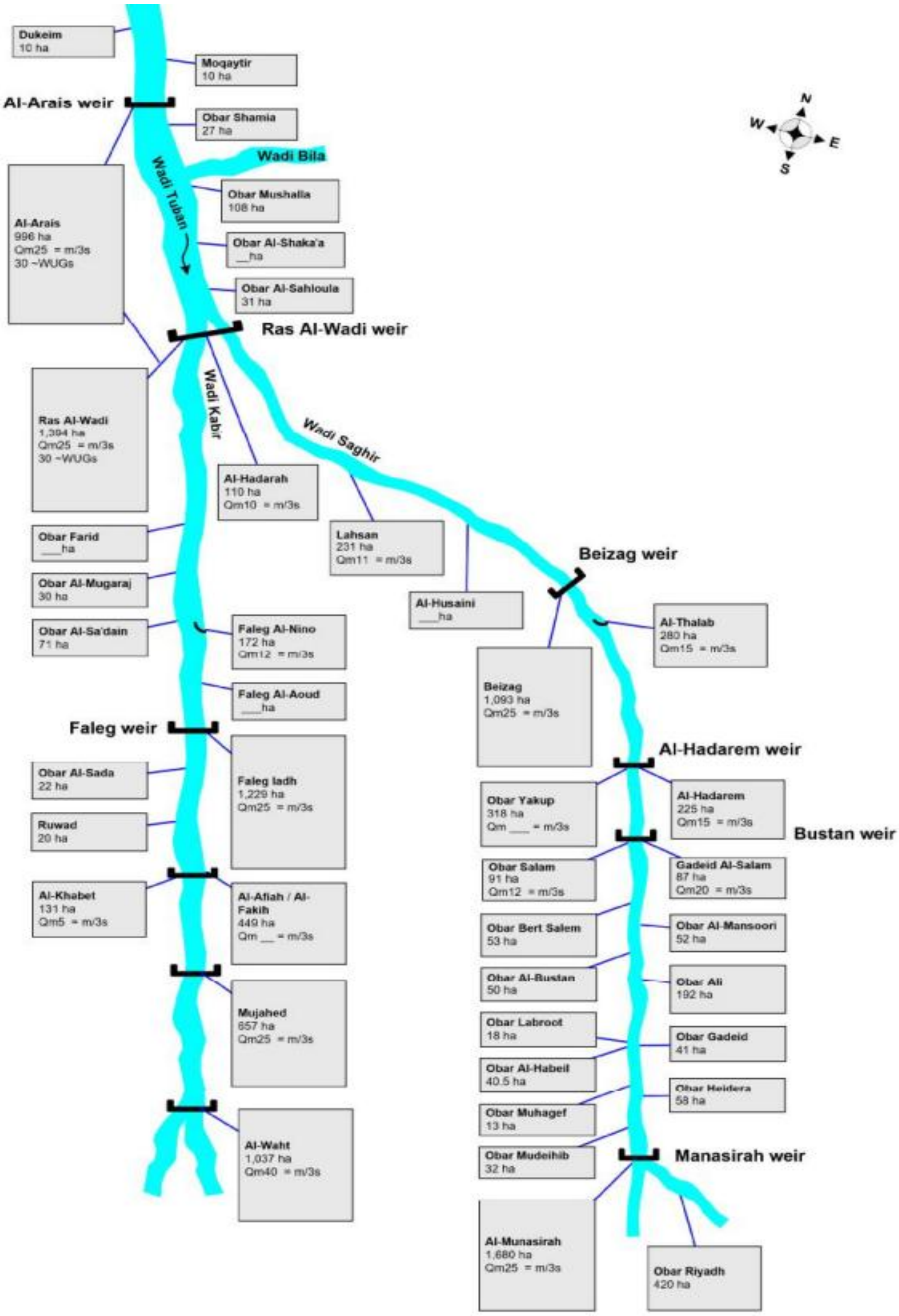


Figure 27. Schematic layout of Tuban Delta Irrigation System (from: n.d.).

Table 18. Total area and number of farmers using water from the Water User Association (2008) at the main weirs constructed along the primary branches of the Tuban Valley (from: Hydrological and agricultural data for Delta Tuban, n.d.).

جدول رقم (63) يبين المساحة والحيازة وعدد المزارعين

وفقاً لجمعيات مستخدمي المياه 2008

م	الحاجز / القناة	المساحة (هكتار)		عدد المزارعين		نوع الحيازة				عدد المجموعات
		الإجمالية	الصافية	العدد الكلي	المزارعات	مالك (عامل)	مشارك	مستأجر	مستفيد	
الوادي الأعظم										
1	العرانس	2,083	1355	1,113	259	119	31	0	963	33
2	رأس الوادي	1,171	1051	757	232	32	4	13	708	21
الوادي الكبير										
3	عبر السعديين	509	332	323	95	138	0	0	185	9
4	فالج النينو	231	160	201	79	33	0	0	175	10
5	فالج عياض	1,090	736	784	171	313	22	12	437	21
6	الأفيح والفقيه	489	338	342	35	76	233	0	33	9
7	مجاهد	706	480	423	103	10	413	1	0	9
8	الوهط	1,395	662	473	84	32	441	0	0	15
الوادي الصغير										
9	لحسان	323	217	87	27	22	0	0	64	2
10	بيزج	1,420	1092	1,007	250	326	0	3	677	26
11	الثعلب	375	264	264	4	118	67	1	78	7
12	الحضارم	341	314	418	115	236	3	1	178	11
13	عبر يعقوب	355	336	413	76	176	232	0	5	12
14	المنطقة الوسطى	1,401	871	884	126	632	243	0	9	22
15	الفرضة	1,731	830	552	7	483	66	3	0	16
16	الرياض	1,982	1015	259	0	23	236	0	0	7
الإجمالي		15,602	10053	8,300	1,663	2,769	1,991	34	3,512	230
%من إجمالي عدد المزارعين			متوسط 1.2هكتار/مزارع		20	33.4	24	0.41	42.3	100

2.5 Water management

From the document *"Legal Survey of Existing Traditional Water Rights in the Spate Irrigation Systems in Wadi Zabid and Wadi Tuban"* (Bahamis, A. A. 2004), the following is a summary of the governance structure for water distribution in Wadi Tuban.

The responsibility for water distribution and the application of traditional water rights falls under the Irrigation Department (ID) of the Ministry of Agriculture and Irrigation (MAI) office. The ID prepares the spate irrigation plans for both modern and traditional schemes during the two main agricultural seasons: the Seif season (March–June) and the Kharif season (July–October). Water distribution, including spate and base flows, is managed by the Irrigation Council (IC), which comprises representatives from MAI offices in Lahej, local authorities, and respected farmers in the area. The IC develops irrigation schedules for each diversion structure—whether modern weirs or traditional uqma (earth dikes)—and the corresponding command areas for each canal. The IC also monitors the implementation of traditional water rules to ensure equity, particularly for downstream fields. These traditional rules prioritize fields that have not yet received water, either from base flow or previous floods. During the Kharif season, spate water is allocated first to fields that have not received any water that year. Only after these requirements are met can previously irrigated land receive additional water.

The traditional irrigation system is supervised by 30 Sheikhs Al-Obar (community water masters), who are appointed by the Tuban District Irrigation Council. These water masters are compensated by farmers at harvest time with 5% of their crops, meaning they are not government employees. The Sheikhs are typically well-respected and experienced members of the farming community, each representing specific canal command areas. Each command area consists of approximately 10 small canals (shrouj), which receive water from primary canals, uqma, and diversion weirs. Sheikh Al-Obar is responsible for organizing farmers whose land is irrigated by these small canals, covering a total area of about 80,200 feddans. Their duties include:

1. Supervise canal maintenance.
2. Supervise irrigation and water allocation to the fields.
3. Assist irrigation Extensionists in implementing the irrigation plan.
4. Assist the ID in resolving water-related disputes among farmers.

The Sheikhs Al-Obar are supported by 36 agricultural extensionists, who are staff members of the MAI office in Lahej. These extensionists help with water distribution, canal maintenance, and report any violations of the irrigation plan or regulations to the ID. They also assist the Sheikhs Al-Obar in resolving water-related disputes among farmers.

Additionally, the Ala'ala Fala'ala principle (locally known as Rada'ah) gives priority to upstream users, who have the right to complete one full irrigation cycle before water is distributed to downstream users.

3. Data inventory

3.1 Obtained data sources

Various local and global datasets have been collected in the course of this study. Where available, local data were collected. An overview of these datasets is presented in Table 19.

Table 19. Collected and accessible local data sources

Parameter	Dataset Source	Spatial resolution and coverage	Temporal resolution and coverage
Precipitation	NWRA	10 stations, Tuban catchment	Daily, 1981–2008 (on average 7 years per station)
Meteorology (wind speed, relative humidity, temperature, radiation, pressure)	NWRA	3 stations, Tuban catchment	Daily, 1981–2008 (on average 9 years per station)
Stream level	NWRA	2 stations, Tuban catchment	Daily, 1997–2004 (1 and 7 years)
Reservoirs/dams	MoWE	Image of Wadi Tuban	NA

However, the spatial and temporal coverage of the local datasets are usually insufficient for the hydrological modelling and water balance analysis to be carried out in the second phase. In addition, not all required parameters are available. Therefore, global datasets have been collected to fill data gaps as much as possible. These datasets are presented in Table 20. For the meteorological parameters, the local datasets can be used to correct for bias in the global datasets in the second phase.

Table 20. Collected and accessible global data sources

Parameter	Dataset name/Source	Spatial resolution and coverage	Temporal resolution and coverage
Precipitation	CHIRPS	0.05°, quasi-global	Daily, 1981–present
Temperature	CHIRTS	0.05°, quasi-global	Daily, 1983–2016
Relative humidity	CHIRTS	0.05°, quasi-global	Daily, 1983–2016
Evapotranspiration	MODIS	500 m, global	Monthly, 2018–present
Land Cover	GlobCover 2009	300 m, global	NA
Soil type and characteristics (clay, sand silt percentage, organic matter)	SoilGrids	250 m, global	NA
Elevation	SRTM	30 m, global	NA
Geology	OneGeology	1:1M, Yemen	NA

3.2 Data gaps

An overview of datasets which have not yet been obtained but are presumed to exist is presented in Table 21. The table also lists one or two potential sources for these data. Due to the centralized nature of Yemen, it is possible that the data are limited to institutions in Sana’a and not available for use. Though images of some of the parameters, such as geology, have been found, it is as yet unclear whether the proposed sources possess the data. If they do, it is also unclear whether an official petition for data would be sufficient to acquire them, or whether there would be costs involved.

Table 21. Data sources not yet obtained.

Parameter	Description	Presumed source
Land cover	GIS-file	MoAIF/MoWE
Soil	GIS-file	MoAIF/MoWE
Geology	GIS-file	MoWE
Aquifer delineation and storage	GIS-file	NWRA
Groundwater monitoring data	GIS-file or csv with coordinates, well depth, and water level and water quality time series	NWRA
Dams and reservoirs	GIS file, with storage information	MoAIF/MoWE
Water demand	Table with current water demand, preferably at subdistrict level	MoWE
Irrigated crop area	Table with area of different irrigated crop types at district (preferable) or catchment level	MoAIF
Water use	Table of water use for all sectors, preferably at sub-district level, including source (i.e. surface water or groundwater)	MoAIF/MoWE

3.3 Data overview

An overview of required parameters for the hydrological study is presented in Table 22. For each parameter, the availability of local data is presented. For datasets where local data is not available or not sufficient, global datasets are proposed which can fill data gaps. Finally, a strategy is proposed on how to obtain the parameter based on available data. The color of the cells in the local and global data columns indicates whether the data is: 1) not available, 2) available, but has insufficient quality or coverage, or 3) available, with sufficient quality and coverage. The colors in the strategy column are similar, but assess whether the data will be available and of sufficient quality and coverage after the proposed strategy has been carried out.

Table 22. Overview of required data, collected local and global sources, and strategy for using or gap-filling the data. Grey colors mean a parameter is not available, yellow indicates insufficient quality or coverage, and green represents a dataset with sufficient quality and coverage

Parameter	Local data	Global data	Strategy
Precipitation	Station data, temporal coverage lacking	CHIRPS	Use local data to bias-correct CHIRPS dataset, thereby ensuring sufficient temporal coverage.
Temperature	Station data, temporal coverage lacking	CHIRTS	Use local data to bias-correct CHIRTS dataset, thereby ensuring sufficient temporal coverage.
Relative humidity, solar radiation wind	Station data, temporal coverage lacking	NA	Use statistics derived from available time series to gap fill data.
Stream flow	Station data, temporal and spatial coverage lacking	NA	Use data for Dukeim station to calibrate model. Stream level at Warazan can be used for general validation since no rating curve is available.
Springs	NA	NA	
Groundwater levels	Well levels, spatial and coverage lacking, generally outdated	NA	During field visits in phase 2, gather additional data for strategic locations
Soil	NA	SoilGrids	Use global dataset, include field verification in phase 2.
Geology	NA	OneGeology	Obtain 1:100000 geological map from Yemen Geological Surveys and Mineral Resources Authority, include field verification and attempt to gather borehole logs in phase 2.
Hydrogeology	Some general information in reports	NA	Obtain 1:250000 hydrogeological map from Yemen Geological Surveys and Mineral Resources Authority, supplemented by characteristics in available reports and expert judgement.
Irrigation systems location	NA	GlobCover 2009	Use global dataset, include field verification in phase 2.
Dams	Image of locations and storage	NA	Convert image to database, field verification in phase 2.
Water use and demand	NA	NA	During field visits in phase 2, gather data about crop coverage, population, and water use. Based on these data, estimate water use per sector.

4. Hydrological model selection

4.1 Relevant hydrologic models

Several methodologies exist for evaluating and selecting the appropriate hydrologic model for a study. For our evaluation and selection process, we used the Guide to Hydrologic Modelling of Natural Infrastructure (Boris et al. 2022) as the primary reference for proposing suitable hydrologic model(s).

To guide the decision-making process for selecting the most suitable hydrologic model for the Wadi Tuban catchment, we propose five key evaluation steps. It is important to note that a single model may not address all project requirements, and multiple models might need to be considered. In line with the hydrological modelling requirements for the Wadi Tuban catchment set by UNDP Yemen, information related to the policy question (Step 1), priority hydrologic ecosystem services (Step 2), and the impacts of proposed interventions: Green infrastructure focuses exclusively on small-scale surface water storage solutions, including dams, ponds, and subsurface damsm(Step 3) has been gathered. Additionally, data on available resources and technical capabilities (Step 4) has been compiled as part of this assessment. Figure 28 summarizes steps 1 to 4 in the context of the project). In this session, we focus on Step 5, which involves comparing the results from Steps 1 to 4 to select the most appropriate hydrologic model.

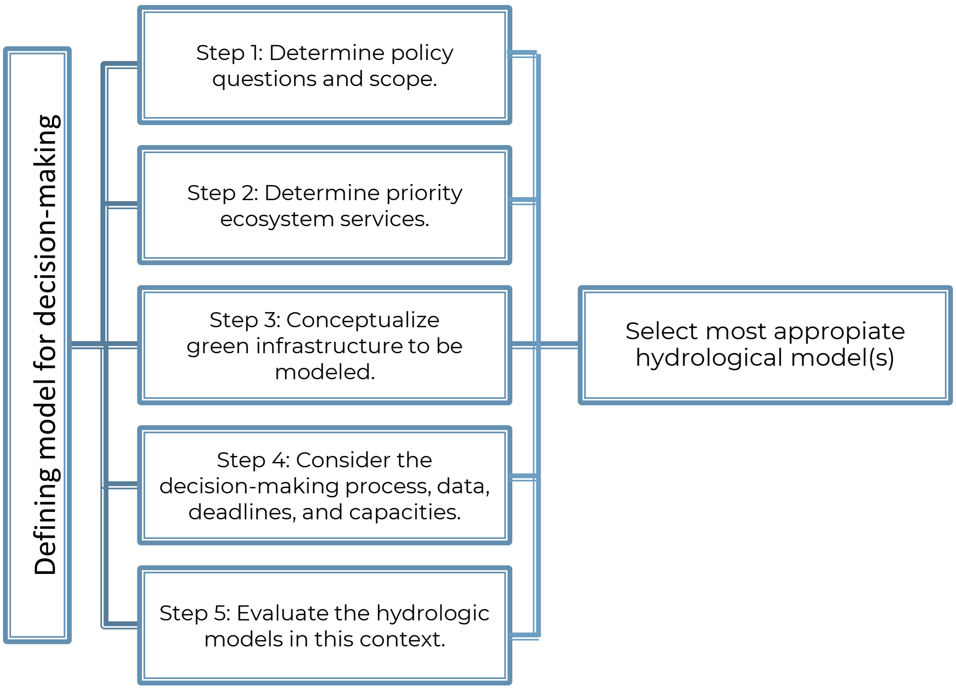


Figure 28. Schematic layout summarizing the steps for selecting the most suitable hydrological model.

There are numerous hydrologic models, continually updated to enhance performance. These models vary in complexity, characteristics, and process representation, affecting their suitability for decision-making. Some models simplify entire river basins into a single element, using basic mathematical relationships to represent processes like water flow.

Others employ more complex, physics-based concepts to simulate factors such as climate effects and water movement. While some models produce aggregated outputs, others provide detailed, spatially distributed results.

Hydrologic models can be classified based on: a) the classification of hydrologic processes, b) the type of spatial disaggregation, and c) the introduction of randomness.

Classification of Hydrologic Processes:
1. **Empirical models** (or "data-driven" models) rely on statistical or machine learning techniques without explicit physical process representation.
2. **Conceptual models** simplify hydrologic processes using parametric relationships, often modelling the system as reservoirs with simplified inflows and outflows.
3. **Physically based models** (or "process-based" models) use detailed physical laws (e.g., conservation of mass, momentum, and energy) and are computationally intensive.

Spatial Disaggregation:
1. **Lumped models** treat the entire catchment as a single unit with average parameter values.
2. **Semi-distributed models** divide the catchment into subunits (e.g., HRUs) that behave similarly hydrologically.
3. **Distributed models** divide the basin into smaller, regular grid cells, capturing spatial variations in hydrologic variables.

Introduction of Randomness:
1. **Deterministic models** produce the same results for given inputs and parameters, allowing for calibration and validation.
2. **Stochastic models** incorporate randomness or uncertainty, useful for modelling unpredictable processes like precipitation.

Below is a list of the most widely used hydrological models, along with a description of their key features (Table 23). These models employ different approaches to water cycle and ecosystem analysis, reflecting the diverse objectives of green infrastructure interventions. And, a summary of hydrological model characteristics under consideration are detailed in Table 24.

Table 23. Description and key features of the most widely used hydrological models.

Hydrological Model	Description	Required Information	Model Output
MIKE SHE (Abbott et al., 1986; Bathurst, 1986).	Mike Surface Hydrology and Energy (MIKE SHE) is a distributed physical model that simulates surface and groundwater interactions to assess the impacts of land use changes, climate variability, and water management on water resources and ecosystems.	DEM; precipitation, evapotranspiration, temperature, shortwave radiation; Irrigation water demand; Soil hydraulic characteristic curve; geological lens; recharge and discharge of groundwater.	Runoff, infiltration, groundwater flows, and evaporation are provided as daily, monthly, and annual time series.

Hydrological Model	Description	Required Information	Model Output
SWAT (Arnold et al., 2012)	The Soil and Water Assessment Tool (SWAT) is a semi-distributed model designed for land and water resource evaluation. It was developed to predict the effects of management practices on flow generation, sediment transport, and agricultural chemical loads.	Digital elevation model (DEM); land use and land cover map; soil type map (texture and structure); and daily climate data including precipitation, as well as maximum and minimum temperatures.	Runoff, infiltration (storage and subsurface flow), evaporation, and sediment transport are provided as daily, monthly, and annual time series.
TOPMODEL (Buytaert & Beven, 2010)	The TOPographic Index Model (TOPMODEL) is a semi-distributed hydrologic model based on the concept of a topographic index. It indicates the susceptibility of specific areas within a basin to become fully saturated, focusing on runoff generation.	Digital elevation model (DEM); precipitation and evapotranspiration data across various time scales; and physical characteristics of the subsoil.	Runoff time series at event on a daily, monthly, and annual scales.
HEC-HMS & HEC–GeoHMS (Scharffenbeg, 2016)	HEC-HMS, with the HEC-GeoHMS interface, simulates complete basin hydrologic processes, supporting both event and continuous (e.g., evapotranspiration, moisture content) analyses.	DEM; land use and land cover map; soil type map (texture and structure); precipitation hyetograph for event scale, and subsurface physical parameters for continuous scale.	Time series: flow rate and infiltration losses for a precipitation event or continuous scale.
MODFLOW (Harbaugh, 2005)	The finite difference groundwater model includes a main program and independent subroutines, organized into packages that handle specific components of the hydrologic system, like river flow.	Topographic information, sources and sinks (rivers, drains, lakes, wells, etc.) and hydrogeological properties.	Water balance results between zones of interest.
WEAP (Sieber & Purkey, 2015)	Water Evaluation and Planning (WEAP) is a software platform designed primarily for water planning and distribution. It also supports continuous-scale hydrologic modeling.	Area, subsurface storage characteristics information, monthly precipitation, and monthly average temperature	Water sheet and flow in a monthly scales.

Hydrological Model	Description	Required Information	Model Output
FONAG 2.1 by ATUK (Ochoa–Tocachi et al., 2019b)	A distributed model for water funds, based on hydrologic regulation zones. It estimates water yield, pollutant, and sediment transport, considering natural water production and human usage.	DEM; climatic raster (prec.,temp., evapotranspiration); land use and land cover map; evapotranspiration coefficients; abstractions and anthropic flow returns; hydrozone correspondence table; hydrologic regulation hydrozone.	Raster maps of monthly average flow and concentration; water stress maps; monthly flow, precipitation, and compound concentrations time series.
WMS Aquaveo	The Watershed Modelling System (WMS) is a complete environment for watershed modelling system. WMS offers automated delineation and serves as a graphical user interface for several hydraulic and hydraulic models.	The Hydrologic Modelling module is linked to hydrologic models such as HEC-1, which is selected by default. It depends on the selected model. WMS uses images to derive data: streams, confluences, land use, and soils.	It depends on the selected model.

Table 24. Summary of hydrological model characteristics under consideration.

Model	Model Outputs			Spatial scale			Temporal scale		Access	
	Water quantity	Water quality	Thematic map	Lumped	Semi-distributed	Distributed	Continuous	Event	Open	Commercial
MIKE SHE	✓	✓	✓			✓	✓			✓
SWAT	✓	✓	✓		✓		✓		✓	
TOPMODEL	✓		✓		✓		✓		✓	
HEC-HMS	✓	✓	✓	✓	✓	✓	✓	✓	✓	
MODFLOW	✓	✓	✓			✓	✓		✓	✓
WEAP	✓			✓			✓		✓	
FONAG 2.1	✓	✓	✓			✓	✓		✓	
WMS Aquaveo	✓		✓		✓		✓	✓		✓

4.2 Models capable of modeling water use and interventions

The purpose of this step is to compare the previously listed hydrologic models to assess their capability in representing interventions as planning scenarios. Our focus is on exploring Green Infrastructure interventions that generate positive environmental outcomes while simultaneously benefiting people. Consequently, a set of interventions will be proposed to evaluate the available models and assess their relevance to the decision-making context and UNDP requirements. These interventions represent a preliminary approximation of general solutions; however, the most appropriate interventions must be defined based on the outcomes of a detailed contextual analysis for each sub-catchment of interest.

Hydrologic models for Green Infrastructure interventions depend on variables such as land use, soil water storage, surface features, and groundwater recharge. For the models to be effective, interventions should be designed around these variables. This enables users to evaluate variations in hydrologic responses and the influence of model complexity, accuracy, and sensitivity. For the present project, three intervention options are contemplated to be modelled through simple processes in the Wadi Tuban catchment: Small water harvesting dams/ponds, Subsurface dams to maximize groundwater recharge, and flood protection works.

Table 25 presents an overview of hydrological modelling into functions that address the intended modelled green infrastructure.

Table 25. Overview of hydrological models by the capacity to simulate Green Infrastructure Interventions.

Model	Green Infrastructure Interventions to be modeled			
	Land use and land cover	Soil water storagecharacteristics	Structural interventions on the surface	Subsurface characteristicsand flows
MIKE SHE	✓	✓	✓	NO
SWAT	✓	✓	✓	NO
TOPMODEL	NO	✓	NO	NO
HEC-HMS	✓	✓	✓	✓
MODFLOW	✓	✓	✓	✓
WEAP	NO	✓	✓	NO
FONAG 2.1	✓	✓	✓	NO
WMS Aquaveo	✓	✓	✓	NO

4.3 Evaluation of selected models

The following process outlines how to select the most suitable hydrologic model for the specific policy questions and decision context in the Wadi Tuban catchment. This involves addressing the guiding questions based on the previous five steps outlined and answered in Table 26.

Table 26. Applying Steps 1-5 for Selecting Hydrologic Models for Green interventions in the Wadi Tuban Catchment.

Steps	Guiding Questions	Answers
STEP 1. Determine the policy questions and define their scope	**Q1.** What is the policy question we want to address using the hydrologic model?	How do we improve the water supply for irrigation in the upstream districts of Al-Mawaset and Al-Selw and downstream districts of Al-Musaymir and Tuban?
	Q2. How can we define the scope of this question so that we get relevant outputs from the model?	Can Green infrastructure interventions support harvesting flows in rainy seasons to: i) Increase potential water harvesting and storage during the dry season; and. ii) Identify the potential groundwater recharge considering upstream and downstream dynamics.
	Q3. What formats (e.g. flow time series, maps of biophysical variables) are required of the model outputs?	1. Geographic-biophysical data 2. Hydro-meteorological (time series of pcp, temp, flow and load at high temporal resolutions at a minimum, daily); spatially disaggregated maps of land use and soil. 3. Water use and infrastructures.
	Q4. What levels of accuracy and precision are needed to make a decision on this question?	A medium to high level of accuracy is required for subcatchment of interest.
STEP 2. Determine priority ecosystem services	**Q5.** What ecosystem services are important for our decision making and at what geographic scale?	1. Water Yield 2. Hydrologic Regulation
	Q6. What hydrologic processes and functions control priority hydrologic ecosystem services?	1. Soil Water Storage Characteristics 2. Surface Interventions in the Terrain 3. Groundwater recharge characteristics
	Q7. What hydrologic indicators can be used to obtain representative responses for these services?	1. Accumulated volume of water during the dry season.
STEP 3. Conceptualize the interventions to be modelled	**Q8.** What Green infrastructure are important for our purpose?	Cost-effective intervention measures for the Tuban catchment include dams/ponds, and gabion structures. Proposed locations and the rationale for these recommendations.
	Q9. What are the interventions in the field to be modelled?	To be defined. But they could be: • Small water harvesting dams/ponds • Subsurface dams to maximize groundwater • Recharge, and flood protection works.
	Q10. How is the performance of the interventions sought to be modelled conceptualized?	Maintain the soil's water storage capacity, as well as the soil's water infiltration capacity
	Q11. How can the performance of interventions be represented in hydrologic models?	Results should be represented in GIS-interface to assist in further planning and development.
STEP 4. Consider the decision-making context, data and capabilities.	**Q12.** What is the intended use of the hydrologic model results?	A useful tool for the Integrated Water Resources Management to Enhance Resilience of Agriculture (ERA) and Food Security project in Yemen. Which supports water infrastructure construction and rehabilitation to boost agricultural production, improve market access, and empower women in the agricultural value chain.
	Q13. What data are available to address the policy question in question?	Tables 19 and 20 display the available local and global data.
	Q14. Is the required data quality available for the preferred hydrologic models?	The acquired data are suitable for hydrological modeling. If GIS information is unavailable, supplementary activities can be undertaken to digitize the obtained maps, such as

		mapping the locations of meteorological stations, dams, and other relevant features. Table 21 lists the data sources that have yet to be acquired.
	Q15. Is there in-house technical capacity and prior experience to operate potentially relevant hydrologic models?	There is technical capacity within the UNDP team and previous experience in some of the identified models.
STEP 5. Select the most appropriate hydrologic model	**Q16.** Which hydrologic model responds positively to the highest number of criteria and how?	The **SWAT** hydrologic model has been selected as the primary option for this project, with the **MIKE SHE** model as an alternative. The following section outlines the advantages and limitations of both models in relation to their applicability to the study at hand.

4.4 Advantages and limitations of the selected model(s)

Tables 27 and 28 describe the key advantages and limitations of the MIKE SHE and SWAT models, respectively, in terms of their potential application to the case study. This evaluation focuses on how well each model can address the policy questions intended to be answered through hydrological modeling.

Table 27. Description of the key advantages and limitations of the MIKE SHE model

	Advantage	Limitation
MIKE SHE	o A fully integrated, spatially and physically-based model that simulates all components of the hydrological cycle, including surface runoff, unsaturated zone flow, groundwater flow, evapotranspiration, river flow, and their interactions. o Provides robust simulation of groundwater and surface water interactions (3-D ground-water flow model), ideal for studies where groundwater dynamics are critical, including flood forecasting, water resources management, land-use planning, and environmental modelling. o Designed for detailed, site-specific hydrological studies, and focuses on capturing the full water cycle in complex watersheds. o An integrated hydrology and hydraulics approach, which is particularly beneficial in deltaic environments. o Flexible and customizable, with a wide range of modules for specific hydrological components. Its modular design means it can be customized to focus on specific aspects without having to simulate unnecessary components. o Provides excellent visualization tools for analyzing results, including time series plots, spatial maps, and animations of water movement across the model domain.	o Highly complex model with significant data requirements (including hydraulic properties), and it is rare to find a watershed where all input data required to run the model has been measured. o Computationally intensive due to its fully distributed nature and high resolution. Requires expertise in hydrology and modeling to set up and interpret results accurately. o Includes many parameters that must be calibrated to fit the specific characteristics of the study area. The uncertainty in these parameters can affect the accuracy of the model's results. o It does not directly capture morphological changes, as it does not include advanced sediment transport or dynamic channel morphology processes. Coupling MIKE SHE with MIKE 21 or other morphological models is usually necessary to simulate morphological changes in Deltas. o May not be suitable for broad-scale or policy-level assessments due to its complexity and focus on fine-scale processes. o Commercial access (735€/month)

Table 28. Description of the key advantages and limitations of the SWAT model

	Advantage	Limitation
SWAT	o Designed primarily for long-term, continuous simulation of water, sediment, and nutrient transport in large watersheds and offering detailed analysis of specific areas of interest (sub-catchments). Focusing on predicting the impact of land management practices on water resources, with an emphasis on agricultural watersheds. o SWAT-MODFLOW is available, an integrated hydrological model that combines SWAT's land surface processes with spatially explicit groundwater flow dynamics. Additionally, QSWATMOD offers a QGIS-based graphical user interface to streamline the linking of SWAT and MODFLOW, facilitate SWAT-MODFLOW simulations, and visualize the results (Below is a brief explanation of the model). o Customizable tool that can focus on specific areas of interest, and generate scenarios for proposed green infrastructure interventions. This enables stakeholders to assess the impact of various strategies on both targeted locations and the entire basin. o SWAT-CUP tool aids calibration, directly coupling it with SWAT would streamline workflows and improve efficiency. o Long term and continuous simulations for understanding how sediment load and flow regimes affect delta morphology over time, especially in response to land-use changes, climate change, or upstream interventions. o A new web-based interactive SWAT modelling system is available to support states, local governments, and other stakeholders in making informed water quality protection decisions.	o Non-spatial representation of HRUs within sub-catchments, which simplifies computation but overlooks the spatial variability of flow and pollutant routing. This aggregation fails to capture interactions between HRUs, so finer sub-basin delineation is recommended to improve spatial resolution and accuracy. o Limited representation of detailed groundwater processes and subsurface flow. o Unaccounted human activities, such as construction or water abstraction, can introduce significant uncertainties, which should be incorporated into the model for better predictions. o Calibration and sensitivity analysis can be time-consuming for complex watersheds. o Parameter adjustments during modelling are often subjective, leading to potential inaccuracies. Emphasizing objective parameter optimization can reduce bias and improve reliability. o SWAT does not inherently model dynamic morphological processes. However, SWAT can be linked with other models (e.g., hydraulic models or sediment transport models like HEC-RAS or Delft3D) to improve the understanding of physical changes in deltas.

SWAT-MODFLOW is a developed coupled hydrologic model that integrates SWAT's land surface and stream hydrology processes with MODFLOW's groundwater hydrology processes, creating a comprehensive modeling tool for watershed systems. The Figure 27 displays the processes simulated by each model: processes handled by SWAT are indicated in green, while those handled by MODFLOW are in blue. Specifically, SWAT simulates land surface, soil, and surface water hydrology, whereas MODFLOW focuses on groundwater hydrology and the interactions between groundwater and surface water (Bailey, R. T. 2015).

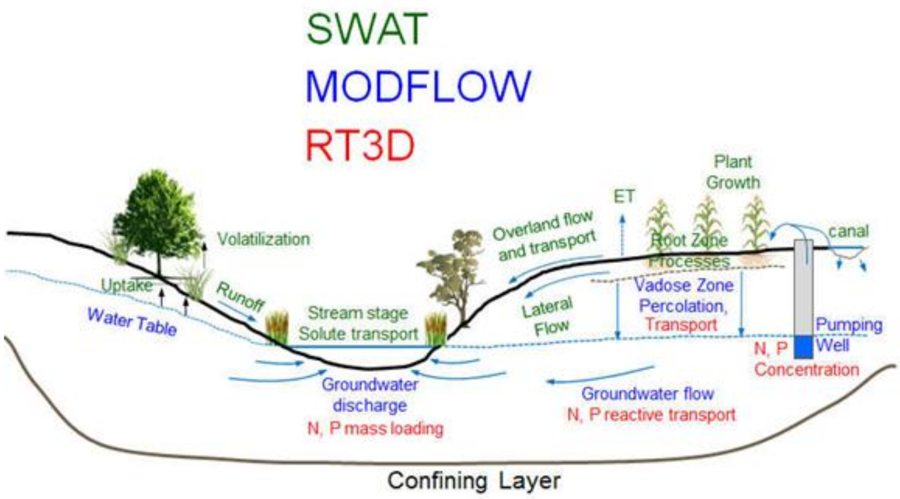


Figure 29. Process simulated by SWAT (green text) and MODFLOW (blue text) for the coupled hydrologic model (modified from Bailey, R. T. 2015).

5. Water balance methodology

5.1 Assessing the water balance

Estimating the water balance in a catchment is a fundamental task in hydrology, involving the quantification of water inputs, outputs, and storage changes within a defined area. However, accurately capturing water management practices can be one of the most challenging aspects of this process. Since water management significantly influences the hydrologic balance, it is crucial to thoroughly understand and quantify water use, including groundwater abstraction and surface water utilization within the catchment. The tools available for water resources assessment range significantly in complexity (as shown in Table 23). For this project, however, SWAT was recommended as the primary tool, with the MIKE SHE as an alternative. Both models provide the capability to develop a comprehensive water balance that integrates groundwater with surface water systems, a critical requirement for the Tuban basin.

The methodology we propose aligns with UNDP requirements and involves using the SWAT model with a GIS interface. This single hydrological model will be applied for water resource assessments at the reconnaissance level for the entire catchment and for more detailed evaluations in four target sub-catchments within the Taiz and Lahj governorates.

For the sub-catchments of interest, we propose conducting detailed water balance assessments incorporating more detailed information on key water management practices such as irrigation, impoundment areas, water transfers, consumptive use, and groundwater abstractions. Furthermore, we propose using the SWAT-MODFLOW model to achieve more accurate representation of land surface processes and spatially explicit groundwater flow dynamics.

Figure 30 provides a concise step-by-step outline of the proposed water balance methodology, aligned with UNDP requirements. It includes a reconnaissance-level hydrological assessment for the Tuban primary catchment and detailed assessments for the four sub-catchments in the target districts of Taiz and Lahj governorates.

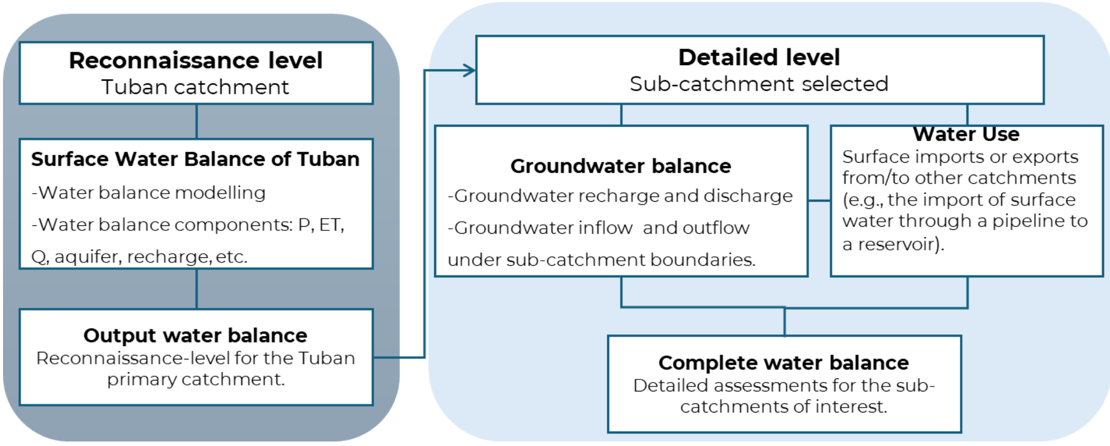


Figure 30. Proposed methodology for the water balance computation.

The estimation of each hydrological component will be customized based on data availability and the complexity of the selected sub-catchment. Many components of the hydrological cycle will be derived from the water balance model developed for the entire catchment. Additionally, primary field data collection will be necessary to ensure proper model parameterization. Finally, the validation of these estimates will involve comparing them with observed data and historical records.

With regard to interpreting the results, an analysis of the water balance components is needed to gain insights into the hydrological behavior of the sub-catchments. This includes identifying periods of water surplus or deficit and assessing their impact on the irrigation sector in the four sub-basins of interest. A comprehensive report will be prepared, detailing the methods, data sources, assumptions, and findings, along with graphical representations (e.g., hydrographs, bar charts, maps) to enhance clarity.

5.2 Data requirements

The most important aspect of the water balance or any other water assessment task is to obtain long-term accurate data over a fairly long period. The approach and methodology can be different from one sub-catchment to another depending on the availability of data for calibration and validation.

All available data collected has been compiled for this assignment. However, each dataset must be carefully reviewed for availability, uncertainties, necessary processing, and the time period it covers. Additionally, primary data collection from the field and secondary sources will be required to meet the minimum data requirements. Table 29 outlines the status of the data necessary for the successful completion of the groundwater assessment during the water balance computation.

Table 29. Data requirements for water balance assessment.

Data category	Data required
Geology	Maps and profiles of spatial variability providing detailed knowledge of the location of geological formations from a variety of data sources. These are needed for 3-dimensional mapping of geological formations and assessing the locations of lineaments/faults.
Hydrogeology	Hydraulic properties are defined to better characterize groundwater systems, including aquifer depth, transmissivity, hydraulic conductivity, and storage capacity. A monitoring network is needed to measure groundwater levels across hydrogeologic units and provide water quality data (e.g., salinity). Borehole locations and groundwater extraction rates for agriculture, industry, and domestic use are essential for assessing local groundwater flow patterns.
Hydrology	The spatial distribution of long-term daily or monthly rainfall totals is essential for understanding time variance and assessing annual, seasonal, and monthly water balance variations through modelling. Daily minimum and maximum temperatures, solar radiation, and wind speed are required for evaporation calculations. Long-term daily or monthly wadi discharge time series are needed to calibrate and validate models, which in turn provide deep aquifer recharge inputs for groundwater flow assessments. Understanding flow and its relationship to groundwater level fluctuations offers better insight into the hydrological regime. Additionally, estimates of wadi bed infiltration capacity are needed to model infiltration and groundwater recharge.
Soils	Soil type distribution, soil layering and depth and soil physical properties are needed for modelling their capacity to store soil moisture and for assessment of groundwater recharge.
Land use	Land use is a critical factor in water balance computation due to its significant water consumption for various activities. Each sub-catchment is expected to have varying land use patterns. Urbanization and new settlements reduce natural recharge while increasing groundwater extraction. Clearly defined land use maps are essential and can be obtained through remote sensing, with irrigation patterns detectable via seasonal NDVI variations.
Water use	In arid and semi-arid zones, irrigated agriculture relies heavily on groundwater. Beyond agriculture, groundwater is also abstracted for domestic, industrial, and commercial use. For groundwater flow modeling, data on water use is needed, including well locations, filter screen depths, and extraction volumes (annually or monthly, as available).
Reservoirs/ dams	A number of dams constructed for different purposes such as artificial recharge, flood protection and retention. Reservoir recharge also plays an important role in the enhancement ground water storage. This requires knowledge about the reservoir bed infiltration capacity (k-value) and on reservoir volumes.

6. Work-plan for hydrological study

This chapter describes the workplan and methodology we propose to conduct the hydrological study (modelling and water balance assessment) for Wadi Tuban and its four sub-catchments within the targeted districts, including the mechanism for delivering the participatory workshops (one workshop/district) with key stakeholders.

The objective of the hydrological study is to conduct hydrological assessments for the Tuban primary catchment at both a reconnaissance level and in detail for the four sub-catchments located in the target districts of the Taiz and Lahj governorates. This study provides a description of the hydrological characteristics of the catchment to understand the overall water availability and utilization patterns within the catchment and its sub-catchments. This study (phase 2) is a follow-up of the current 'Desk Study on Data Collecting for a Hydrological Study of the Tuban Catchment in Yemen' (phase 1) and can start immediately after completion of phase 1 of the project.

Acacia Water project approach is segmented into four work packages:

1. **Hydrological Baseline (WP1).**
   Catchment Hydrological Analysis and Modeling: We will analyze, model, and describe the hydrological processes of the catchment, including precipitation patterns, runoff generation, groundwater recharge, evapotranspiration, and water retention. This comprehensive assessment will help us understand the overall water availability and utilization within the catchment using a hydrological model.
   Sub-Catchment Water Balance Assessment: The water analysis will cover the entire catchment area. However, the analysis of the impact of upstream development (mainly storage) will be conducted for the sub-catchments with the targeted districts. The goal is to understand the conditions in the delta, where low water fluxes are impacting irrigation. In hydrological modeling, the water balance typically represents natural processes, whereas in this context, it also accounts for human interventions. Therefore, for the sub-catchments which cover the districts of interest, we will incorporate additional detailed data on water management practices, including irrigation, impoundment areas, water transfers, consumptive use, point source loadings, and groundwater abstractions.
2. **Potential Water Harvesting Sites (WP2).** Identify and prioritize potential water harvesting and storage locations within the sub-catchments of interest, and assess groundwater recharge potential, considering upstream and downstream dynamics.
3. **Proposal of Interventions (WP3).** Propose cost-effective Wadi Training interventions for the sub-catchments of interest, detailing types (trenches, dykes, check dams, gabion structures, etc.), proposed locations, and reasons for each recommendation.
4. **Water Monitoring System Evaluation and Recommendations (WP4).** Evaluate the existing water quantity and quality monitoring system. Assess the number and locations of hydrometeorology stations in the catchment based on accessibility,

proximity to water sources, and existing data collection infrastructure. Provide recommendations for improvement.

The project will be conducted using a participatory approach, involving relevant stakeholders at all levels. This includes the Ministry of Water and Environment (MoWE) and its affiliated body, the National Water Resources Authority (NWRA); the Ministry of Agriculture, Irrigation, and Fisheries (MoAIF) and their offices/branches in Taiz and Lahj; and other relevant institutions identified. In collaboration with key ministries, **we will conduct four participatory workshops** for the targeted sub-catchments during the development of the models and water balance assessment. Furthermore, **the results will be integrated into a GIS interface** to facilitate subsequent planning and development efforts.

Below is the description of the work plan and main activities proposed:

Activities	Short Description
WP1. Hydrological Baseline.	
Activity 1. Participatory workshops	A total of four participatory workshops will be held—one for each target sub-catchment—during the development of the models and water balance assessments, in collaboration with key ministries.
Activity 2. Field Data Collection	Develop a field data collection plan detailing measurement types (for parameters needed) and frequency, followed by ground surveys to assess water use, land use, soil, and groundwater conditions in the target sub-catchment.
Activity 3. Input data configuration and model setup.	Configure data and directory structure using the data collected in Phase 1 of the project. And, setup of the selected hydrological model based on Phase 1 findings.
Activity 4. Calibration and validation.	Calibrate and validate the model (only if basin measurements, e.g. flow, runoff, total suspended solids, are available,). If not, we propose use the evapotranspiration global dataset as a alternative to calibrate.
Activity 5. Assessing water balance for four sub-catchment selected.	Detailed water balance assessments for the selected sub-catchments which cover the districts of interest (Figure 27 describes the methodology).
Activity 6. Interpret and visualize results for decision making.	Water yield, precipitation patterns, runoff generation, groundwater recharge, evapotranspiration, and water retention for each sub-catchment and different seasons.
Activity 7. Analyses for the four sub-catchments.	Detailed and separate analysis of the model results for the four sub-catchments of interest, highlighting the specific characteristics that affect the hydrological processes in each sub-catchment.

Activities	Short Description
WP2. Potential water harvesting and storage locations.	
Activity 1. Map of runoff potential.	The map of runoff potential is generated and reclassified into areas of no, low, and high runoff potential.
Activity 2. Contour density maps.	Create contour density maps of high and low runoff.
Activity 3. Selecting suitable sites.	Extract agricultural, rural, and protected areas, followed by the definition of weights and scores.
Activity 4. Identify potential sites.	Identify and prioritize potential water harvesting and storage locations within the Tuban catchment, considering groundwater recharge potential and upstream and downstream dynamics.
WP3. Proposal of Interventions.	
Activity 1. Water use plan and managed aquifer recharge interventions.	Prepare a conjunctive water use plan for coordinated and balanced use of surface water and groundwater for irrigation purposes in Tuban catchment, including proposals for Managed Aquifer Recharge interventions such as recharge ponds and floodwater spreading systems.
Activity 2. Propose appropriate interventions	Propose appropriate cost-effective Wadi Training intervention measures for Tuban catchment outlining in detail the type of intervention (e.g., trenches, dykes, check dams, gabions structures, etc), proposed locations, and reasons for recommendation.
Activity 3. Participatory workshop (online)	Conduct participatory online workshop in each of the four sub-catchments for endorsement and approval of proposed interventions.
WP4. Water Monitoring System Evaluation and Recommendations.	Evaluate the current monitoring system for surface water and groundwater quantity across the Tuban catchment. This assessment will consider the number and locations of hydrometeorology stations, taking into account factors like accessibility, proximity to water sources, and existing data collection infrastructure. Recommendations for necessary improvements will be described.

7. Conclusions and recommendations

Within this project, a comprehensive effort has been made to collect data required for the hydrological assessment of Wadi Tuban and the four target areas. As part of this effort, a large number of reports and other available literature were collected and assessed, which were complemented with global data. Datasets include hydro-meteorological data, related biophysical characteristics, and water use information. The hydrological assessments themselves will be carried out in the second phase of the project.

An inventory of the available data is presented in Table 21. The table highlights significant gaps in the biophysical, hydrometeorological, groundwater levels, and water use data needed for building a reliable hydrological model. Many of the local datasets either lack sufficient temporal or spatial coverage, or are completely missing, which makes it difficult to use them accurately for hydrological modeling. The table also highlights strategies to bridge data gaps. In some cases, global data can serve as useful secondary sources of data. For example, CHIRPS and CHIRTS can be used to fill in missing recent hydrometeorological data. Local data should be used to bias-correct these global datasets, ensuring adequate temporal coverage. For biophysical data, global datasets such as SoilGrids, OneGeology, and GlobCover can be used, but field verification will be necessary in phase 2 to ensure accuracy. As for water use, current irrigation systems, and groundwater levels, field verification and additional data collection are crucial to address these gaps in the area of interest.

Choosing the right model to support decision-making is not straightforward, as it depends on several factors: the complexity of the models available, local technical expertise, resources, and the specific decision-making context. Given these challenges and the scope defined by decision-makers along with the data available, we suggest using the SWAT hydrological model as the first option, with MIKE SHE as a backup alternative. SWAT is a good fit because it allows for a general water balance across the entire basin, while also offering the flexibility to zoom in on specific sub-basins. By adding more detailed data to those sub-basins, we can get a more precise water balance. The level of detail we achieve will depend on how much updated field information is gathered, especially regarding water use and groundwater characteristics. On the other hand, MIKE SHE is more robust and detailed, but it's not ideal for conducting a water balance at a broad, reconnaissance level for the whole basin. This model requires more granular data, which is not currently available for the entire basin, so it would be better suited for smaller, data-rich watersheds.

The work plan for the phase 2 hydrological study has been proposed, consisting of four work packages. It includes both general and detailed assessments, combining field data collection, participatory workshops, and a hydrological baseline to create a water balance for the entire basin and its key sub-catchments. The plan also proposed to identify potential water harvesting sites, suggest specific interventions, and evaluate the current monitoring system. A key focus is the involvement of local stakeholders and key ministries to ensure the study remains practical and relevant to the local context.

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Annex 1 - Groundwater quality data

Table 30. Water quality data for wells at Bir Ahmed, Wadi Kabir (from: FAO 2000)

Appendix 1: Water Quality Data from Wadi Tuban

Table 1: Water Quality Data for a Selected Wells at Bir Ahmed, Wabi Kabir, February 1989

Well No.	pH	ECw, dS/m at 25° C	TDS g/L	Cations and Anions, meq/L Ca	Mg	Na	K	CO3	HCO3	Cl	SO4	SAR	Water Quality
810	8.4	3.87	2.6	5.19	9.01	27.9	0.12	0.6	3.8	18.6	16.9	10.3	C4S3
814	8.3	3.98	2.7	4.45	10.75	27.3	0.13	0.8	3.3	21.7	15.1	9	C4S3
815	8.4	3.61	2.4	4.4	11.4	22.8	0.13	0.6	3.5	20.1	12.3	8.4	C4S3
817	8.3	3.13	2	5	11.7	14.6	0.15	0.4	3.6	19.5	7	5	C4S2
818	8	6.56	4.5	7.95	17.85	47	0.15	0.6	3.3	37.2	29	33.1	C4S4
822	8.5	5.9	4.1	5.46	12.34	46	0.12	0.8	3.8	29.5	24.5	15.4	C4S4
824	8.5	4.52	2.9	2.96	8.44	36.1	0.12	0.8	4.4	21.5	20.5	15.2	C4S4
825	8.3	6.49	4.5	5.89	15.11	50.1	0.17	1.2	3.8	33.8	29.5	·15.5	C4S4

Source: The problems of Salinity and Treatment in Agricultural Soils in PDR Yemen. Prepared by Anwar Abdulkarim, Feruary 1989.

Table 31. Water quality data for wells at Al Shajariat Farm (from: FAO 2000)

Table 2: Water Quality Data for a Selected Wells at Al Shajariat Farm, March 1991

Well No.	pH	Sol. Salts mg/l	Cations and Anions, meq/L Ca	Mg	Na	K	CO3	HCO3	Cl	SO4	Total Salt %	SAR
East Side												
3	7.8	1341.9	98.0	76.8	204.7	3.5	0.0	446.6	237.6	274.7	0.13	30.97
4	8.4	1442.2	113.8	66.6	310.4	3.9	0.0	473.4	265.9	243.9	0.14	46.22
5	8.1	1215.8	94.9	20.0	207.0	4.7	0.0	419.7	230.5	240.2	0.12	38.62
West Side												
1	7.5	1797.4	104.2	12.3	363.4	7.8	0.0	436.8	326.3	484.1	0.17	67.33
2	7.7	1605.0	89.8	70.9	312.8	3.1	0.0	385.6	297.8	445.7	0.16	49.35
4	7.6	1495.0	86.6	69.1	230.0	3.9	0.0	494.8	294.3	376.5	0.15	·36.86
5	7.6	1452.7	85.0	66.2	243.8	5.1	0.0	463.7	262.4	326.6	0.15	39.65
6	7.6	1677.7	112.8	85.6	271.4	7.8	0.0	436.8	326.2	436.1	0.18	38.54
7	7.4	1409.0	76.9	75.9	243.8	7.8	5.4	287.9	315.6	395.8	0.14	39.45

Source: Soil and Water Laboratory, Irrigation and Reclamation Department, March 1991.

Annex 2 - Traditional spate irrigation

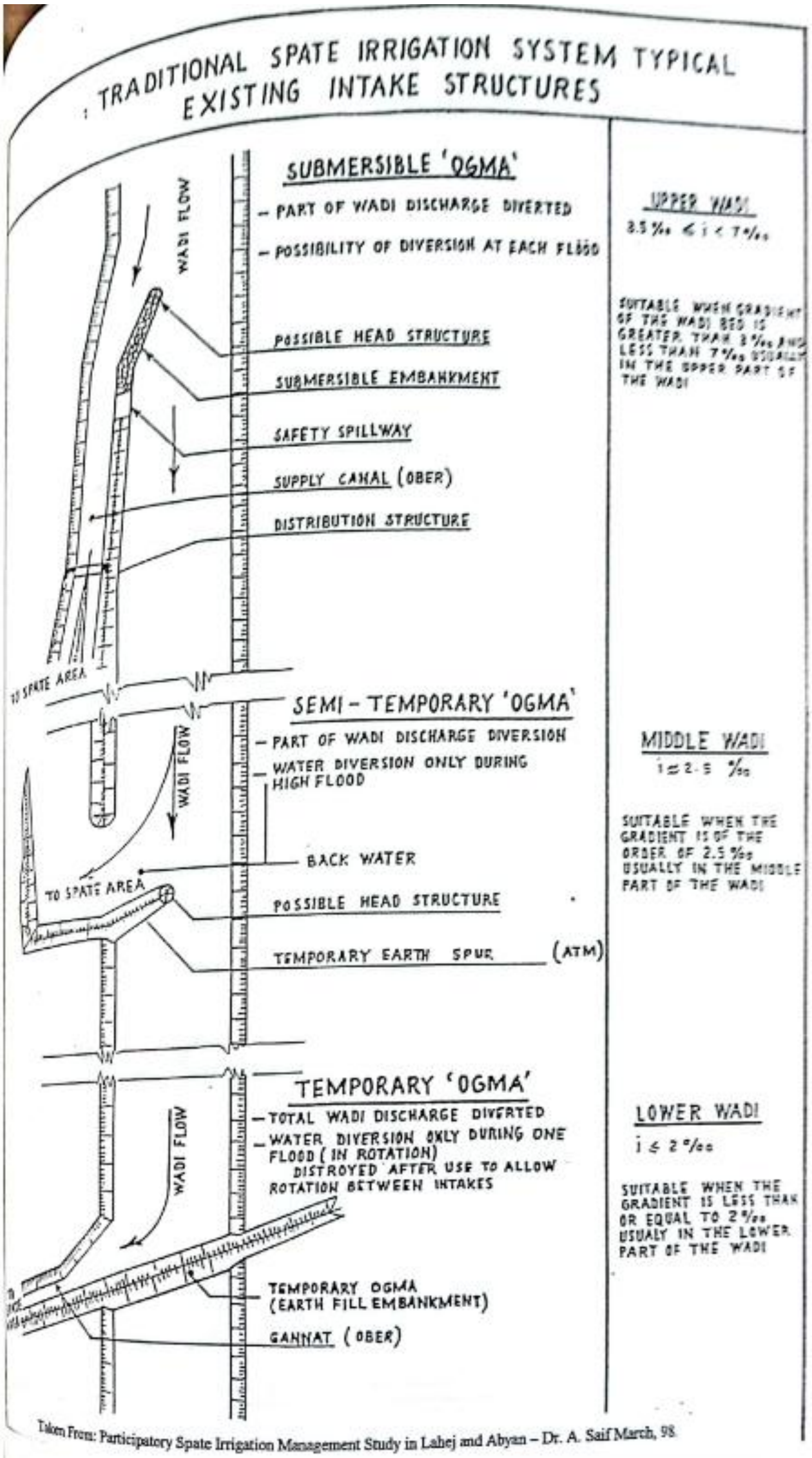

Figure 31. Overview of water infrastructure for a typical traditional spate irrigation system (from: Participatory Spate Irrigation Management Study in Lahej and Abyan – Dr. A. Saif March, 98).

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