Hydrological Study for Tuban Catchment in Yemen

Annexes - Draft Report

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Hydrological Study for Tuban Basin in Yemen

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Annex 1 – Desk review

The reviewed documents (see Table 1) reveal urgent issues, including groundwater depletion, inefficient irrigation and dam operations, poor institutional coordination, and the impacts of climate change. Notably, water use efficiency remains low, infrastructure underperforms, and a lack of integrated data systems hampers decision-making.

Based on this review, a set of strategic, evidence-based recommendations is proposed, focusing on improving hydrological monitoring, strengthening groundwater governance, enhancing water and sanitation infrastructure—especially in Aden—and promoting institutional integration and the adoption of modern technology. These strategies aim to improve water security, operational efficiency, and sustainability throughout the Wadi Tuban basin.

Table 1: List of the Key reviewed studies and reports

Ref.	Author / Institution & Year	Title	Key Outputs Related to Wadi Tuban
A4	World Bank, 2014	Policy Note: Landscapes and Resilience in Rural Yemen	Discusses ecosystem-based adaptation and natural resource management; promotes resilience strategies suitable for Wadi Tuban's exposure to droughts and floods.
A6	World Bank, 2007	Water Sector Reform Program - Socioeconomic Impact Assessment	Reviews the social and economic impacts of water sector reforms, including lessons on participatory water governance, as seen in Wadi Tuban.
A7	World Bank, 2008	Water Conflict in Yemen	Analyses water-related tensions, including spate irrigation conflicts; highlights Wadi Tuban as a potential hotspot due to upstream-downstream inequality.
A8	USAID, 2016	Groundwater Governance in MENA	Discusses groundwater depletion and institutional failures in the region; Wadi Tuban's crisis aligns with these challenges.
A9	UNDP, 2022	Holistic Approach to Address Water Resource Management Challenges in Yemen	Provides an integrated basin management framework, suitable for Wadi Tuban's needs in balancing agriculture and groundwater recharge.
A10	UNDP, 2021	Water Availability in Yemen	Identifies critical basins including Tuban-Abyan; discusses water decline and impacts on spate-based agriculture.
A11	UNDP, 2022	Final Conflict Analysis Report – Resilience in Irrigation and Agriculture	Highlights governance gaps and conflict drivers in water-scarce areas; user tensions in Wadi Tuban serve as a clear example.
W12	UNDP, 2011	National Strategy for the Water and Climate Change Sector in Yemen	Advocates basin-level planning and implementation of IWRM; identifies Wadi Tuban as a basin under climate stress.
G2	World Bank, 2021	Water Security Diagnostic: Assessment	Identifies critical basins in Yemen and recommends improved monitoring, governance, and infrastructure relevant to Tuban's issues of groundwater depletion and salinity.

Ref.	Author / Institution & Year	Title	Key Outputs Related to Wadi Tuban
TB1	World Bank, 1979	Wadi Tuban Agricultural Development Project: P005855	Initiated agricultural development planning in Wadi Tuban, including goals, cost estimates, water use strategies, and productivity enhancement to supply Aden.
TB2	Ministry of Agriculture, World Bank, Halcrow, et al., 2002	Water Management in Wadi Tuban and Wadi Zabid	Developed detailed water management plans; defined a 6,500 ha intensive irrigation zone, promoted high-value crops like bananas and vegetables, recommended modern irrigation infrastructure and stakeholder coordination.
TB3	FAO/UNDP, Ital Consult, 1975	Soil and Water Conservation in Wadi Tuban Basin	Provided baseline assessments of soil quality, water availability, and irrigation potential—formed foundation for future agricultural and water management interventions.
TB4	NWRA, UNDP, COMEX, 2002	Water Resource Management Studies – Tuban Area	Conducted hydrological studies and groundwater monitoring using graphs and sensitivity analyses to estimate the yield coefficient; contributed to sustainable water planning.
TB5	UN-Habitat et al., 2024	Climate Change Impact on Tuban Delta Hydrology	Analysed Tuban Delta hydrology under climate change, assessed risks like floods and saltwater intrusion, and proposed regional adaptation strategies.
TB6	Mekonnen et al., 2024	Land Use Change in Tuban District	Used satellite data to monitor land use changes in Wadi Tuban (1993–2023); identified impacts of conflict and population pressure; proposed strategies to reduce environmental degradation.
TB7	Jin et al., 2018	Water Allocation Model in Abyan (Relevant to Tuban)	Although focused on the Abyan Delta, it offered a water allocation model based on equal priority that can be applied to Tuban to mitigate upstream-downstream conflicts and ensure equitable distribution.
TB8	NWRA, Qaid Darwish, 2023	Groundwater Monitoring – Tuban Delta	Presented detailed geological, geomorphological, and hydrogeological criteria for Tuban Delta; documented water level trends, sediment thickness, and aquifer properties.
TB9	Ministry of Water and Environment, 2004	National Water and Sanitation Program – Focus on Tuban	Highlighted Wadi Tuban as a hotspot for groundwater depletion; recommended IWRM and pilot projects like tradable water rights.
TB10	Ital Consult, GDC, 1971–1986	Integrated Development Studies for Wadi Tuban	Reconstructed dams for flood protection, redesigned irrigation canals to improve efficiency, and facilitated joint use of spate irrigation.
TB11	NWRA, UNDP, Acacia Water, 2021	Tuban-Abyan Delta Water Plan	Focused on water allocation in the Tuban-Abyan Delta system; addressed salinity and overuse issues; proposed integrated management strategies and institutional reforms relevant to Tuban.
TB12	Ministry of Agriculture (Irrigation Improvement Project), 2005	Participatory Irrigation and Environment Management	Collected data on 16 Water User Associations managing 15,602 ha in Wadi Tuban, including gender-disaggregated data and canal information to support participatory irrigation management.
TB13	Ministry of Agriculture, Awad Bahmeesh, 2004	Legal Survey of Traditional Water Rights	Documented traditional spate irrigation systems, analysed legal frameworks, and proposed the formation of water zone committees to improve governance and equity.

Ref.	Author / Institution & Year	Title	Key Outputs Related to Wadi Tuban
TB14	Dr. Khaled Qassem Qaed, Ministry of Agriculture, 2007	Agricultural Extension Program Evaluation	Evaluated Agricultural Extension Program in Tuban; recorded yield increases for crops like cotton and tomatoes, improved livestock rearing, and identified market and irrigation challenges.
TB15	Dr. Ayoob Al-Muhab, 2009	Evapotranspiration Estimation Using SEBAL	Used modified SEBAL model to estimate regional evapotranspiration in Wadi Tuban using Landsat TM and NOAA-AVHRR satellite data; verified using lysimeter devices; proposed a decision support system.
TB16	Dr. Ayoob Al-Muhab, Ministry of Agriculture, 2016	Assessment of Dams and Water Structures in Wadi Tuban	Surveyed 182 dams in Wadi Tuban Basin; found 35% silted, 40% had low irrigation efficiency, with environmental concerns; recommended sediment removal, water treatment, and better management.
TB17	Sustainable Agricultural Communities Program, World Bank, 2011	Groundwater Monitoring Trends	Reported historic groundwater level decline in Wadi Tuban at a rate of 70–80 cm/year up to 2010; recommended improved monitoring and policy interventions.
TB18	World Bank, 2020	Irrigation Improvement Project (IIP)	Described the role of the project in rehabilitating spate irrigation systems in Wadi Tuban, establishing irrigation councils and water user groups; focused on participatory planning and infrastructure improvement.
TB19	MetaMeta, Bahmeesh, 2004	Water Rights in Wadi Tuban	Analysed customary spate irrigation systems, especially the "upstream priority" rule; highlighted justice and legal conflicts; proposed comprehensive reforms.
TB20	Garcia et al., 2007	Women and Water Rights in Tuban	Studied gender roles in water access and decision-making in Tuban; found Water User Associations reinforced male dominance and limited women's rights to land and water.
TB21	FAO, 1983	Soil Condition Assessment in Tuban	Assessed soil fertility and salinity in Wadi Tuban; findings helped guide irrigation practices and crop selection for improved performance in arid environments.
TB22	UN-Habitat, MDPI, 2025	Hydrological Assessment Under Climate and Economic Scenarios	Integrated remote sensing, QGIS, and climate modelling to assess future water availability in Tuban Delta; evaluated sustainable planning scenarios.
TB23	NWRA, 2016	Bir Ahmed Wellfield Assessment	Assessed the status of Bir Ahmed wellfield, a major groundwater source in Wadi Tuban supplying Aden; focused on production capacity, water quality, and sustainable withdrawal strategies.
TB24	NWRA, Social Fund for Development, 2023	Agricultural Resilience in Tuban and Warazan	Identified key challenges in agricultural systems post-flood; analysed infrastructure vulnerability and proposed community-based resilience strategies.
TB25	SFD – Taiz Branch, 2020	Development Report – Al-Mawasit District	Documented natural water resources (springs, valleys) and analysed issues like seasonal source depletion and remoteness from settlements.
TB26	NWRA, SFD – Taiz Branch, 2023	Enhancing Agricultural Resilience in Wadi Warazan	Identified challenges in the water and agriculture sectors in Warazan and Tuban; analysed flood-related damages.

Phase 1: Summary of Available Data and Identified Gaps

Hydrological and Meteorological Data

Rainfall
Available data encompass daily rainfall records from 13 meteorological stations in and around Wadi Tuban, spanning the years 1981 to 2008. Notably, only two stations, Al-Dhalea and Shua'ir Dam, possess recent records from 2021 to 2024, resulting in a substantial data gap from 2008 to 2024 for the remaining 11 stations. Satellite-derived rainfall estimates, calibrated with ground data, have been used to partially bridge these gaps. Nevertheless, a comprehensive long-term spatial coverage of daily and monthly rainfall data—sourced from both local and global datasets—remains to be established.

Temperature
Monthly temperature records are available from five ground stations up to the year 2008. No data is accessible for the period from 2008 to 2024. To enhance climate assessments, it is essential to gather daily maximum and minimum temperature data through new field surveys or global datasets.

Evapotranspiration and Climatic Variables
Evapotranspiration data from WaPOR (2009–present) are available and could be supplemented with MODIS data. Additional climatic variables, such as relative humidity, solar radiation, wind speed, and air pressure, were recorded at only three stations up to 2008. These datasets require expansion and integration with global sources

Surface Runoff
The Dokeim gauging station, located downstream in Wadi Tuban, provided annual and monthly flow data from 1955 to 2000, with an average annual flow of approximately 125 million cubic meters. Significant data gaps exist, particularly from 1962 to 1967 and from 1981 to 1997. Only three years post-1980 (1998–2000) have available data, with no measurements after 2000.

Variability in flow volumes was considerable, largely due to fluctuations in rainfall. The lowest flow, recorded in 1976 at 45.8 million cubic meters, and the highest, in 1999 at 805 million cubic meters—likely due to extreme events such as floods or cyclones—are notable. The 1998 flow was estimated indirectly, and data from 1999 to 2000 were excluded from the long-term averages due to their anomalous nature.

Excluding these outliers, the long-term average surface water flow approximates 123 million cubic meters per year, serving as a baseline for water availability during periods with reliable monitoring.

Note:

- 1998 flow data were estimated from stage-discharge relations rather than direct measurements. Data from 1999 and 2000 were excluded from long-term average calculations due to their outlier nature.

- The average flow (excluding 1999–2000) was 123 million m^3/year—providing a reference indicator for surface water availability during periods with reliable data.

Table 2: Historical records of surface water flow in Wadi Tuban at the Dokeim gauging station downstream. Note: Calculated from the stage-discharge relationship for 1998, as described The 1999-2000 data are not included in the mean value

Year	Gauged flow at Dukeim (Mm^3)	Year	Gauged flow at Dukeim (Mm^3)
1955	103	1973	62.8
1956	138	1974	81.2
1957	120	1975	116
1958	74.1	1976	45.8
1959	183	1977	222
1960	206	1978	170
1961	150	1979	91.8
1962-1967	No data	1980	85.7
1968	128	1981- 1997	No data
1969	90	1998	111.8*
1970	126	1999	805*
1971	145	2000	638*
1972	140	**Mean**	**123**

Regarding springs, only an outdated map of the upper basin's springs is available. It is essential to update the spring locations, categorise them (for example, contact springs or fault-related springs), and evaluate water quality by measuring electrical conductivity and discharge rates. Figure 1 illustrates water flow in Wadi Warzan from 1997 to 2010, showing variations and the impact of agricultural activities, such as qat cultivation, on these flows. This analysis is crucial for understanding water system dynamics and informing water management decisions.

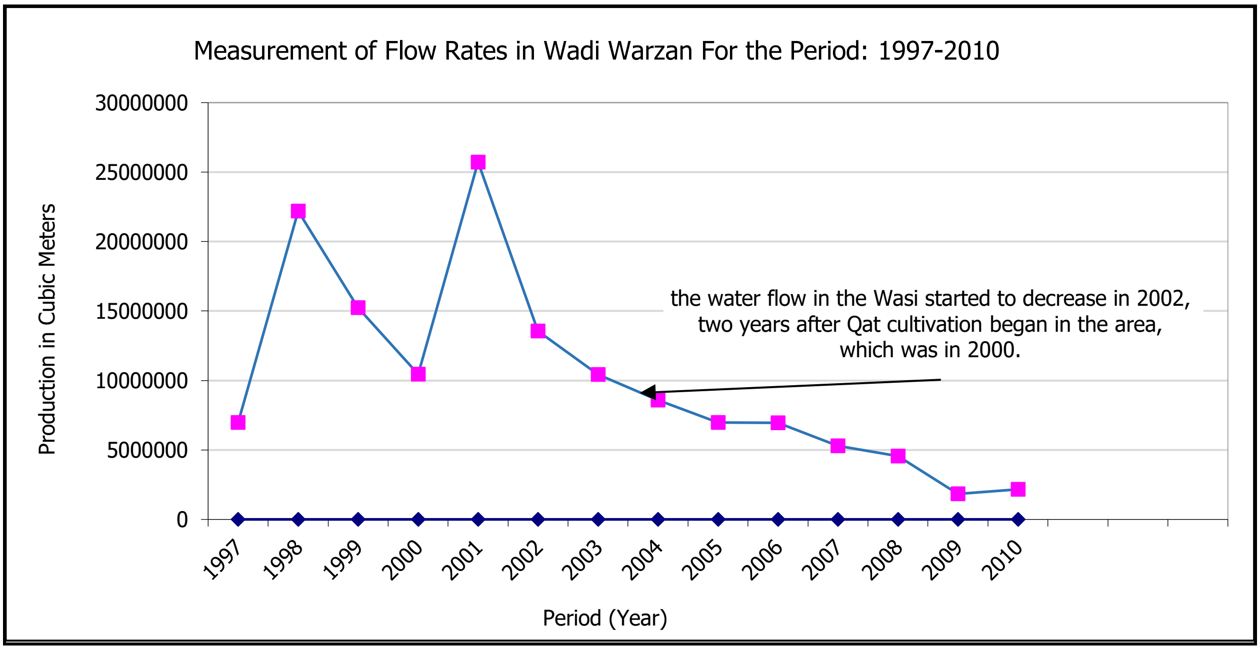


Figure 1: Measurement of spring discharge in Wadi Warzan, part of the Wadi Tuban watershed

Figure 2 shows the Water Level Variation in the Wadi Tuban basin (coastal plain – Tuban Delta) from November 2008 to October 2010. The figure presents two maps displaying the same data with different visualisation methods. The data highlight groundwater deficits in the northern and western parts of the basin due to excessive groundwater depletion. Conversely, the coastal and southern areas of the delta exhibit signs of relative improvement or stabilisation.

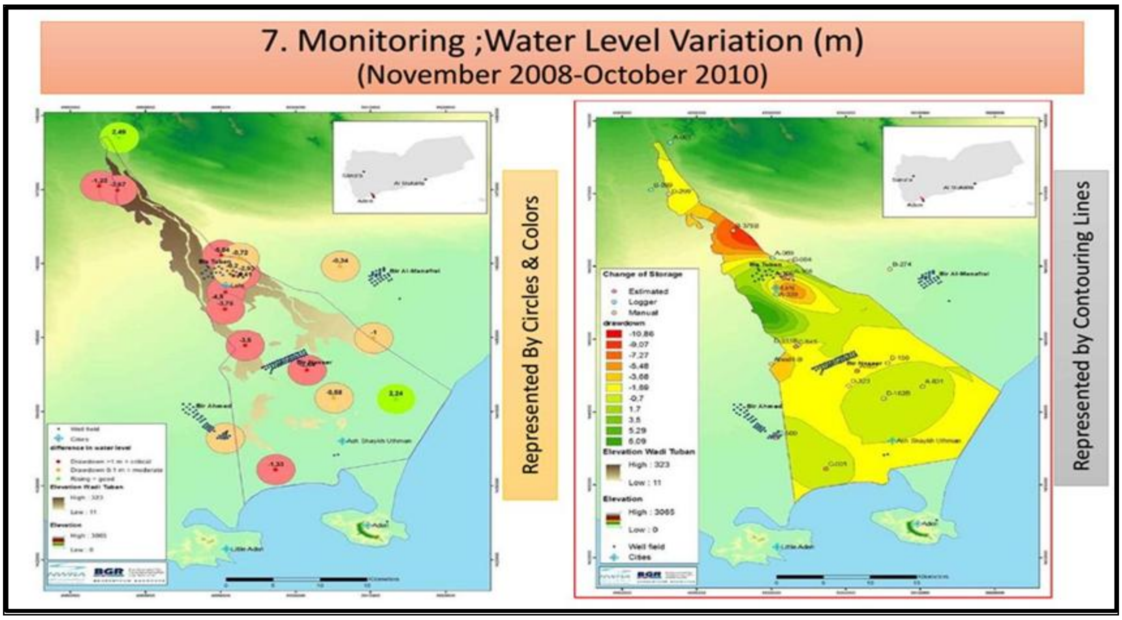


Figure 2: Groundwater levels in Wadi Tuban from 2008 to 2020

Hydrogeological Data

Groundwater data in Wadi Tuban is insufficient, impeding effective management. Major insufficiencies include:

- *Limited Well Data:* Only 94 wells in the Warzan sub-basin were surveyed in 1997. There is an urgent need for comprehensive water level and depth monitoring across all areas, along with a review of NWRA's archived records.

- *Missing Aquifer Data:* Key information on aquifer depth, permeability, storage, and pumping test results is lacking. Coordinated efforts are needed to access well drilling reports, licensing databases, and geophysical profiles.

- *Insufficient Water Quality Data:* Measurements of electrical conductivity and nitrates are unavailable, with a 2013 GPR survey providing limited insights into lower delta salinity. Updated, geology-stratified sampling is required to assess current conditions.

- *No Piezometric Monitoring System:* There is no mechanism to observe long-term water level changes. Establishing new monitoring wells and locating past sites is essential.

- *Imbalance Between Recharge and Extraction: Recharge* decreased from 112 million m^3 in 2000 to 87 million m^3 in 2023, while extraction increased from 162 million m^3 to 360 million m^3. Verifying pumping rates and mapping wells by usage is critical.
- *Unknown Groundwater Storage:* There is no available data on groundwater storage, which needs to be formally requested.

- *Over-Extraction Driven by Solar Pumping:* By 2025, over 4,000 wells, mainly powered by solar energy, have been drilled. While improving energy access, this has significantly accelerated groundwater depletion, increasing the risk of desertification, particularly with declining rainfall and reduced spate flows.

Figure 3 displays the locations of water wells operated by the Local Water and Sanitation Authority (LWSA) – Aden, in the Tuban Delta (2007), including the Upper Tuban Field, Al-Mansoura Field, Bir Nasser Field, and Bir Ahmed Field. These wells provide drinking water and meet domestic and industrial needs for the city of Aden. By 2025, the Aden Water Authority mainly relies on three well fields—Bir Ahmed, Bir Nasser, and East Mansoura—which together have around 120 wells with an annual production of approximately 3.5 million cubic metres, supplying Aden's population with potable water and household needs (Source: LWSA Well Field manager)

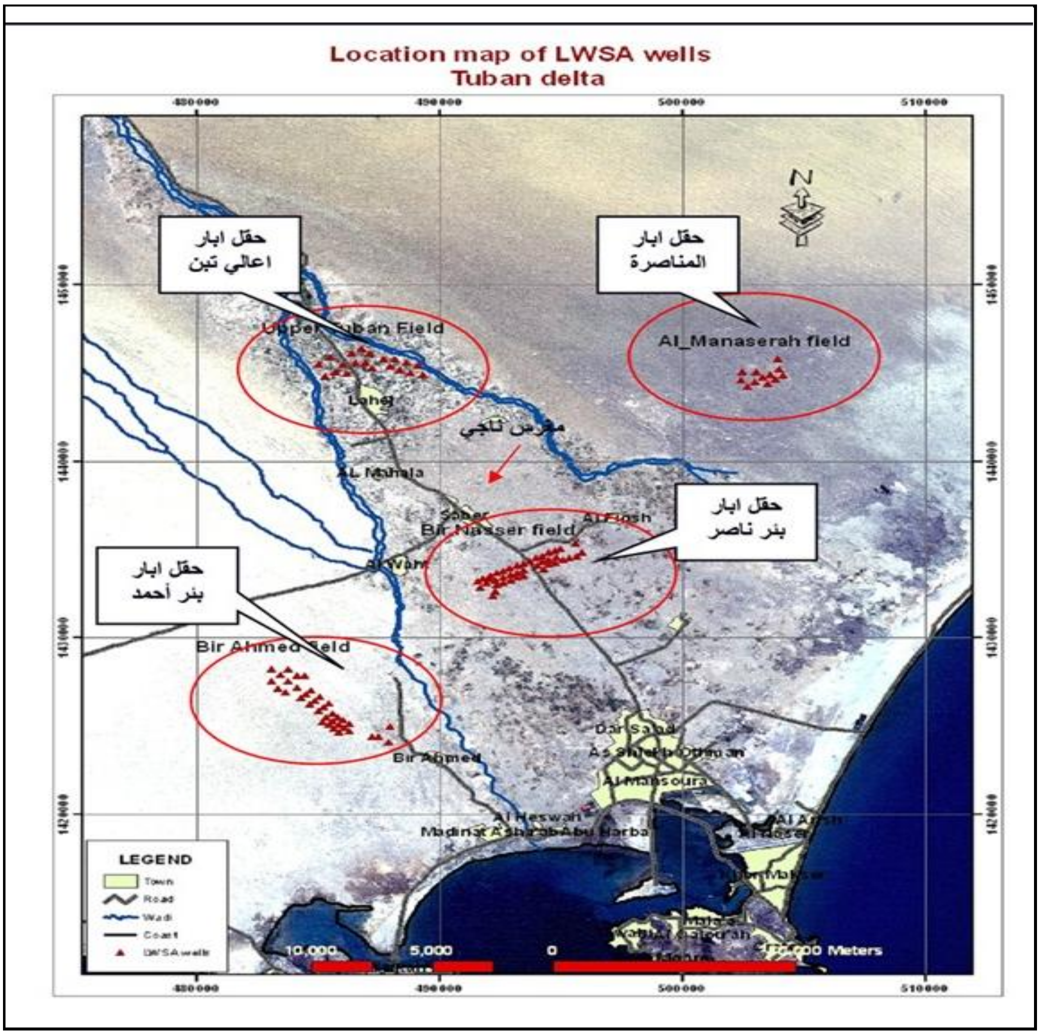


Figure 3: Locations of well fields operated by the Local Water and Sanitation Corporation in Aden

Geological Data

For surface geology, relying on the available, outdated, small-scale maps (1:1,000,000) from the KOMEX 2002 study is inadequate. It is crucial to obtain higher-resolution maps (1:250,000) from the Geological Survey Authority as soon as possible, preferably in digital shapefile format. In terms of subsurface geology, although two cross-sections are available for the basin and delta, they are insufficient. Comprehensive lithological data is necessary, which should be collected from well samples strategically placed throughout the basin. Identifying rock types accurately demands detailed field observations complemented by photographic records. Importantly, there is currently no data on aquifer boundaries, which hampers understanding of groundwater flow. A prompt and thorough review of all existing geological and geophysical maps from relevant agencies is crucial for delineating aquifer extents and properties.

Soil Data

There is insufficient data on soil types, composition, and physical properties such as water retention capacity and soil depth—essential elements for hydrological modelling. This information should be gathered either through field surveys or global soil databases.

Land Cover and Land Use Data

Land cover maps from WorldCover 10m (2021) are available. However, analysing land cover change with indices like NDVI is essential. For agricultural land use, detailed data on crops, crop rotations, agricultural calendars, irrigation types, water sources, and economic yields is required. This information will be gathered through field visits and government sources.

Water Use Data

Estimates for agricultural water use were based on crop water needs; however, there's a lack of actual usage data from previous years that needs to be updated to match current conditions. For domestic water use, estimates suggest a consumption of around 22.05 million m^3; however, a more detailed breakdown over the past years is necessary, including a separation between rural and urban areas. In the upper basin in 1997, 21 artesian wells, 98 traditional wells, and two springs were recorded. In the delta, the number of wells grew from roughly 1,150 in 1998 to 3,600 in 2022, according to the Ministry of Agriculture and Irrigation. The main well fields serving Aden are Mansoura (29 wells), Bir Nasser (46 wells), and Bir Ahmed (40 wells). Updating the well inventory, especially in the upper basin, and linking it to official licensing records is essential.

Water Infrastructure Data (Dams and Hydraulic Structures)

Data on the location, storage capacity, and groundwater impact of 53 dams and 22 reservoirs within the basin is available, along with recharge information for weirs in the Tuban Delta. However, this data requires updating, and further evaluation of the ongoing effects of these structures on water resources is necessary. Most of the spate irrigation diversion structures in the delta urgently require rehabilitation and maintenance. Studies revealed that although most storage dams are operational, they face technical, administrative, and environmental challenges. It recommends implementing comprehensive policies to enhance performance, including equipment upgrades, the adoption of smart technologies, improved stakeholder coordination, and enhanced monitoring systems. Updating databases is also crucial for enhancing water-use efficiency, supporting agriculture, and ensuring sustainable resource management in the long term.
All documents and datasets collected during the initial phase were thoroughly reviewed to identify information gaps prior to the commencement of the second phase. Table 3 summarizes key findings from the first phase and highlights the specific data gaps that need to be addressed moving forward.

Table 3: Summary of desk review data collected in the first phase of the study and identification of data gaps

Main Component	Subcomponent	Type of Data Collected in Phase One	Gaps in Phase One	Data Required from Fieldwork in Phase Two
Hydrology and Meteorology	Rainfall	Daily rainfall data from 13 meteorological stations within or near Wadi Tuban Basin (1981–2008); only two stations (Al-Dhalea, Shaeir Dam) recorded rainfall data during 2021–2024	Data gap for the other 11 stations from 2008 to 2024. Satellite data was used to fill the gaps after validation	Spatial distribution of daily or monthly rainfall for 2008–2024. Collect data from 11 stations. Use global datasets to fill gaps
	Temperature	Monthly average data from 5 ground stations (1981–2008)	Data gap for the period 2008–2024	Daily maximum and minimum temperatures. Use global datasets to fill gaps
	Evapotranspiration	Data from WaPOR portal (from 2009 to present)	No gaps	Use global datasets such as WaPOR and MODIS
	Relative humidity, solar radiation, wind speed, atmospheric pressure	Daily data from 3 meteorological stations (1981–2008)	Data gap for the period 2008–2024	Identify existing stations in the area and collect data. Use global datasets
	Surface runoff	Annual and monthly flow data for Wadi Tuban at Dokeim station (1955–2000). Average annual flow is around 125 million m³	Need to assess recent flow changes	Daily or monthly water level or surface runoff data for all stations; map permanent and seasonal networks; identify number of flow days and flood zones
	Springs	Old map of spring locations only in the upper part	Need to update spring locations and discharges throughout the basin, identify spring types and measure electrical conductivity	Update spring location map, names, types (e.g., contact or fracture), conductivity, discharge, with field photos
Hydrogeology	Groundwater levels in wells	Static water levels for 94 wells in the Warazan Basin only (1997)	Need for historical groundwater level data for the entire basin, and to measure current levels in selected wells	Measure groundwater levels and total depth for wells representing the upper and lower basins. Search historical data from NWRA
	Groundwater aquifer characteristics (depth, permeability, hydraulic conductivity, storage capacity, pumping tests, drilling reports)	Not available in the Phase One report	Missing data	Review relevant institutions, verify the existence of a database on wells, including location, geological details, and geophysical logs.

Main Component	Subcomponent	Type of Data Collected in Phase One	Gaps in Phase One	Data Required from Fieldwork in Phase Two
	Groundwater quality	Electrical conductivity and nitrate concentrations were measured in selected wells in Warazan; salinity of some wells in the lower Tuban Delta was assessed using GPR in 2013	Need for recent measurements of salinity and conductivity in some wells in the lower Tuban Delta.	Measure salinity in some wells in the lower delta, with stratified sampling by geological formation.
	Groundwater monitoring and piezometers	Not available in Phase One report	Missing data	Identify locations of former monitoring wells and propose new locations
	Groundwater recharge	KOMEX (2002) and Ministry of Agriculture (2023) studies indicate recharge was 112 and 87 million m^3 in 2000 and 2023, respectively	Need to study groundwater recharge trends over multiple years	Verify groundwater recharge data
	Groundwater abstraction	Estimates indicate withdrawals were 162 and 360 million m^3 in 2000 and 2023, respectively.	Need multi-year data to analyse withdrawal patterns	Verify withdrawal rates and identify well locations by usage (agricultural, industrial, domestic)
	Groundwater storage	Not available in Phase One report	Missing data	Search for this data from relevant institutions
Geology	Surface geology	Small-scale geological maps (1:1,000,000) from the KOMEX 2002 study	Need for more detailed maps (1:250,000)	Obtain geological maps from the Geological Survey Authority (preferably in digital format)
	Subsurface geology	Two geological cross-sections for Tuban Basin and Delta (KOMEX 2002)	Need lithological data from wells covering the entire basin	Collect lithology data from field wells, identify rock types, and take photos
	Aquifer boundary delineation	Not available in Phase One report	Need to delineate aquifer boundaries	Obtain maps from relevant institutions
Soil	—soil type	—No data	Need data on soil types and properties (depth, layers, moisture storage capacity)	Collect soil data to feed into hydrological models; use global maps as needed.
Land Use and Land Cover	Land cover	Land cover maps from ESA WorldCover 10m (2021)	Seasonal change analysis using NDVI	Use remote sensing data for 2024
	Agricultural land use	—No data	Need detailed data on crops, crop cycles, agricultural calendar, irrigation systems, water source, and economic return.	Collect data from field visits and government sources.
Water Use Data	Agricultural water use	The table includes estimated water consumption for several crops	Need actual water use data for recent years	Update water consumption data in agricultural activities
	Domestic water use	Estimated water consumption (22.05 million m^3)	Need to understand household water use patterns in recent years	Update household water use data in urban and rural areas

Main Component	Subcomponent	Type of Data Collected in Phase One	Gaps in Phase One	Data Required from Fieldwork in Phase Two
	Wells	21 artesian wells, 98 traditional wells, and two springs in the upper part in 1997. The number of wells in the Tuban Delta increased from 1,150 in 1998 to 3,600 in 2022 (MOA, 2023). Wells in Aden: Al-Mansoura (29), Bir Nasser (46), and Bir Ahmed (40) (UN Habitat 2020)	Need to assess changes in the number of wells in the upper part	Update data on well numbers and locations (using license data if available)
Water Infrastructure	Dams and Reservoirs	Locations, storage capacities, and impact of 53 dams and 22 reservoirs on groundwater	—	Update data on dams and reservoirs.
	Weirs	Information on the location of weirs and their recharge areas in the Tuban Delta	—	—

Highlights from Relevant Studies

Both surface and groundwater resources in the Tuban Delta are under significant stress due to a combination of climate change, over-extraction, and the lack of a long-term, sustainable water management strategy. These overlapping challenges point to an urgent need for comprehensive and effective water governance policies to ensure the basin's future viability.

Groundwater, which serves as the primary water source for Aden City and parts of Lahj Governorate in southern Yemen, is particularly at risk. Depletion is being driven by several factors, including reduced recharge linked to changing climate conditions and the widespread drilling of unauthorised wells. A 2023 assessment recorded approximately 3,600 wells in the area, of which 1,200 had already run dry. On average, groundwater levels are dropping by about one meter each year, mainly due to an unsustainable imbalance between extraction and natural recharge. If this trend continues at the rate observed in 2022, most wells—especially those in the coastal zone—are expected to either dry up or become increasingly saline by 2060.

Adding to the concern, a UN study conducted in November 2023 reported a water deficit of 84 million cubic meters in the lower Tuban Delta for that year alone.
In this section, we will delve into two studies that have examined the major water-related challenges facing the Wadi Tuban and summarise the recommendations proposed to address these challenges.

Highlights from Relevant Studies
Climate Change Impact on Tuban Delta Hydrology
Source: UN-Habitat, GCF, EPA, 2024 (Ref: TB5)

In 2022, the estimated water supply in Wadi Tuban comprised approximately 59 million cubic meters of renewable surface water, 139 million cubic meters of renewable groundwater, and 10 million cubic meters from non-conventional sources. Conversely, the total water demand amounted to approximately 194 million cubic meters for agricultural purposes and 50 million cubic meters for domestic use, thereby rendering agriculture responsible for nearly 80% of the overall consumption. This imbalance resulted in an approximate water deficit of 36 million cubic meters. Although the construction of dams and the implementation of rainwater harvesting techniques in upstream regions have contributed to mitigating flood risks, they have concurrently significantly reduced the flow of surface water downstream to the Tuban Delta. Consequently, minimal water now reaches the lower basin, with no flow reaching the sea. This scarcity has compelled communities and farmers to increasingly depend on groundwater extraction, often powered by solar energy, which has further expedited aquifer depletion. Coupled with the impacts of climate change, these pressures have exacerbated saltwater intrusion, accelerated desertification, and led to a dramatic decline in groundwater levels. Numerous wells have dried up, and the fertile soils in the lower delta have experienced severe degradation. This study has thoroughly examined the current situation in Wadi Tuban from multiple perspectives, identifying the most pressing challenges and proposing actionable recommendations. The principal areas of focus include:

Groundwater Conditions

Wadi Tuban encompasses approximately 3,600 wells, of which 1,200 have already become non-operational. The groundwater table is declining at an average rate of one meter annually, primarily due to an imbalance between extraction rates and natural recharge processes. If this trend continues, it is anticipated that by 2060, the majority of wells—particularly those located near the coastal zone—will either become dry or be affected by salinisation.

Water Supply and Demand Estimates

The sources of water supply include renewable resources, runoff from highland areas, and non-conventional water sources, with a total volume of approximately 10,175.73 million cubic meters. Conversely, water utilisation is estimated at 244 million cubic meters for agricultural purposes and 36 million cubic meters for domestic use, demonstrating that 82% of water consumption is allocated to agriculture.

Given the disparity between available water and water demand, the system is experiencing a water deficit estimated at 53 million cubic meters.

Future Climate Risks

Climate models indicate an increasing likelihood of extreme weather in Wadi Tuban, with major floods expected between 2060 and 2063 and 2074 and 2076, and drought conditions anticipated from 2029 to 2034 and 2069 to 2072. The coastal zone is particularly vulnerable, facing multiple threats, including flooding, prolonged droughts, rising sea levels, and saltwater intrusion. In 2022, the region experienced severe droughts in terms of meteorological, economic, and social conditions, which are likely to persist unless alternative water sources are developed.

Management and Climate Adaptation Options

A 2024 UNDP study reveals that the lower Tuban Delta, encompassing Aden city and parts of Lahj Governorate, is the most vulnerable to climate-related impacts, with four primary hazards: floods, droughts, sea-level rise, and saltwater intrusion.

These threats pose a significant risk to water supplies and coastal infrastructure, necessitating prompt adaptation measures.

The study emphasises the urgent need for sustainable solutions to enhance water supply in the lower delta and mitigate saltwater intrusion. It also highlights deficiencies in current management practices, emphasising the need for a sustainable water distribution strategy.

Furthermore, it highlights weak water governance and calls for an immediate and sustainable resource allocation strategy amid growing climate, social, and economic pressures. Through national consultations and stakeholder workshops, priority actions include upgrading irrigation to drip systems, rehabilitating wastewater treatment for agricultural reuse, enhancing groundwater recharge with floodwater, installing solar-powered desalination units to meet rising water demand in Aden, and establishing a disaster management and early warning system at the head of the Tuban Delta to address flood risks when streamflow exceeds 150 m^3/sec.

Institutional and Legislative Framework

Despite the existence of water laws and policies in Yemen, their insufficient enforcement diminishes the effectiveness of water resource management. To protect groundwater and promote public welfare, immediate actions are required to revise legislation to incorporate climate risk considerations, enhance institutional capacity, and develop a comprehensive strategic framework for water governance in the Tuban Delta.

Impacts of Dams and Water Harvesting

The study indicates that the development of multiple dams and rainwater harvesting techniques, alongside overuse of surface water in the upper part of the Tuban Delta (upstream), has contributed to reduced surface water availability in the lower region (downstream).

Possible Alternative Options

Water flow to the lower delta is limited, and no water reaches the ocean. This has compelled residents and farmers to depend heavily on groundwater powered by renewable energy, resulting in a water deficit of 84 million cubic meters in 2022. Water balance assessments project a deficit of 696 million cubic meters under the baseline scenario and 369 million cubic meters under the improved scenario by the year 2100. The water shortages projected under the baseline scenario are anticipated to surpass 400 million cubic meters by 2100 under both climate pathways, SSP3 and SSP5. The lower region is expected to face the most severe water scarcity, driven by increasing demand stemming from traditional irrigation practices and population growth. To address these water deficits, the following alternatives have been evaluated:

Table 4: Overview of Potential Water Management Measures and Their Estimated Contribution to Reducing Water Deficits

Measure	Potential Impact	Remarks
Drip Irrigation	Could reduce the deficit by 45–50%	Requires extensive implementation
Wastewater Reuse	Could compensate for ~10% of the shortfall	Based on treated septic tank effluent
Greywater Reuse	Potentially offsets ~5%	Currently not feasible
Artificial Recharge	Could contribute an additional ~5%	Using floodwater and treated water
Groundwater Oversight	Helps prevent overextraction and saltwater intrusion	Requires improved monitoring and regulation

Seawater Desalination as the Strategic Option

The Lower Region of the Tuban Delta is projected to be most adversely affected, with deficits ranging from 60 to 80 million cubic meters even under the improved scenario. To mitigate this issue, the study recommends the immediate development of a solar-powered seawater desalination plant with a capacity of 50 million cubic meters, followed by the incremental addition of plants with 10 million cubic meters capacity at intervals of five to ten years to satisfy future water demand.

Summary of Findings

There are significant temporal gaps in climate data (over 10 years between 2008 and 2020), which highlights the need for continuous field monitoring or supplementing the data from alternative sources.
The presence of only two surface runoff (flood) monitoring stations is insufficient to cover the hydrological spatial diversity of the basin. It is recommended to expand the monitoring network and rehabilitate the existing stations.
The available data provides a solid foundation for initiating hydrological modeling, but it requires further temporal and spatial enhancement.

Recommendations

1. *Water Level Dynamics Monitoring:* Fluctuations between static and moving averages reflect the effects of pumping and natural recharge. Analysing data weekly or monthly can help identify critical periods and inform operational adjustments.
2. *Optimising Operation and Maintenance:* Implementing smart monitoring systems and remote sensing technologies is crucial for maintaining efficient well performance and enabling early detection of technical problems.
3. *Modern Pumping and Renewable Energy***:** Incorporating advanced pumping methods and exploring solar energy options can enhance productivity and cut operational costs, especially in key fields like Bi’ar Nassar and Bi’ar Ahmed.
4. *Functional and Economic Feasibility:* Performing detailed feasibility studies for each field will aid in effective resource allocation and ensure sustainability, taking into account productivity variations and climate factors.
5. *Integration with Aden’s Water Management***:** Coordinating well data with urban planning and engaging technical stakeholders are vital for efficient management. A unified database is necessary to support planning and meet rising demand.

Highlights from Relevant Studies

Assessment of Dams and Water Structures in Wadi Tuban

Source: Dr. Ayoob Al-Muhab, Ministry of Agriculture, 2016 (Ref. TB16)

The study identified a total of 182 dams and water barriers, of which 129 are reservoirs specifically designated for water collection or storage, located both inside and outside administrative boundaries. Detailed data (see Figure 4) provide a comprehensive overview of the locations of these structures, their watershed areas, and their annual storage capacities. This information supports the evaluation of current water resource capacities and guides future efforts to improve water resource management in the region.

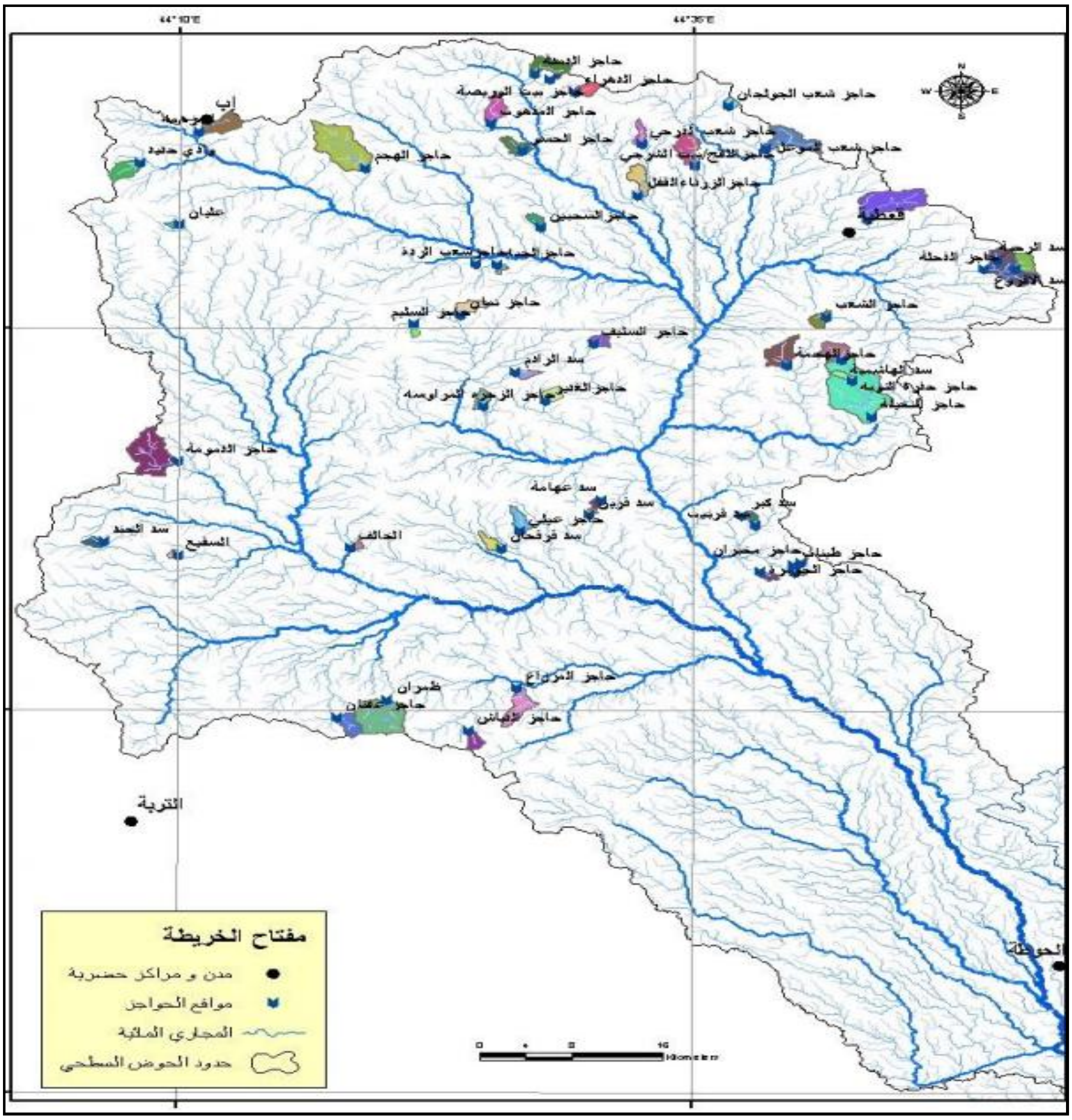


Figure 4: Locations of Dams in the Wadi Tuban Basin

The study also indicates that 74.5% of the dams remain operational, whereas the remaining facilities experience issues such as being halted, inactive, or incomplete.

Quantitative and relative data were collected concerning the condition of dams and various water structures to evaluate hydrological status, infrastructure, and operational efficiency. The study assessed each of the following:

Water Management and Usage Efficiency

The efficiency of water use from the dams does not exceed 40%, relying on traditional transport methods that result in considerable losses.
The study recommends adopting modern techniques for distribution regulation and efficiency enhancement.

Impact on Groundwater

The impact varies according to location; predominantly, adverse effects are observed upstream, characterised by reduced water levels, whereas some positive changes are noted downstream.
96% of the dams do not influence upstream wells except in cases of specific geological conditions.

Water Quality

The results exhibited variability in the physical and chemical characteristics.
Some samples demonstrated favourable qualities; however, considerable data gaps of 49–59% were identified, indicating a need for enhanced monitoring efforts.
Pollution levels from sewage and algae remain relatively limited, ranging from 6 to 10%, yet they still necessitate careful oversight.

Technical and Engineering Condition

The majority of dams are deficient in sedimentation basins and cleaning outlets, thereby posing a risk to the long-term efficiency of storage. However, the presence of minimal construction debris suggests a comparatively favourable physical environment.
Environmental and Health Standards
Indicators reveal an almost complete absence of environmental protection requirements; 89% of dams lack such provisions, necessitating immediate intervention to enhance protection and environmental health.

Geological Aspects

The presence of strong rock types like basalt and granite (12%) provides a good foundation, while fragile rocks pose engineering challenges.
Site Suitability
Over 88% of the proposed dam sites are considered suitable from a topographical and hydrological perspective, subject to reservations regarding land use and burial sites.

Current Status of Dams

The study offers a thorough overview of the dam situation in the Wadi Tuban basin, indicating that the majority of projects operate effectively but encounter technical, administrative, and environmental challenges. It advocates for comprehensive policies that aim to enhance performance through equipment upgrades, the adoption of smart technology, and improved coordination among stakeholders. Furthermore, it emphasises the necessity of implementing enhanced monitoring systems and maintaining updated databases to optimise water utilisation, support agricultural activities, and secure sustainable water resources.

The field survey evaluated the overall condition of the dams across seven categories describing their operational or structural status, as shown in Table 5.

Table 5: Current status of dams in the Wadi Tuban basin watershed

Category	Number of Dams	Percentage	Notes / Remarks
Working	38	74.5%	Operates efficiently and performs its required operational functions
Not Working	4	7.80%	Needs intervention or maintenance for rehabilitation
Under Construction	1	2.0%	In a development stage that has not yet been completed
Stalled	4	7.80%	Faces technical or administrative obstacles
Demolished	1	2.0%	Has been demolished for technical or safety reasons
Vacant	3	5.90%	Not currently in use or designated for future purposes
Total	51	100%	Total number of studied dams

Purpose of Dam Construction

Although primarily intended for irrigation and multi-purpose applications, highlighting their significance in agriculture and the economy, the majority of these structures are not functioning adequately. Figure 5 illustrates the various purposes for which dams are constructed.

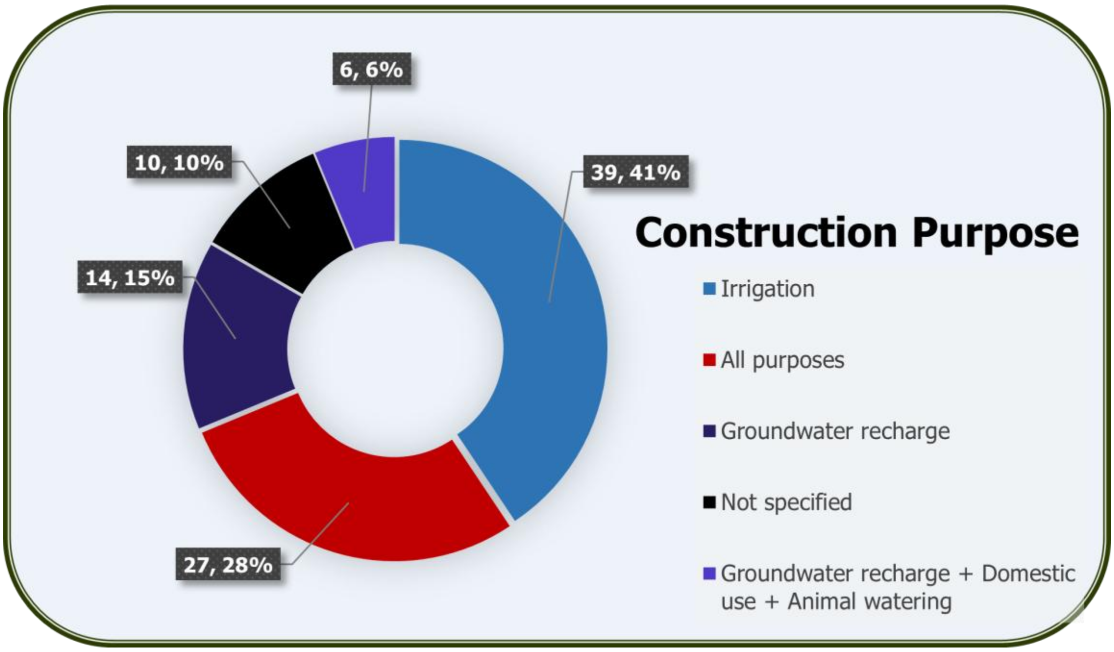


Figure 5: Purposes of Dam Construction

Below is Table 6, summarising potential reasons why dams may fail to perform their intended functions, categorised by type with brief explanations.

Table 6: Potential causes of a dam's failure

Function / Category	Cause
Technical and Engineering	Errors in design or construction leading to structural weakness
	Deterioration of components due to a lack of preventive maintenance
	The accumulation of sediments causes storage weakness and affects performance.
Administrative and Regulatory	Absence of monitoring and early evaluation programs for malfunctions
	Weak funding hinders the maintenance and modernisation of deteriorating or stalled dams.
	Weak coordination among entities leads to conflicting standards and procedures.
Structural and Geotechnical	Climate change affects the operational efficiency of older-designed dams.
	Soil movement or foundation settlement can lead to structural weakness.
	Lack of recharge or absence of sedimentation basins leads to a decrease in dam capacity and operational problems.

Sites' Suitability in Terms of Topography, Hydrology, Environment, and Land Use
The assessment indicates a high degree of suitability for dam and barrier construction across the majority of evaluated criteria, including topographic, geological, environmental, and hydrological factors, with suitability rates exceeding 88%. Conversely, land use and burial site considerations demonstrate lower acceptance, with suitability levels ranging from 69% to 73%, and 18% identified as unsuitable, while 14% remain unspecified. This highlights the need for further analysis in projects with significant impact, as shown in Figure 7. Such analysis facilitates the identification of optimal sites, whilst also emphasising areas that require mitigation measures or further investigation prior to investment. Although most locations prove viable, it is essential to address environmental and urban planning concerns to ensure the project's long-term sustainability.

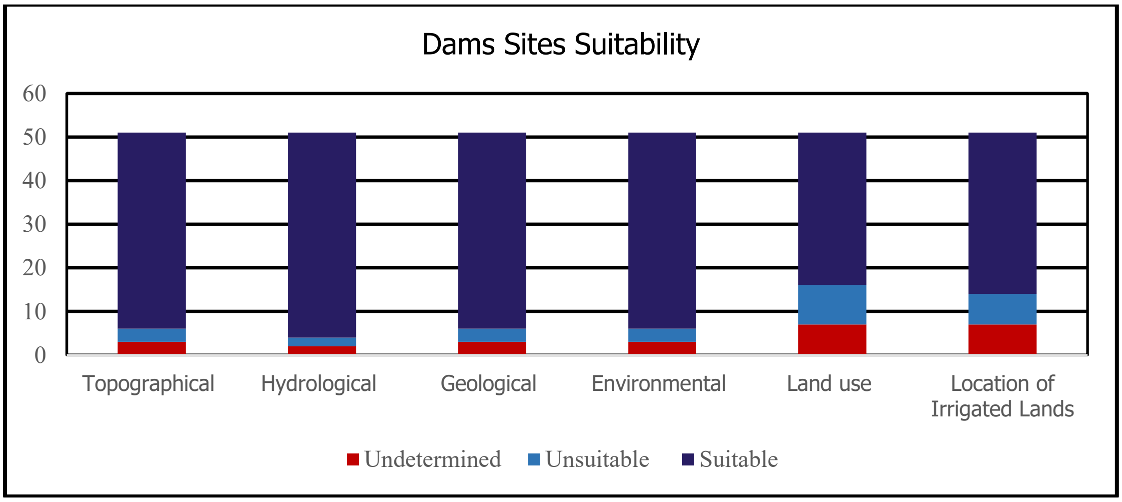


Figure 7: Suitability of Sites in Terms of Topography, Hydrology, Environment, and Land Use

Based on the field data, forty-five dam and barrier sites within the Wadi Tuban basin, accounting for approximately 88% of the total sites, are considered suitable from a topographical standpoint (as illustrated in Figure 7). Conversely, only three sites, representing about 6%, are deemed unsuitable, namely the Shuaib Al-Radah barrier, the Al-Lafh/Bayt Al-Sharhi barrier, and the Al-Khalifa barrier. The case of the Al-Khalifa barrier highlights the challenges associated with sediment disposal.
Beneficiary Satisfaction with Dam Construction
The study's findings concerning beneficiary satisfaction with the Proximity of the Site, Water Quality, and Ease of Water Access (see Table 7):

Table 7: Beneficiary Satisfaction with Dam Construction

Beneficiaries' Satisfaction						
Evaluation	**Location**	**Percentage**	**Ease of Access to Water**	**Percentage**	**Water Quality in the Dam**	**Percentage**
Good	25	49%	20	39%	22	43%
Acceptable	16	31%	21	41%	17	33%
Poor	3	6%	1	2%	3	6%
Unspecified	7	14%	9	18%	9	18%

Geological Indicators of Dams in the Wadi Tuban Basin

The geological analysis of dam distribution is based on the types of rocks that constitute their foundations. They are categorised into three primary groups that facilitate an understanding of the structural capabilities and engineering behaviour of each class of installations: (i) Granite and similar Paleozoic formations (Type A) support 12% of dams, including Othman and Khirazan, and offer superior stability owing to their high load-bearing capacity and resistance to weathering; (ii) the delicate Al-Tawila/Majzah sedimentary rocks underpin only 4% of structures, exemplified by Majzah Dam, and present stability challenges that necessitate mitigation; (iii) the most prevalent category, Tertiary volcanic formations, support 27% of dams (14 structures), though their variable porosity and anisotropic properties require careful evaluation. This classification enables targeted maintenance and informed site selection, with granite demonstrating the highest reliability, while volcanic rocks dominate regional construction despite their complex characteristics.

Hydrological Indicators of Dams in the Wadi Tuban Basin

The hydrological assessment emphasises the vital importance of hydrological indicators in evaluating water resources and formulating management decisions. An analysis of the dam's storage capacity (total system: 4.8 million m^3) indicates that 76.5% of the system attains full capacity annually, whereas 4% exhibit partial filling, and 19.5% lack monitoring data. This highlights both operational success and notable knowledge gaps that necessitate attention to enhance water management strategies.
Impact of Dams on Groundwater and Springs in the Wadi Tuban Basin
Dams significantly influence groundwater dynamics by substantially decreasing levels upstream by 96%, while concurrently increasing recharge downstream by 96%.

Additionally, they facilitate the formation of new springs in 96% of cases. Although water quality typically deteriorates, natural purification processes tend to improve at the majority of sites, accounting for 96%. These effects highlight the dual role of dams: depleting upstream aquifers and enhancing downstream water availability through redistribution and the formation of springs. Table 8 illustrates the impact of dams on groundwater.

Table 8: Impact of Dams and Barriers on Groundwater and Springs

Type of Impact	Groundwater Levels Downstream	Spring Productivity Downstream	Groundwater Levels Upstream	Spring Productivity Upstream	Emergence of New Springs	Groundwater Quality
Increase	36	29	17	16	22	34
Decrease	1	2	2	2	8	-
Undetermined	14	20	32	33	21	17

Operation and Maintenance

The study reveals significant inefficiencies in water management, as overall utilisation rates remain below 40% across both dam and irrigation systems. This suboptimal performance primarily results from the dependence on conventional water transportation methods at the agricultural level, which causes substantial distribution losses and a lack of intelligent allocation. The consequent stress on water resources diminishes agricultural productivity, highlighting an urgent requirement for the deployment of modernised infrastructure and monitoring systems to enhance water utilisation in this water-stressed basin.

Policies and Procedures

The study outlined several proposed policies and procedures to upgrade dams and improve their efficiency:

1. Perform regular assessments and maintenance using modern techniques to detect faults early.
2. Implement preventive maintenance systems and connect stakeholders via centralised platforms to monitor dam conditions.
3. Standardise criteria and enhance institutional coordination to ensure better resource use.
4. Invest in technologies such as smart monitoring devices and geographic information systems.
5. Encourage scientific research and community involvement to enhance dam management and raise environmental awareness.

Below is Table 9, which summarises the proposed policies and procedures for dam efficiency improvement, organised by main themes with the suggested actions listed for each area.

Table 9: Proposed actions for dam efficiency improvement

Category	Proposed Actions
Updating and evaluating infrastructure	Conducting a comprehensive technical evaluation using modern technologies (laser, drones) - determining maintenance priorities based on the degree of deterioration and financial impact.
Upgrading maintenance and management systems	Implementing preventive maintenance programs based on artificial intelligence and machine learning, and establishing centralised monitoring systems to display operational status in real-time.
Enhancing institutional integration and coordination	Unifying technical and procedural standards for dams - coordinating modernisation projects through joint committees to ensure efficient implementation and funding.
Investing in technology and innovation	Installing IoT sensors to monitor the structural and operational condition of the dam. Using GIS systems to integrate data and identify critical areas.
Encouraging research and community participation	Partnering with universities to conduct advanced studies on deterioration and technical solutions. Involving the local community to collect field data and raise awareness.

Recommendations

Modernisation and Smart Technologies

Deploy IoT sensors to monitor water quality and sediment levels.

Utilise satellite imagery and advanced technological tools for continuous environmental surveillance.

Develop interactive databases and dashboards to facilitate data-driven and informed decision-making.

Enhancing Management and Maintenance

Implement preventive maintenance strategies based on predictive analytics.

Perform routine sediment removal to optimise storage capacity.

Schedule regulated water gate operations to support irrigation and groundwater recharge.

Governance Reform and Institutional Coordination

Establish joint committees comprising government authorities, stakeholders, and community representatives.

Revise policies and allocate specific budgets for dam maintenance.

Improve integration between dams and irrigation systems to maximise agricultural water efficiency.

Community Engagement and Awareness

Involve local communities in monitoring and reporting water quality changes.

Conduct targeted awareness initiatives around dam locations to foster stewardship.

Desk Review Based Recommendations

Proposed action points for enhancing monitoring data, risk management, and well operations in the Wadi Tuban basin:

- Enhancement of Hydrological Data Monitoring
- Fill climate data gaps for the period 2008–2020 by reactivating field monitoring efforts or supplementing with satellite and regional meteorological data to ensure a comprehensive time series.
- Expand surface flow monitoring capabilities by increasing the number of stations from two to a minimum of five across major basins, and rehabilitate existing equipment.
- Enhance temporal and spatial coverage by implementing scheduled monthly or seasonal measurements for rainfall, runoff, and sediment; additionally, deploy automated sensors capable of transmitting real-time data.
- Conduct geological and topographic studies to update groundwater basin maps, thereby identifying optimal recharge zones and safe locations for drilling.
- Implement regular hydraulic testing to measure essential well parameters, including static levels, pumping rates, transmissivity, and storativity, at a minimum of biennial intervals.
- Sustainable Water Risk Management
- Monitor Over-extraction and Subsidence: Install digital meters in main wells, connected to alert dashboards, to notify when extraction limits are exceeded.
- Establish an Integrated Monitoring System: Track water levels, quality, and pumping rates with quarterly reports submitted to the relevant authorities.
- Standardise Pumping and Discharge Tests: Set safe extraction thresholds and regulate drilling permits accordingly.
- Improve Surface-Groundwater Interaction Knowledge: Observe seasonal floods and utilise harvesting and filtration structures to recharge reservoirs.
- Enhancing Water and Sanitation Services – Aden
- Analyse Water Level Dynamics: Utilise weekly and monthly data to identify stress periods and adjust pumping schedules accordingly.
- Implement Intelligent Maintenance Systems: Deploy vibration and temperature sensors on pumps to provide real-time fault alerts through a centralised application.
- Adopt Energy-Efficient Pumping: Replace conventional pumps with high-efficiency, solar-powered units.
- Conduct Feasibility and Resource Allocation Studies: Prioritise investments in productive wells; rehabilitate or decommission inefficient ones.
- Institutional Integration and Data Sharing: *Link field data with urban planning databases and establish an open platform to facilitate inter-agency coordination and informed decision-making.*

Annex 2 - Input Data Preparation and Processing for the SWAT Model

Topography

The topography forms the basis of the SWAT model because it determines the flow of water through the landscape. The ALOS digital elevation model was used to provide elevation data at 30 m spatial resolution (Takaku et al., 2014). The SWAT model uses slope as one of the landscape characteristics to define Hydrological Response Units. Slope bands therefore need to be determined. The Tuban Basin landscape is characterised by high variation in slope with the Tuban Delta and some areas in the upland being rather flat with the bulk of the pixels having a slope of less than 8%. In the upland areas slopes are much steeper, often above 40%. This resulted in the definition of three slope classes being 0-8%, 8-32% and above 32%. The slope map with the class bands is shown in Figure 8Figure 8: Slope map [%] as determined from the ALOS 30 m topography map. Colour bands are 0-8% red, 8-32% green and slopes above 32% white..

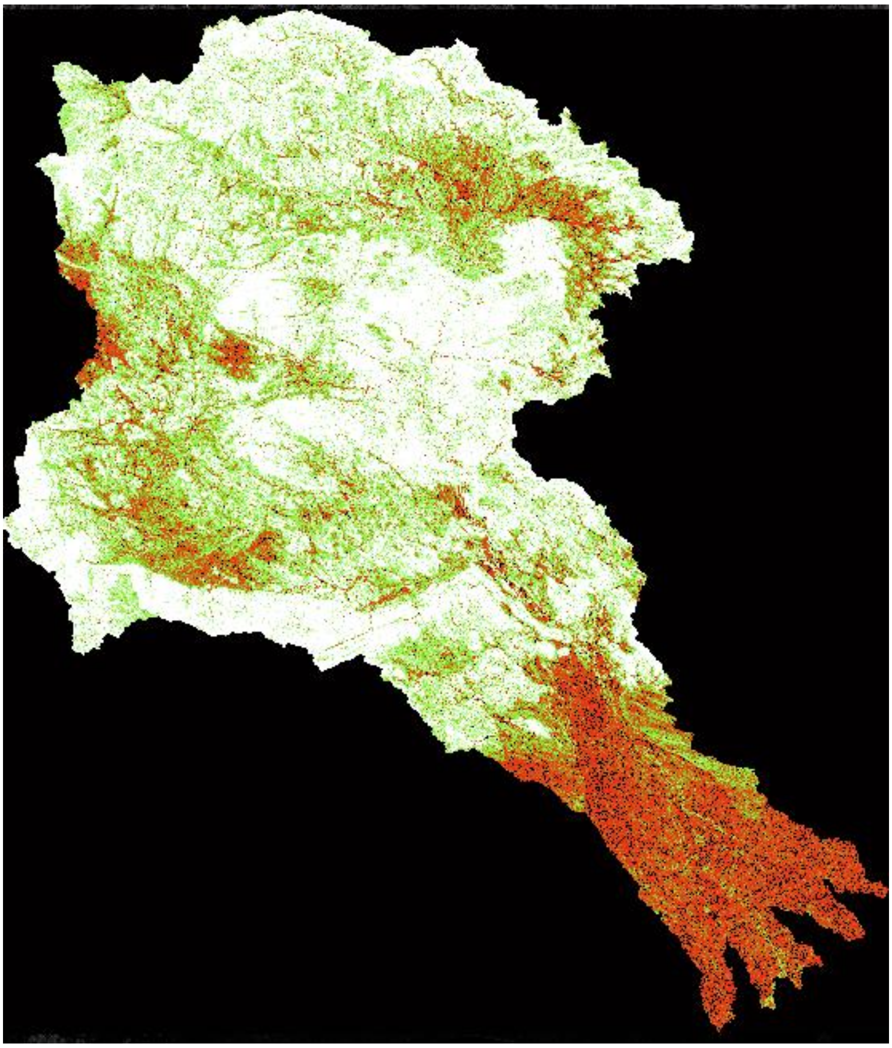


Figure 8: Slope map [%] as determined from the ALOS 30 m topography map. Colour bands are 0-8% red, 8-32% green and slopes above 32% white.

Land use- Land cover

Three dataset options were studied for the land use / land cover map. These were the 300 m resolution GlobCover 2009 (ESA, n.d.), the Copernicus Global Land Cover Layers CGLS-LC100 collection 3 at 100 m spatial resolution (Buchhorn et al., 2019) and the European Space Agency (ESA) WorldCover 2021 at 10 m resolution (Zanaga et al., 2022). The land use types distinguished by the ESA WorldCover dataset are presented in Table 10.

Two irrigation water sources are used in the area. The first one is spate irrigation with water that has been diverted from the wadi channels into a network of storage basins and irrigation channels. This type of irrigation system depend on the availability of surface water and is therefore related to the rainy season. The second source is groundwater, which can be used independently of the rainy period.

The higher resolution and more recent Copernicus CGLS and ESA Worldcover maps do not distinguish between irrigated and non-irrigated crop land. Irrigation results in areas being cultivated in dry periods, which increases the greenness of the land surface as indicated by a higher Normalised Differential Vegetation Index (NDVI). Cropland areas with relatively high NDVI were therefore considered irrigated. The annual average NDVI was obtained from the USGS Landsat 8 Collection 2 Tier 1 TOA Reflectance dataset at 30 m resolution (Loveland and Irons, 2016) for the five-year period 2020-2024. Irrigated cropland was set to ESA Worldcover cropland cells of which the corresponding annual median NDVI value was higher than 0.25. Irrigated cropland was given a code of 45 (Table 10). Alternatively, an estimate of irrigated cropland was made based with average January NDVI larger than 0.20. This map presented a higher irrigated cropland cover in the Tuban Delta and was deemed more realistic.

The field work provided information on the locations where irrigation occurred using surface water (spate irrigation) or groundwater. A comparison was made with irrigated cropland and orchards in the land use map of Figure 9 and the comparison was good with 63% of the irrigated land being recognized. Cropland that was not identified as irrigated but was observed to be irrigated accounted to 11% of the observations.

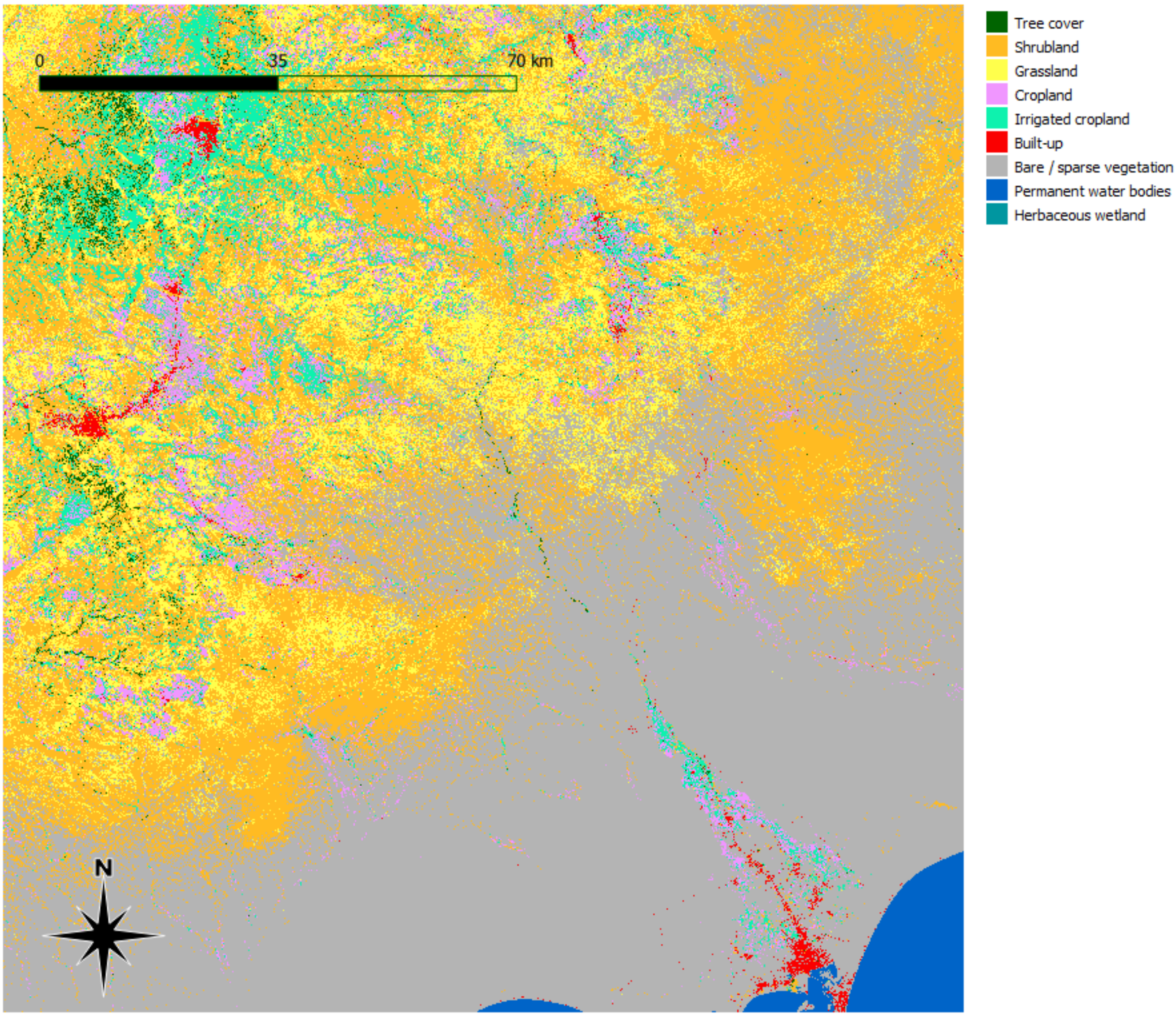


Figure 9: Land use map for the Tuban Basin with irrigated cropland derived from NDVI data.

Table 10. Land use codes, types and corresponding SWAT land use code. Tree cover was represented by mango and guava orchards.

ESA Code	Colour code	Type	SWAT LU code	Area (Ha)
10	#006400	Tree cover	ORCD	
20	#ffbb22	Shrubland	SHRB	
30	#ffff4c	Grassland	RNGB	
40	#f096ff	Cropland	DHWT	
45	#61e17b	Irrigated cropland[1]	AGRL	
50	#fa0000	Built-up	URBN	
60	#b4b4b4	Bare / sparse vegetation	BARR	
70	#f0f0f0	Snow and ice	n.a.	
80	#0064c8	Permanent water bodies	WATR	
90	#0096a0	Herbaceous wetland	WETL	
95	#00cf75	Mangroves	n.a.	
100	#fae6a0	Moss and lichen	n.a.	

[1] Based on ESA Worldcover cropland and an NDVI median value larger than 0.25.

Geology

The geological map is used for background information in the modelling process, where the soil map forms one of the main inputs for the SWAT model. Geology impacts soil formation and type and the spatial distribution of soil types therefore reflects changes in geology to a certain extent. The geology varies from non-consolidated deep young aeolian and alluvial formations in the Delta in the South of the basin to trachyte, rhyolite, granite, basalt, migmatite and sedimentary (calcareous) sandstone rock formations in the North upland areas.

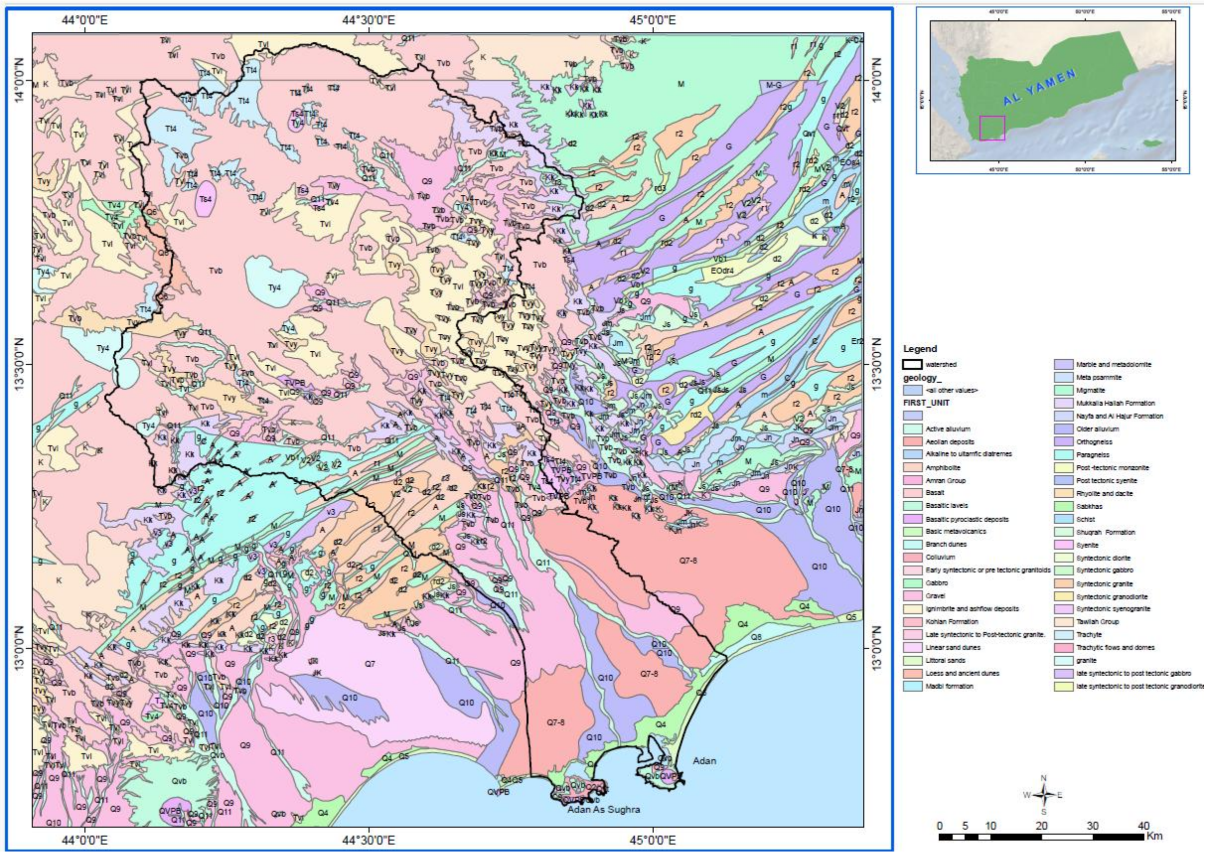


Figure 10: Geological map of the Tuban basin.

Faults in the area can act as barriers to groundwater flow, but also form increased groundwater recharge areas. Soils on fault zones should therefore have increased percolation fractions to groundwater instead of the regular default groundwater recharge fraction of 5%. The recharge fraction of percolating water was therefore set to 15% for soils within 500 m of a fault line.

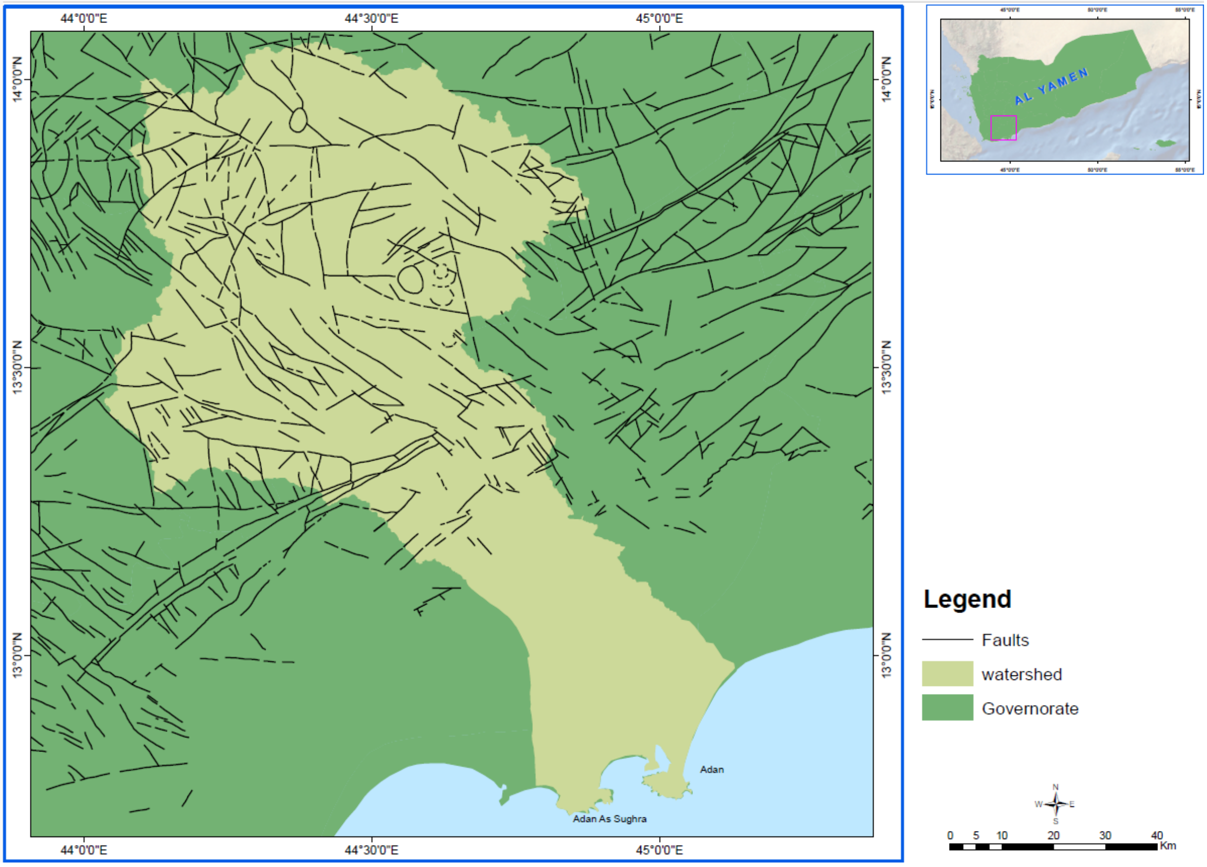


Figure 11: Fault map of the larger Tuban region.

Soil

Soil properties, such as infiltration and water holding capacities and depth are important parameters for the response of a catchment to precipitation. It is therefore important to have a good soil map, which should also include impacts of terracing on soil properties. Two soil maps were identified to characterise the soils in the Tuban Basin. These were the South Asia map (FAO-UNESCO, 1977) the Most Probable Reference Soil Group (Figure 12) from SoilGrids250m (Hengl et al., 2017), and the Soil map of the world (Figure 13). These maps provide soil classification information but not the soil physical data that SWAT uses for its simulations. However, the data from the FAO-UNESCO classification is provided in the SWAT database.

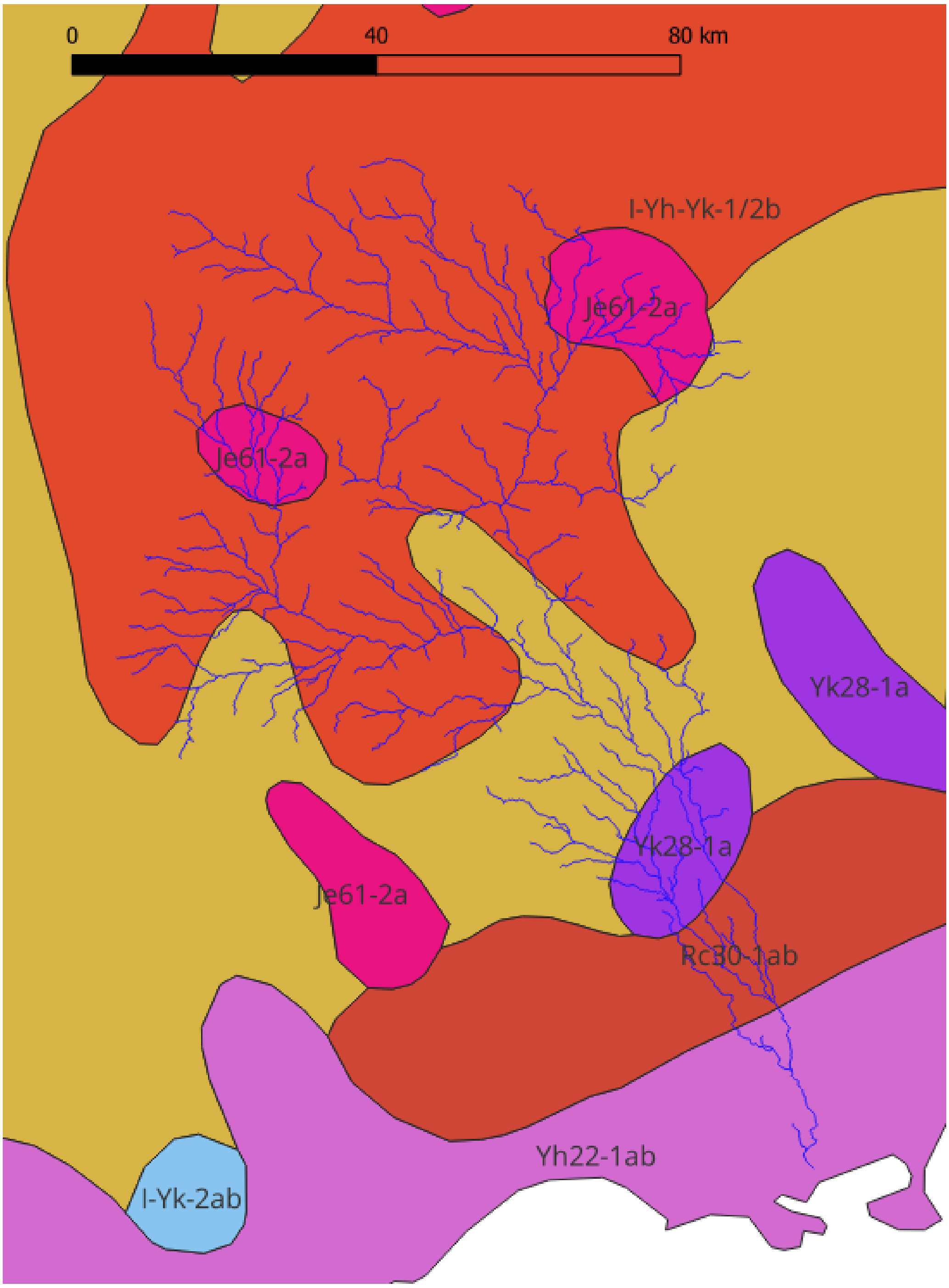


Figure 12. FAO-UNESCO South Asia soil map for the Tuban catchment area.

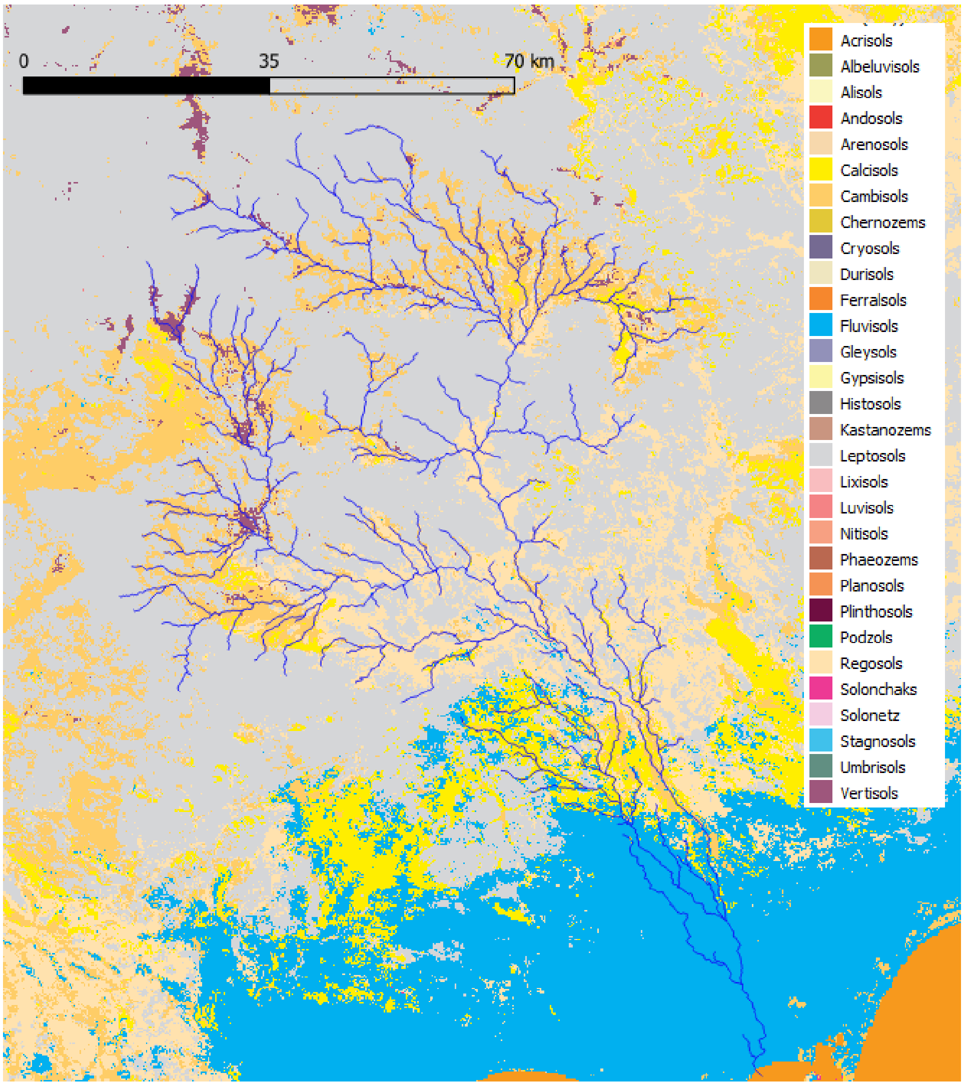


Figure 13. Soilgrids World Reference Base for Soil Resources map of the Tuban Basin.

The soil map for the Tuban catchment area was a modified version of the Soilgrids (Hengl et al., 2017) World Reference Base for Soil Resources (WRB) most probable soil type. Soil types with less than 100 pixel occurrence frequencies were converted to the most common Leptosol soil type (code 16), reducing the number of soil types to seven. In Table 11 the WRB codes and soil types are listed that are present in the catchment area.

Table 11. WRB soil codes, frequency of occurrence and types in the4 Tuban Basin and observed soil depths in the southern part of the basin.

WRB code	Pixel count	Type/ phase	Observed depth [m]	Depth range [m]
0	6904	Acrisols		
4	60	Arenosoil		
5	25806	Calcisols		
6	44602	Cambisols	3.33	1.25 – >4
11	67373	Fluvisols	>4	
15	5	Kastanozems		
16	208775	Leptosols	3.80	2.5 – >4
18	26	Luvisols		
20	10	Phaeozems		
24	62489	Regosols	2.00	
25	16	Solonchaks		
29	3262	Vertisols		

To develop a soil map that more accurately reflects the characteristics of the study basin, several key factors were taken into account. These included field-verified soil depth, the presence of shallow soils and rock outcrops, the influence of agricultural terraces on soil properties, soil conditions along geological faults, and areas with exposed bedrock. Based on these considerations, the base soil map was refined and updated. Additionally, a correspondence was established between the WRB (World Reference Base) soil classification codes and the SWAT-specific soil codes to ensure compatibility with the SWAT model. The parameters used to generate the final soil map, the defined SWAT soil classifications, and the resulting map applied in the model are presented below.

Soil depth from ground truthing

Field observations of soil depth were only possible in the southern part of the Tuban Basin due to permission and security issues. Most soils were of clay texture and their condition was deemed “good”. The depth observations indicated that the soils were generally much deeper than would be expected from their classification, with observed depths ranging from 0 for a rock outcrop on a Shallow Leptosol (code 100) to “deep” for Fluvisols and in the delta region in in agricultural areas. Taking a soil depth of 4 m for deep soils, the average soil depth was assessed at 3.36 ±1.09 m. This included the Fluvisols in the delta as well as Leptosols, which are normally of limited depth. These higher depth could be biased by the sampling of agricultural land. Depth ranges of different soils have been presented in Table 11. For the deep Fluvisols the depth of the soil was changed to 4 m.

Shallow soils and rock outcrops

On satellite imagery, rock outcrops are clearly visible with limited soil cover. Soil type code 100 for rock outcrop was therefore added to soils of the WRB soil map. Satellite imagery showed that where land use type was classified as ‘bare soil’, in the higher, Northern part of the catchment, mainly bare rock was present. While the soil map on these locations showed different varieties of soils not corresponding to bare soil. However, in the southern part of the catchment the land use type ‘bare soil’ is not corresponding to bare rock mainly because it is at lower altitude and has fluvial soils. Therefore the soil type rock outcrop was created at the locations were land use was classified as ‘bare soil’ except for the locations where there are Fluvisols (Figure 13), making sure that the soils in the lowlands were not classified as ‘rock outcrop’.

Leptosols are very shallow soils over hard rock, with depths of less than 250 mm. Soil type code 200 was created to represent Shallow Leptosols (Lithic Leptosols). This means that on locations where the land use type was grassland in combination with the Leptosol soil type, the new soil type ‘shallow Leptosol’ was created. For shallow Leptosol the soil depth Z was reduced to SOL_ZMX = 200 mm with SOL_Z1= 100 mm.

Impact of terraces on soil

The SWAT models creates HRUs based on slope, soil and land use. In terraced landscapes, the slope may still be calculated as steep from the terrain analysis, which would lead to increased surface runoff at these sites in comparison to runoff from terraced landscape. In reality, terraces form flat areas in the landscape, where surface runoff would be reduced and infiltration increased in comparison to adjacent non-terraced areas. In addition, the construction of terraces increases the soil depth leading to a higher moisture storage potential.

To reflect the impact of terraces on the hydrology,. the properties of the soil in terraced landscapes needed to be modified. This was done as follows:

1. Soil depth for soils in terraces (SOL_Z2) was increased to 3 m;
2. Maximum rooting depth SOL_ZMX was increased to 1.5 m;
3. Top soil infiltration was increased by 300%;
4. Soil erodibility factor decreased by 20%;
5. The soil group was changed to a group with better drainage (A or B);

And for terraced HRUs:

1. The curve number CN2 value was decreased by 10%;
2. Manning’s roughness coefficient was increased to that of Conventional tillage, residue, at 0.19.

Data from the global terrace dataset developed by Li et al. (2025), based on Sentinel-2 imagery, were requested but not obtained in time. As such Metameta digitised the terraces in the Tuban catchment based on remotely sensed images of the landscape. However, this was not complete in its cover. Due to time restrictions this map, with its flaws, was used to identify terraced areas in the Tuban catchment.

Soils on faults

All the soil types starting with 1000, represent soils lying on faults. Since fault zones have higher permeability and groundwater recharge potential it is important to take these into consideration and adapt soil parameters at these locations, for example by increasing the hydraulic conductivity of the bottom layer (SOL_K2). The map of the faults presented in Figure 11 area was used to define these new soil types using a 250 m buffer area to delimit the fault zone. For soils in fault zones the variable saturated conductivity SOL_K1 or SOL_K2 of the bottom layer was tripled in value;

Rock outcrops

Rock outcrops are common in the area but these were not indicated in the Soilgrids soil map. For these locations a very thin soil was defined with the following properties:

- For normal rock outcrop: SOL_ZMX = 10 mm, SOL_Z1 = 10 mm (furthermore, soil physical properties taken as for Leptosol I-Y-bc-3515);
- For rock outcrop in fault zone: SOL_ZMX = 10, SOL_Z1 = 10, SOL_K1 = doubled in value.

Matching the WRB soil codes to SWAT soil codes

Before being able to run the model the soil codes of WRB should be linked to the soil codes used in SWAT, SNAM (which are FAO soilcodes). In the QSWATRef2012 database, in the tabsheet 'usersoil' (which contains the SNAM and also physical specifications of the soil) new soils should be added, with new physical characteristics. Already existing soils should be written in an excel look up table with the QGIS code and the SNAM code. This table should be selected as soil look up table.

Linking the WRB codes to SNAM codes is done by using the existing FAO soil codes and try to match them as good as possible to the WRB soil codes. The matching has been done with the help of Table 4 of the FAO document (FAO-UNESCO soil map of the world, 1:5000000; v. 7: South Asia). For the Arenosols, Cambisols, Fluvisols and Regosols this matching could be done quite well since it was found that these soils occur in Yemen. However, for the other soils it was more difficult since the FAO document did not mention these specific soils in Yemen. Therefore ChatGPT was asked to match the WRB soil codes to the most likely FAO codes (which correspond to SNAM codes in SWAT). This resulted in the following matches, this should be checked based on expert knowledge.

The codes used by the FAO are explained as follows (FAO-UNESCO, 1977) for soil type Ao52-3bc-5121:

- The first characters represent the dominant soils type, e,g. Ao is Orthic Acrisol
- The 3 after the dash represents the soil texture class (1 = coarse, 2 = medium, 3 = fine);
- The next small-caps characters indicate the slope class (a- level to undulating; b- rolling to hilly; c-steeply dissected to mountainous), bc represents rolling to steep terrain;

Since for most soils this still results in a lot of possible matches, the next step is to find for which matches there are 'associated soils' that are also in the soil map. Second step in this selection was looking at the slope classes (characters are (a) level to undulating, (b) rolling to hilly, (c) steeply dissected to mountainous. This reflects the total procedure of matching the WRB soil classes with the FAO soil classes. The result can be found in Table 12.

1. Calcicols → Lk (Calcic Luvisols)

- **Reasoning:** Calcicols usually refer to soils with **accumulated calcium carbonate**, common in **semi-arid to arid** zones. These are often classified as **Calcic Luvisols** in FAO, especially in **upland valleys and footslopes** in Yemen.
- **Best match:** Lk – Calcic Luvisols

2. Vertisol → Vp (Pellic Vertisols)

- **Reasoning:** Vertisols in Yemen usually form in **low-lying, seasonally wet plains and basins**, often with **cracking clay**. In FAO, **Pellic Vertisols** are the most widespread type in arid and semi-arid regions.
- **Best match:** Vp – Pellic Vertisols

3. Cambisol Be (Eutric cambisol)

- **Reasoning:** Found on **upland terraces, moderate slopes**, with some **profile development** (but not as much as Luvisols or Acrisols)
- Tend to be **moderately deep, fertile, and loamy** → supports using **Eutric Cambisol**

The soil map resulted from overlay with fault and terrace data is shown in Figure 14.

Table 12. Translation of soil classifications to SWAT database soils. Soils ending with _f were modified to represent soils in fault zones, whereas those with _t represented soils in terraced areas.

WRB Code	Type / phase	SWAT SNAM	Depth [m]	Note
0	Acrisols	Ao52-3bc-5121	0.96	Fine texture, sloping terrain
5	Calcisols	Lk5-3ab-3534	0.74	Only one option for Calcic Luvisol
6	Cambisols	Be73-2c-3673	0.30	Cambisol with Leptosol as associated soil
11	Fluvisols	Je61-2a-3530	1.00	Medium texture, level to undulating landscape, Depth set to 4.00 m
16	Leptosols	I-Y-bc-3515	0.55	Leptosols (WRB) are the modern equivalent of Lithosols (FAO).
24	Regosols	Rc34-3b-4033	1.00	Fine textured, sloping terrain
29	Vertisols	Vp39-3b-3563	1.00	Pellic Vertisol with associated soil Vertic Cambisol
3000	Water	Water-1972	0.02	Open water body
100	Rock outcrop	Rock_Tuban	0.1	
200	Leptosols shallow	I-Y-bc-3515_s	0.2	
1000	Acrisols_fault	Ao1-3a-5357_f	1.00	
1005	Calcisols_fault	Lk5-3ab-3534_f	0.74	Soil in fault zone
1006	Cambisols_fault	Be73-2c-3673_f	0.3	Soil in fault zone
1011	Fluvisols_fault	Je61-2a-3530_f	1.00	Soil in fault zone
1016	Leptosols_fault	I-Y-bc-3515_f	0.55	Soil in fault zone
1024	Regosols_fault	Rc30-1ab-3546_f	1.00	Soil in fault zone
1029	Vertisols_fault	Vp39-3b-3563_f	1.00	Soil in fault zone
1100	Rock_outcrop_fault	Rock_Tuban_f	0.1	Soil in fault zone
1200	Leptosols_shallow_fault	I-Y-bc-3515_s_f	0.2	Soil in fault zone
2000	Acrisols_terraced	Ao1-3a-5357_t	1.50	Terraced soil
2005	Calcisols_terraced	Lk5-3ab-3534_t	1.50	Terraced soil
2006	Cambisols_terraced	Be73-2c-3673_t	1.50	Terraced soil
2011	Fluvisols_terraced	Je61-2a-3530_t	1.50	Terraced soil
2016	Leptosols_terraced	I-Y-bc-3515_t	1.50	Terraced soil
2024	Regosols_terraced	Rc30-1ab-3546_t	1.00	Terraced soil
2029	Vertisols_terraced	Vp39-3b-3563_t	1.00	Terraced soil
2100	Rock_outcrop_terraced	Rock_Tuban_t	0.1	Terraced soil
2200	Leptosols_shallow_terraced	I-Y-bc-3515_s_t	1.5	Terraced soil

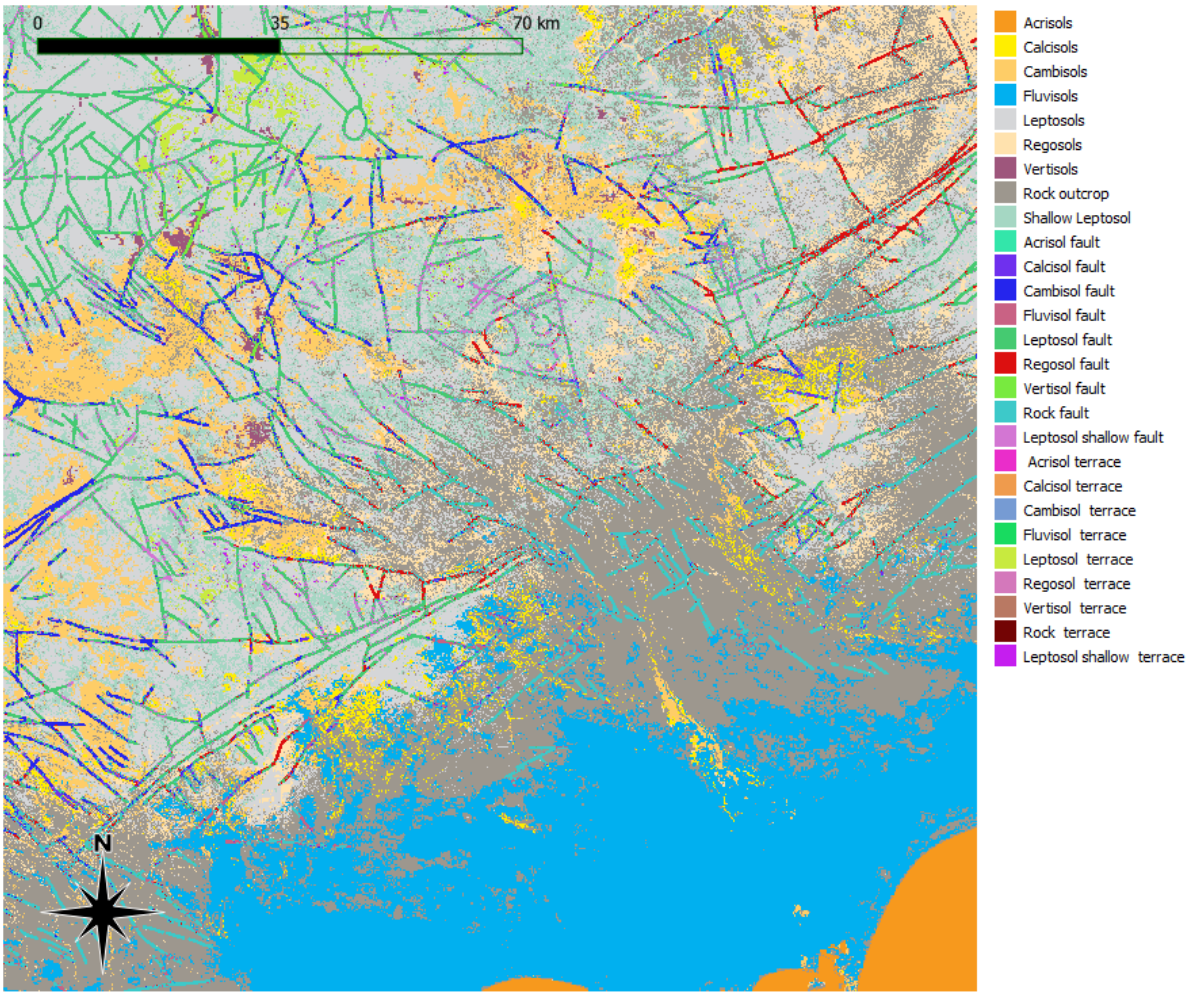


Figure 14. Tuban Basin soil map incorporating soils on faults and terraces with different properties than the regular soils.

Meteorology

Due to the absence of a consistent dataset containing daily precipitation measurements in the Tuban watershed, public datasets were used to predict the daily precipitation values for the area based on the limited local station data. The objective of this process was to generate a gap-free dataset that could be used as an input to the SWAT model for hydrological simulations.

To build this prediction model, daily precipitation data were extracted from two sources: CHIRPS and ERA5. The CHIRPS (Climate Hazards Group InfraRed Precipitation with Stations) dataset provided high-resolution daily precipitation estimates derived from satellite imagery and ground station data. Additionally, the ERA5 dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF) was used for its high-resolution climate data, including daily precipitation estimates. Elevation data was extracted from the Shuttle Radar Topography Mission (SRTM) dataset, which provided global elevation data critical for capturing topographical variations in precipitation patterns.

ERA5 is known to overestimate precipitation in the region, particularly in lower-lying areas, but performs more reliably at higher elevations. In contrast, CHIRPS aligns better with observed values in lower elevation zones. Therefore, a conditional rule was applied to assign the final precipitation value per point: ERA5 was used for points above 1050 meters, and CHIRPS for points below this threshold. This rule was based on the comparison of elevation and observed precipitation values at the local weather station, as illustrated in Figure 15.

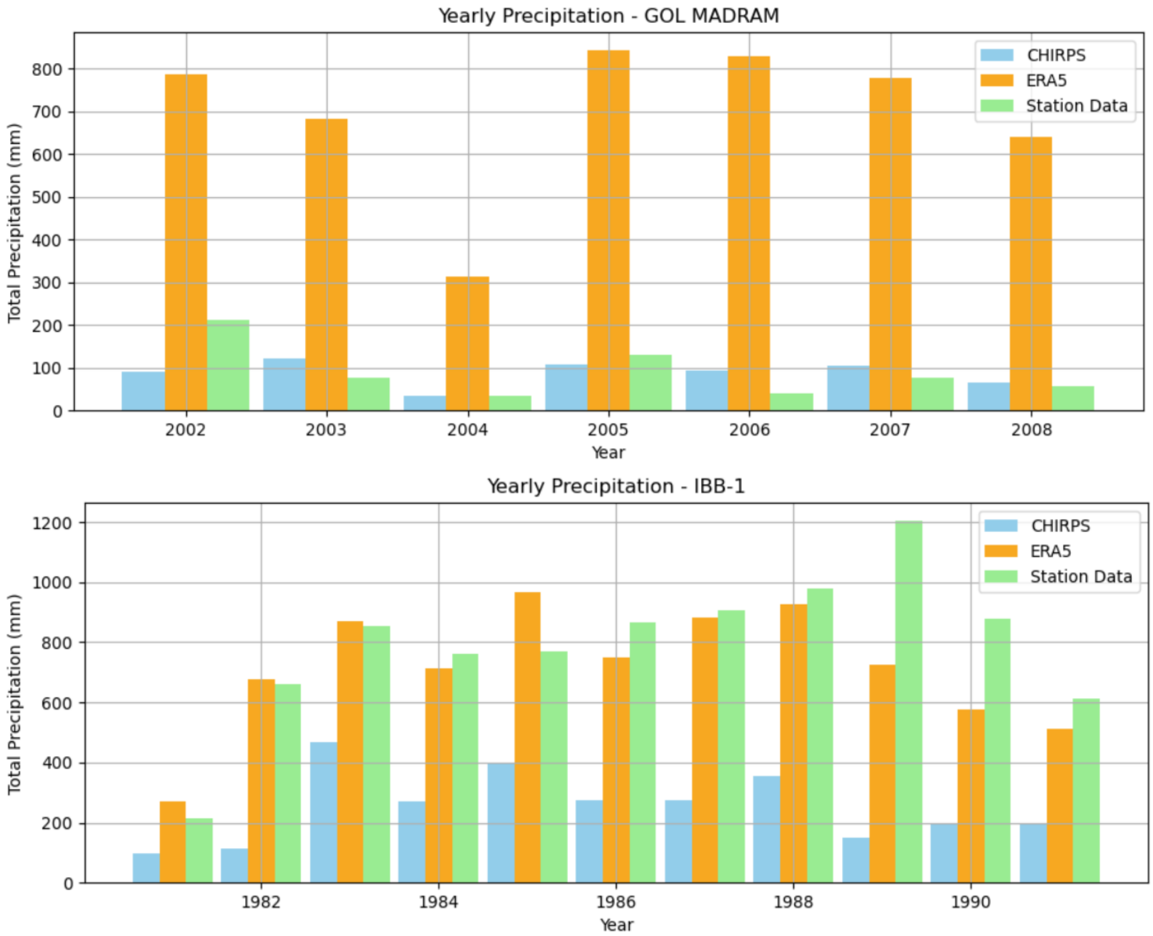


Figure 15. Comparison of yearly total precipitation from CHIRPS, ERA5, and weather station data at two locations in the study area. The top panel shows GOL MADRAM (465 m elevation, SRTM), where ERA5 consistently overestimates precipitation compared to CHIRPS and station data. The bottom panel shows IBB-1 (2405 m elevation, SRTM), where ERA5 aligns more closely with station observations, while CHIRPS tends to underestimate precipitation. These results support the elevation-based rule for selecting the most suitable precipitation dataset: ERA5 performs better in higher elevation areas, while CHIRPS is more accurate in lower elevation zones.

The first step in the process was to preprocess and clean the datasets to match the station data. This is done by making sure that the timeframes are similar, since the stations have measurements in different time periods. The next step was the development of the prediction model. A multiple linear regression approach was used, where CHIRPS precipitation, ERA5 precipitation, and SRTM elevation data served as the independent variables, and the observed station-based precipitation data was used as the dependent variable. The model was trained using available station data to learn the relationship between the features and observed precipitation, allowing it to predict daily precipitation values.

The model struggles to predict daily precipitation values accurately. However, when the data is aggregated on a monthly or annual basis, the predictions improve significantly (see Figure 16). This improvement occurs because daily precipitation data tends to be highly variable, influenced by many short-term atmospheric factors, such as storms or localized weather patterns, that the model may not fully capture. On the other hand, aggregating the data over longer periods, such as months or years, helps smooth out these fluctuations and reduces the impact of short-term variability, allowing the model to better capture the overall trends and patterns in precipitation.

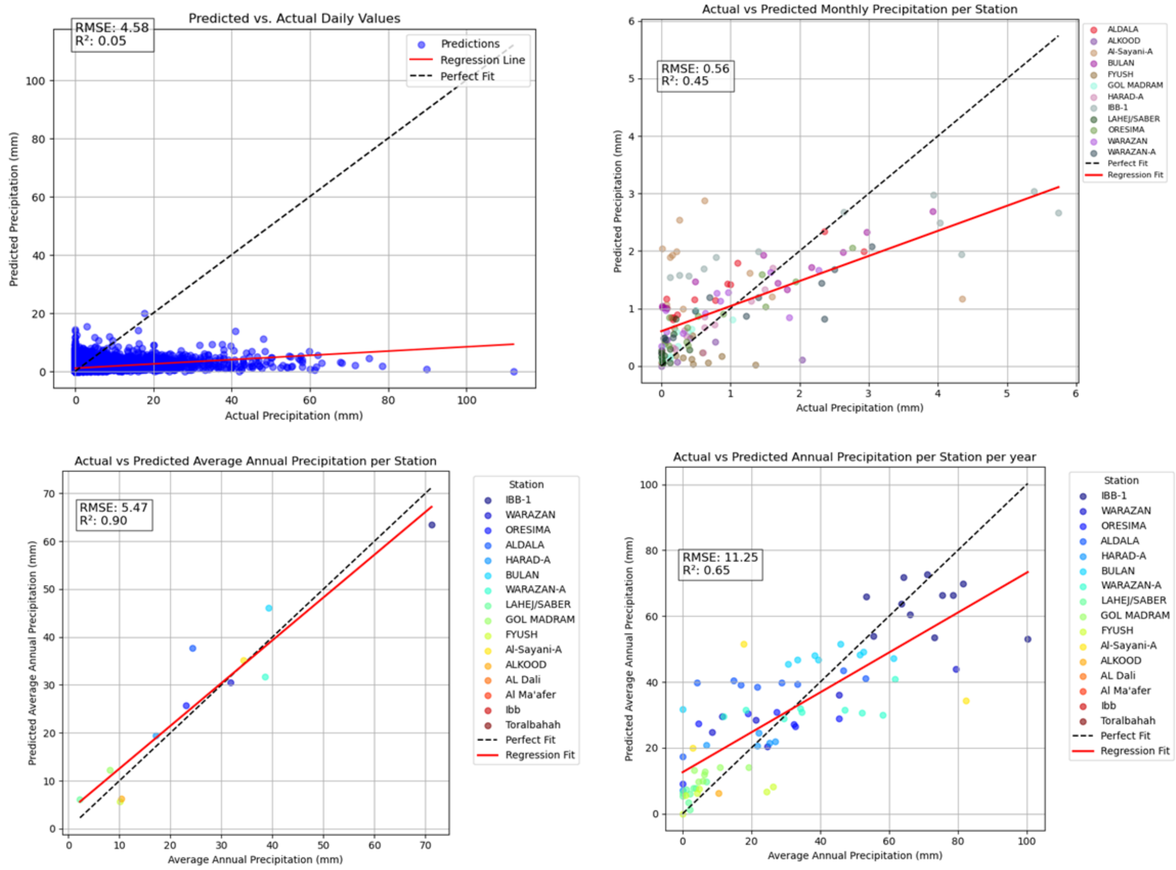


Figure 16. Model performance based on the (time-aggregated) data.

With the model trained, the next step involved creating a 5x5 km point grid as the sampling framework within the focus area over the Tuban watershed. This grid was designed to ensure full coverage of the area, with grid points spaced 5 km apart. Using Google Earth Engine (GEE), daily CHIRPS and ERA5 precipitation values, as well as elevation data from SRT, were extracted and stacked into multiband images

These values were then input into the trained model to predict the daily precipitation for each grid point and to obtain daily time series per point. The resulting predictions provided a continuous spatial distribution of precipitation across the watershed (Figure 17).

NOTE: Instead of performing raster-based calculations in GEE's cloud environment, use point sampling to extract raw CHIRPS, ERA5, and Elevation data for the grid. Then, compute the predicted values locally using python pandas for data frame manipulation.

This approach is significantly more efficient, reducing computation time from hours to minutes.

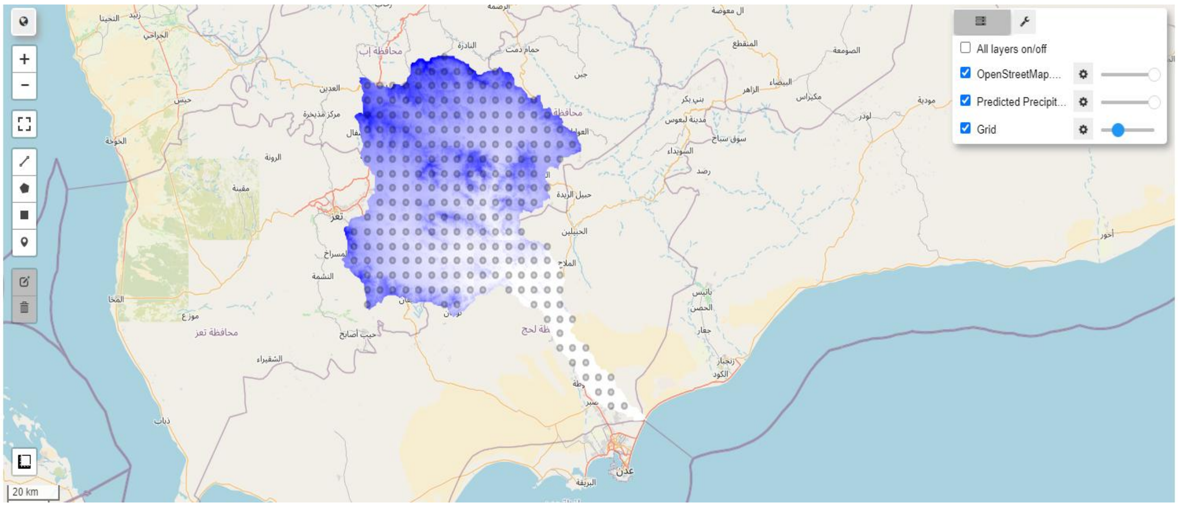


Figure 17. The 5 x 5 km grid for extracting the daily CHIRPS, ERA5, and SRTM data. The model is used to predict the final precipitation values. Just for illustration purposes one day has been processed through the earth engine to get a raster showing the relation between elevation and precipitation in the predicted dataset. Color scale: white: 0 mm, blue: 2mm.

In addition to precipitation, other meteorological variables were extracted from the ERA5-Land dataset to support SWAT modeling. These variables are:

- Temperature
  - Minimum temperature at 2 m (K)
  - Mean temperature at 2 m (K)
  - Maximum temperature at 2 m (K)
  - Dew point temperature at 2 m (K)
- Windspeed
  - U component of windspeed at 10 m (m/s)
  - V component of windspeed at 10 m (m/s)
- Surface net solar radiation (MJ/m²)

Data retrieval was performed for the same 5×5 km spatial grid points used in the precipitation analysis, ensuring spatial consistency across all meteorological inputs. The daily values for each variable were collected using Google Earth Engine, stacked, and sampled at each grid location the same way as the precipitation dataset.

Two variables, wind speed and relative humidity, were not directly available in the required form and were derived from primary ERA5 variables:

Wind speed was calculated from the u- and v-components of wind at 10 meters height using the following formula:

$$U = \sqrt{u^2 + V^2}$$

Relative humidity (RH) was calculated using 2-meter air temperature and 2-meter dewpoint temperature data obtained from the ERA5 dataset. The calculation is based on the ratio of actual vapor pressure to the saturation vapor pressure, expressed as a percentage.

The relative humidity is computed using the following formula:

$$RH = 100 \times \left(\frac{e}{e_{sat}}\right)$$

Where:

- e is the actual vapor pressure, derived from the dewpoint temperature (T_{dew})
- e_{sat} is the saturation vapor pressure, derived from the air temperature (T)

Both vapor pressures are calculated using the empirical Magnus formula (Lawrence, 2005):

$$e = 6.112 \times exp\left(\frac{17.67 \times T}{T + 243.5}\right)$$

$$e_{sat} = 6.112 \times exp\left(\frac{17.67 \times T_{dew}}{T_{dew} + 243.5}\right)$$

SWAT-MODFLOW coupling

Purpose of modeling

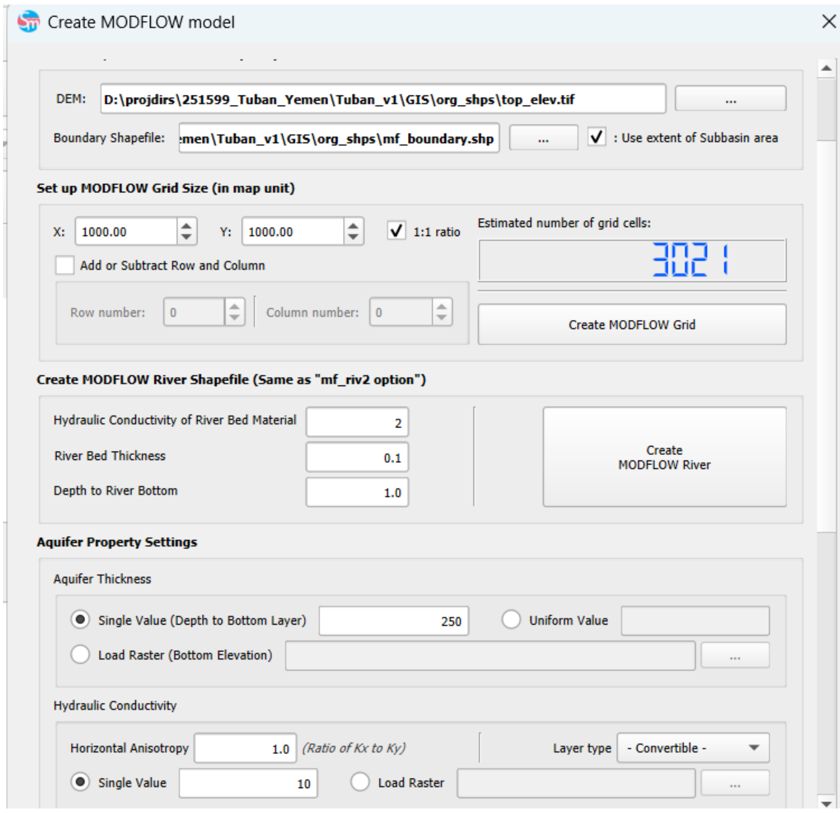
- Link the existing SWAT model in the Tuban District area to a simple MODFLOW groundwater model
- Determine the effect of groundwater abstraction for irrigation on the level of the groundwater table, and determine if the yield is sustainable or not.

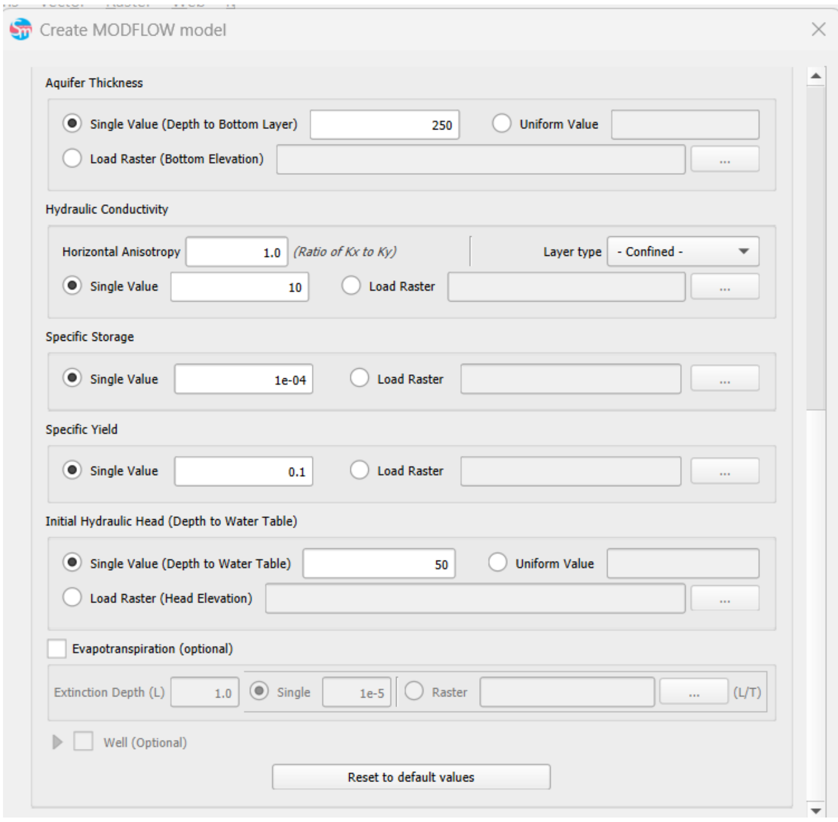
Model setup

1. Add QSWATMOD2 and SWAT as plugins to QGIS
    a. link for downloading QSWAT: https://swat.tamu.edu/software/qswat/
    b. link to downloading QSWATMOD: SWAT-MODFLOW | SWAT | Soil & Water Assessment Tool
2. **Tuban_v1**: model using the "tuban_district_v3" SWAT model as a test to make sure the interface is working: R:\251599_tuban_phase_2\swat\tuban_district_v3\Scenarios\Default
    a. Use the QSWATMOD interface to create the MODFLOW model.
    b. Initially try values that are constant across the model area, then test using a raster to differentiate areas based on values that were used in the 2002 report that created a modflow model of the region
    c. In Tuban_v1: created some random observation points rather than using a well point shapefile.
3. Need to close the "create a simple MODFLOW model" once confirmed that it generated the MODFLOW files required to be able to continue to the next step. Then you can check the option 1: MODFLOW files and grid already exist, and link to the directory where you just saved your MODFLOW files.

4. If you created a river network (.riv package) using the SWAT model rivers, then you should select "Use ONLY SWAT river network", and overwrite the MODFLOW river package

Tuban_v2 and Tuban_v3: some edits were made to the SWAT model, so re-created the model. Still used "create simple MODFLOW model" with single values for the whole model extent based on the 2002 modflow model in the KOMEX Water Resources Management Studies in the Tuban-Abyan Region Report:





Errors with creating output files! Only some of the required output files are created. E.g., you can create the river stage graphs, but there are issues creating hydraulic head in the time series that is selected. Tuban_v4, v5 and v6 attempt to solve this error. In v6, use default values for the MODFLOW model creation, perhaps there were issues with the aquifer properties we input. Error with reading empty values for delr, so opened the linking_processes.py file and manually entered the values for delr and delc.

- If there is an error about the top_elevation when you click "write MODFLOW model", this is a glitch that happens if you open a new project and you see that the SWAT input files have already been loaded. You have to close QGIS and reopen it, then open QSWATMOD and start a new project again.

Tuban_v6: with GW model in the "SWAT-MODFLOW" folder within the "Tuban_v6" folder, and with manual entry of grid sizes in flopy, model ran successfully.
Tuban_v7: re-try with simple values from the Komex report. Model crashes after running for 88 days.
Tuban_v8: only alter the layer thickness and initial head from the default values, keep other model parameters at default to see if that fixes convergence error. This works.

TO DO:

- Add pumping wells to the model. Issues because there are >1 well per model grid cell, so we need to calculate a reasonable pumping rate and create a new shapefile with a reasonable number of representative wells.
- QSWATMOD cannot create a MODFLOW .wel file. We can add a well file as observation points, then tell the model that these observation points are also pumping wells, and SWAT will calculate the pumping rate.

- We need to figure out how we can define the pumping rate ourselves.

Flopy model exists in the folder directory, but it was decided to generate the MODFLOW model with the QSWATMOD interface, so this flopy model is not complete.

Annex 3 – Monte Carlo calibration results

Table 13: Best-fit results based on the highest R^2 scores per subbasin.

SUB	r2_score	rmse	r	ESCO	EPCO	CN2	CANMX	MCid
1	-2.12	38.06	0.53	1.05	1.20	0.65	1.48	985
2	-2.30	49.11	0.49	1.05	1.20	0.65	1.48	985
3	-2.52	38.59	0.51	0.60	0.29	0.58	0.58	26
4	-1.94	39.93	0.64	0.51	0.31	0.62	0.77	199
5	-1.10	29.41	0.62	0.51	0.31	0.62	0.77	199
6	-2.15	47.03	0.59	0.75	0.33	0.59	0.48	1676
7	-2.72	43.43	0.18	1.05	1.20	0.65	1.48	985
8	-0.69	32.34	0.62	0.81	0.20	0.62	1.02	1338
9	-0.49	21.81	0.57	0.95	0.29	0.55	1.18	1
10	-0.60	29.58	0.61	0.81	0.20	0.62	1.02	1338
11	-0.32	23.45	0.67	0.92	0.29	0.64	0.13	222
12	-2.76	42.10	0.43	0.60	0.26	0.63	0.04	1447
13	-3.35	65.40	0.55	0.51	0.31	0.62	0.77	199
14	-2.37	32.26	0.55	0.53	0.76	0.62	1.36	1231
15	-0.09	30.94	0.45	0.81	0.20	0.62	1.02	1338
16	-0.33	34.24	0.45	0.63	0.21	0.70	1.40	1483
17	-0.52	24.81	0.35	0.88	0.52	1.18	1.48	1856
18	-4.11	48.24	0.44	1.05	1.20	0.65	1.48	985
19	-1.88	39.67	0.50	0.50	1.40	0.85	0.25	1004
20	-2.36	47.30	0.47	0.50	1.40	0.85	0.25	1004
21	-2.42	46.68	0.43	1.05	1.20	0.65	1.48	985
22	-2.55	38.97	0.54	0.50	1.40	0.85	0.25	1004
23	-2.34	45.52	0.61	0.50	1.67	0.74	1.00	1394
24	-2.43	47.15	0.59	0.51	0.31	0.62	0.77	199
25	-1.98	36.92	0.64	0.51	0.31	0.62	0.77	199
26	-3.15	53.64	0.49	0.81	0.20	0.62	1.02	1338
27	-0.30	16.50	0.60	0.95	0.29	0.55	1.18	1
28	-0.40	18.42	0.35	1.29	0.25	1.44	0.19	1363
29	-0.81	21.25	0.61	0.70	0.29	0.60	1.48	1136
30	-0.16	21.10	0.43	1.07	0.20	1.21	1.37	1223
31	-0.03	27.41	0.40	0.74	0.32	1.22	0.91	665
32	-0.37	37.38	0.38	0.63	0.21	0.70	1.40	1483
33	-0.30	25.91	0.37	1.13	0.21	1.36	1.24	228
34	-0.32	22.49	0.29	1.13	0.21	1.36	1.24	228
35	-0.33	31.59	0.32	0.89	0.86	1.17	1.04	1481
36	-0.30	34.66	0.35	0.83	0.20	1.10	0.93	1131
37	-0.83	38.69	0.38	0.87	0.27	0.73	0.55	1558
38	-0.40	29.30	0.39	1.13	0.21	1.36	1.24	228
39	-0.68	23.39	0.30	1.13	0.21	1.36	1.24	228
40	-1.92	37.75	0.39	0.92	0.29	0.64	0.13	222