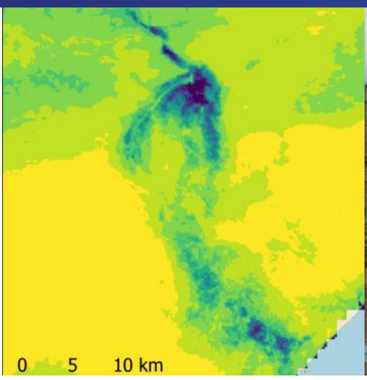
Oct 1, 2021

Water availability in Yemen

Literature review of the current and future water resources and water demand in Yemen

Final report



Rijksdienst voor Ondernemend Nederland

KFW

ACACIA WATER

UNDP

Colophon

Document title	.	Water availability in Yemen
Client	.	Rijksdienst voor Ondernemend Nederland (RVO)
Status	.	Final report
Datum	.	Oct 1, 2021
Project number	.	211246
Author(s)	.	H. van den Berg, S.J. van Meijeren, A. Gevaert, J. Bazin
Reference	.	AW_185_HB_211246
Peer review	.	M.J. Waterloo & V. Langenberg
Released by	.	A.C. de Vries

Executive summary

Yemen is facing a severe water crisis. While the current conflict has markedly increased Yemen's water scarcity, Yemen was one of the world's most severely water-stressed countries even before the conflicts. UNDP, through the Netherlands Enterprise Agency (RVO), requested Acacia Water to perform a literature review on water resources in Yemen. The current study highlights existing knowledge on water resources, identifies main knowledge gaps and recommendations towards improved water resources management. Specific attention in the literature study is given to three wadi catchments (Hadhramaut, Rima/Siham and Abyan Delta). **As field studies in these areas are conducted prior to 2010, the existing data gap has been bridged by an additional unique approach using satellite and remote sensing data to derive updated water balances within the data scarce context of Yemen.** The analyses helped to better draft concrete, usable and ready-to-implement recommendations.

Water resources in Yemen

Surface and groundwater form the main source of water in Yemen. Although rainfall is limited, being less than 50 mm along the coast and inland desert areas and between 250-800 mm in the western mountainous regions, times of heavy rain bring about violent spate torrents and occasionally catastrophic floods causing damage to vital (irrigation) water infrastructure. During these floods only rapid recharge of shallow groundwater occurs due to the often steep slopes, sparse vegetation and limited soil permeability. In major wadis the rush floods ultimately drain into the sea.

The groundwater resources, mainly consisting of the highly productive alluvial, sandstone, limestone and volcanic formations, are distributed throughout Yemen. With an estimated 100,000 tube wells of which an increasing number tapping from non-renewable (deep) groundwater resources, about two-thirds of the irrigated areas in Yemen rely on groundwater resources. Most of the illegal rigs/wells are found in water critical basins; Sana'a, Taiz, Tuban-Abyan, Middle Highlands, and Tehama, Ramlet al Sabatain, where most wells have gone dry and the average drop of groundwater levels range between 3-7 m/year. **Estimates of the annual water demand for domestic (8%), industrial (2%) and agricultural (90%) use of 3.9 Billion Cubic Metres (BCM) far exceed the estimates on annual renewable resource from both surface water (1 BCM) and groundwater (1.5 BCM) of 2.5 BCM per year.** To meet the growing demand, it is estimated that the total amount of water required in the next decade will be about 4.5 BCM/y.

Challenges in effective IWRM implementation

Apart from the ongoing conflict, Yemen faces a challenging arena for the effective implementation of integrated water resources management (IWRM) across national and local level. **Yemen potentially has sufficient annual renewable water resources available to fulfil the drinking water demand for its population**, still though a large share of the population is in acute water shortage. Competing sectoral water demands, agriculture taking 90% of the countries water share, and inability to allocate available water resources, form the core challenges to overcome. Related are the challenges posed by the growing population and urbanization, overexploitation of natural resources and land degradation, high non-revenue water losses, and the inability to combat the adverse climate change effects. Actual data on the current state of wate resource use and availability is lacking though, which poses difficulties to fact-based decision making, planning and management among relevant stakeholders, irrespective of the

laws and regulations that are in place. Historic data is repeatedly published and used as a guide for management, whereas there is hardly any field monitoring data after 2009 to support the various strategies posed. Apart from this, conflicting interests and powers on national and local water management level further hamper effective IWRM implementation. This is mirrored by high non-revenue losses, continuation of uncontrolled drilling, unpermitted groundwater abstraction and subsequent falling groundwater tables, posing a serious threat to the water resources base of many areas in Yemen.

Urban water supply

Water supply in the urban centres best displays the current humanitarian crisis in Yemen, with an annual per capita availability of renewable water of 85 m^3, well below the recognized water scarcity threshold of 1000 m^3. The current water supply infrastructure, let alone the inefficiencies and significant non-revenue water (NRW-) losses up to 50% due to conflict-related damages, poor performance and lack of maintenance, is not designed to supply the needs of growing population and highly dynamic inflows of internally displaced people (IDPs). At the same time, **NRW-values up to 50% means that half of the water produced is being lost, or put differently: water availability for the urban poor could be twice as high**. Exemplary are the steep growth of population in Marib city from 40,000 in 2014 to 630,000 (of which over 90% IDPs) in 2019, the doubling of population in Aden city, while water supply had gone down by about 50% in the same period. This shows the enormous challenges and increased pressures to keep up with domestic water supply. Furthermore, water supply systems have insufficient storage capacities to store available surface water run-off or buffer for technical breakdowns. This leads to limited access to water in urban areas, where population in some areas receive less than three litres per capita per day (l/c/d), which is far below the Sphere standard of at least 15 l/c/d. Structural investments to rehabilitate or expand water supply capacity hardly take place due to the ongoing conflict, precarious financial abilities and the lack of effective planning and management.

Water balances

Existing available literature and past hydrogeological studies have been reviewed to present water balances for three wadi areas across Yemen. The existing data gap in field studies from roughly 2010 onwards, posing a major constraint to the literature baseline initially aimed for in this study, has been bridged by adopting a novel approach. The study has additionally combined literature with recent remote sensing and satellite data analyses techniques, resulting in **updated and improved insights into the water balances of three wadi areas across Yemen**. Using precipitation data from the Climate Hazards group InfraRed Precipitation with Station data (CHIRPS), evapotranspiration data from WaPOR, streamflow data from FLO1K and deriving groundwater anomalies from Gravity Recovery and Climate Experiment (GRACE), **this study confirms the existing imbalance between water availability and use and indicates the excessive use of fossil groundwater resources to overcome this deficit**.

In general, the water balances in the three wadi areas show a heavy and concentrated (e.g. wadi valley, delta area) reliance on groundwater, **with water use exceeding water availability in all reviewed catchment areas. Rainwater and runoff harvesting and infiltration as well as runoff protection is limited, though the potential in the three areas seems considerable**. At the same time spate water infrastructure is old, poorly maintained or damaged by floods, and is therefore increasingly substituted by groundwater. At first, farmers were using hand-dug and shallow wells, but due to over abstraction these shallow wells ran dry and deeper groundwater layers are tapped in an uncontrolled environment, leading to unlicensed abstractions. The shift from shallow to deep (drilled wells), at the same time meant a shift from renewable to mining of fossil, non-renewable, groundwater sources. Declining groundwater levels are reported in all major agricultural areas, and the ongoing overexploitation will result in further lowering of groundwater levels.

Wadi Hadhramaut catchment, Hadhramaut Governorate

In Wadi Hadhramaut majority of water use and agricultural activities take place in the wadi valley. As spate water infrastructure got damaged by major flash floods in 2008, with an estimated loss of 1.64 billion USD, irrigated agriculture since then heavily relies on groundwater resources. The main wadi bed only carries water during heavy rains, resulting in flash floods leaving little opportunity time for water to infiltrate or recharge shallow groundwater. Downward leakage from abstraction out of localized saline aquifers, result in increased salinity levels in the principal aquifer system and abandoning of water wells. A study from 2002 shows water demand is exceeding sustainable water availability in Wadi Hadhramaut, with an estimated 15 MCM/y for domestic and 110 MCM/y for agricultural use. The water balance analysis supports this by showing average annual outflow to exceed average annual precipitation, suggesting groundwater abstraction to overcome this deficit. **The catchment deficit amounts to 10% of annual precipitation and is ten times bigger than annual natural groundwater recharge in the area**. Trends in precipitation deficit (difference between precipitation and evapotranspiration) between 2009 and 2020 exhibit a decrease, especially from 2015 onwards, suggesting groundwater availability decreases.

Abyan Delta catchment, Abyan Governorate

The Abyan Delta, receiving inflows from Wadi Bana, Wadi Hassan and Wadi Suhaybiyah, is marked by year-round and double cropping season patterns near the mouth of the delta. Evapotranspiration values of up to 1300 mm/y related to cultivation of water-intensive crops such as bananas, well exceed the limited rainfall of about 50 mm/y in the delta region. Part of this deficit is compensated by wadi flow from the upper reaches of Wadi Bana in Ibb, Al Bayda and Ad Dali Governorates, and provides water to the various spate water irrigation infrastructure. Remainder share of the water originates from groundwater sources. Farmers in the southern delta areas report soil salinity resulting from saltwater intrusion and irrigation with high saltwater content as an increasing problem. Various literature sources report declining groundwater levels by up to 1 m/y due to the over-abstraction and suggest groundwater abstractions have been increasing in recent decades. This is supported by the water balance analysis showing an annual water balance deficit in the studied wadi catchments to exceed annual groundwater recharge more than seven times. In an analogy to Earth Overshoot Day, **the date in which abstraction of groundwater resources exceeds the amount of groundwater that is replenished in that year is February 16th**. Local groundwater depletion could lead to local groundwater decline in the order of 1125 mm/y. Relating the local groundwater abstraction to the natural groundwater recharge rate of 1.3 mm/y shows that irrigation of the water intensive crops in Abyan Delta has a large area of impact.

Wadi Rima and Siham upstream catchment, Dhamar Governorate

The Jabal Al Sharq District in Dhamar Governorate is part of the Wadi Rima and Wadi Siham basins, both of which originate in the western highlands and drain in the Tihama plain. These wadis, and especially the upland areas, have been poorly studied. Although located in the highland areas, annual rainfall is limited to 100-400 mm. In Wadi Siham, only about 5% of total annual rainfall results in wadi flow, mainly contributing to floods downstream, which tend to occur about 15 times per year. Agricultural activities are clustered and take place around a few localities only (of which Al Jum Ah lies within the district boundaries), whereas majority of the area is marked by shrubland and grassland. A recent study identified the expansion of qat cultivation areas in the Western mountains, most probably increasingly relying on groundwater reserves, though on-the-ground monitoring data to support this in general is unavailable for the entire district area. The analysis done in our study, however, confirms a water balance deficit amounting to twice the natural groundwater recharge rate, indicating groundwater over abstraction in the area. **Local groundwater depletion could lead to local groundwater decline in the order of 500 mm/y**, assuming that the losses to groundwater and surface water are 20%. Trends in precipitation deficit, used as a proxy for trends in groundwater recharge, suggest that groundwater availability is decreasing at catchment scale.

Conclusions, recommendations and follow-up

Based on the available literature data, this study shows there is insufficient water available to adequately serve all present water demand functions, causing an imbalance which is currently bridged by excessive groundwater abstraction. This is additionally supported by insights from recent satellite and remote sensing data. At the same time, the analysis of data shows ample opportunities for implementing a catchment-based approach. **The study provides several key recommendations for each wadi catchment (table below) as well as a list of short-, mid- and long-term options** to invest in improved knowledge base, mitigate water scarcity, use non-conventional water resources, adapt to climate change and adopt IWRM at all levels. These options may well be implemented applying a step-wise approach, using one wadi as a start and multiplying the blueprint approach in other wadi catchments. Decentralization in water governance is an upcoming concept as it promotes awareness at local levels (e.g. basin and WUA level). This implies for example the monitoring of groundwater, analysis and interpretation of data, and to a lesser extent decision making. The latter depends on the interplay between the available capacity at lower levels and national or regional institutional arrangements. It is therefore recommended to focus on enhancing capacity building (i.e. monitoring, analysis, decision making) at WUA, NWRA and basin level and to subsequently agree on tasks and responsibilities.

Wadi Catchment	Water supply management action	Water demand management action
Abyan		Spate irrigation infrastructure performance assessment and targeted rehabilitation
		Pilot water allocation planning, using bottom-up approach (starting from and together with the users)
Hadhramaut	Develop and implement flood forecasting system, incl. mobile warning and link towards water harvesting and spate irrigation	

		Pilot water efficient technologies and improved irrigation practices to use the scarce water sources more effectively
	Potential mapping and piloting off-stream rainwater harvesting to reduce flood impacts and increase infiltration/recharge and storage	
Rima/Siham		Feasibility and pilot study on less-water intensive cropping patterns with focus on rainfed agriculture
	Feasibility mapping and pilot study on application 3R (recharge, retention, reuse) techniques, with special focus on rehabilitation of traditional RWH structures and terrace rehabilitation	

Table of contents

List of Figures

List of Tables

Abbreviations

CEOBS	Conflict and Environment Observatory
CHIRPS	Climate Hazards group InfraRed Precipitation with Station data
FAO	Food and Agriculture Organization
FLO1K	Global maps of annual streamflow at 1 km resolution
GARWSP	General Authority for Rural Water Supply Projects
GRACE	Gravity Recovery and Climate Experiment
IDP	Internally Displaced People
IWRM	Integrated Water Resources Management
JICA	Japan International Cooperation Agency
LULC	Land use and land cover
MAI	Ministry of Agriculture and Irrigation
MWE	Ministry of Water and Environment
NGO	Non-Governmental Organisation
NWRA	National Water Resources Authority
NWRA-SB	NWRA Sanaa Branch
RVO	Rijksdienst voor Ondernemend Nederland (The Netherlands Enterprise Agency)
SBC	Sanaa Basin Commission
ToR	Terms of Reference
UN	United Nations
UNDP	United Nations Development Programme
WaPOR	Water Productivity Open-access portal
WB	World Bank
WFP	World Food Program
WSLC	Water and Sanitation Local Corporation
WUAs	Water user associations
WWTPs	Wastewater treatment plants

Units

µS/cm	microSiemens per centimetre
BCM	Billion Cubic Metres
km2	square kilometres
l/c/d	Litre per Capita per Day
m	meter
mbgl	meter below ground level
m3	cubic meters
M	million
masl	meter above sea level
MCM	Million Cubic Metres
mm	millimetres
y	year

1 Introduction

1.1 Background

Yemen is facing a lot of challenges in terms of water availability. While the current conflict has markedly increased Yemen's water scarcity, Yemen was one of the world's most severely water-stressed countries even before the conflicts. UNDP, through the Netherlands Enterprise Agency (RVO), requested Acacia Water to perform a literature review on water resources in Yemen.

1.2 Objectives

The aim of the study is to map the current and future water resources in Yemen, based on the available information.

The following sub-questions will be answered in this assignment:

1. What are the potential groundwater and surface water sources available, relevant for agriculture and drinking water provision?
2. What is the future water demand from literature for groundwater or surface water in Yemen?
3. What is the current state of affairs of planned infrastructure projects, if any, for agricultural irrigation and to provide the major urban centres with water (Sana'a, Aden, Taiz, Hodeidah, Marib)?
4. Data gap analysis - what additional information or data is needed to gain a better insight into both current and future water demand as well as potential water sources in Yemen?
5. Preliminary recommendations regarding improving water governance, including the possibility of and need for establishing decentralized water governance systems.

The main focus areas of this assignment are:

- Wadi Hadhramaut catchment within Yemen's largest Governorate Hadhramaut;
- Wadi Bana, Wadi Hassan and Wadi Suhaybiyah, contributing to Abyan Delta in the Abyan Governorate;
- Wadi Rima and Wadi Siham sub-catchments in the Dhamar Governorate.

In the course of the project it was agreed with UNDP and RVO to focus mainly on water availability in the three wadi catchments as an example to show what water resources analysis can be done with existing open source data and to assess the status en trends in water availability for agricultural water use to set the baseline for recommendations and follow up study. Hence, less attention was paid to water supply in the major urban centres.

1.3 Updated approach

The current study firstly maps the existing knowledge on water resources, secondly identify the gaps in knowledge and thirdly draft recommendations.

The existing knowledge on water resources in Yemen is derived from an extensive inventory of available reports and studies on identified water sources, water availability, source development and production volumes. This inventory forms the base of this report. A full list of reviewed literature is presented in Annex 7.

Using the available literature, a baseline of water resources, supply and demand in Yemen in general as well as for the three specific wadi catchments was drafted. **Most of the available literature and monitoring data, however, provided a rather outdated view on current state of water resources** as majority of the field studies are conducted prior to 2010.

Towards drafting concrete, usable and ready-to-implement recommendations, additional insights were required to bridge the existing data gap from 2010 onwards. The data gap has been filled using recent remote sensing and satellite data analyses techniques, which provided unique updated insights into the water balances of three wadi areas across Yemen. The analysis not only provides insights in the status of groundwater development in Yemen in recent years, but also shows the added value of Remote Sensing data to generate catchment water balances. The analyses use precipitation data from the Climate Hazards group InfraRed Precipitation with Station data (CHIRPS), evapotranspiration data from WaPOR, streamflow data from FLO1K and derives groundwater anomalies from Gravity Recovery and Climate Experiment (GRACE).

The document is concluded with recommendations for follow-up research and actions to improve knowledge base, mitigate water scarcity, use non-conventional water resources, adapt to climate change and adopt the IWRM principles and process at all levels to promote the co-ordinated and integrated development and management of water, land and related resources under the current circumstances in Yemen.

2 Water resources in Yemen

2.1 Water management

2.1.1 Key governmental organisations

The management of water resources falls under the oversight of several government entities. The **Ministry of Water and Environment** (MWE, established in 2003) is the cabinet-level supervisory body that brings the water sector as a whole, and water management in particular, under the purview of the central government, thus facilitating the allocation of necessary funds. Yet, the responsibility of water uses for irrigation purposes falls under the **Ministry of Agriculture and Irrigation** (MAI), which shares jurisdiction over surface spate water infrastructure with the MWE. The **National Water Resources Authority** (NWRA, established in 1995) is a decentralized government agency with wide ranging legal powers to implement water laws and regulations, allocate water rights, approve permits for drilling wells, and undertake various other water resource management functions. The NWRA, which falls under the MWE, is developing the institutional capacity for sustainable use of water resources (Figure 1; UN Habitat, 2020a).

The MWE was established in May 2003 to reorganize the water sector, with the aim of creating an institutional structure for IWRM and prepare the necessary institutional and investment conditions to face the worsening water situation. The ministry was charged with a most complex development problems in Yemen, namely the water scarcity problem and the challenges of providing drinking water to the urban and rural population, treating wastewater, overseeing water resources management and planning its use in light of the Water Law (MWE, 2004).

Local councils are also relatively new organizations, their establishment having been facilitated by the issuance of the Local Authority Law in 2000. Local councils exist at governorate and district levels. They are tasked at the basin level with supervising and enforcing rules and regulations around water resources management (Huntjens et al., 2014).

An overview of the various other public and private organisations and governmental bodies involved in national and local water management is given in Figure 1 and is further elaborated upon in Metameta and WEC (2014). An elaborate overview of the different stakeholders involved in the Yemen water sector is provided in Annex 1.

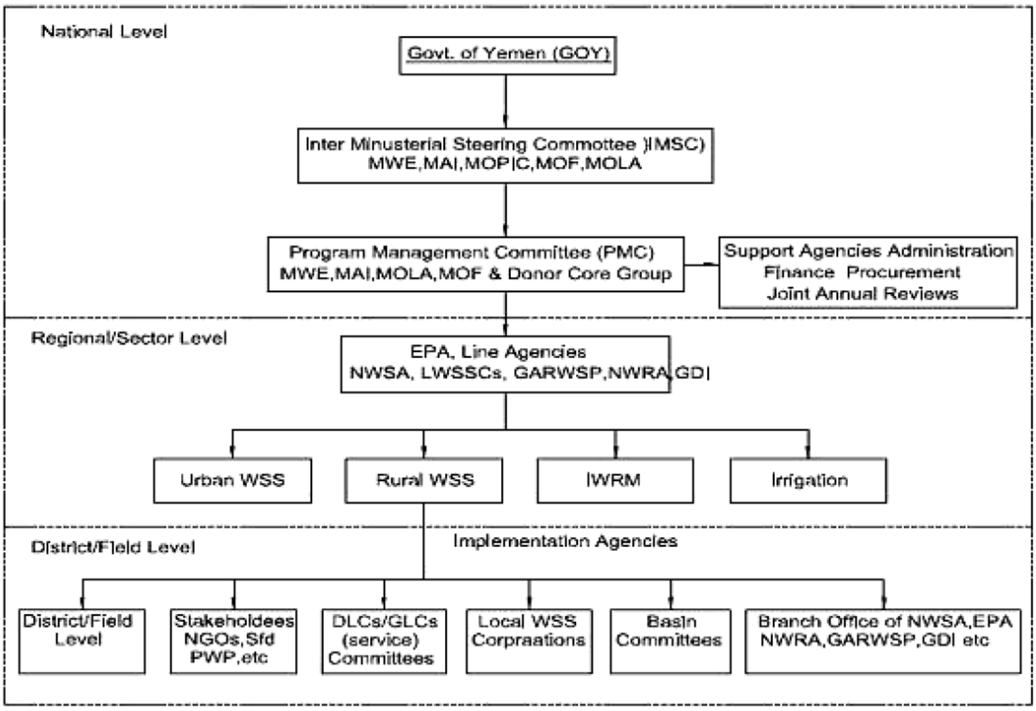


Figure 1. Institutional setup of water sector in Yemen (Source: Metameta and WEC, 2014).

Developing an integrated water resources management plan is one of the main policy goals for the agricultural sector going forward and aims to decentralize decision-making and transfer operating and maintenance costs to water users and the private sector. Since the late 1990s, the government has transferred some responsibility for agricultural water resources management to non-governmental organizations such as water user associations that manage ground and surface water in some regions (Huntjens et al., 2014).

2.1.2 Laws and regulations

The **Water Law**, ratified in 2002, is one of the two main regulations dealing with the exploitation and protection of water resources and its distribution among the population. The second relevant regulation, the **National Water Sector Strategy and Investment Program** (NWSSIP), was the outcome of a multi-stakeholder initiative led by the MWE, to prepare a consolidated strategy, an action plan, and an investment program for the sector as a whole (UN Habitat, 2020a).

The NWSSIP is of fundamental importance in defining the policy position of the Government with respect to water resources management and development. In brief, the strategy emphasises (Hellegers et al., 2008):

- ensuring the maximum possible degree of sustainability;
- allocative efficiency, subject to priority for domestic uses;
- demand management, including economic incentives;
- regulatory measures (including community self-regulation);
- assignment of water rights linked to specific uses.

The Water Law provides a legal basis for controlling groundwater abstractions. It includes measures like licensing and registration requirements for wells and rigs and stricter control regimes in water-stressed catchments. Based on the Water Law, the NWRA was delegated to formulate a water resources management plan, to execute IWRM and to establish Basins Committees in the critical water basins in Yemen (MWE, 2004 & Noaman et al., 2021).

The long history of Yemen suffering from water scarcity has laid the foundation for the agricultural norms and traditions to regulate water distribution, maintenance of the irrigation infrastructure, and dispute resolution mechanisms. In many areas in Yemen, people mainly rely on traditional rules (*Urf*) and other agreements to regulate the rights and restrictions regarding water access, use and distribution. These rules are unwritten and are specific to the area. Sometimes the rules are locally applied by Water User Associations (WUAs). Regarding the three main sources of water in Yemen, the following summary on existing rules applies (Huntjens et al., 2014):

- Surface (or otherwise known as flood) water: there are restrictions concerning the distribution of water, but they are in many cases out-dated as they do not accommodate for the presence of permanent structures (check dams) and the impact of these structures on groundwater recharge and hence the availability of drinking water;
- Groundwater: historically, rules for groundwater are not specified, though in several cases a distance rule is used, which in the water law is specified as a distance of at least 500m between wells. In some cases new informal rules have been developed, for example regarding the purpose for which the water may be applied, who is allowed to use it, and embargo zones;
- Subsurface flow: Subsurface flow is the water in-between the surface water and the groundwater. Any physical interference, for example through the construction of impermeable structures in ephemeral streams, may have large impacts on the available surface and groundwater downstream. Nevertheless, this source is often overlooked and consequently, no formal water rights or allocation rules have been formulated for subsurface flow.

2.1.3 Private sector

As a result of pre-existing challenges exacerbated by the conflicts and regional military intervention, there is a considerable gap in the urban water supply. This gap is being filled largely by private tanker trucks, on which urban Yemenis are increasingly dependent. While the tanker truck system plays a critical role in filling this gap in the formal water supply system, it raises serious questions with respect to affordability, health, environment and water resources management (Abu-Lohom et al., 2018). The use of solar systems is expanding due to the general collapse of the electricity supply. Solar systems are considered an alternative power source, *e.g.* for pumping groundwater, and the import and supply of these systems is considered the role of the private sector (CEOBS, 2020).

2.1.4 Public awareness and education campaigns

Growing public awareness of and education around new water regulations and increasing involvement of WUAs in local water management has led to new informal rule-making that often protects the local community as a whole rather than only the elite (van Steenbergen et al., 2010). A major incentive for farmers to join WUAs is the authority to co-design and co-implement spate subprojects. Farmers pay subscription and annual fees and play an active role in selecting the types of irrigation structures needed and contributing to subsequent implementation/supervision of civil works contracts (Noaman et al., 2021).

The Ministry of Water and Environment, in cooperation with donors, adopted water conservation as a strategy for managing limited water resources and designed and implemented a public awareness and education campaign to raise awareness among members of the community (Huntjens et al., 2014).

2.2 Water infrastructure

There are over a thousand hydraulic structures in Yemen including dams, spate water diversion structures and small water harvesting structures. The latter includes cisterns, pits and reservoirs with a storage capacity ranging from 500 m^3 to 50 000 m^3 (FAO, 2008).

2.2.1 Dams

Yemen has a long history of dam construction and the ancient civilization was founded upon the great dam of Marib, the destruction of which marked the end of its existence. After the revolution, the government carried out the reconstruction of the Marib Dam financed by the United Arab Emirates. The new dam has a capacity of 400 MCM. The remaining dams have a total capacity of 62.5 MCM, giving a total dam capacity of 462.5 MCM (FAO, 2008).

In general, dams in Yemen function to recharge groundwater and provide water for irrigation, as well as domestic uses. The National Water Sector Strategy and Investment Plan (NWSSIP) points out that in spite of the tremendous efforts to construct dams, they have not stopped the continuously declining levels of groundwater or helped replenish the depleted aquifers in many basins (MWE, 2004).

Based on the FAO (2008), there are 347 dams in Yemen. An overview of the major dams is given in Figure 2, majority of which lies in Sanaa Basin. According to the capacity, the dams are divided into three categories:

- large dams with a capacity larger than 500 000 m^3;
- medium dams with a variable capacity from 200 000 to 500 000 m^3;
- small dams with a capacity of less than 200 000 m^3.

A full list of dams in Yemen is available at the country profile page of FAO (http://www.fao.org/aquastat/en/countries-and-basins/country-profiles/country/YEM).

Name of the Dam	Location	Basin	Operation/ completion year	Height (m)	Capacity (MCM)
Semnah	Sana'a	Sana'a Basin	1985	16	0.6
Ma'areb	Marib	Arabian Sea Basin	1987	40	400
Raya'an	Sana'a	Sana'a Basin	1993	22	1.02
Al-Amerah	Taizz	Taiz Siham Basin	1996	25	0.785
Arishah	Sana'a	Sana'a Basin	1997	13	0.5
Bait Al-Khardal	Sana'a	Ma'areb BasinSana'a basin	1999	20.5	2
Ghayman	Sana'a	Sana'a Basin	2001	15	0.73
Al-Gargoor	Sana'a	Sana'a Basin	2001	16	1
Muogif	Al Mahwit	Tehama Surdud Basin	2002	18	0.5
Al-Wakr-AlHaythem	Sana'a	Sana'a Basin	2002	17.2	0.54
Al-Hajar	S,adah	Sa'ada Basin	2004	23	0.777

Figure 2. Overview of major dams in Yemen (Source: Noaman et al., 2021).

2.2.2 Spate water diversion structures

Spate irrigation is an ancient water harvesting system by which floodwater is diverted from its riverbed and channelled to basins where it is used to irrigate crops and feed drinking-water ponds, serve forest and grazing land and recharge local aquifers. In Yemen, large traditional spate systems consisting of numerous individual intakes and canals irrigating areas of up to 30,000 ha were developed in individual wadis. Sophisticated water sharing arrangements were formalized, with rules relating to water rights that exist in written records dating back at least 600 years (Noaman, 2004). Spate irrigation areas depend on groundwater irrigation as complementary irrigation source.

There are different types of spate water diversion structures, each having their own name. The name may vary from area to area. The terms used depend on the size, order length, type of building material, shapes, way of built and position in the wadi. Examples of names are: Oqmas, Obars, Atm (in the coastal area), Saqiya (in Hadhramaut and Shabwa) and Rozzum (in some parts of the highlands). The 'Ogma' is an earthen dyke (bund) constructed across the main stream of the wadi to divert the entire low stage flow of flood to be used in upper parts of the wadis. While, the 'Obar' is a temporary bund or spurs (a small earth fill embankment), which is used at wadis middle part, and the 'Atum' is a temporary earth spurs surrounding the field (Noaman et al., 2021).

The spate irrigation areas in Yemen varies, depending on the availability of the rainfall and flood waters, and is therefore difficult to quantify. According to FAO (2008), 33 of these structures have been constructed in the main wadis for spate water regulation and diversion. It is estimated that the area equipped for spate irrigation (command area) may be as large as 217,541 ha, which was the area also actually irrigated in 2001, while in 2002 only 124,683 ha were actually irrigated and in 2004 only 89,363 ha. The government constructed many spate water diversion and canal control structures in some of the main wadis, such as wadi Zabid, Tuban, Abyan, Mowr, Seham and Bayhan (FAO, 2008).

2.2.3 Small water harvesting structures

In dry and semi-dry areas, rainwater harvesting is the collection of large quantities of rainwater and storing them for a long period for the benefit of agriculture, household purposes, and others. It additionally helps to reduce the waste of floodwater and rainwater and to protect its loss due to seepage, evaporation, or pollution.

In Yemen, traditional water harvesting structures are practiced for many centuries, leaving different types of sophisticated structures in the landscape. The most predominant are specified below:

Naqab

Naqaba are cisterns dug out by man to collect rainwater for drinking water and for different daily needs. Naqaba is considered to be a model technique from the Hadhramaut Plateau from the Jardan Plateau and Arama in Shabwa in the west to most areas of Hadhramaut until Mahara in the East. They can store enough water to last several months, according to what is used for and how many people benefit from it (Figure 3; Baquhaizel, 2011).

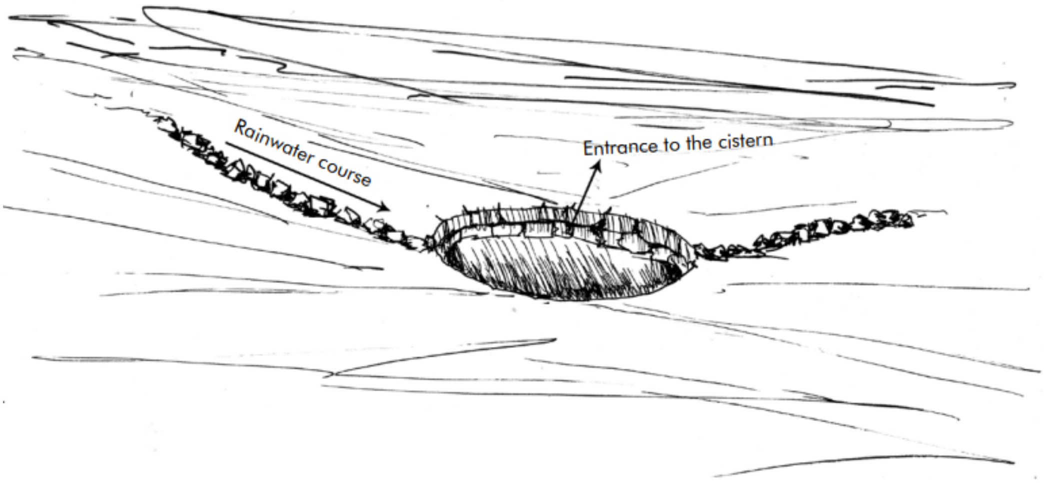


Figure 3. The opening of a naqaba (cistern) on ground level (Source: Baquhaizel, 2011).

Karfaan

Karfaan is a natural basin or wide hole where rainwater gathers from surrounding slopes or water courses. Man very often intervenes to hold back this water with a clay barrier to prevent water from seeping out. This water is mainly used to water cattle and to cover the domestic needs, as in the dry areas of Sitan in the Hadhramaut Plateau. Usually, some sawaqi or water channels are set up from the feeding areas to the kareef to gather the largest possible quantity of water from different directions (Baquhaizel, 2011).

Jawaabi

Jawabi are tanks or open reservoirs built to collect rainwater and floodwater for different purposes. The jawaabi we mention here differ in terms of form and purpose from those known in many other areas. There are two types of jawaabi. The first is oval and open at the top and is widespread in the Jardan Valley in the Shabwa Governorate. The second is cylindrical or barrel-shaped and becomes narrower at the base. It is covered at the top with a dome-like structure (Figure 4; Baquhaizel, 2011).

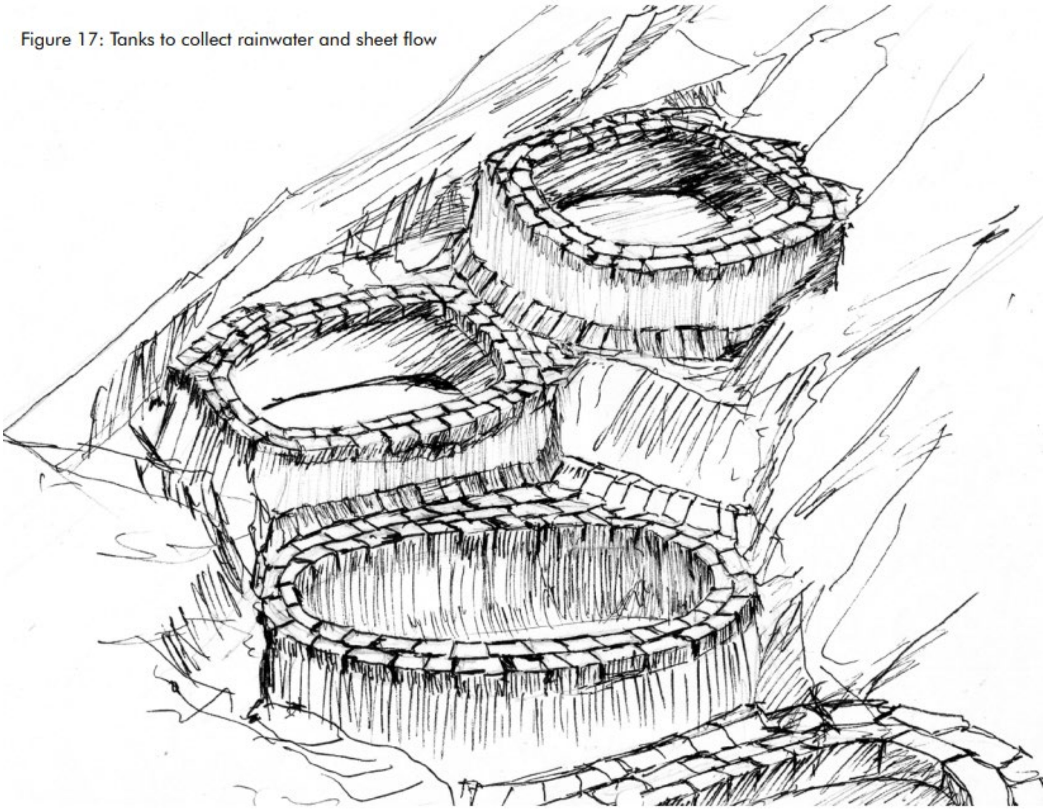


Figure 4. Jawaabi to collect rainwater and sheet flow (Source: Baqyhaizel, 2011).

Shurooj

Shurooj are delimited areas of land that formed in natural depressions. They are formed by the breaking up of local rocks as a result of natural erosion, notably by rain that falls on the area or in its immediate surroundings. Locals call 'sharj' (plural: shurooj) land that is supplied directly by rainwater, not by floodwater. One study indicates that up to 5% of total agricultural land in southern and eastern governorates is rain-fed. Due to the scarcity of rain in the area, agricultural production is weak. Cultivation focuses on grains that have a short growth cycle, like local variety of sorghum called 'tahf' and millet whose growth cycle is three months for the three first crops. If the cycle is not completed, then the land is used for cattle grazing (Baquhaizel, 2011).

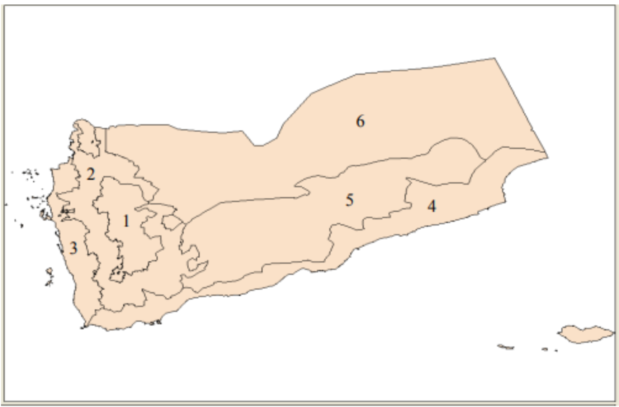
2.2.4 Wastewater treatment network

Yemen has more than 17 urban and more than 15 rural wastewater treatment plants (WWTPs) in operation. Several others are under construction. It has been reported that waste stabilization ponds as a means of treating wastewater are underutilized, with more than 80% placed in nine urban and rural areas (Aden, al-Hodeidah, Bajil, Thamr, Yarim, al-Baidha, Radaa, Amran and Baitalfaqih). The other WWTPs are either activated sludge in Sanaa and Ibb, Imhoff tanks or trickling filters in Hajjah or a combination of more than one technology, such as Imhoff tanks followed by stabilization ponds as in Zabid, or septic tanks followed by stabilization ponds as in al-Mahwet (Noaman et al., 2021). Stabilization ponds are considered the best treatment process, with the potential to reduce pathogens in effluent to make it suitable for irrigation (Veenstra et al., 1995). Furthermore, the WWTPs receive industrial and hospital wastewater from different facilities.

The total flow of the treated wastewater in the WWTPs is around 300,000 m^3 per day, or around 100 MCM/y. The amount produced has exceeded the design capacity of plants in places such as Sanaa and Ibb while others, as in Aden, are still under designed. The BOD of the influent is characterized out of the range of the known characteristics in the world, which was anticipated due to the water scarcity (Noaman et al., 2021). Al-Nozily et al. (2006) showed that the BOD increased significantly in Sanaa from 550 milligrams per litre (mg/L) in 1985 to 800 mg/L in 1992 and reached 1,100 mg/L in 2000-2004.

2.3 Water resources

Yemen is physically water scarce due to its limited rainfall and geographic location with no shared international rivers. It is currently the seventh most water-scarce country in the world, with the per capita share of renewable water resources only around 80 m^3 (McCracken, 2012). Yemen can be subdivided into six agro-ecological zones, based on temperature and rainfall distribution throughout the year (Figure 5).



Zone 1: Upper highlands | Zone 2: Lower highlands
Zone 3: Red Sea and Tihama Plain | Zone 4: Arabian Sea coast
Zone 5: Internal Plateau | Zone 6: Desert

Figure 5. Agro-ecological zones of Yemen (Source: Breisinger et al., 2011).

2.3.1 Rainfall

Two thirds of the country is classified as hyper-arid with less than 50 mm rainfall per year, and most of the rest is classified as arid with less than 200 mm rainfall. Average rainfall above 250 mm is only found in the western mountainous regions, where most of the population is concentrated, with some areas receiving more than 800 mm (Figure 6; UNDP & FAO, 2020).

Some areas of the western highlands, most notably Ibb and Ta'izz, receive from about 1,000–1,500 millimetres of rain each year. The capital, Sana'a, receives around 300 mm a year, it is not uncommon for the northern and eastern sections of the country to receive no rain for five years or more.

Annual rain volume all over the country varies between 67,000 and 93,000 MCM (FAO AQUASTAT, 2008). In most areas, evapotranspiration far exceeds rainfall during the largest part of the year and the rainfall is insufficient for rain fed agriculture. Only the mountainous areas receive significant rainfall, which provides the water resources used in agricultural areas, either through spate flows or indirectly through pumping from groundwater for irrigation

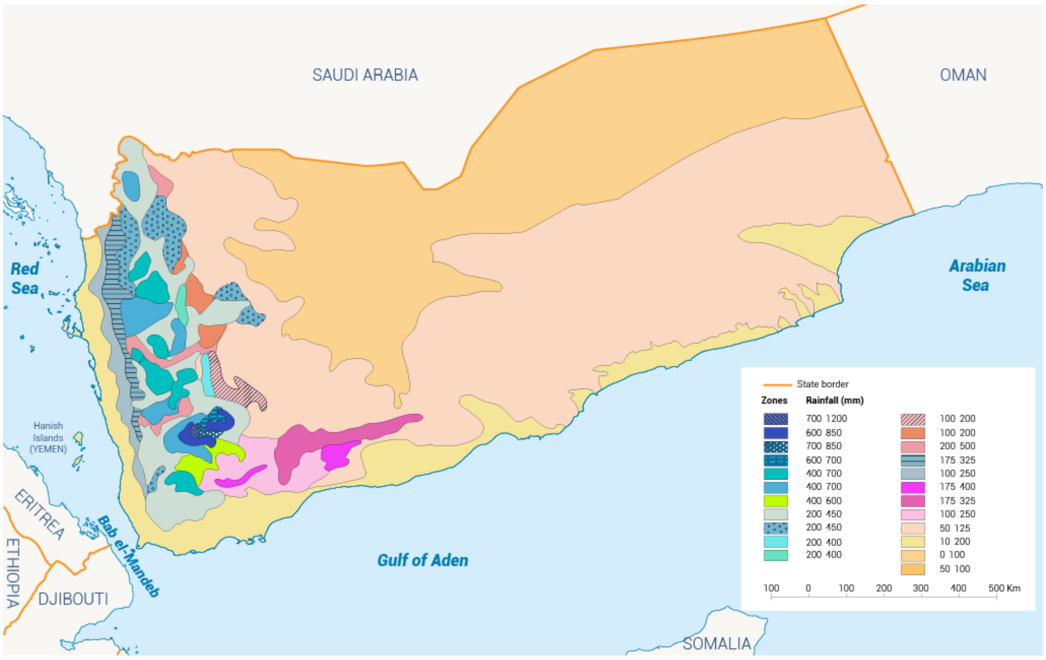


Figure 6. Rainfall map of Yemen (Source: Noaman et al., 2021).

2.3.2 Surface water

Four main surface water basins

Surface water is an important source for irrigation in Yemen. Surface water consists of seasonal spate water and springs, with differing quantity and quality depending on the area. Surface water resources are estimated to be about 1,000 MCM/y, but this quantity corresponds to the runoff from major wadis and does not include the runoff produced within the smaller catchments (Noaman et al., 2021). Past hydrological assessments revealed that the total water yield for Yemen was 2,100-2,400 MCM/y in the 1980s (MWE, 2004). World Bank (2010) reports that only about 6 % of rainfall is captured in the surface-water systems in wadis as spate (flood) flow amounting to about 2,000 MCM annually. 30% of Yemen's total freshwater withdrawal is derived from surface water, and the remaining 70% is derived from a variety of aquifer types (UNDP & FAO, 2020).

Yemen can be subdivided into four main drainage basins: The Red Sea basin, the Gulf of Aden basin, the Arabian Sea basin and the Rub al-Khali basin (Figure 7).

<u>The Red Sea Basin</u>: A number of large wadis drain the steep western escarpment and lose most of their water in the permeable sediments of the coastal Tehama. All wadis have catchment areas larger than 1,000 km2 - Wadi Mawr is the largest (approximately 8,000 km2). Rainfall in the highlands in spring and summer generates significant run off in the upper and middle catchment. Flood peaks are high as rainfall in the catchment area is high and slopes are steep. In the coastal plain, some of the wadi flow is diverted for spate irrigation and lost to ET, some percolates below the soil profile into the aquifer and recharges groundwater, and some reaches the sea, generally by groundwater outflow. The flows of several wadis have been monitored for short periods, shedding some light on the rainfall-runoff relationships in these wadis. This is Yemen's most important basin, contributing 36% of total run off (World Bank, 2010).

<u>Gulf of Aden Basin</u>: The main wadis, all of which have catchments over 1,000 km2, drain south from the southern highlands. The large spate flows are extensively diverted in the broad coastal plain, but a larger share of flows still reaches the sea than in the Red Sea

systems. In recent years, spate flows have dwindled due to continuing diversion upstream (World Bank, 2010).

Arabian Sea Basin: In ancient times, this large complex basin area supported Yemen's great trading kingdoms. Its topography would allow water to flow from the eastern slopes of the highlands, down through the Ramlat as Sabatayn to Wadi Hadhramaut, and out towards the sea via Wadi Masila. However, as rainfall rates are low and much of the soils of the basin allow for rapid recharge, the "basin" is more a series of discontinuous segments. Runoff volumes can be large, as witnessed during the flooding of 2008 in Wadi Hadhramaut, which caused a large number of fatalities and substantial economic damage to property and agriculture in the region (World Bank, 2010).

Rub al Khali Basin: The northern and north-eastern slopes of the highlands drain into the sands of the Empty Quarter where infiltrates into groundwater (World Bank, 2010).

The Mountain Basins: Scattered through the highlands, a series of plains surrounded by mountains constitute self-contained basins, with little or no surface water draining outside the basin: Sa'adah, Huh/al Harf, Amran/Raydah, Sana'a, Dhamar, Rad'a. The recharge of groundwater in these small basins is limited, but they are centres of high population concentration and hence of heavy water use (World Bank, 2010).

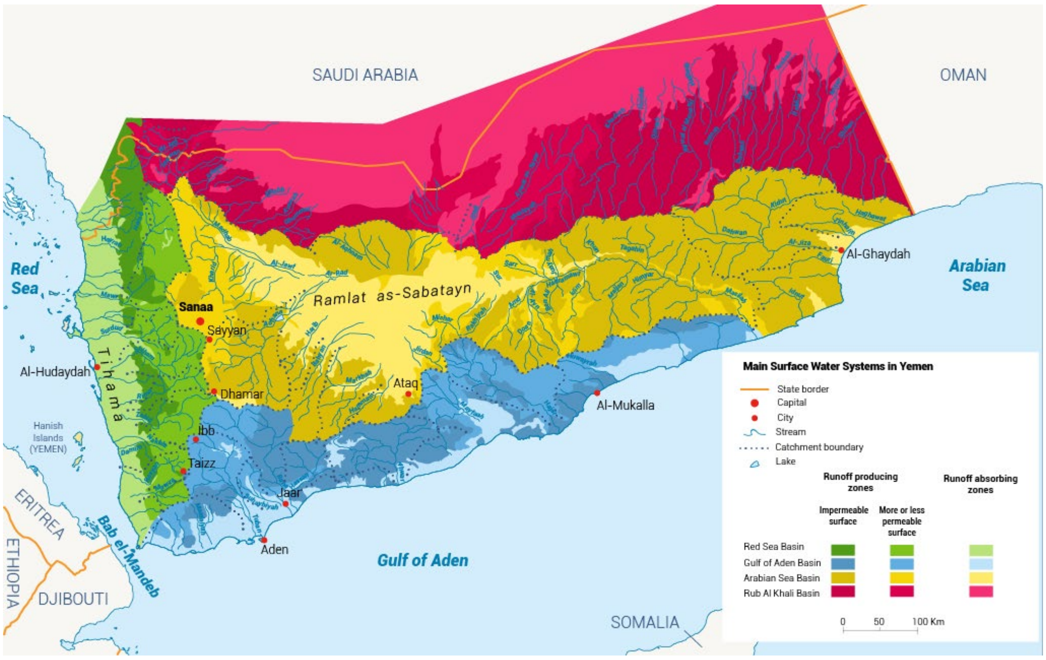


Figure 7. Main surface water systems (Source: Noaman et al., 2021).

Spate (flood) water

The surface water flow in the stream beds is characterised by violent spate torrents, and occasionally catastrophic floods. In times of heavy rain, runoff moves rapidly to the nearest branch of the drainage system and rushes downstream as a spate flow into ever larger wadi beds. As in all arid zones, wadi flows in Yemen tend to be ephemeral. Typically, the wadi beds are dry for most of the year, and floods come and go quite quickly. Some wadis may remain dry for several years, and then become the bearer of a huge flash flood. The flood peaks are often quick and torrential (causing disastrous floods as in Hadhramaut and al-Mahra in 2008), because rainfall events are violent, slopes are steep, and recharge in the catchment area is reduced by sparse vegetation and

limited soil permeability. Much of the spate flow recharges the alluvial groundwater system thereby improving the groundwater stocks. Because of this rapid recharge in the stream beds, and because of diversion for farming, very little storm flow ever reaches the sea. Some of the water that infiltrates groundwater reappears above ground to contribute to surface flows in the wadi beds as base flow or as springs. All the major wadis draining to the west coast have permanent base flows in the foothills zone that may make up about 40% of total flow (World Bank, 2010).
Surface runoff to the sea measured in some major wadis is estimated at 270 million m^3/y and groundwater outflow to the sea at 280 million m^3/y. There might be some groundwater flowing into Saudi Arabia but no data are available. The existence of surface drainage crossing into Saudi Arabia suggests that some sharing of surface flows could be possible, but details are not known (FAO, 2008).

2.3.3 Groundwater

Groundwater is a vital resource for water use throughout Yemen. Groundwater withdrawals were estimated at 2,500 MCM/y, which amounts to about 70 % of total water use of the country. The aquifers contain large water reserves of about 35,000 MCM with an annual recharge of about 1,300 MCM (World Bank, 2010) to 1,500 MCM (Noaman et al., 2021 & FAO, 2008). The annual recharge predominantly comes from infiltration in the main wadi beds, estimated at 1,400 MCM/y (FAO AQUASTAT, 2008). The rate of groundwater overdraft is currently more than twice the recharge rate and is increasing, bringing depletion of water reserves, inequity, and shortages, with negative socio-economic consequences. Some major aquifers are being depleted even more rapidly. **At this rate, it might be less than 20 years, and all groundwater sources in Yemen will be dry** (UNDP & FAO, 2020).

The annual water demand for domestic and industrial use and agricultural consumption is estimated at 3,900 MCM/y (Noaman et al., 2021), which far exceeds estimates on the annual renewable resource from both surface water (1,000 MCM/y) and groundwater (1,500 MCM/y) of 2,500 MCM/y (Hellegers et al., 2008). Overall, the water availability is only 85 m^3/capita/y, which is well below the World Bank's water poverty level of 1,000 m^3/capita/y. As in many other countries in the region, agriculture is by far the biggest consumer of over 3,510 MCM/y, or 90% of total water use (Noaman et al., 2021). In 2000, 90 percent of water withdrawal was used for agricultural purposes (FAO AQUASTAT, 2008).

Aquifer systems

The aquifers in Yemen, which are distributed throughout the country, consist mainly of alluvial, sandstone, limestone and volcanic formations. Alluvial aquifers which are formed in wadi beds from sand and gravel unconsolidated deposits are the most common (World Bank, 2010).

Figure 8 demonstrates the diversity of aquifer systems across the country and the variation in hydrogeological conditions that have led to a wide range of groundwater development systems. Highly productive aquifers exist along the coast in alluvial-filled wadis and in the fans and deltas created by the continuous process of flooding and sedimentation. Important aquifers exist in the Tihama plain, Tuban Abyan, Ahwar and Maiah in the south, Ramlat as-Sabatayn in the west and Wadi Hadhramaut in the east (Noaman et al., 2021). It is cheap and easy to extract water from the alluvial aquifers. The water table fluctuates rapidly, depending on seasonal inflows and discharges (World Bank, 2010).

Solid rock aquifers of sandstone and limestone tend to be deeper and much more extensive. Most productive are the deep sandstone aquifers, sedimentary rocks with porous characteristics that allow water to seep in (World Bank, 2010). In the highland plains are the important sedimentary aquifers in Sa'adah, Amran, Sanaa, Mabar-Dhamar and the Rada basins. They have good transmissivity and favourable recharge conditions. In the east are the Mukalla sandstones, which constitute the largest aquifer complex in Yemen with moderate productivity that continues over into Saudi Arabia and Oman (Noaman et al., 2021).

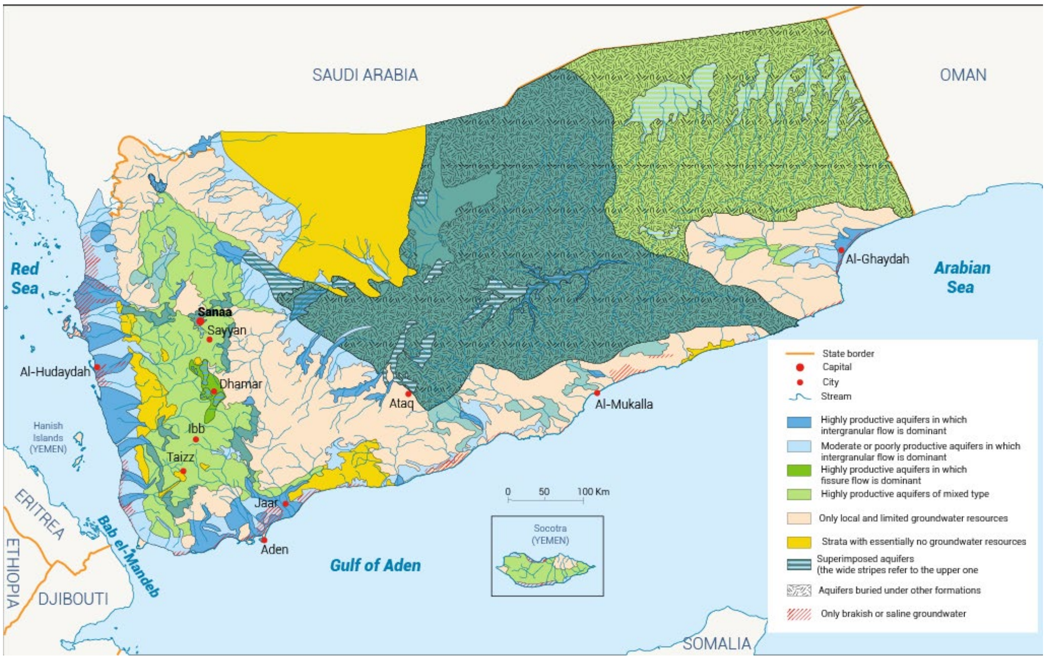


Figure 8. Main groundwater aquifers (Source: Noaman et al., 2021).

Van der Gun & Ahmed (1995) provide a brief description of the main groundwater systems in Yemen outlined below.

Alluvial wadi fills or strip aquifers

Alluvial deposits in wadi valley bottoms constitute aquifers of limited dimensions. They are the most convenient sources of shallow subsurface water and until recently groundwater abstraction in Yemen was largely confined to this type of aquifer. Because their width (a few metres to a few hundred metres) is small compared to their length, they are known under the name strip aquifers. The deposits are usually unsorted but coarse and uncemented, and, thus, are highly permeable. Their thickness tends to increase in downstream directions and normally does not exceed a few tens of meters.

Wadi aquifers have extremely favourable recharge conditions: their permeable deposits cause part of wadi floods to be intercepted by infiltration, and they may also collect water from springs and seepage zones along the wadi. But due to their small aquifer volumes and relatively high permeabilities they can be depleted during prolonged dry periods, especially in the higher parts of the wadi channel network.

Quaternary aquifers of plains, alluvial fans and deltas

Quaternary aquifers of plains, alluvial fans and deltas are usually situated in the alluvial plain of larger wadis. They are actively recharged by these wadis, partly by subsurface flows (underflows) via the interconnected wadi fill aquifers. The most important

Quaternary aquifer complexes are the Timaha and the southern coastal plains (incl. Abyan Delta), those at the western and southern edges of the Ramlat Sabatayn, and the Pliocene-Quaternary deposits of Wadi Hadhramaut. They also occur in isolated small tectonic basins, scattered over the country, *e.g.* in the Highland Plains zone. Recharge is concentrated in limited zones around the main wadi beds and produces "pockets" of relatively fresh water that laterally become increasingly saline.

Groundwater basins of the Highland Plains

Highland Plains are scattered over the Yemen Mountain Massif. Most of them are located relatively near the main water divide that separates the Red Sea Basin from the other three drainage basins of the mainland. Many of these plains constitute small, but relatively favourable areas for groundwater development. This is because of a number of factors:

- Groundwater levels are, or used to be,) within a few tens of metres below the ground surface;
- The hydraulic conductivity of their rocks is higher than that of the surrounding rock units;
- Sub-horizontal topography and the presence of alluvial deposits favour groundwater replenishment;
- Surface water leaves the plains only on rare occasions and in insignificant amounts;
- Natural discharge from these areas is mainly by evapotranspiration and subsurface outflow.

The most important highland groundwater basins from north to south: the Sadah Basin, the Amran Basin, the Sana'a Basin, the Ma'bar-Dhamar Plains, and Rada Basin.

During the literature study, many reports were encountered that thoroughly study the Sanaa basin aquifer system and water management of which most important ones are listed below:

- WEC (2001) – Sanaa basin water management technical report discussing in-depth surface and groundwater resources, use and availability;
- WEC (2005) – Sana'a well inventory maps, including well density, depth, yield and abstraction;
- JICA (2007a & 2007b) – Extensive study presenting a water resources management action plan for Sana'a Basin, including underlying hydrogeological investigations;
- Hydrosult, WEC, TNO (2008) – Various reports presenting hydro-geological and water resources monitoring and investigations in Sana'a Basin as part of the Sana'a Basin Water Management Project;
- Ward et al. (2010) – Evaluation of Sana'a Basin Integrated Water Resources Management process;
- Chevalking (2010) - A technical-institutional analysis of small dams in the Sana'a Basin, Yemen;
- Hydrosult, WEC, TNO (2010) - Assessment of Water Resources of the Sana'a Basin & Strategic Options for the Sustainable Development of the Basin's Water Resources;
- RTI International (2011) – On water issues and options for Sana'a Basin;
- Aklan (2011) – Assessing the potential of rooftop rainwater harvesting for Sana'a;
- Taher et al. (2013) – Discussing IWRM approaches for Sana'a Basin.

Regional Mukalla Sandstone Aquifer
East of the shield and north of the Al Ghaydah basin and of the rifted zone along the Gulf of Aden is an extensive basin where thick strata of Mesozoic and Tertiary sediments have been deposited. This basin extends far northwards over the platform zone of the Arabian Peninsula.

The Mukalla Sandstone, averaging 300-400 m in thickness, is widely present in this basin and forms a continuous regional aquifer of large lateral extent. In the western part (Ramlat-as-Sabatayn zone), it rests upon Jurassic sediments, a thick series containing saline water, and with oil-bearing zones. In the Ramlat-as-Sabatayn, it is overlain by Quaternary continental deposits, a few meters to more than 150 meters-thick and probably largely unsaturated. In the Plateau Region, it is capped by a thick sequence (around 300-400 m) of carbonate rocks.

The Mukalla Sandstone aquifer constitutes the largest groundwater system in Yemen, storing large quantities of groundwater. The Mukalla sandstones generally have high porosity and transmissivity (in the range of 3,000 to 3,500 m^2 /day). The Mukalla sandstone is in direct hydraulic contact with the overlying Quaternary deposits in the Ramlat As Sabatayn desert and, as a consequence, the two aquifers (Quaternary and Mukalla) form only one aquifer in this area.

Groundwater wells

Many farmers are pumping groundwater from wells using diesel or electric pumps. The yield of wells is between 5 and 50 l/sec. The estimates on the existing number of groundwater wells differ greatly. This has partly to do with (unregistered) illegal drilling of wells or wells that have run dry over time. It is estimated that there are 52,000 to 55,000 active wells in Yemen (FAO AQUASTAT, 2008), but the World Bank (2010) reports an estimated 100,000 tube wells to exist in Yemen. The volume of the water that is pumped every year from these wells is about 1,500 MCM. About 800 water well drilling rigs are in use that are owned by individuals or companies which generally do not have any permits despite government legislation limiting the drilling of wells. In 2005, the National Water Resources Authority started a programme of registrations & licensing for the water well drilling companies; the records show that in May 2005 only 70 rigs were licensed and only 1 000 wells were registered and licensed (Al-Asbahi, 2005).

> Mr. Job Kleijn, *First Secretary Embassy of the Kingdom of the Netherlands*, in 2010: "The country has more drilling rigs available than India, and still they get imported. The water level drawdowns of up to 6 m/y in Sana'a Basin are reality and several studies show that Sana'a will dry up in 20 years of time."

Most of the illegal rigs/wells are found in water critical basins; Sana'a, Taiz, Tuban-Abyan, Middle Highlands, and Tehama, Ramlet al Sabatain. The quantity of water exploited exceeds the average of groundwater recharge, resulting in a decrease in groundwater levels. In some basins the average drop of groundwater levels range between 3-7 m/y (Figure 9) and as a result, many wells have gone dry.

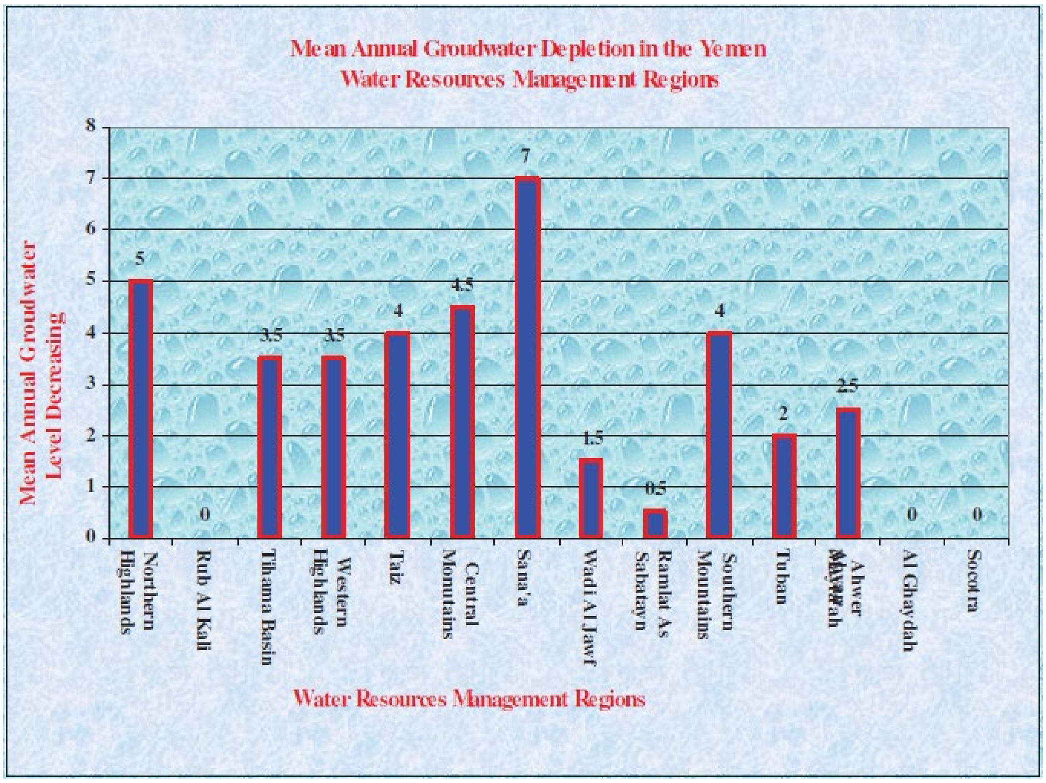


Figure 9. Mean annual groundwater depletion in different water resources management regions in Yemen (Source: NWRA, 2009).

Groundwater trends

The oil boom in the 1980's made a notable contribution to such groundwater depletion by enabling diesel-powered water pumps through subsidies for deep-water abstractions. That encouraged sourcing more water from this limited resource to keep planting water-consuming crops instead of adopting water-conservation through repairing leaking infrastructure and switching to water-wise crops. The fact that the mandate for water management was given to the Ministry of Agriculture may have also resulted in exploitative supply-oriented approaches, that evolved from predominantly coffee and grapes cultivation to the more economically lucrative Qat cultivation, especially on the western hilly terraces (UNDP & FAO, 2020). Nationwide, irrigated areas have expanded from 37,000 ha to more than 680,000 ha between 1970 to 2004, of which two-third depends on groundwater (FAO AQUASTAT, 2008).

More recently, the introduction of solar power tends to further accelerate groundwater depletion, as shown by of CEOBS (2021). The study evaluates trends in groundwater storage estimates based on GRACE satellite observations (Figure 10). In seven of ten areas analysed groundwater levels decreased (Figure 11). Interestingly, the analyses in the southern deltas (including Abyan Delta) and western mountains (including Rima/Siham wadi catchment) do not reflect this groundwater decrease (see also Annex 2). It is important to note that the GRACE-based values are sensitive to storage in all aquifers. It is likely that analysed groundwater depletion or replenishment is limited to the shallow, renewable aquifer. Replenishment of deeper aquifers, however, is assumed to be negligible. There is anecdotal evidence that groundwater is increasingly being abstracted from these deeper, non-renewable aquifers. Therefore, while the balance of shallow aquifers could be positive in the recent, relatively wet years, the balance of deeper aquifers is most likely negative.

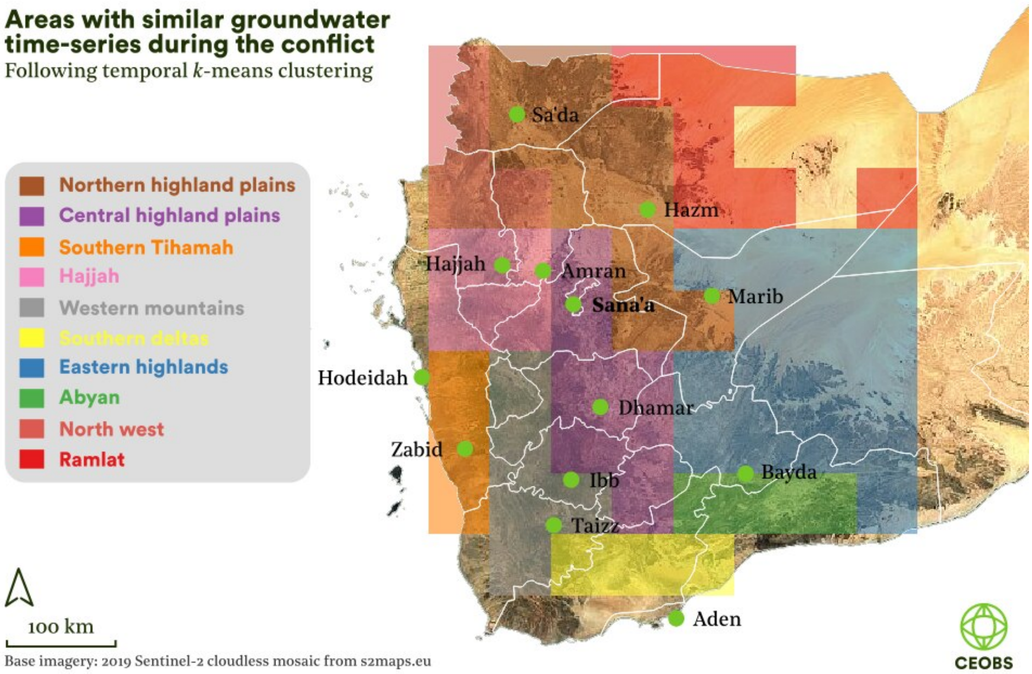


Figure 10. Yemen map showing the clusters for which CEOBS (2021) analysed groundwater trends using GRACE.

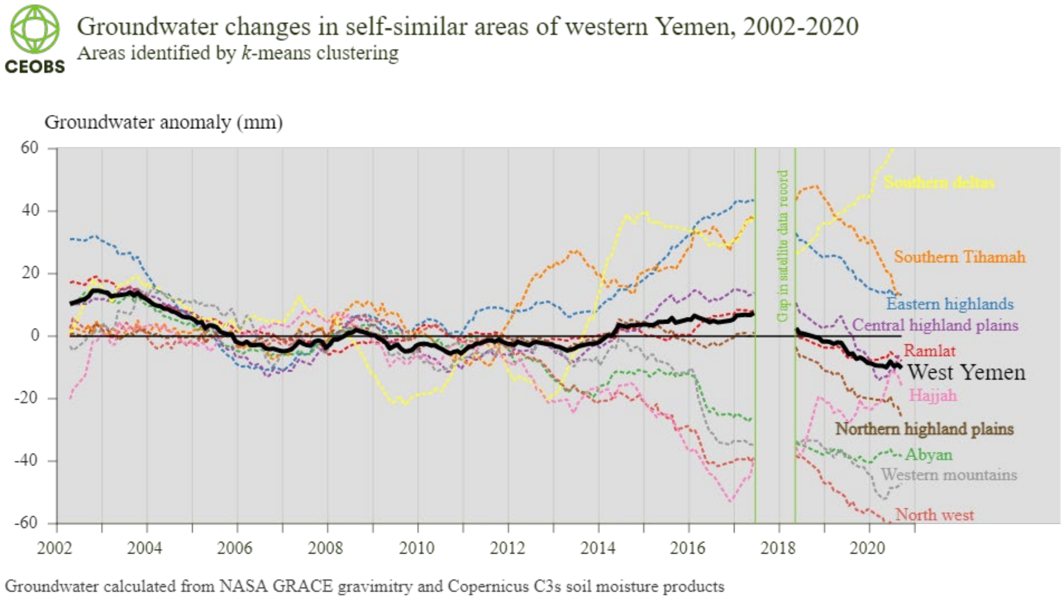


Figure 11. Groundwater time-series in each of the regions studied by CEOBS (2021).

2.3.4 Non-conventional water resources

Unconventional water resources are those that are generated as a by-product of specialized processes such as desalination; or that need suitable pre-use treatment; or pertinent on-farm management when used for irrigation; or need a special technology to collect/access water. Examples of these water resources relevant for Yemen include desalinated seawater and highly brackish groundwater, micro-scale capture of rainwater where it otherwise evaporates, fog water, collection and treatment of wastewater, grey water, and storm water, and collection and use of agricultural drainage water.

Desalination

Desalinating water for use as a possible future source is one of the proposed solutions to prevent Yemen's water crisis reaching catastrophic levels. However, desalination is expensive because of the high costs to Build and Operate, and these costs would raise the price of water for the population as a whole, potentially making it unaffordable (Glass, 2010). Furthermore, desalinisation has the potential to increase fossil fuel dependence, increase greenhouse gas emissions, while the use of chemicals and discharge of large quantities of the by-product warm brine presents a threat impacting the environment and human health.

There are at least two desalination stations in Yemen, one of which is in Aden called Al-Haswah Electricity Station. This station used to supply electricity mainly for Aden city through the heating of seawater, producing about 69,000 m^3/day of freshwater. This amount of water is mixed with the network of Aden water supply. The second desalination station is located in Al-Mokha area 100 km south of Taiz Governorate (Al-Sabri & Halim, 2012). It has been reported to be destroyed by airstrike in 2016 and yet it is not confirmed whether it has been rehabilitated (Clifford and Triebert, 2016). In 2002, the total installed gross desalination capacity (design capacity) was 76,596 m^3/day or 28 million m^3/y (Wangnick Consulting, 2002). The production of desalinated water reached 25.1 MCM in 2006 (Al-Sabri & Halim, 2012)

In many places in the country, brackish water appears naturally either in surface water or in groundwater. However, the extensive withdrawal of groundwater caused the increase of salinity in many basins particularly in the coastal areas. The actual brackish water quantity has not been determined for the whole country. However, the usable brackish water for agriculture in Yemen is about 300 MCM/year and mostly in the coastal areas particularly in Tehama region (Al-Sabri & Halim, 2012). On the other hand, the amount of brackish water used in the water supply for Taiz city is about 3.1 MCM/y (ACWUA, 2010).

Rainwater harvesting

Rainwater harvesting aims to prevent as much rainfall as possible from being wasted. The government has constructed many small water harvesting and diversion structures to collect rainwater for irrigation and domestic use. These structures could either recharge the groundwater or be used as surface water. *It is much easier and more effective to use surface water than to drill and pump groundwater* (van Steenbergen et al., 2010). The Social Fund for Development and the Public Work Project are both implementing hundreds of additional rainwater harvesting structures all over Yemen, either as open structures or covered structures, especially in rural areas but also in urban areas such as Sanaa, enabling the harvesting of storm water from streets or smaller amounts from the roofs of houses and schools (Noaman et al., 2021). In recent research at Sanaa University's Water and Environment Centre looked at the viability of water harvesting along the Sanaa to Hodeidah road where water rights, water ponding and water structures are the main issues considered for irrigation (Al-Maswari et al., 2020).

In the Manakha region in Yemen, UNDP investigated the use of fog water harvesting, by which fog is collected and conveyed to storage tanks (UNDP, 2013). The use of fog harvesting is however limited to the higher elevated areas (2000-2500 above sea level) and may serve as a supplementary, spare and resilience technology at household level (Naoman & Al-Washali, 2019).

Considering the estimated 270 MCM/y that flows from the major wadis into the sea (FAO, 2008), the potential for in-stream and off-stream water harvesting in Yemen is present. Studies showing the water harvesting potential are lacking though.

2.4 Water demand

Demands for water in Yemen show an ongoing increase in the last decades (Table 1). Demand estimates for 2000 were as high as 3,400 MCM per year, showing increased demand that significantly exceeds supply in many catchments (MWE, 2004). Latest demand estimates refer to 3,900 MCM per year (Al-Eshlah et al., 2013; Noaman et al., 2021), however it is unclear how these numbers are derived and whether they are based on the estimates from Table 1. Apart from the increase of domestic water use due to high population growth, urbanization and internal displacements, the agricultural water demands have increased even more. Reported causes for this increase lie in the introduction of subsidies for diesel-operated water pumps and increased cultivation of qat and other water intensive crops.

Table 1. Sectoral water use (MCM/y) over a period of 20 years (Source: Yehya & Al-Asbahi, 2005).

Water use	1990	2000	2005*	2010*
Agriculture/irrigation	2,600	3,145	3,235	3,328
Domestic/urban/rural	168	210	265	552
Industrial & mining	31	45	65	90
Total	**2,799**	**3,400**	**3,565**	**3,970**

**Estimated*

2.4.1 Agricultural water use

The agricultural sector in Yemen is the dominant water user (90%) whereas the domestic and industry sectors use 7-8% of the water resources. Yemen's cultivated area was estimated in 2018 to be about 1.1 million ha, of which 50% is dependent on rainfall and roughly 50% is irrigated by groundwater or surface water from seasonal floods (spate irrigation) (Table 2 & Figure 12; MAI, 2019). Whereas rainfed agriculture decreased from 1,285,000 in 1970 to 507,000 ha in 2018, groundwater-irrigated agriculture increased from 37,000 ha (Hellegers et al., 2008) to 340,000 ha (MAI, 2019) in the same period (Table 2). This is the equivalent of a third of the national cropped area. Most of this is under high-value crops: fruit, vegetables and qat often mixed with timber and firewood trees. Hellegers et al. (2008) mention that qat occupies at least half of the irrigated area in Yemen, growing at an annual rate of 9% (double the growth rate of other crops). According to McCracken (2012) qat consumes 36% of Yemen's total renewable water resources and 32% of all groundwater withdrawals. The Ministry of Agriculture and Irrigation (MAI) provides annual overviews of cropping areas, specified by governorate.

Table 2. Development of cultivated areas (x 1,000 ha) in Yemen according to the source of irrigation between 1975 and 2018 (Adjusted from Hellegers et al., 2008 and MAI, 2019). * Others include spring, streams, dams and reservoirs and water trucking.

Year	Rainfed	Well	Spate	Others*	Cropped area
1975	1,285	37	120	73	1,515
1990	685	310	101	25	1,121
1995	579	368	100	20	1,067
2000	515	457	126	46	1,144
2005	609	393	137	34	1,202

2018	507	341	159	58	1,065

General Summary of Areas in (ha) & Production in (MT) of Agricultural Crops in R.Y 2014- 2018

ار) والانتاج
هورية اليمنية

Crop /Year		2014	2015	2016	2017	2018
Cereals	Area	727,069	585,658	519,765	512,659	504,737
	Prod	700,962	460,246	357,068	358,355	344,648
Fodders	Area	149,652	137,730	133,257	133,813	131,415
	Prod	1,868,411	1,623,546	1,579,896	1,587,944	1,605,753
Fruits	Area	93,968	91,447	89,092	88,832	85,708
	Prod	993,643	938,523	906,955	903,472	808,433
Cash Crops	Area	84,152	80,288	78,371	77,645	74,778
	Prod	85,538	77,017	74,172	73,590	65,839
Vegetables	Area	81,911	69,616	65,670	65,198	63,502
	Prod	968,323	902,852	821,003	817,847	828,293
Legumes	Area	45,422	40,889	39,288	39,155	37,927
	Prod	92,216	75,988	73,409	72,630	62,486
Qat	Area	169,386	166,557	167,405	166,699	166,745
	Prod	193,940	184,749	186,285	185,621	186,167
Total	Area	1,351,560	1,172,185	1,092,848	1,084,001	1,064,812

Figure 12. Summary of production areas of major agricultural crops in Yemen from 2014-2018 (Source: MAI, 2019).

2.4.2 Agricultural sector developments

Since 1975, the government, through different ministries, regional development authorities, and the cooperative and Agricultural Credit Bank supported a major investment programme to expand the cultivated area under well irrigation. The public and private sectors have drilled thousands of wells and equipped them with pumps and motors to extract underground water resources for the expanding agricultural economy especially the production of fruits, vegetables and most importantly qat (Hellegers et al., 2008).

In addition to the direct investments by the government in irrigated agriculture, subsidies were provided to the private sector to import pumps, motors and rigs. The Cooperative and Agricultural Credit Bank provided low-interest loans at subsidised rates for irrigation. Diesel and electricity prices were kept very low compared to international prices. Consequently, virtually all aspects of groundwater development and exploitation have been supported and subsidised by government actions over the last 30 years (World Bank, 2015; Hellegers et al., 2008). Since the mid-1990s the government of Yemen has been aware of the water crisis and has begun taking steps to mitigate the water problem. This was done by establishing the NWRA and drafting the NWSSIP (Hellegers et al., 2008).

In recent years and as a result of the conflict in Yemen, the power grid collapsed and diesel prices showed a steep increase. This led to the introduction of solar power, which has now spread to health, education and agriculture. Especially in the agricultural sector, previously dependent on diesel for extraction of groundwater, a rapid shift to solar power is noticed. Part of which is boosted by international development agencies supporting in investment costs. Irrespective of the availability of fuel, farmers are now able to abstract groundwater year-round, potentially further increasing water use. CEOBS

(2021), based on satellite imagery analysis, recently opted that a significant drop in groundwater since 2018 is likely a result of the spread of solar in agriculture, and argue that interventions are required on multiple levels and by all stakeholders to halt severe groundwater depletion.

2.5 Overall water sector challenges

2.5.1 Population growth and urbanization

Population growth

The population of Yemen is estimated at 30 million, of whom 74% live in rural areas. Yemen's population grew almost five times in half a century, from ~6 million in 1970 to almost 30 million in 2020 (Figure 13; UNDP & FAO, 2020). Per capita availability of the renewable water stands at 85 m3 per year, drastically below the recognized water scarcity threshold of 1000 m3 (UN-Habitat, 2020c). Following Noaman & Al-Washali, 2013, this might decrease even more in the near future, even further amplified under influence of climate change (Figure 13). The World Bank reported that in 1990, 71% of the population had access to water. In 2010, that figure had decreased to 65%.

Population growth, increased urbanization and conflict-related displacements increased the pressure on existing water supply networks. Apart from the population size, the dynamics of the ongoing conflict can suddenly put additional pressure on local water supplies, when influx of IDPs show a large increase. The current infrastructure, let alone the inefficiencies and significant water losses (non-revenue water up to 50%, *e.g.* Upper Abyan-Bir Nasser pipeline, UNDP-NWRA, 2009) due to poor performance, conflict-impacts and lack of maintenance and rehabilitation works, is not designed to supply these growing needs. On the sanitation side, leakages of wastewater from local sewage systems and free drainage in areas with no sewage system at all, locally contribute to the contamination of groundwater. Furthermore, water supply systems have insufficient storage capacities to store available surface water run-off or buffer for technical breakdowns. This leads to limited access to water in urban areas, where population in some areas receive less than three litres per capita per day. Structural investments to rehabilitate or expand water supply capacity do hardly take place due to the precarious financial abilities and the lack of effective planning and management. Additionally, the ongoing conflict leads to an unfavourable investment climate in which lifetime of investments are unsure and new infrastructure is prone to damages.

> "The infrastructure projects focus on establishing new infrastructure for example through solarization or rehabilitate existing infrastructure, but there is no clear long-term strategy on the decision making around new construction or rehabilitation, which is ineffective from a resource and cost point of view."
> Mrs. Gerrianne Pennings – ZOA Yemen Manager of Programme Quality
> (p.c. 31-08-2021)

Above quote regarding infrastructure investments is resembling the situation in more countries than only Yemen. Often this is related to the ease of formulating and financing new infrastructure programmes, rather than aiming at long-term sustainable investments in infrastructure (*e.g.* combined with strategic urban planning). Additionally, it often involves pre-feasibility/performance studies to indicate where necessary maintenance works are required, which proves to be difficult to conduct prior to receiving a major fund for rehabilitation.

Urbanization

Urbanization is a serious challenge, as evidenced by the rapid growth of cities like Sanaa, Aden, Mukalla and Taiz over the past decades. The growth of Sanaa in particular and the increase of the cropped area under irrigation have seen the deficit between water demand and water availability grow over the years. This overexploitation has led to a continuous lowering of the groundwater table and the need to drill deeper and deeper wells. As a result, water is becoming increasingly expensive and inaccessible to the wide majority of urban dwellers (Republic of Yemen, 2016).

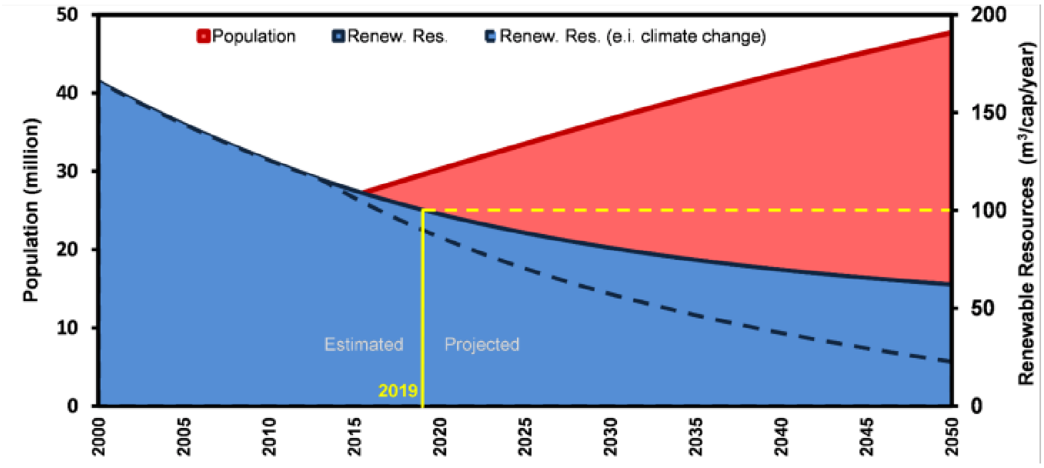


Figure 13. Projections of population growth and per capita availability of renewable water resources in Yemen (Source: Noaman & Al-Washali, 2013).

Non-revenue water

> "While agriculture has received most attention (and criticism) for low water use efficiency, the situation is far from satisfactory in other water consuming sectors. The proportion of unaccounted for water (losses) of urban water supply utilities is very high, sometimes approaching 45-50 % of water production. A significant part of these losses is system losses due to poor maintenance."
> Adapted from NWSSIP, MWE (2004)

As stressed in the above box, frequently mentioned non-revenue water (NRW)-values for urban water supply and distribution systems in Yemen are in the range of 50%. This means that half of the water produced is being lost, or put differently: water availability for the urban poor could be twice as high.

2.5.2 Agriculture and food security context

Agri-food crises

Prior to the conflict, agriculture and fisheries contributed between 18 and 27 percent of Yemen's GDP, 25 to 30 percent of the annual food requirement and employed more than 50 percent of the country's workforce. These percentages are now shrinking as the agriculture sector has become one of the worst hit by the current crisis and local food production has been severely compromised. Some of the factors contributing to this, and attributed directly to the crisis, include:

i. limited availability and high cost of agricultural inputs;
ii. low availability and high cost of animal feed;
iii. inability to control plant and animal pests and diseases;

iv. **increasing production of water intensive cash crops (*e.g.* qat), which reduces the amount of land available for food production and contributes to the depletion of the water table;**
v. damage to water irrigation infrastructure ;
vi. an emigrating workforce; and
vii. limited public resources allocated to the sector.

Other more structural factors include:

viii. diminishing natural resources, in particular groundwater mining (following uncontrolled extraction, misguided policies promoting the use of water, and inefficient water management practices) and the degradation of land (following deforestation, lack of terrace maintenance, soil erosion and soil salinity);
ix. the effects of climate change and variability, causing more extreme weather events; and
x. inequitable access to arable land (Al-Eshlah et al., 2013; Glass, 2010; FAO, 2018).

Out of the 10 above mentioned factors, four show a direct link with water management. **Based on this, one could conclude water playing a major role both in the problem (*i.e.* the ongoing agri/food crises for over the last 20-30 years) as well as the solution.** The problems reflect the imbalance between supply and demand, and majority follow from the assumption that there is sufficient water available for agriculture. The road towards solution lies in water allocation following the priority needs as per available water supply, and decision making on what is considered a priority (*e.g.* drinking water above agriculture?).

Employment shifts

Given the ongoing urbanization in Yemen, amplified by the ongoing conflict and internal discplacements, main employment shifts are noticed between agricultural towards the services sector (*e.g.* wholesale and retail trade and restaurants and hotels; transport, storage, and communications; financing, insurance, real estate, and business services; and community, social, and personal services). The ongoing conflict though has severely impacted the country's GDP, resulting in high poverty numbers and insecurities in income generation (World Bank, 2020). At the same time agriculture remains the main income source in rural areas. Given the uncertainties in water availability, declining water tables and depletion of water reserves, this may increasingly pose a threat to rural income generation as well. Sectoral diversification and alternative income source generation will help to decrease water dependency and to adapt and anticipate to increased water shortages in the near future.

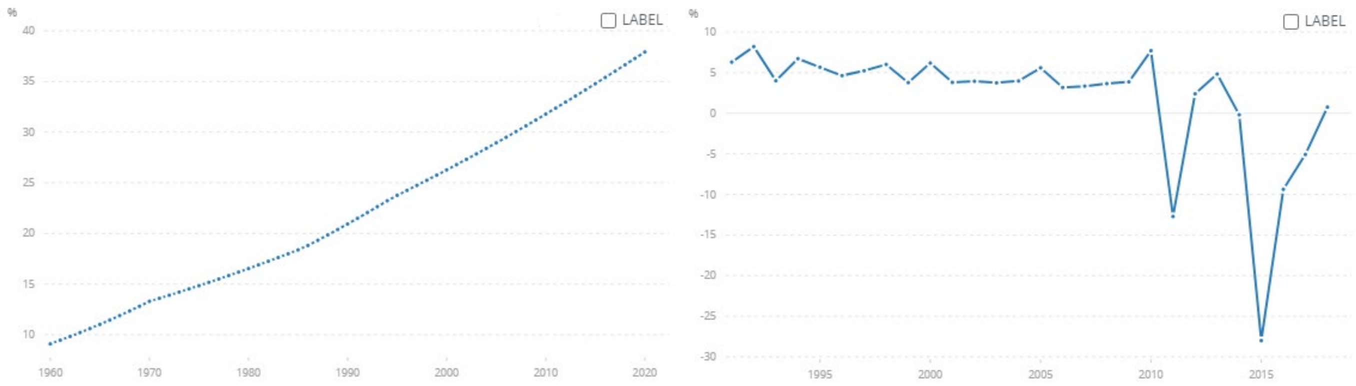


Figure 14. Urban population (% of total population; left) and GDP growth (annual %; right) in Yemen (Source: World Bank, 2020) World Bank national accounts data, and OECD National Accounts data files.

Low irrigation efficiencies

Low irrigation efficiencies in the agricultural sector have often been cited as the main reason for unsustainable water use patterns and resource depletion. The irrigation efficiency in agriculture is indeed low – in some cases only around 35%. However, the case for potential water saving in irrigation is rather overstated. Return flows to the aquifer are usually not considered and focus is on water use efficiency at the farm level instead of the basin level. While 4 to 15 percent water saving in irrigated agriculture can be realized by improved irrigation methods, a dramatic intervention is required to reverse the increase in agricultural water consumption (MetaMeta Research and PAN Yemen Consult, 2013). Irrigation efficiency improvement efforts have targeted conveyance efficiency rather than the adoption of a comprehensive on-farm water management approach, which would have been more effective at preventing unproductive non-consumptive losses such as excessive evaporation (MWE, 2004). The area irrigated by improved systems (pipes, localized systems, sprinklers) is around 25,000 ha (year of reporting unknown; Noaman et al., 2021).

Groundwater resource depletion

In the past decades the agricultural sector in Yemen is marked by shifts from rainfed to irrigation agriculture. The irrigation sector in Yemen used to be characterised by spate irrigation schemes. However, these often old structures, part of which constructed by Soviets in the 1970s, suffered from insufficient maintenance, resulting in excessive water losses and poor performance. Other spate irrigation structures, like in Hadhramaut, are washed away by rush floods and are not rehabilitated. As a result, most water for agriculture nowadays comes from groundwater sources.

At first, farmers were using hand-dug and shallow wells, but due to over abstraction these shallow wells ran dry and deeper groundwater layers are tapped in an uncontrolled environment, leading to unlicensed abstractions. The shift from shallow to deep (drilled wells), at the same time meant a shift from renewable to mining of fossil, non-renewable, groundwater sources. Declining groundwater levels are reported in all major agricultural areas, and the ongoing overexploitation will result in further lowering of groundwater levels.

Shallow groundwater in Yemen is mainly recharged by seasonal floods. These floods are also named ‘rush floods’, as they rapidly advance through a wadi bed, indicating that the time for infiltration and thus recharge is limited. Most water is flushed directly into the sea (left unused) as water is not retained, captured or slowed down by in-stream or off-stream structures. Due to climate change the intensity of floods are expected to increase, as well as its destructive capacity.

Fossil groundwater can locally have large reserves, but the groundwater recharge is much smaller than the rate of abstraction. With the current rate of abstraction and supported by the figures on groundwater level decline in all areas of Yemen, it is well possible that these groundwater aquifers will also run dry shortly.

2.5.3 Water scarcity

The scarcity of water resources, conflicts, and the manifolds of crisis led to 70% of farmer's tenants losing their income opportunities and, as a result, leading to 80% poverty in the country. In 2018, an estimated 16 million people were dependent on humanitarian assistance to establish or maintain access to safe water, basic sanitation, and hygiene facilities, out of which 11.6 million are in acute need (UNDP & FAO, 2020)

On paper, Yemen's water resources are sufficient to meet domestic water demands. The combination with intensive agriculture and growth of water-intensive crops, result in high groundwater abstraction rates and falling water tables. To meet the growing demand, it is estimated that the total amount of water required in the next decade will be about 4,500 MCM/y. The water deficit in 2000 was 700 million cubic metres (MCM), rose to 900 MCM in 2010 (Ali & Al-Kadasi, 2011) and is expected to reach 2,500 MCM in 2025 (Noaman et al., 2021).

In essence, with the conflicts and past institutional failures, Yemen's ability to combat water scarcity faces three major challenges (Aklan et al., 2019; Moyer et al., 2019):

- the lack of coordinated and integrated planning and allocations - between sectors using water and vertically across the various governance levels;
- most laws and policies remain on paper with clear lack of needed monitoring for compliance and enforcement, and necessary monitoring (open data) to support policy making; and lastly
- the lack of clear institutional responses especially to the recent extreme water events due to climate change (UNDP & FAO, 2020).

2.5.4 Internal disputes over water

Historically, Yemenis have been adept at managing their water. They have used elaborate terracing and runoff management systems, spate diversion and shallow groundwater management, according to the nature of the resource and the local social organization. Elaborately negotiated rules and organization accompanied the development and management of each water resource. Even so, frequent disputes arose. Critical for improving water-allocation policy is the recognition of water's multiple uses (Lichtenthaeler, 2010).

A study by Sana'a University researchers and presented in Al-Thawra (Yemen's pro-government newspaper) found that between 70-80 percent of all rural conflicts in Yemen are related to water (Glass, 2010; Climate Diplomacy, 2021). The Yemeni ministry of the interior says that 4,000 people die each year in violent disputes over land and water (Whitehead, 2015, Almohsen, 2015). Whitehead (2015) point towards rapidly decreasing water availability as a consequence of mismanagement, overexploitation and climate change as the main causes for local disputes over water and land distribution turning violent. Zeitoun (2009) mentions the use of firearms as both explosive and deterrent power may be nowhere in the world more prevalent in the water sector than in Yemen.

Conflicts over water are carried out on various levels. Sometimes, only between few individuals, *e.g.* when a villager builds a well more proximate to another villager's than customarily accepted. Often, however, the violence over water involves whole tribes or villages fighting each other, by inflicting considerable damage to the competitors' water infrastructure, *e.g.* through the blowing up of wells and pumps, or also by killing members of the other community directly. Although they cause large numbers of casualties, the vast majority of these conflicts are highly localised (Climate Diplomacy, 2021).

Moreover, disputes are increasingly likely as internal migration rises and land sales have led to a mixed make-up of villages where cohabiting tribes with diverging economic interests compete for access to dwindling water resources. In this context, resentments are likely to surge and ancient feuds can be revived. Water disputes are often closely connected to land disputes and may be the trigger for conflict against a background of other grievances (Climate Diplomacy, 2021).

Huntjens et al. (2014) provides an extensive overview of the causes and stakeholders playing a role in water related conflicts, supported by a large number of case studies in Yemen.

2.5.5 Climate change

The precarious water situation is exacerbated with the regional climate projections in which Yemen will experience more rains and higher temperatures. In recent years, Yemen's rainfall patterns have shown increasing extremes – attributed to climate change and variability. Frequent droughts and flash floods have further affected crop production, livelihoods and income generation for a significant percentage of the population (UNDP & FAO, 2020). The floods expose the countries vulnerability to land degradation and erosion. The absence of vegetation in most areas, combined with steep slopes and weakly developed soils, limit the buffering capacity. Climate change projections predict the southern part of the Arabian Peninsula, including Yemen, to face an increase in annual rainfall, rainfall intensity and inter-annual rainfall variability (IPCC, 2013). As a result, it is likely that in Yemen, climate change will result in an increase of frequency and severity of extreme weather events such as droughts, flash floods and sandstorms.

> "The severe floods in Wadi Hadhramaut destroyed majority of the spate water irrigation infrastructure, resulting in agricultural practice since then relying for more than 90% on groundwater. This further increased the pressures on groundwater resources."
> Mr. Salem Bashuaib - Former chairman NWRA (p.c. 31-08-2021)

As an example, the flash floods in Wadi Hadhramaut in 2008 resulted in estimated damage and losses of 1.64 billion USD (Ali & Al-Kadasi, 2011). More recently, the floods in April 2020 affected water infrastructure across the whole of Yemen. World Bank (2010) shows that under the 'warm and wet' climate scenario, floods in Wadi Hadhramaut could increase by 40% in the 2030s and large flooding events would occur twice as often.

The impact of floods is related to the limited buffering capacity and is also reflected by FAO (2008) estimate on surface runoff to the sea measured in some major wadis and estimated at 270 MCM/y and groundwater outflow to the sea at 280 MCM/y. This reveals unused potential for in-stream and off-stream storage, soil and conservation and protection and restoration opportunities to reduce the peak flow and sediment load and increase the buffering capacity. Capturing the unused surface runoff, could increase recharge of shallow groundwater and/or enhance local offseason water availability. Helder et al. (2020) provide a useful analysis for in-stream and off-stream storage potential for Marib catchment area.

Many households also face the threat of crop failure due to the effects of pests and diseases, sandstorms and land (FAO, 2018). These pronounced extreme events which are likely to become more frequent and extreme will increase pressure on water institutions, infrastructure and communities, further compromising their health (due to poor sanitation), food security, livelihood resilience and will lead to reduced adaptive capacity (UNDP & FAO, 2020).

Ali and Al-Kadasi (2011) discuss the relevant climate change studies and policy frameworks in Yemen and pose that the current NWSSIP II is inadequately responsive to adapt to the climate change impacts. Furthermore, World Bank (2010) provides a vast study on the impacts of climate change on water resources in Yemen.

3 Water balance approach

A water balance analysis is an accounting of inflows and outflows of water. The insight it provides into how water is distributed over different flows is crucial to estimating water availability and evaluating and informing sustainable water use development plans. In this study, a water balance analysis was performed for each of the three focus areas based on open data.

The water balance of a geographic region can, in general, be written as:

$$P = ET + q_s + q_N + \Delta S;$$

where P is the precipitation (mm/y); ET is the evapotranspiration (mm/y); q_s is the streamflow (mm/y); q_N is the net flux (mm/y) of any water entering or leaving the region other than precipitation (*e.g.*, water diversions, groundwater flux across the basin boundaries); and ΔS is the change in stored water (mm/y) within the area.

A negative value for ΔS means that the storage of water in the soil and in groundwater is declining. This is an indicator that (ground)water use is not sustainable, which can lead to various socio-economic and environmental impacts, including falling groundwater levels, drying springs, and higher pumping costs.

Below, the different components of the water balance and the sources used for their estimation are presented.

3.1 Precipitation

Satellite precipitation data for the period 2009–2015 were obtained from the Climate Hazards group InfraRed Precipitation with Station data (CHIRPS) version 2 dataset developed by the U.S. Geological Survey (USGS) and the Climate Hazards Group of the University of California (Funk et al., 2015).

3.2 Evapotranspiration

Estimates of the actual evapotranspiration rates, and the individual components of soil evaporation, canopy transpiration and rainfall interception, were obtained from the FAO WaPOR database (Mannaerts et al., 2020) for the period 2009–2015. WaPOR uses remotely sensed data to calculate evapotranspiration and rainfall interception loss with a 250 m resolution on a 10-day basis. The quality of the WaPOR dataset seems sufficient for understanding hydrological processes and use in water management.

The average annual evapotranspiration was differentiated into estimates for irrigated cropland, rainfed cropland, and non-cropland areas using land cover information. The annual land cover dataset in the WaPOR database, which is based on the CGLS-100m land cover map for 2015 (Buchhorn et al. 2020), was used for this analysis.

3.3 Streamflow

Streamflow data measurements are not available for the three focus areas. Therefore, the global FLO1K dataset (Barbarossa et al., 2018) are used. The dataset consists of mean, maximum and minimum annual naturalized streamflow estimates at a resolution of ~1 km. In this analysis, data for the years 2009–2015 were used.

3.4 Groundwater recharge

The amount of water that percolates to the groundwater is defined as groundwater recharge. In arid regions, recharge occurs mainly through infiltration in the ephemeral stream beds in the wadi and through flow in preferential flow paths in the soil and rock, but most of the water is absorbed in the unsaturated zone and evaporates, with only a small part reaching the aquifer. In semi-arid and arid regions, the recharge is irregular and occurs only in the periods of heavy rainfall.

Groundwater recharge represents the amount of water that can be abstracted without depleting the aquifer and is therefore an important indicator in the evaluation of current and future sustainable development and use of the groundwater resources. However, estimating groundwater recharge is challenging and highly uncertain because direct measurements are typically not feasible. This means that indirect methods are commonly used.

In this project, groundwater recharge is assumed to be 1 to 5% of the total precipitation (Ajami, 2021). The upper value is used in the Dhamar Governorate, where precipitation is relatively high, and the lower value is used in the drier Abyan and Hadhramaut Governorates.

3.5 Groundwater anomaly

Estimates of regional groundwater anomalies are based on Total Water Storage anomalies obtained from the Gravity Recovery and Climate Experiment (GRACE) (Watkins et al. 2015, Wiese et al. 2016). TWS represents the sum of all water storage above and below the surface, including groundwater, soil moisture, canopy water, and rivers and lakes. The data have a resolution of ~300 km. Though this is relatively coarse compared to the scale of the study areas, it is uniquely suited to providing insight into regional trends in water storage, and groundwater in particular, in data scarce areas.

In this study, the TWS anomalies are corrected with soil moisture and canopy water anomalies derived from Global Land Data Assimilation System (GLDAS) (Rodell et al. 2004). Assuming that anomalies in river and lake storage are negligible in the (semi-)arid study areas, the resulting dataset represents groundwater storage anomalies.

3.6 Domestic water use

Domestic water use in each of the three focus areas is based on the population size of the governorate and an average per capita water use. Population data were obtained from the WASH Cluster (2021) census. Average water consumption per capita was assumed to be 30 litres per capita per day. This estimate is based on data collected in household surveys including rural and urban areas, host communities and IDPs (REACH, 2018). This value is approximately twice the SPHERE Minimum Standard for water supply, which indicates that 15 l/c/d is the minimum quantity of safe water required to realise minimum essential levels for health and hygiene in emergency situations.

4 Water availability in Wadi Hadhramaut catchment

This chapter takes a closer look at the water availability for agricultural activities and food production in Shibam District and Al Qtan District in Hadhramaut Governorate (named "Wadi Hadramout" in the ToR). This focus area is selected as it is one of the implementation areas of the FAO Resilience Programme in the Irrigation and Agricultural Sector (UNDP & FAO, 2020). To carry out the water balance analysis, the study must take account of the drainage area of the districts. Thus, this study analyses the water availability of Wadi Hadhramaut catchment more specifically.

The available literature and past hydrogeological data studies were reviewed, notably:

- The extensive report released by the National Water Resources Authority (NWRA) and United Nations Development Programme (UNDP) in 2009, W*ater Resources Management for the Wadi Hadramawt Region (Updated and Revised),* that describes the major outputs of the remote sensing and geological study carried out by KOMEX International Ltd. (Calgary, Canada) in 2001. It should be noted that the main outcomes of the 2009 report are similarly reflected in the NWRA report of 2011, *Wadi Hadramawt. Changes in groundwater chemistry between 2001 and 2011.*
- The research of Soliman et al. (2015), *Hydrological analysis and flood mitigation at Wadi Hadramawt, Yemen*, on flood events.

Combined with recent remote sensing and satellite data analyses techniques using digital elevation data from SRTMGL1 dataset (NASA-JPL, 2013) and land cover data from ESA Land Cover Maps v2.0.7 dataset (ESA, 2017), the study results in unique updated insights into the water balance of Wadi Hadhramaut.

4.1 Overview of the wadi catchments

Wadi Hadhramaut - also spelled Hadramawt or Hadramout - is located in a desert region in the east-central part of Yemen in the Hadhramaut Governorate, as shown in Figure 15. It is one of the most important agricultural areas, famous for its date palm plantations and some irrigation crops and other vegetation (Almhab, 2009).

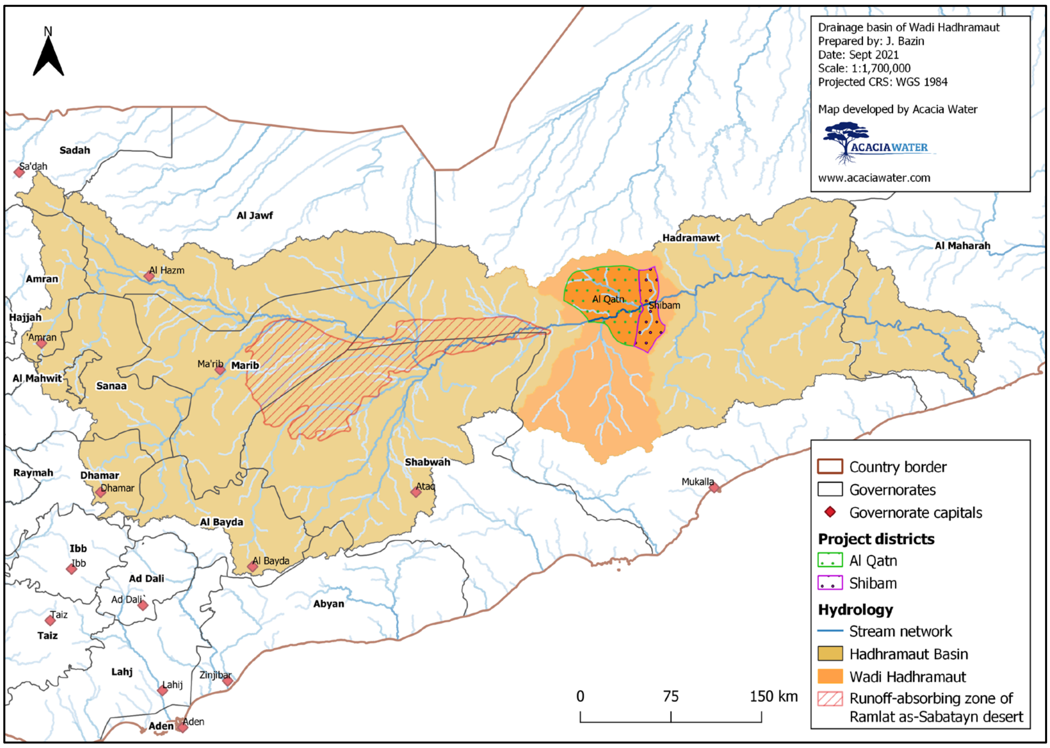


Figure 15: Drainage basin of Wadi Hadhramaut, derived from DEM data of the SRTMGL1 dataset (NASA-JPL, 2013).

The study area covers **approximately 14,500** km2 **between the desert of Ramlat al-Sab'atayn and the city of Tarim**, following the main wadi valley over a length of 100 km. The main southern tributaries include (from east to west): Wadi Amd, Wadi Do'an, Wadi Al Ayn and Wadi Bin Ali; the main northern tributaries are Wadi Saar and Wadi Juaymah (Noaman et al., 2021, NWRA, 2011, UNDP-NWRA, 2009). Thus, the catchment area is not only limited to Shibam District and Al Qatn District, but it extends to 12 other districts. In particular, it encompasses the districts of Ad Dulay'ah, Amd, Daw'an, Haridah, Wadi Al Ayn and Sayun.

4.2 Socio-economic characteristics

4.2.1 Population

The population of Hadhramaut Governorate in 2019 is approximately 1.4 million across 28 districts, of which 93,000 are in Al Qatn District and 71,000 in Shibam District (Alsabri, 2021).

Based on the census of WASH Cluster (2021), t**he population of Wadi Hadhramaut is estimated at approximately 490,000 inhabitants, of which 5,000 are IDPs**. The population density is relatively low, with 5-15 p/ km2 (Almhab, 2009). In fact, the main wadi valley is home to two-third of the population (NWRA, 2011).

4.2.2 Land use

The remote-sensing study of land use and land cover determined that Wadi Hadhramaut is comprised of bare areas and scattered vegetation for 96% of its total surface area, as shown in Figure 16. The vegetation in this eco-region is sometimes referred to as a pseudo-savanna. The spaces between the scattered trees and larger shrubs are occupied by smaller shrubs and herbs; grass cover might sometimes appear, but only after a good rainfall (UNDP-NWRA, 2009).

The wadis and gullies tend to support the most vegetation, due to generally higher soil moisture levels (UNDP-NWRA, 2009). This remote-sensing study confirms this statement; cropland extends along the main wadi in the valley while grassland is more present in the upper reaches of the southern tributaries (see Figure 16). **Cropland is mainly irrigated, accounting for 1.2% of the total land use and land cover (LULC) in Wadi Hadhramaut, or a total of 17,800 ha**. About 3,800 ha are fallow agricultural land. However, the lack of rainfall does not allow the development of rainfed agriculture.

This remote sensing study shows that built-up areas amount to 31 km2. Although it represents only 0.2% of the total surface area of the wadi, it is important to highlight the on-going urban expansion. A previous study showed that built-up areas had already increased by more than 200% between 1977 and 2001 (UNDP-NWRA, 2009).

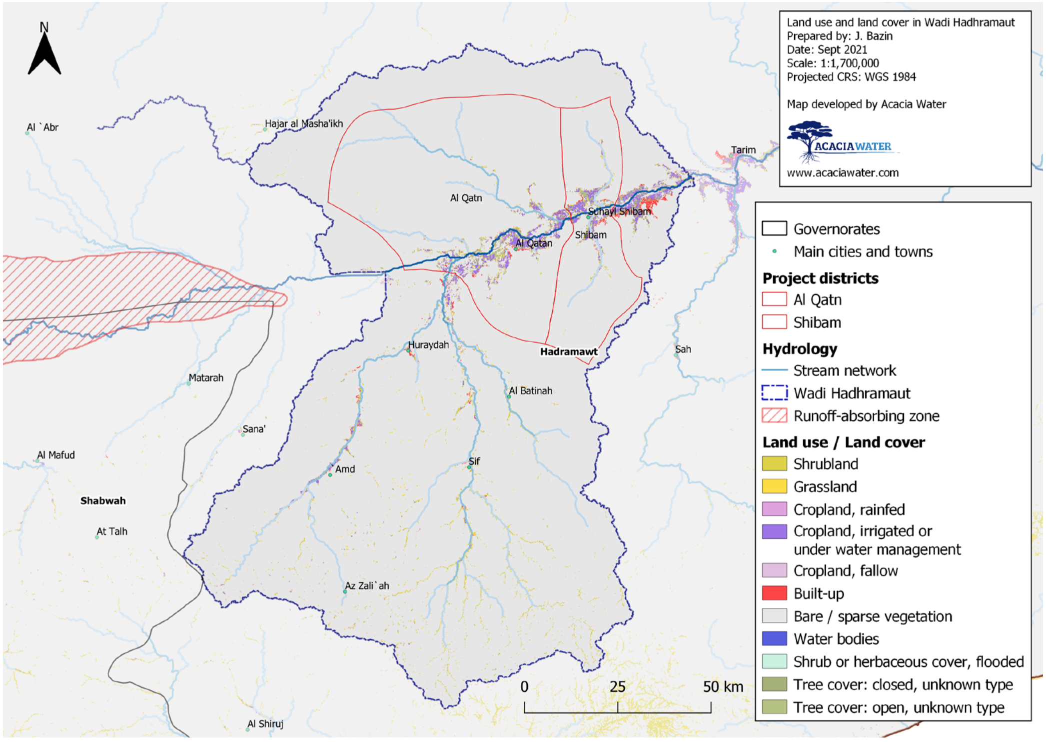


Figure 16: Wadi Hadhramaut and land use, derived from land cover data of the ESA Land Cover Maps v2.0.7 dataset (ESA, 2017).

4.2.3 Livelihoods and conflicts

According to population estimates from the Census 1994, the rural population was reported at 75% (UNDP-NWRA, 2009). Today, a growing proportion of the population lives in urban areas. Based on the livelihood zones identified and defined by FEWS NET (2010), the sub-catchment includes three main farming systems:

- **YE03, in the plateaus of Wadi Hadhramaut: agro-pastoral zone**. Unimodal rains precipitate less than 60 mm of moisture annually, rendering crop production a risky livelihood option. If conditions permit, households can produce wheat and sorghum; however, the amounts they harvest are insufficient to meet their food needs. Therefore, most households are dependent on the market for their food, followed by livestock products;
- **YE04, in the valley of Wadi Hadhramaut: wheat, sorghum, vegetables, palm and livestock**. The zone's residents take advantage of the wadis to irrigate their fields providing sufficient moisture to grow vegetables and date palms.

In October 2008, Wadi Hadhramaut was hit by a destructive flood event in the wake of a tropical storm. Overall, about 700,000 persons—over 50% of the total population in the affected areas have had their livelihoods destroyed or significantly affected (World Bank and GFDRR 2010, in NWRA, 2011). More than 25,000 people were displaced seeking temporary shelters, thus shifting water demand, and agricultural lands and irrigation infrastructures sustained significant damage (Soliman et al., 2015). The impacts of the flooding on water resources and infrastructures are further described in Sections 4.3 and 4.4.

4.3 Water availability

4.3.1 Surface water

Hydrology and sub-catchments

As shown previously in Figure 15, Wadi Hadhramaut is part of the major water basin draining to the South in the Arabian Sea. In the upper catchment lies the Ramlat as-Sabatayn desert in central Yemen, which receives water flow from Sana'a Basin and Dhamar Basin among others. However, studies have indicated that the water flow of the upper catchment does not reach Wadi Hadhramaut; the Ramlat adeserts-Sabatayn desert is in fact a runoff-absorbing zone as a result of very deep layers of alluvium (Noaman et al., 2021, Farquharson et al., 1996). This runoff-absorbing zone may contribute to baseflow runoff, but it generates negligible surface runoff. Thus, the intake part of Wadi Hadhramaut starts from the eastern limit of the Ramlat as-Sabatayn desert.

This remote sensing study located the main wadi at an altitude between 700 and 620 m above mean sea level. It is boarded by the 200 to 300 m high cliffs of the Northern and Southern Jawl plateaus that are dissected by many stream channels and wadi tributaries. The western part of the valley is about 15 km wide, while it is only 1.5 km wide in proximity of Tarim (UNDP-NWRA, 2009). The bed of Wadi Hadhramaut lies some 300 m below the level of the plateau, in a gorge (Alsabri, 2021).

The annual rainfall is less than 100 mm in the main valley and less than 50 mm in the Northern Jawl. Some parts of the Southern Jawls might receive from 100 to 300 mm/y. **So far, the adopted mean annual runoff for Wadi Hadhramaut was estimated at 82 MCM/y** (Van der Gun and Ahmed, 1995, in UNDP-NWRA, 2009). **Based on the FLO1K streamflow dataset, average annual streamflow in the years 2009–2015 is much lower, at 5.4 MCM/y**.

It is important to note that Wadi Hadhramaut is a seasonal watercourse. During the wet seasons, the surface water is mostly available only in the upper and middle reaches of main tributaries; in tributary Wadis Amd and Al Ayn, the spate is received every year. The availability of surface water in the main valley is restricted only to periods with extremely heavy rains (UNDP-NWRA, 2009). **Large amount of annual precipitation may fall within a few days during occasional rainstorm events.**

In exceptional cases, the wadi channels are unable to accept the sudden arrival of heavy floods when rainfall is particularly intense or prolonged. Indeed, the catchment areas of the tributaries of the Wadi Hadhramaut tend to consist of steep, rocky slopes with little vegetation and are prone to flash flooding. The wadi channels thus overflow, filling the wadi beds to beyond their capacity. The overflow washes away fertile topsoil and can cause great destruction to life and property (UNDP-NWRA, 2009).

Major flash flood events

This area experienced major floods in 1989 and 1996. For example, in June 1996 the climate station at the Seiyun airport registered 74 mm of rain. This corresponded to almost 75% of the annual precipitation in that year (NWRA, 2011).

In October 2008, Yemen was hit by a tropical storm that led to one of the worst natural disasters that devastated Hadhramaut Governorate, in particular Wadi Hadhramaut. Within two days, Wadi Hadhramaut received a total volume of 91 mm of rainfall on a catchment area of 2 million ha. In total, the catchment area collected a**round 2 BCM of water**. Given the topography of the affected area (mountainous terrain, flat valleys and riverbeds), this large quantity of water in the catchment area led to **severe flash floods in the valleys**, with water surges exceeding 10 m in some areas. (Soliman et al., 2015, World Bank and GFDRR 2010).

The total value of the disaster effects caused by the October 2008 storm and floods in Yemen was estimated at Y 327,551 million (US$ 1,638 million), which is equivalent to 6% of Yemen's Gross Domestic Product (GDP). Some 25,000 people were displaced seeking temporary shelters as a result of the loss of their house. Infrastructure was particularly badly hit, with major roads, communications, power, and water supply networks. Wadi Hadhramaut was the worst hit region by 67.5% of the total damage and loss in the Hadhramaut Governorate, with almost all districts were reported damaged (Soliman et al., 2015).

Surface water infrastructures

Spate irrigation using the available wadi surface water flow, used to take place in Wadi Hadhramaut as described by the former NWRA chairman, Mr. Salem Bashuaib (p.c. 31-08-2021). However, **the disastrous flood events of 2008 caused significant damage to the infrastructure for irrigation**. All the dams, weirs and channels were washed away. To this day, it is not clear whether the infrastructure has been rehabilitated and to what extent.

4.3.2 Groundwater

KOMEX (2002) carried out extensive hydrogeological studies in the study area, involving pumping tests and groundwater modelling. The main results are presented below as summarized in UNDP-NWRA (2009) and further analyzed in Soliman et al. (2015).

Geology and groundwater occurrence

The general geology of the Wadi Hadhramaut region is a series of thick flat-lying sedimentary rocks that were deposited in marine and/or continental environments. Since then, they have been deeply eroded into a complex pattern of wadis.

There are **four main aquifers** in Wadi Hadhramaut, as depicted in Figure 17. The steep walls of the wadi are formed by limestone above outcropping sandstone:

- **Eocene and Paleocene carbonates** (Layer 1, in Figure 17): On both plateaus, the Jeza and Umm Formation (about 40 m thick) and the underlying er Radhama Formation (about 200 m thick) are composed of shales, limestones and dolomites. These formations have only secondary permeability due to fractures and/or karstification. The maximal thickness of these formations may reach 250 m. On the southern plateau (Jowl), the carbonates of the Jeza and Umm er Radhama Formations have a crucial role in the recharge mechanism of the Wadi Hadhramaut region through downward percolation to the underlying sandstone;

- **Mukalla Sandstone** (Layer 2-5): This aquifer is the **most important groundwater source in Wadi Hadhramaut** and is a part of the largest regional aquifer in the country. It is made up of 250 to 400 m of mostly friable sandstone, with some interbedded mudstone, ironstone and shale. The sandstone is fractured and, therefore, the groundwater can penetrate both the primary pores and the secondary fractures. The sandstone aquifer can store and transmit a large volume of groundwater.

In the valley, the layers above the sandstone have been removed by erosion, but the valley is backfilled by a limestone conglomerate, overlain by Quaternary alluvium:

- **Quaternary alluvium** (Layer 3): Clay, sand, gravel and silt deposited by Wadi Hadhramaut and its tributaries in recent times form the upper aquifer. The alluvium can be up to 150 m thick in the centre of the valley, where it overlies the Neogene conglomerates. It thins towards the valley sides and in the tributary wadis, where it lies directly on the Mukalla Sandstone. Groundwater flows in the main valley follows the eastward downstream direction;
- **Neogene conglomerates** (Layer 4): This aquifer is composed of fractured and fissured calcareous conglomerates. Locally, evaporites are present that is important in terms of groundwater chemical composition. The conglomerate varies in thickness, reaching 100 m in the centre of the main valley.

The conglomerate and the overlaying alluvium are hydraulically connected. Their combined thickness ranges between 10 and 200 m. Their maximum thickness is reported in the central part of Wadi Hadhramaut.

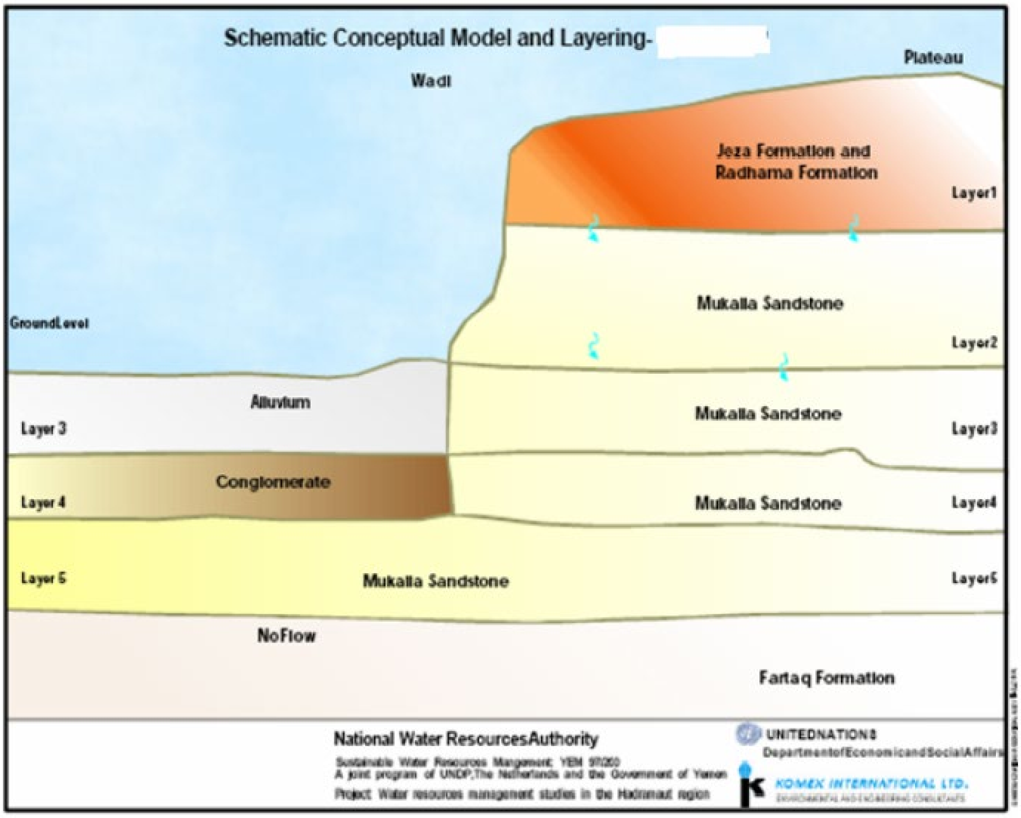


Figure 17. Schematic cross section of Wadi Hadhramaut, showing the major aquifers. Retrieved from UNDP-NWRA, 2009.

Although the aquifer system in Wadi Hadhramaut is in general hydraulic continuity, it does not behave as a single unconfined aquifer, but rather as a **stratified system comprising of layers with distinct hydraulic properties**.

Groundwater recharge

Based on the hydrogeological investigations, KOMEX (2002) described and quantified the natural recharge components as follows:

- The main supply of water originates from **infiltration of surface flows** on the southern plateau and in the tributary wadis. The **surface water percolates to the Mukalla sandstone aquifer** by leakage through the overlying aquifers and through the alluvium in the wadis. The estimated average annual recharge to the area is 71 MCM/y;
- The recharge on the plateau is supplemented by **recharge in the valley from major flood events**, approximately every 3 to 5 years. The recharge from this source averages approximately 43 MCM/y;
- There is also a component of down-valley flow but inflow from the sandstone beneath the Ramlat as Sabatayn desert in the west is less than 1 MCM/y.

The total natural groundwater recharge amounts to 115 MCM/y. In addition to the natural recharge, annually 33 MCM of water are estimated to **infiltrate as excess irrigation water, wastewater from domestic use and leakage from urban supply pipes**. Total annual recharge is then estimated at 148 MCM/y.

Groundwater abstraction

The inventory of 3068 wells, carried out in 2001, indicated that **depths to groundwater vary between 10 and 70 m**. Shallow groundwater level (< 20 m) is observed in the eastern part of the main wadi, downstream Wadi Bin Ali. Water level depths between 20 and 30 m are found in the main wadi and lower reaches of major tributaries. The deepest groundwater (> 30 m) levels exist in the middle part of major tributaries, as shown in Figure 18 (UNDP-NWRA, 2009).

The groundwater in the Wadi Hadhramaut region must be abstracted through shallow dug wells and drilled wells (boreholes). In the past, the groundwater in the Wadi Hadhramaut region was abstracted only from shallow dug wells, sited in alluvial sediments along the main wadi. **With the introduction of drilling rigs, the number of wells increased dramatically** from about 1500 wells in 1970 to more than 3000 wells in 2001. The explosive increase in number of boreholes after 1990 is related to the uncontrolled drilling activities in the Wadi Hadhramaut region after the unification (UNDP-NWRA, 2009).

- It appeared from the 2001 survey that **maximum depths for dug wells and dug-bored wells amount to, respectively, 50 m and 100 m**. These are generally located at sites with shallow groundwater and high population density, *i.e.* at junctions of tributaries. More than 40% of dug wells and 15% of dug-bored wells were not operational during the 2001 survey. These abandoned wells were mainly located towards the upstream part of the main wadi in the areas with high salinity and/or deep groundwater table;
- **The depth range for boreholes is 50 m to more than 275 m**. More than 90 % of the boreholes were operational, and mostly located in the middle part of the main wadi and the lower reaches of major tributaries (UNDP-NWRA, 2009).

Overall, **groundwater is largely abstracted from Mukalla sandstone aquifer** (Bauman et al., 2003). **The latest figures of groundwater abstraction**, as received from FAO Yemen (Alsabri, 2021), **give a total of 250 MCM/y.**

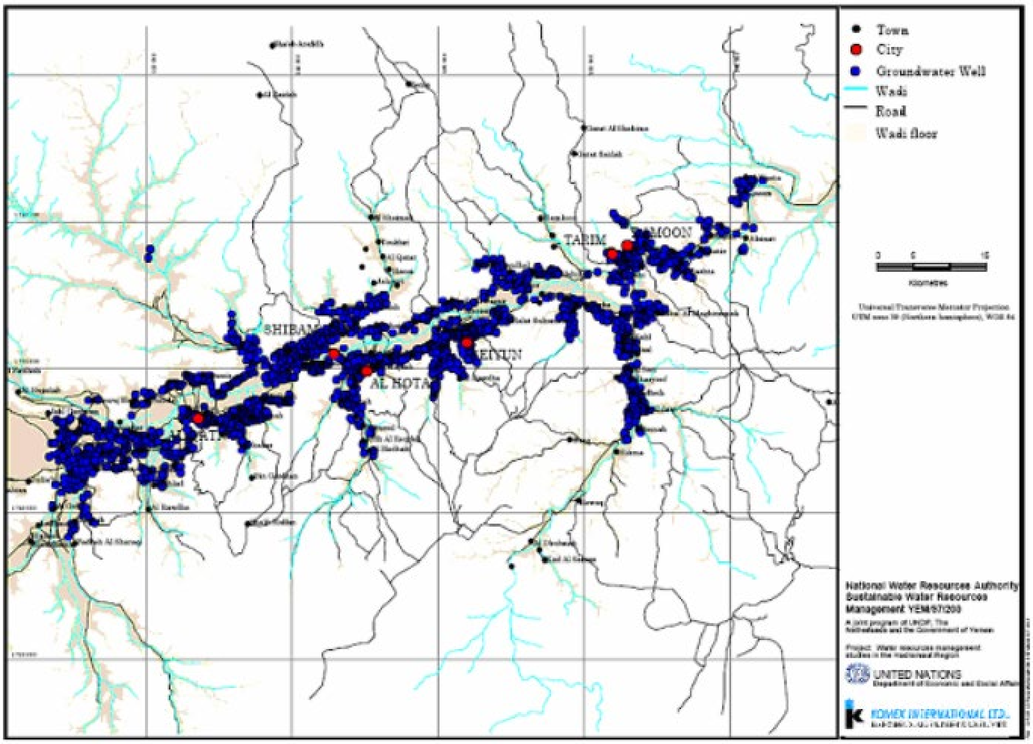


Figure 18. Wells with depth to groundwater >30 m, based on the 2001 well inventory carried by KOMEX. Retrieved from UNDP-NWRA (2009)

4.4 Water demand: overview and current status

4.4.1 Agricultural water demand

Food production and farming systems

The alluvial soils of the Wadi Hadhramaut region allow for an extensive agriculture, mostly of **cereals, fodder and fruits**. In 2005, the main crops were millet (37%), sorghum for fodder (17%), palm trees (14%), wheat (11%), alfalfa for fodder (8%), tobacco (1%) and other fruits and vegetables such as onions and tomatoes; hardly any qat is cultivated (Hellegers et al., 2008). Cropping calendar can be found in Annex 3.

The remote-sensing study identified that **the cultivated area only accounts for 1% of the total surface area of Wadi Hadhramaut, for a total of 21,500 ha in 2020**. The arid to semi-arid climate of the region does not allow to practice rainfed agriculture. More than **80% of cropland is irrigated (17,800 ha)**; for the rest, fallow agriculture represents 17% of the farming systems (3,700 ha).

Irrigated agriculture water demand and practices

In 2005, total irrigated cropland amounted to 14,000 ha in Wadi Hadhramaut. More than 40% of actual irrigation water used was applied to alfalfa (2,900 ha) and about 24% to wheat production (3,900 ha). The rest was applied to onion crops (15%), bananas (5%), dates (5%) and mango (4%). **Average water use was 7,500 m^3/ha, which corresponds to a total irrigation water use of 107 MCM/y** (Hellegers et al., 2008). Since then, irrigated areas have increased and now account for 17,800 ha.

Spate and spring irrigation used to be in practice in Wadi Hadhramaut. These farming systems concerned 55% of the total cropland, while 35% of the cultivated area was under well irrigation (UNDP-NWRA, 2009, Hellegers et al., 2008). Figures received from FAO-Yemen (Alsabri, 2021) tend to confirm the literature findings. In Al Qatn District, the cultivated area amount to 4,600 ha of which 65% is under flood irrigation (3,000 ha) and 35% are irrigated by wells (1,600 ha). The cultivated area of Shibam District amounts to 2,000 ha that is irrigated by wells for 75% and by floods for the rest.

However, **the disastrous flood events of 2008 caused significant damage to the irrigation infrastructure**. In addition, thousands of palm trees and fruit trees were uprooted and agricultural land was damaged due to soil erosion (Soliman et al., 2015). The former NWRA chairman, Mr. Salem Bashuaib, reported that, since then, **about 90% of the agricultural activities depend on groundwater** (p.c. 31-08-2021).

According to the field survey carried out by KOMEX (2002), **most of the farms use drilled wells** (dug-well/borehole) for irrigation. The shallow dug wells are used only on 17 % of farm, usually for irrigation of fields smaller than 4 ha. The average distance from the water source to the field amounts to 560 m. The great majority of irrigation channels are earthen channels (86 %), which usually implies large losses of water. The irrigation efficiency might further decrease due to the poor maintenance of the channels, which concerned 50% of the network (UNDP-NWRA, 2009).

Livestock appears to also play a very significant part in local agriculture. The estimates by KOMEX (2001) assumed that about 51,000 goats and sheep, 2,350 heads of cattle and 2,600 camels were kept in the planning area (including wadi and tributaries further east up to Tarim). The total water demand for livestock watering was estimated from the abstraction figures of about 900 wells. These wells are used for multiple purposes including domestic use, irrigation and livestock watering. It was assumed that **20% of total abstracted water was used for livestock watering. The total livestock demand was thus estimated at about 2 MCM/y**.

4.4.2 Domestic water demand

Estimated domestic water demand

Based on the census of WASH Cluster (2021), the population of the entire catchment area is estimated at approximately 489,000. If the average water use per capita is 30 l/c/d (see Chapter 7), **the total domestic water demand of the Abyan Delta catchment is approximately 15 MCM/y.**

Domestic water supply

The most recent information on domestic water supplies was obtained during the 2001 well inventory carried out by KOMEX, which results were presented in UNDP-NWRA (2009).

- **In 2001, the public water supplies consisted of 19 boreholes, distributed over four well fields at Tarim, Seiyun, Shibam and Al Qatn,** operated by the National Water and Sewerage Authority (NWSA)**. The total water production amounted to 6.2 MCM/y, and losses were estimated at 40**%;
- Regarding the rural water supplies, a socioeconomic survey reported a very **high coverage of rural water supplies, with more than 95% of houses connected.** The great majority of the schemes were operated by the NWSA. Community operated

schemes accounted for 34 % of water supplies. These supplies included 34 wells operated through private water supply projects.

Overall, KOMEX (2002) estimated the annual total groundwater abstraction for domestic use at about 13 MCM/y. The abstraction estimates include combined wells, used for irrigation and livestock watering.

4.4.3 Overview of groundwater exploitation

In the absence of surface water resources, **groundwater is the main source of drinking water and water for irrigation in Wadi Hadhramaut.** The great majority of the wells are used for irrigation. **The annual total groundwater abstraction over the Wadi Hadhramaut region for 2001 was estimated at 250 MCM/y**. In comparison, the total abstraction rate in 1952 was only 20 MCM/ y. The introduction of powerful pumps and the use of drilling rigs for construction of deep boreholes had an enormous effect on the total volume of abstracted water. As shown in Figure 29, the steep upward gradient in the graph after 1990 relates to uncontrolled drilling activities in the Wadi Hadhramaut region after the unification. The abstraction rate of almost 250 MCM/y implies that **already in 2001, the annual recharge of 150 MCM/y was exceeded by nearly 100 MCM** (UNDP-NWRA, 2009).

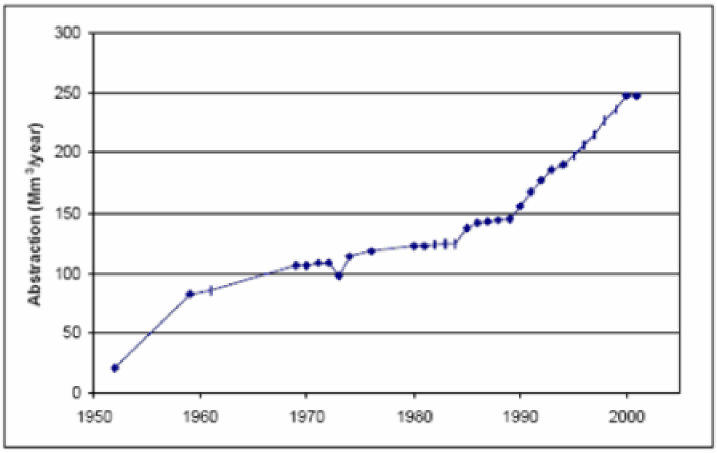


Figure 19. Historical groundwater abstraction over the period 1952-2001. Retrieved from UNDP-NWRA, 2009

Generally, the long-term trends of groundwater fluctuations are difficult to estimate in Wadi Hadhramaut due to intermittent observations of groundwater levels and influences of localized flooding and pumping. According to Wadi Hadhramaut Agricultural Development Project (personal communication, 1999), **the average drawdown in the wells in the period 1952 and 1992 was estimated at 0.6 m/y.** Considering the uncontrolled drilling of wells and the exceptional increase in groundwater abstraction in the last decades, it can be assumed that **the groundwater depth is declining even more rapidly** (UNDP-NWRA, 2009).

> "The quaternary alluvial aquifer is nowadays running dry. Consequently, current wells are now going deeper than 400 m in some places, thus abstracting fossil water. In these deep wells, the water level would be declining by 3-5 m/y."
> *Mr. Salem Bashuaib - Former NWRA chairman* (p.c. 31-08-2021)

It is important to mention that irrigation, especially with high salinity water, causes formation of salt crusts in the topsoil. It also enhances return flows of saline water into shallow aquifers. Locally, groundwater with high salinity occurs. **The higher salinity of the groundwater in the Mukalla Sandstone is related to high abstraction**, which causes mixing of the saline or polluted groundwater from upper aquifers of waters the original fresh water stored in the sandstone. Poor well construction might also provide a short cut between the aquifers. In addition, there is widespread evidence of nitrate contamination in the alluvium and to a lesser extent in the conglomerates, which indicates pollution from sewage and possibly from agricultural fertilizers. In the absence of impermeable layers (*e.g.*, clay), the pollutants can spread widely into the aquifer system. (UNDP-NWRA, 2009).

4.5 Water balance evaluations

The water balance of the Wadi Hadhramaut catchment follows the physical, hydrological boundaries rather than administrative boundaries of the districts (Figure 15). The different components of the water balance have been estimated using the methodology and datasets outlined in Chapter 3. Since water use is highly variable within catchments, an irrigation area is used to illustrate the water balance at the local scale. Finally, a trend analysis illustrates changes in water balance components in the recent past.

4.5.1 Catchment water balance

The water balance results are presented in Table 3. Since inflow from qanats is assumed to be negligible, precipitation is the dominant source of water in the catchment. The total annual evapotranspiration estimate based on the WaPOR database is 156 mm/y. Evapotranspiration in irrigated areas (196 mm/y) is relatively high compared to rainfed cropland (107 mm/y) and other land cover types (102 mm/y).

There are, however, a few important side notes regarding these results. First, it is unlikely that evapotranspiration of non-cropland land cover types exceeds average annual rainfall. Remote sensing datasets such as those used for precipitation and evapotranspiration are reliable in terms of relative spatial and temporal patterns, though the absolute value may contain bias. To avoid differences in absolute values between the datasets having a large impact on the water balance, *i.e.* in an adjusted water balance, evapotranspiration in natural areas is assumed to be 98% of catchment average rainfall (Table 3). Second, the disaggregation of evapotranspiration by land cover type was based on land cover datasets obtained from the WaPOR database. The variability in evapotranspiration from these areas is very high (see local scale analysis in the next section), suggesting that the amount of irrigation applied may vary significantly, or that the extent of the irrigated areas is in reality smaller then reported. In that way, if a more precise delineation of irrigated areas were available, it is likely that the evapotranspiration estimates would be substantially higher.

Table 3. Water balance of focus area in Wadi Hadhramaut catchment (average of 2009-2015)

Water balance term		Value [mm/y]	Source	Adjusted value [mm/y]
In	Precipitation	67	CHIRPS	67
	Qanats	0	Assumption	0
Out	Evapotranspiration (average)	156	WaPOR	67*
	Irrigated cropland	196	WaPOR	196
	Rainfed cropland	107	WaPOR	107
	Other	102	WaPOR	66*
	Wadi outflow	0.4	Flo1k	6*

	Groundwater recharge	0.7	Assumption	0.7
Balance		**-90**		**-7**

* Value adjusted based on expert judgment, see text for details.

Wadi outflow based on Flo1k is less than 1 mm/y, or 5 MCM/y. However, other sources cite a value of 82 MCM/y for the wadi (Vasak, 2002). Therefore, in the adjusted water balance a higher value of 6 mm/y is assumed.

The variability in precipitation and evapotranspiration throughout the year is shown in Figure 20. The bulk of rainfall occurs in July and August, with dry periods in February, June, and from September to October. Evapotranspiration is higher in summer months than in the winter. On average, precipitation exceeds evapotranspiration in three months of the year. During these months, soil moisture and groundwater storages are replenished to sustain evapotranspiration in drier months and for the generation of wadi flow. In other months of the year, there is a precipitation deficit. This deficit is largest in February, June, and September.

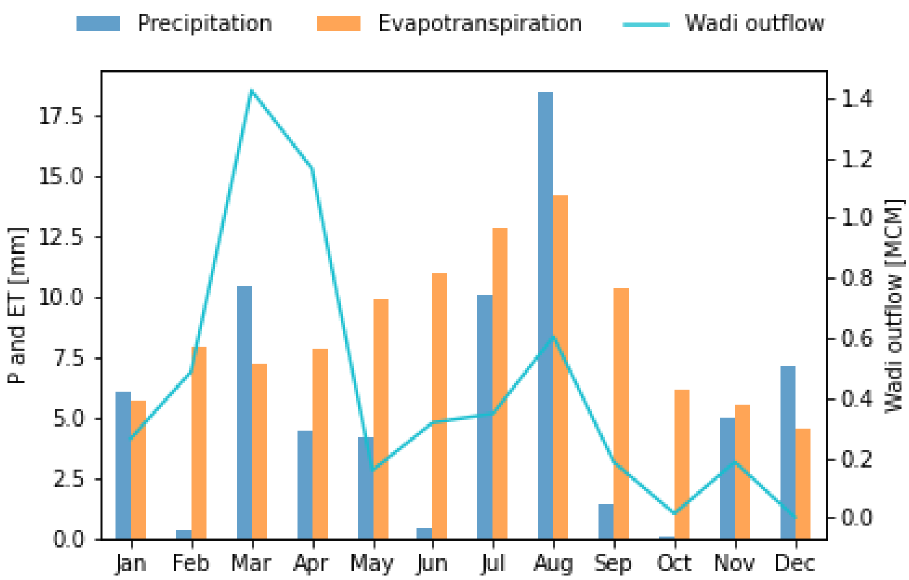


Figure 20. Average monthly water balance for Wadi Hadhramaut catchment for the period 2009-2015. P = precipitation, ET = evapotranspiration, Q = wadi outflow.

Both the data-based and adjusted water balance show that the average annual outflow exceeds average annual precipitation (Table 3). It is assumed that the precipitation deficit is compensated by groundwater abstraction. The deficit is smaller in the adjusted water balance than in the data-based water balance, it is by no means unsubstantial, amounting to just under 10% of annual precipitation and ten times natural groundwater recharge. **This means that groundwater is being abstracted about ten times faster than it is being replenished.** In an analogy to Earth Overshoot Day, the date in which abstraction of groundwater resources exceeds the amount of groundwater that is replenished in that year is February 6th.

4.5.2 Local scale

While catchments are the natural unit to study the water balance, effects of over-abstraction of groundwater can be very local in nature. Therefore, it is important to account for local variability in water availability and water use. Evapotranspiration is highly variable in the catchment (Figure 21). Evapotranspiration in the irrigation areas in the northern part of the catchment is clearly higher than in most natural drainage features, which is again higher than the surrounding natural areas. In comparison, the variability in precipitation is somewhat lower (Figure 22).

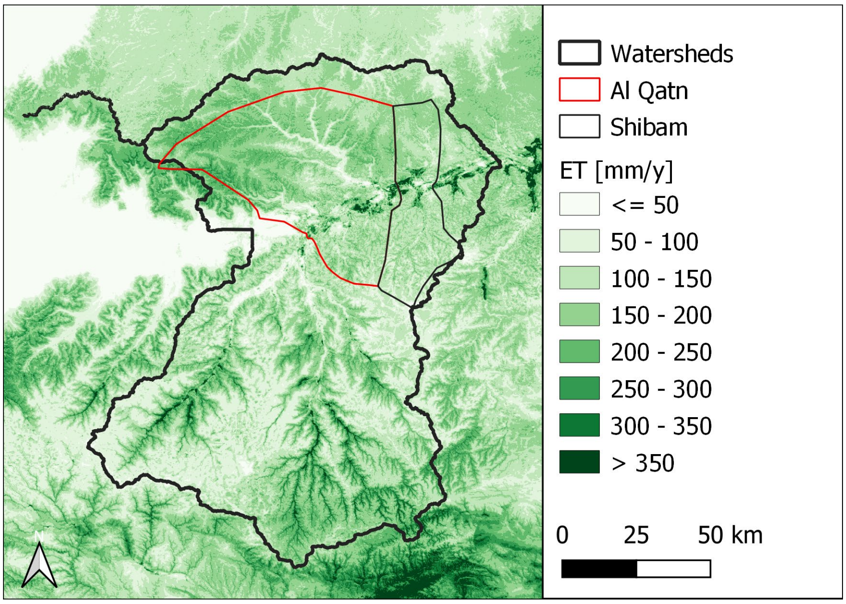


Figure 21. Spatial variability in average annual evapotranspiration.

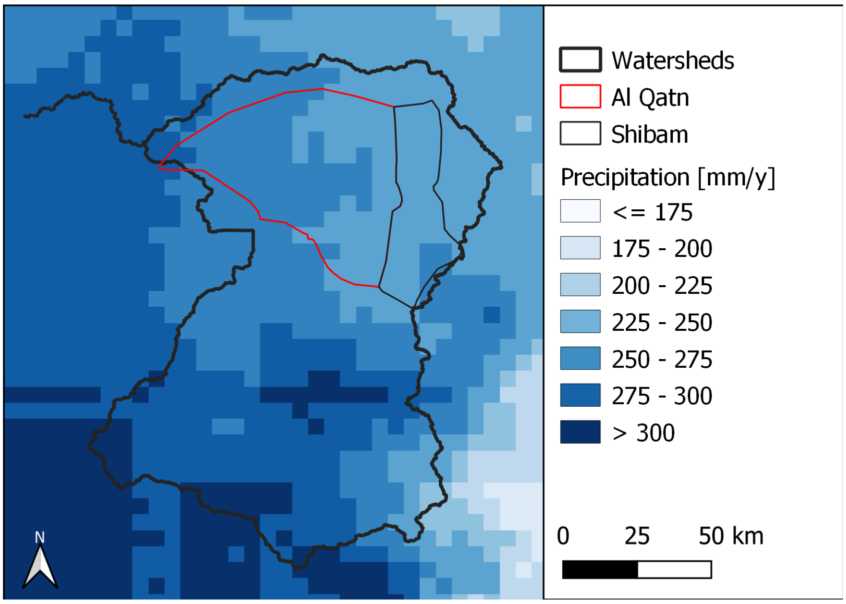


Figure 22. Spatial variability in average annual precipitation.

For the local scale, irrigation along the main channel of the wadi in the Shiba district is used as an example. Annual evapotranspiration in the irrigated areas is 500–800 mm/y based on the WaPOR database. These values are consistent with irrigation of a single season of crop. It is assumed that groundwater resources are used to supply the difference between evapotranspiration and average annual precipitation, a value in the order of 600 mm/y. **This is substantially higher than the estimated natural recharge rate of 7 mm/y to shallow aquifers.**

Actual abstraction rates for irrigation are likely to be higher than the evapotranspiration-based estimate of 600 mm/y, as part of the abstracted water will return to groundwater or run off as surface water. If abstraction and return flow are in the same aquifer, this return flow does not need to be taken into consideration. However, it is more likely that abstraction takes place from a deep aquifer, while irrigation losses recharge the shallow aquifer. In this case, local groundwater depletion could lead to local groundwater decline in the order of 750 mm/y, assuming that the losses to groundwater and surface water are 20%.

4.5.3 Trends

Trends in annual precipitation and evapotranspiration between 2009 and 2020 are presented in Figure 23. It should be mentioned that this period is much too short to reflect any long-term trends that may be due to climate change. The figure shows that precipitation increases slightly during the study period, mainly driven by the wet year of 2020. In comparison, trends in evapotranspiration are stronger. Evapotranspiration from each studied land cover type increases sharply from 2015 onwards, with the strongest trend observed in irrigated areas, while the trend in non-cropland areas is relatively weak. As a result, precipitation deficit (the difference between precipitation and evapotranspiration) exhibits a decreasing trend during the study period, but especially from 2015 onwards (Figure 24). The trend in precipitation deficit can be used as a proxy for trends in groundwater storage, for which direct measurements are not readily available. The direction of the trends using this proxy are more reliable than their magnitude. **The trends in precipitation deficit suggest that groundwater availability is decreasing at catchment scale.**

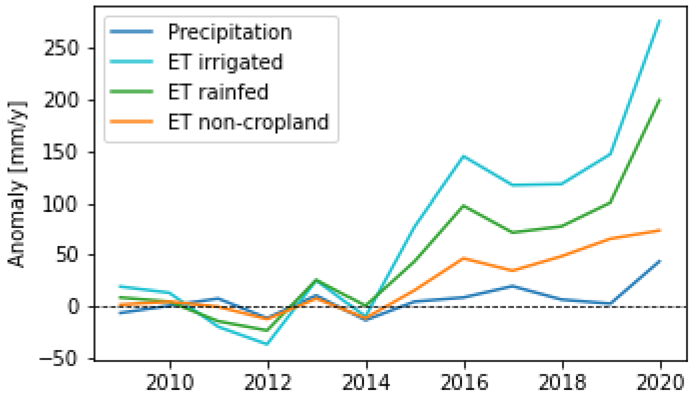


Figure 23. Anomalies of annual precipitation and evapotranspiration from different land cover types compared to the average annual value between 2009 and 2013.

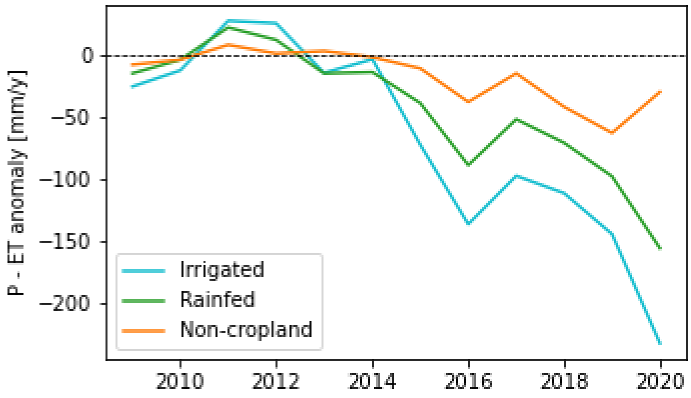


Figure 24. Anomalies of precipitation deficit for different land cover types compared to the average annual precipitation deficit between 2009 and 2013.

A second approach focuses on regional groundwater availability and is based on GRACE observations. The total water storage estimates are converted into groundwater storage anomalies through correction with trends soil moisture and plant canopy water (see Chapter 3).

Trends in groundwater storage based on this method are compared to annual precipitation in Figure 25. The figure shows a decreasing trend in groundwater availability between 2003 and 2017. Between 2017 and 2020, groundwater availability increased. This is likely related to higher rainfall in those years, with 2020 being particularly wet. The results suggest that until 2017, regional groundwater stores were being depleted due to over abstraction, while after this time groundwater use was sustainable.

It is important to note that the GRACE-based values are sensitive to storage in all aquifers. It is likely that groundwater replenishment is limited to the shallow, renewable aquifer. Replenishment of deeper aquifers, however, is assumed to be negligible. There is anecdotal evidence that groundwater is increasingly being abstracted from these deeper, non-renewable aquifers. Therefore, while the balance of shallow aquifers at regional scale could be positive in the recent, relatively wet years, the balance of deeper aquifers is most likely negative.

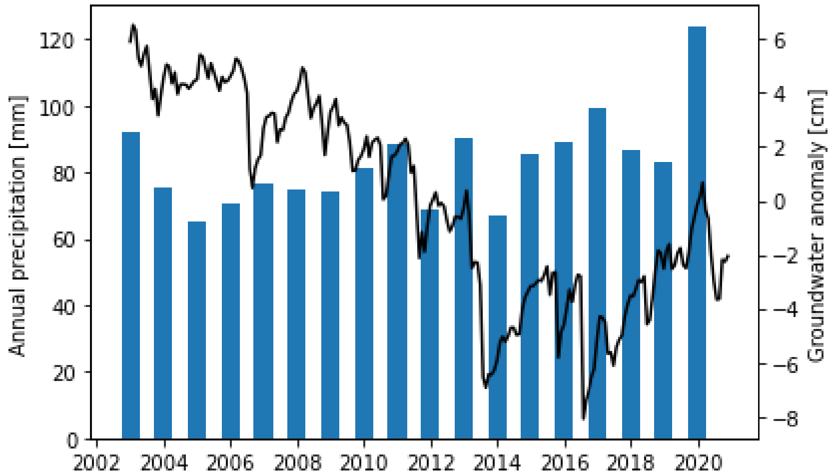


Figure 25. Groundwater anomalies based on GRACE and GLDAS compared to annual precipitation totals in the Hadhramaut region.

4.6 Conclusions and recommendations

A combination of literature study and remote sensing datasets have been consulted to gain insight into water availability in the Wadi Hadhramaut catchment. Previously published reports often contain direct measurements and provide context, but may be outdated and information availability can vary within a given study area. Remote sensing data, on the other hand, provide insight into spatial and temporal patterns and trends in physical variables in a consistent manner for a study area, though the absolute values can be uncertain. In this way, the two data sources are complementary and allow for optimal use of existing data.

4.6.1 Conclusions

The literature study indicates that:

- Water demand is exceeding sustainable water availability in Wadi Hadhramaut, with an estimated 15 MCM/y for domestic use and 110 MCM/y for agriculture;
- There has been a rapid growth in the number of boreholes and in the total abstraction of groundwater, from 150 MCM/y in 1990 to 250 MCM/y in 2001, thus exceeding the annual recharge of 150 MCM/y by nearly 100 MCM;
- Various sources report declining groundwater levels in the order of 0.6 m/y or more as a result of the over-abstraction;
- The rapid increase in groundwater abstraction has caused high salinity water to begin to leak into the principal aquifer, through to downward leakage from localized saline aquifers in overlying alluvium and conglomerate aquifers (KOMEX 2003; abstract);
- The mean annual runoff of Wadi Hadhramaut was estimated at 82 MCM/y over the period from 1952 to 1992;
- The availability of surface water in the main valley is restricted only to periods with extremely heavy rains that result in (severe) flash floods in the valley. These flooding events not only damage or destroy infrastructure, but also represent the loss of an opportunity to benefit from the large volume of fresh water passing through the catchment;
- In the absence of surface water resources and with a lack of reliable spate irrigation infrastructure, groundwater is the main source of drinking water and water for irrigation in Wadi Hadhramaut. Since the major flood event of 2008, local sources have reported that groundwater now provides 90% of the total irrigation supplies;

- Irrigation efficiency is low, due to the prevalence of earthen channels and spate irrigation techniques.

Based on the updated water balance insights from satellite data:
- Groundwater is being abstracted about ten times faster than natural groundwater recharge rates;
- Proxies for groundwater availability support the conclusion of the water balance, showing decreasing overall trends in the past 10–20 years;
- Agriculture is the main water user, with water demand up to eleven times higher than average precipitation. Cropland is in fact mainly irrigated, accounting for 80% of the total cropped areas;
- Trend analysis suggests that agricultural water demand is increasing.

4.6.2 Recommendations

The following key recommendations are suggested for Wadi Hadhramaut (Table 4):

Table 4. Key Wadi Hadhramaut recommendations.

Water supply management action	Water demand management action	Explanation
	Pilot water efficient technologies and improved irrigation practices to use the scarce water sources more effectively	Precipitation and surface water resources in Wadi Hadhramaut are limited. Together with the water supply management action of improving RWH and increasing available surface waters, on-field use of groundwater can be decreased by improved irrigation management. This may limit on-farm water losses through introduction of efficient technologies (sprinkler, drip, piped conveyance) and improved practices (irrigation scheduling, irrigating using CWR, or remote sensed irrigation advice. Improved practices can also well be adopted in surface water irrigation schemes. Key is to ensure that water savings do not lead to expansion of irrigated areas but are allocated to domestic use. Apply lessons-learned from water allocation pilot in Abyan Delta to ensure this.
Develop and implement flood forecasting system, incl. mobile warning and link towards water harvesting and spate irrigation		Setting up of a flood early warning system to provide timely warning so that harm to people and economic assets can be minimized. This to prevent similar damage to infrastructure as with the 2008 floods in Wadi Hadhramaut. At the same time, use this as an asset for

		spate flood forecasting to provide advance information on incoming spate flows that helps farmers to better plan agricultural activities and take good planting decisions. Investigate possibilities of mobile warning, either or not combined with irrigation advice.
Potential mapping and piloting off-stream rainwater harvesting (RWH) to reduce flood impacts and increase infiltration/recharge and storage		With its sparse vegetation, Wadi Hadhramaut is susceptible to high velocities of storm and runoff water. At the same time, the undulating landscape provides opportunities for off-stream water harvesting, both reducing power and velocity of storm water and enhancing infiltration/recharge and storage. By potential mapping, the intervention areas can be identified as well as the most suited technique to apply. Interventions in areas with high runoff, steep slopes and loos, sandy soils will be most effective. In areas with (some) soil development, storm water can be retained on-site. In areas with developed calcisols and low slopes, water could be stored in unlined ponds or hafirs. For other soil types, unlined retention structures will enhance groundwater recharge. Lined ponds or underground cisterns (birkads) are good alternatives when the retained water is for meant for immediate reuse.

Suggested further research should focus on efforts to:

- Validate proxies for groundwater availability trends based on remote sensing datasets with local data on groundwater abstractions and/or groundwater levels;
- Investigate with new techniques groundwater availability (storage, abstraction rates, groundwater recharge rates) through (geophysical) surveys;
- More precise delineation of irrigated areas to improve groundwater abstraction and water availability estimates based on remote sensing data. Higher (*i.e.* 30 m) resolution estimates of evapotranspiration can contribute to this;
- Study the potential for more efficient irrigation techniques and technologies;
- Perform feasibility studies for techniques to increase water availability, including water harvesting and artificial recharge.

5 Water availability in Abyan Delta catchment

This chapter takes a closer look at the water availability for agricultural activities and food production in Zinjibar District and Khanfir District in Abyan Governorate (named "Wadi Bana" in the ToR). This focus area is selected as it is one of the implementation areas of the FAO Resilience Programme in the Irrigation and Agricultural Sector (UNDP & FAO, 2020). To carry out the water balance analysis, the study area must take account of the drainage area where lie the districts. Thus, this study analyses the water availability of three main basins of the Abyan Delta catchment, namely Wadi Suhaybiyah, Wadi Bana and Wadi Hassan.

The available literature and past hydrogeological data studies were reviewed, notably:

- The major outputs of the remote sensing and geological study carried out by KOMEX International Ltd. (Calgary, Canada) in 2001 (KOMEX, 2002).
- The advice prepared by the Commission for the Minister of Water and Environment (EAI, 2007) to review the existing EIA reports for the dam planned in Wadi Bana and provide guidelines for supplementary information, in case necessary, *Advice on Terms of Reference for EAI for Wadi Bana Dam Project – Yemen.*
- The *Water Resources Management Plan for Tuban-Abyan Delta Region* released by the National Water Resources Authority (NWRA, n.d.) within the National Program on Integrated Water Resources Management supported by UNDP.
- The study of Atroosh et al. (2012), *An estimation of the probability distribution of Wadi Bana flow in the Abyan Delta of Yemen.*
- The study of Ewea (2007), *Assessment of potential water resources in Abyan area-southern Yemen.*
- The study of Marchant et al. (2018), *Simulating Water Allocation and Cropping Decisions in Yemen's Abyan Delta Spate Irrigation System.*
- The study of Haidera & Noaman (2008), *Application of Decision Support Tools for Water Resources Management in Coastal Arid Areas (Case study: Aden, Yemen).*

Combined with recent remote sensing and satellite data analyses techniques using digital elevation data from SRTMGL1 dataset (NASA-JPL, 2013) and land cover data from ESA Land Cover Maps v2.0.7 dataset (ESA, 2017), the study results in unique updated insights into the water balance of the Abyan Delta catchment.

5.1 Overview of the wadi catchments

As shown in Figure 36, the focus area is part of the southwestern drainage basin of Yemen and covers wadi catchments that originate within the higher rainfall areas of the southern highlands and midlands of the country and drain toward the Gulf of Aden coastal plain (Alderwish & Al-Eryani, 1999). Also referred to as the Abyan Delta, the flat plain is located in an arid to sub-tropical area that lies in the Gulf of Aden, about 55 km east of Aden city (Atroosh & Moustafa, 2012). Such a delta is considered a vital source of water for irrigation and water supply purposes. In addition, it is the most promising area for agriculture development in Yemen (Al-Mashreki et al., 2015; Ewea, 2007).

The three main basins are – from West to East – Wadi Suhaybiyah, Wadi Bana and Wadi Hassan (Van der Salm et al., 2012). The wadis have large catchment areas of 1,600, 7,550 and 3,250 km2 respectively; thus, not only limited to Zinjibar and Khanfar districts. In fact, these encompass 34 other districts over the Governorates of Abyan, Lahj, Al Bayda, Ad Dali, Ibb and Dhamar.

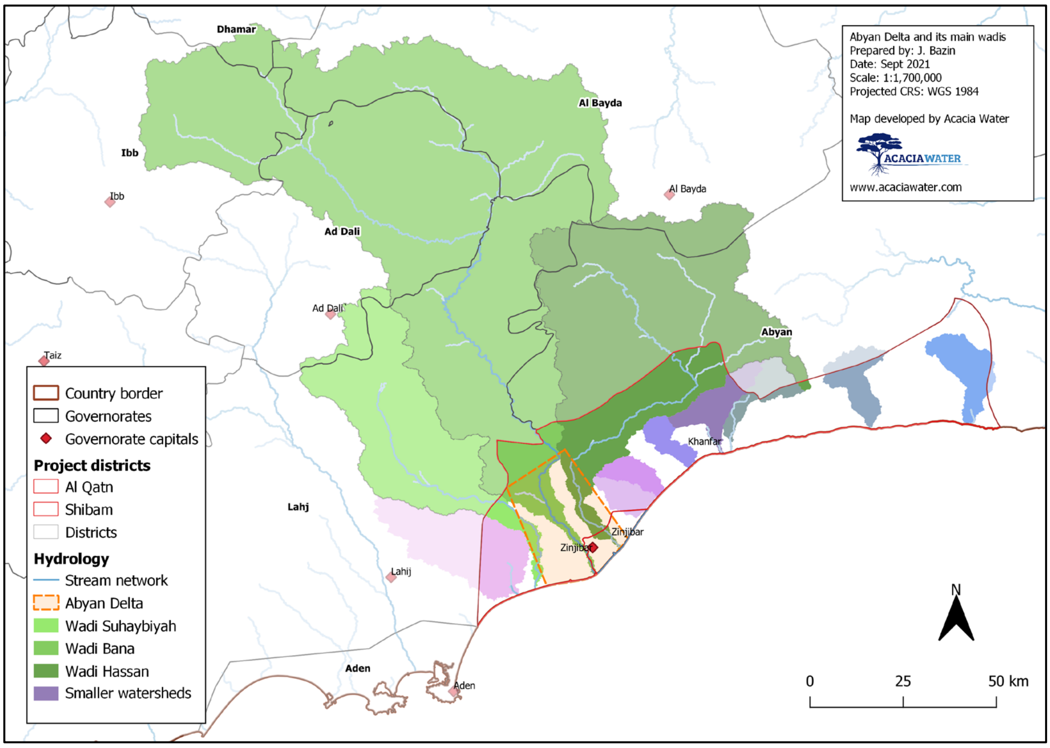


Figure 26: Abyan Delta catchment and its main wadis in Zinjibar and Khanfar districts, derived from DEM data of the SRTMGL1 dataset (NASA-JPL, 2013).

5.2 Socio-economic characteristics

5.2.1 Population

The population of Abyan Governorate in 2019 was 568,000, of which 34,000 were in Zinjibar District and 144,000 in Khanfar District (Alsabri, 2021).

Based on the census of WASH Cluster (2021), **the population of the entire catchment area** (see Figure 26) **is estimated at approximately 2 million, of which 110,000 are IDPs**. The upper reaches of the wadis are relatively densely populated (Alderwish & Al-Eryani, 1999; EAI, 2007).

5.2.2 Land use

As shown in Figure 26, **the Abyan Delta catchment is primarily composed of bare or sparse vegetation in the downstream areas** (44% of the whole catchment, for a total of 5,500 km2), **and of shrubland in the mountainous highlands** (40%, for a total of 5,000 km2). Grassland is mainly located in the upstream part of the catchment, for about 10%

of the total land use and land cover (LULC). Overall, irrigated cropland occupies about 450 km2 of land, which is less than 4% of the whole catchment area.

Still, the Abyan Delta is considered as one of the most prime farmland areas in Yemen's southern coastal plains (Al-Mashreki et al., 2015). Wadi Bana especially includes major agricultural activity near the mouth of the delta and its upper reaches are also agriculturally developed in Ibb Governorate, as shown in Figure 27. The remote-sensing study of LULC determined that **cropland in Wadi Bana is mainly irrigated, accounting for about 5% of the total surface area of the wadi** (see Table 5). For the rest, Wadi Bana is mostly characterized by shrubland (49%, mainly in the upper catchment) and by bare or sparsely vegetated areas (30%, mainly in the delta).

Table 5. Main land use and land cover (LULC) in the Abyan Delta catchment and its 3 main wadis, obtained from the land cover data of the ESA Land Cover Maps v2.0.7 dataset (ESA, 2017).

Major Land use / Land cover type	Wadi Suhaybiyah		Wadi Bana		Wadi Hassan		Abyan catchment	
	Surface area (km2)	Cover-age (%)	Surface area (km2)	Cover-age (%)	Surface area (km2)	Cover-age (%)	Surface area (km2)	Coverage (%)
Bare / sparse vegetation	1068	**67.4**	2345	30.6	2058	**63**	5472	**43.7**
Shrubland	399	25.1	3745	**48.9**	894	27.4	5037	40.2
Grassland	82	5.2	993	13	245	7.5	1320	10.5
Cropland, irrigated	14	0.9	396	**5.2**	35	1.1	445	**3.6**

There is very little occurrence of irrigated cropland in Wadi Hassan and Wadi Suhaybiyah. As shown in Figure 27, the few agricultural plots are situated for Wadi Hassan in the delta and for Wadi Suhaybiyah in the middle reaches of the catchment along the main stream. Both wadis consist of 65% bare soil and scattered vegetation, and 25% of shrubland.

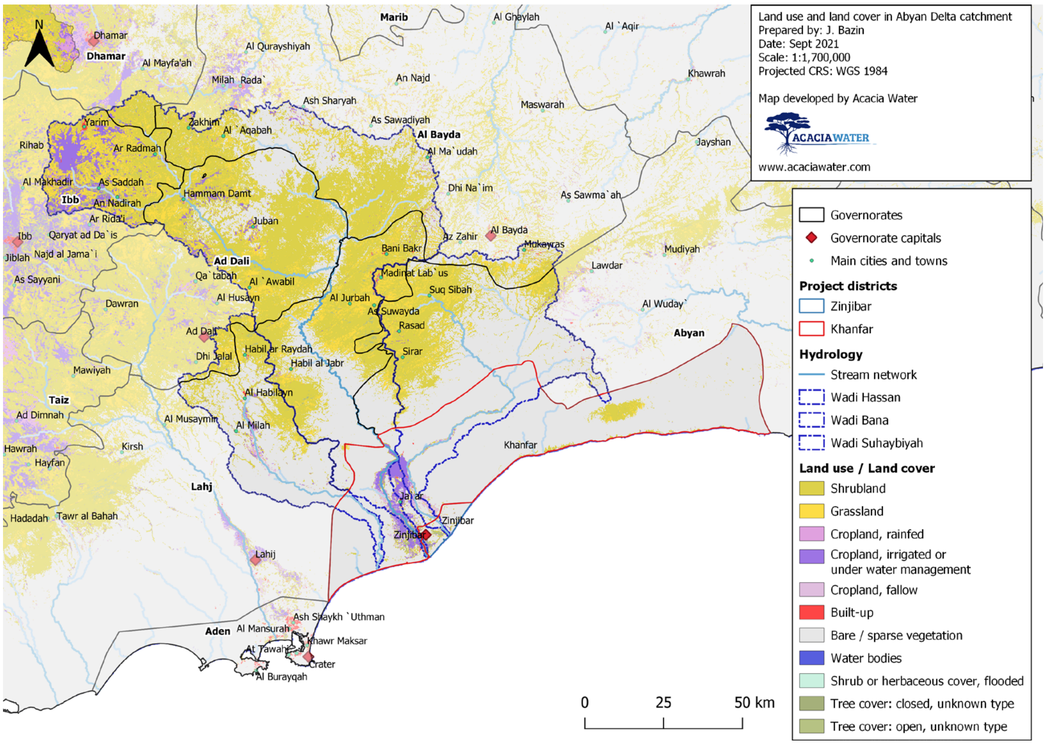


Figure 27: Abyan Delta catchment and land use, derived from land cover data of the ESA Land Cover Maps v2.0.7 dataset (ESA, 2017).

5.2.3 Livelihoods and conflict

Based on the livelihood zones identified and defined by FEWS NET (2010), the sub-catchment includes five main farming systems:

- **YE07 on the shoreline: fishing zone**. Livelihoods in this zone are driven by fishing-based activities;
- **YE11 in the Abyan Delta: sorghum, millet, vegetable, fruit and livestock zone**. Livelihoods are dependent on wadi-irrigated agriculture, in particular the cultivation of grains, fruits, and vegetables. This zone is affected by an array of hazards including insufficient rainfall, crop diseases and pests, livestock diseases and high agricultural input prices;
- **YE12 in the middle part of Wadi Bana and in Wadi Suhaybiyah: coffee, qat, sorghum and livestock**. This densely populated, mountainous, agriculture-based livelihood zone receives between 800-1,200 mm of rainfall annually. The main hazards affecting household access to food and income are erratic and insufficient rainfall, crop pests, and crop and livestock diseases;
- **YE13 in the mountainous highland of Wadi Bana: wheat, sorghum, qat and livestock zone**. In this densely populated area, most households in the relatively fertile livelihood zone rely on 600-900 mm of rainfall annually, while those that can afford the resources needed to implement an irrigation system may compliment the rainfall with groundwater extraction;
- **YE14 in the coastal plain of Wadi Hassan: sorghum, millet and livestock zone**. This livelihood zone is moderately populated. Erratic and insufficient rainfall, lack of ground water and crop pest are ranked as the major hazards in the zone. Water salinity may also become an increasing problem to farmers.

The conflicts have deeply affected the Abyan Governorate, including the Khanfar district, by the displacement and the massive destruction. People lost their livelihoods as a result of the conflict, and lack of job opportunities (Murgham et al., 2013). As described in the community profiling undertaken by UNOCHA (2012), civil unrest, in some instances involving violence, has severely disrupted the delivery of basic social services, exacerbating widespread and chronic vulnerabilities. The water networks were damaged (totally or partially) and irrigation systems were looted (UNOCHA, 2012). The water demand shifted consequently to the IDPs surge.

5.3 Water availability

5.3.1 Surface water

Hydrology and sub-catchments

Wadi Bana is a major wadi of southwestern Yemen reportedly receiving the most rainfall in the entire country. It is the main contributor of the Abyan Delta catchment, flowing from the mountainous highlands where it receives considerable amount of erratic rainfall. The remote-sensing study gives a **mean annual rainfall in the mountains and foothills of Wadi Bana that ranges between 150 to 250 mm/y and beyond, compared to 50-100 mm/y in the delta.** The rains are predominantly of the convective type and usually of short duration. The relatively scarce rains tend to occur in clusters of a few consecutive days, for 70% during the Kharif season (June – August), and the rest during the Sief season (March-May) (Marchand et al., 2018). **The flow of Wadi Bana is therefore distinguished by flood fluctuation**, *i.e.* flood peaks and steep recessions (flash floods). **Floods occur in both summer and autumn seasons and are a source to spate irrigation schemes in the Abyan Delta**, thus offering agricultural opportunities (Atroosh & Moustafa, 2012; Ewea, 2007). No recent studies have assessed the current flood regime of Wadi Bana. As per latest information, the annual frequency of flood is fairly high and reaches 19 floods per year. Average annual peak flood is 980 m3/s, and baseflow is estimated 400 MCM (Atroosh & Moustafa, 2012; Alderwish & Al-Eryani, 1999). **Under normal condition, the average annual flow is 160 MCM. The flow in autumn season occupies about 70% of total annual flows. For the remainder of the year, the annual flow is low and the outflow to the Arabian Sea is limited** (Atroosh & Moustafa, 2012). **Average streamflow estimates for the period 2009-2015 from the global FLO1K dataset** (Barbarossa et al., 2018) **are much lower, suggesting 7 MCM/y.**

Wadi Hassan provides a similar story to that of Wadi Bana. Flood fluctuation is also characterizing the streamflow of the wadi. **Its annual flow is lower overall. Literature cite estimates of 10-30 MCM/y** (Riaz et al., n.d.**) and 40 MCM/y** (Alsabri, 2021)**, while the average annual value according to FLO1K is 0.5 MCM/y**.

The hydrological characteristics of Wadi Suhyabiyah differs as the catchment does not comprise highland areas, thus receiving less precipitation. The total flow is therefore low, and comprises fewer peaks in the rainy season**. Based on the FLO1K dataset, average annual streamflow is 0.4 MCM/y.**

Surface water infrastructures

The former NWRA chairman, Mr. Salem Bashuaib, reported a **developed network of irrigation canals in Wadi Bana** (p.c. 31-08-2021). This canal system for spate irrigation, designed by the Soviets in the years 1970-1979, is **dependent on floods**. **Such spate irrigation infrastructures are also reported in Wadi Hassan to divert the high intensity floods of short duration**.

The floods of 1982 (2000 m3/s) damaged most of the irrigation infrastructures and the repair of the system was delayed by the recent conflicts. Construction works funded by the World Bank are currently on-going, with the objective to control floods and secure irrigation supplies, as reported by Mr. Abdulkarim Naji AlSabri from FAO Yemen. This includes, among other things, a diversion dam in the lower Wadi Bana that diverts water to Wadi Hassan via a 4 km long channel.

5.3.2 Groundwater

Geology and groundwater occurrence

The bedrocks uncovered in the northern piece of the Abyan Delta comprise of the centre to upper Proterozoic metamorphic and intrusive rocks of the southern piece of the Arab Shield. These metamorphic rocks incorporate metavolcanic, amphibole biotite schists and gneisses, and also higher-standard migmatites. The intrusive rocks incorporate granites and gabbros (KOMEX, 2002).

The unconsolidated fills within the wadi channels and plains in Wadi Bana-Hassan represent the main groundwater potential. As appears to be typical for such catchments originating in the Highland and Midland areas, a study carried out in 1980 concluded that no significant water bearing horizons exist that could be developed to yield reliable supplies. Wadi fills, terrace deposits and fractured development in the underlying basement contained **inadequate storage for sustainable supply** (Ewea, 2007).

At the mouth of Wadi Bana-Hassan, the Quaternary Aquifer of Delta Abyan is situated. It is the most important aquifer in the southern coastal plains. It is actively recharged by these wadis, partly by subsurface flows (underflows) via the interconnected wadi fill aquifers. In Abyan Ddelta, the distribution and character of the alluvial deposits varies across the delta. Drilling activities for the Greater Aden well field in the inland delta have shown the existence of clear palaeo-channels which contain deposits of higher permeability but which give rise to complex and variable aquifer hydraulics **The maximum thickness is 100 m in the southern zone, some 50-60 m in the central zone, and more than 100 m in the northern zone** (Ewea, 2007). The electrical conductivity varies between 1,200 and 10,000 µS/cm (Al-Sabri, 2012).

Groundwater recharge

Rainfall and the resulting surface runoff furnish the prime sources contributing to groundwater recharge (Ewea, 2007).

- The contribution of rainfall on the delta of Abyan may be neglected as a source of recharge;
- Direct recharge is taking place into the distinct fissures, weathered bare rocks of the upper mountains of Abyan Governorate;
- Another part infiltrates when wadi channels are filled with water during heavy rainfall;
- Flow onto the delta occurs as groundwater baseflow along each main wadi course and also as flood and baseflows within each wadi channels;
- The surface flows entering Abyan Delta are also diverted into a network of canals distributing water for irrigation which, therefore, increase the area of potential aquifer recharge.

Groundwater abstraction

The majority of the groundwater abstracted in the Abyan Delta is used for irrigation purposes. A great number of **hand-dug wells** are reported to be operational in the study area, in addition to a considerable number of **tube wells** which are used especially in Abyan Delta. **Generally, abstractions for irrigation increase particularly in the**

southern part of Abyan Delta, suggesting the poor reliability of irrigation of surface water in such area. Wells are used also for domestic supply and livestock (Ewea, 2007).

5.4 Water demand: overview and current status

5.4.1 Agricultural water demand

Food production and farming systems

Food production in the Abyan Delta is continuous all-year round. The main crops cultivated are mango, watermelon, banana, papaya, lemon, cotton, sesame, groundnut, tomato, sorghum, millet, wheat, and maize. Sorghum, millet, wheat, and maize are the main subsistence crops. Cash crops such as cotton or sesame are usually grown only after a staple crop has been harvested and a minimum annual income has been achieved (Marchant et al., 2018). Cropping calendar can be found in Annex 4.

The remote-sensing study identified that **Wadi Bana accounts for 84% of the total cultivated areas in the Abyan Delta catchment with nearly 44,000 ha of cropland of which 40,000 ha are irrigated**, compared to 9,400 ha in 1980 (EAI, 2007). In its lower part in the Abyan Delta more specifically, the total maximum area irrigated so far has been reported to be around 23,000 ha, out of which spate irrigation accounts for 11,000-19,000 ha depending upon the availability of spate (Alsabri, 2021). Wadi Hassan and Wadi Suhyabiyah contribute less than 10% of total cultivated land, with an estimated cropland area of 5,500 and 3,000 ha, respectively. Their farming systems differ in that these do not consist of irrigated cropland exclusively. **In Wadi Hassan, fallow agriculture occupies 33% of the cultivated land**. Irrigated cropland represents less than 50% of cultivated areas **in Wadi Suhyabiyah; more than 35% of the agriculture area is rainfed and almost 20% is fallow ground**. On the contrary, fallow systems and rainfed agriculture are barely in place in Wadi Bana.

Irrigated agriculture water demand and practices

The primary water source for irrigating the delta used to come from spate irrigation, which was developed to divert the flush floods and create crop production opportunities (Marchant et al., 2018, Haidera & Noaman, 2008, NL Commission for Environmental Assessment). **Most spates come from runoff in Wadi Bana and a smaller fraction from Wadi Hassan** (Van der Salm et al., 2012). **Two irrigation seasons account for nearly 90% of the annual runoff.** The wet Kharif season, which occurs between 1 July and 15 October, receives 66% of annual runoff. Another 24% arrives during the Seif season between 16 March and 31 May. The remaining inflow volumes arrive during “off-season” months (Marchant et al., 2018, Atroosh & Moustafa, 2012; Ewea, 2007).

Wadi Bana has five main weirs that function as irrigation diversion points, namely Bateis, Hayja, Diyya, Makhjan and Al-Gharib (see Figure 28). The weirs are connected by a canal system, which allows distribution to all irrigated areas. Within the Abyan Delta region, water is traditionally allocated to upstream fields first, with the constraint that they achieve only one “saturation irrigation” per season. Once the demand of upstream users is satisfied, the water is passed to those fields further downstream (Marchant et al., 2018). **The irrigation infrastructure was severely damaged in the flood event of 1982**. The Bateis weir was rebuilt in 1984, but the repair of the remaining system struggled to proceed due to lack of funds and conflicts. **To date, it is not clear whether the irrigation system has been fully rehabilitated or not**. There are risks to the lack of proper downstream diversion weirs, beside hindering agricultural activities and development. A former study reported considerable erosion of irrigated land along the wadi due to spates entering the main canals. In addition, water did not reach the tail end of the canal system, resulting in water shortages and abandoned farms. Water that otherwise would serve these farms now recharges the aquifer and discharges into the sea (EAI, 2007).

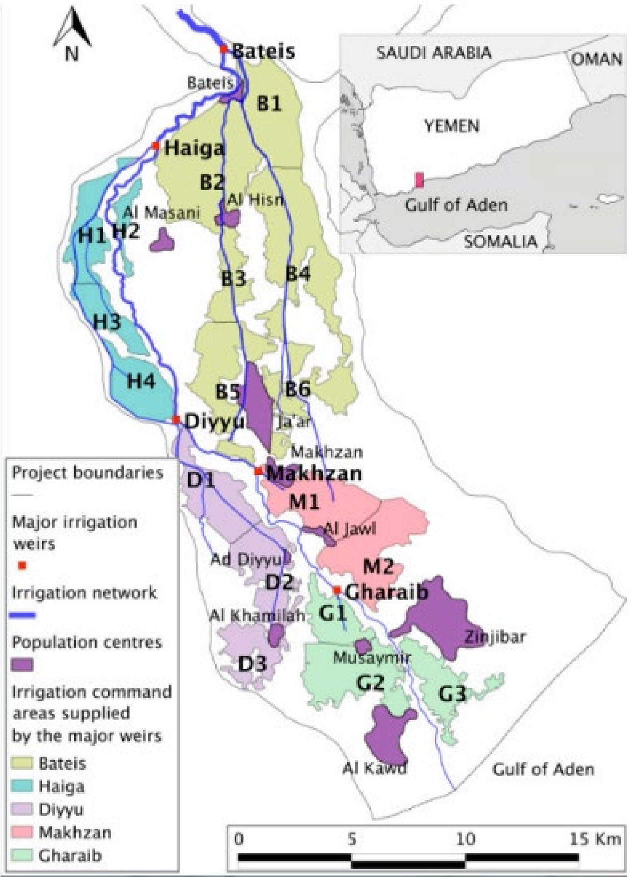


Figure 28. Major irrigation weirs, irrigated command areas, and population centres of Wadi Bana in Abyan Delta. Source: Marchant et al., 2018

Data collected in Delta Abyan shows that **the average loss of irrigation water through earth-channels is more than 50 percent in irrigating of vegetable crops**. Irrigation is applied at intervals ranging from 7 to 9 days for vegetables in Delta Abyan without considering the available soil water content in the root zone. The interval between irrigations is a farmer's decision. Results also indicate that irrigation is applied when the soil water content reaches 83 percent from field capacity. This percentage is much higher than the recommended water content, which ranges from 75 percent to 65 percent under special conditions of vegetable cultivation and type of soils (Atroosh, 2006).

Wadi Bana supplies Abyan Delta agriculture catchment's area with about 60% of its irrigation demand while the rest is supplied from Abyan aquifer (Haidera & Noaman, 2008). Groundwater is used as an additional source of irrigation water to amend the shortage of surface water resources, especially for the fruit plantations in both the upper and the lower end of the wadi (Van der Salm et al., 2012). The supply of groundwater is provided by private wells. **In 2006, groundwater abstraction for irrigation purposes from Abyan Delta was estimated at nearly 95 MCM/y** (Haidera & Noaman, 2008, KOMEX 2002).

These sources of water are not enough to meet the Abyan Delta's full economic irrigation potential. **Due to water shortages within the region, most crops are irrigated at only 80% of their water requirement or lower** (Marchant et al., 2018). In addition, about 25% of the farms in Abyan Delta reported moderate to high soil salinity. High salinity was largely confined to southern part of the delta and to a lesser extent Wadi Hassan. In the south, this could be a result of saltwater intrusion, but more likely of irrigation with water with greater salt content found in this part of the delta (NWRA, n.d.).

5.4.2 Domestic water demand

Estimated domestic water demand

Based on the census of WASH Cluster (2021), the population of the entire catchment area is estimated at approximately 2 million. Assuming that the average water use per capita is 30 l/c/d (see Chapter 7), **the total domestic water demand of the Abyan Delta catchment is approximately 22 MCM/y**.

Domestic water supply

The public drinking water supply depends largely on underground sources from Abyan aquifer which supplies the Abyan Delta with its total water demand in addition to Aden City with 25% of its domestic water demand (Haidera & Noaman, 2008). Numerous operating well fields have been reported.

The Al-Ruwa well-field, also known as Upper Abyan well-field or Rowa, consists of 19 wells presented as three well rows (northern, central, and southern row) between Subaybah and Giar (Haidera & Noaman, 2008, EAI, 2007). **In 2006, total abstraction of the Al-Ruwa well-field was estimated at 12.4 MCM/y** of which 8.4 MCM/y was supplied to Aden city and 4 MCM /y was for local use (Haidera & Noaman, 2008). The National Water and Sanitation Authority (NWSA) Aden branch operated this wellfield at the time. However, Mr. Salem Bashuaib reported that the Al-Ruwa well-field has not been in use to supply drinking water to Aden city since 2015 approximately, though it is still operational (p.c. 31-08-2021). Mr. Adeeb Al-Maqaleh, from UNDP Yemen, indeed specified that the Al-Ruwa well-field has been transferred from the Local Water and Sanitary Corporation (LWSC) Aden to LWSC Abyan (p.c. 04-09-2021).

In addition, NWSA-Giar branch operates several small well-fields for local town water supply. These are the Giar well-field (9 wells), El-Kod (3 wells), and Al-Husn (2 wells). Finally, there is a well-field (3 wells) from a cooperation in the vicinity of Subaybah. **Total abstracted amount of all these smaller well-fields collectively is some 5 MCM/y**. Most of the wells is located in between Wadi Hassan and Wadi Bana in the central part of the Delta. (EAI, 2007).

5.4.3 Overview of groundwater exploitation

The total volume of groundwater abstraction from Abyan aquifer was estimated to be 86 MCM/y in the 1990s decade. **Continuous storage depletion of the groundwater reservoir had been estimated to range between 10 and 15 MCM/y** based on the decline of the piezometric levels and water balance equation, respectively. At this time, there was contradictory information whether the level of exploitation exceeded the annual recharge from rains and floods from Wadi Bana and Wadi Hassan (Alderwish & Al-Eryani, 1999). **According to the latest estimates for 2006, groundwater abstraction from Abyan aquifer amounted to 107 MCM/y** (Haidera & Noaman, 2008).

In both cases, trends tend to indicate **an increasing pressure on groundwater resources and unsustainable exploitation of Abyan aquifer**. The uncontrolled drilling of wells that is on-going suggest an increase in groundwater abstraction. The Water resources Management Plan for Tuban-Abyan Delta region mentions that **groundwater levels are declining by an average of 0.02 – 1.0 m/y** (NWRA, n.d.). **The over-abstraction has led to sea water intrusion along the coast** (Bauman et al. 2003).

5.5 Water resources management and institutional environment

The history of the Abyan Delta is shaped by powerful regional tribes with the capacity to exert influence given the relative absence of a strong national government. Throughout the 20th century, the Fadhli sultanate inhabited the southern half of the delta while the Yafa'e sultanate occupied the northern half. With Abyan water flowing north to south, the Yafa'e have historically been the first to divert and utilize wadi flood waters. This left the downstream Fadhli with water shortages during dry years, forcing them to grow fewer crops. As the two sultanates were in a constant conflict over this inequitable water distribution, the colonial administration of Great Britain initiated the Abyan Scheme, a project that modernized the existing irrigation scheme in 1938 as an attempt to resolve regional conflict. Between 1947 and 1967, the Abyan Board managed the scheme which included responsibilities such as distributing irrigation water to different fields and prescribing the acreage to be allotted for different crops. Control of the board was transferred from the British government to Yemen's Ministry of Agriculture in 1967. After the 1994 conflict, the board lost power and could no longer enforce water distribution agreements. Consequently, the farmers downstream resorted to groundwater extraction while the Yafa'e farmers upstream continued to irrigate their fields using water from Wadi Bana. With groundwater volumes decreasing the Fadhli are again facing water shortages (Marchant et al., 2018).

5.6 Water balance evaluations

The water balance of the Abyan Delta catchment is based on the three largest subbasins draining into the Abyan Delta: Wadi Bana, Wadi Hassan, and Wadi Suhyabiyah (Figure 26). In this way, the water balance follows the physical, hydrological boundaries rather than administrative boundaries of the district. The different components of the water balance have been estimated using the methodology and datasets outlined in Chapter 3 and provide insight in the availability of water resources.

5.6.1 Catchment water balance

The combined water balance of the three subbasins is presented in Table 6. Since inflow from qanats (from outside the subbasin) is assumed to be negligible, precipitation is the dominant source of water in the catchment. The average total annual evapotranspiration in the three subbasins according to the WAPOR database is 222 mm/y. Evapotranspiration in irrigated areas (359 mm/y) is relatively high compared to rainfed cropland (105 mm/y) and other land cover types (217 mm/y).

There are, however, a few important side notes regarding these results. First, it is unlikely that evapotranspiration 'other' or non-cropland land cover types exceeds average annual rainfall. Remote sensing datasets such as those used for precipitation and evapotranspiration are reliable in terms of relative spatial and temporal patterns, though the absolute value may contain bias. To avoid differences in absolute values between the datasets having a large impact on the water balance, in an adjusted water balance, evapotranspiration in natural areas is assumed to be 98% of average annual rainfall (Table 6). Second, the disaggregation of evapotranspiration by land cover type was based on land cover datasets obtained from the WaPOR database. While these are considered to be the most consistent land cover dataset with the other datasets used, visual inspection has proved that reported irrigated areas tend to be larger than expected based on satellite imagery (Figure 29). Note that the vegetated areas include both irrigated and non-irrigated vegetation. Therefore, if a more precise delineation of irrigated areas were available, it is likely that the evapotranspiration estimates would be substantially higher (see also Annex 6).

Table 6. Water balance of focus area in Abyan Delta catchment (average of 2009-2015) based on open data and an adjusted balance incorporating expert judgement

Water balance term		Value [mm/y]	Source	Adjusted value [mm/y]
In	**Precipitation**	126	CHIRPS	126
	Qanats	0	Assumption	0
Out	**Evapotranspiration (average)**	222	WaPOR*	130
	Irrigated cropland	359	WaPOR	359
	Rainfed cropland	105	WaPOR	105
	Other	217	WaPOR*	122
	Wadi outflow	0.4	FLO1k*	5
	Groundwater recharge	1.3	Assumption	1.3
Balance		**-98**		**-10**

* Value adjusted based on expert judgment, see text for details.

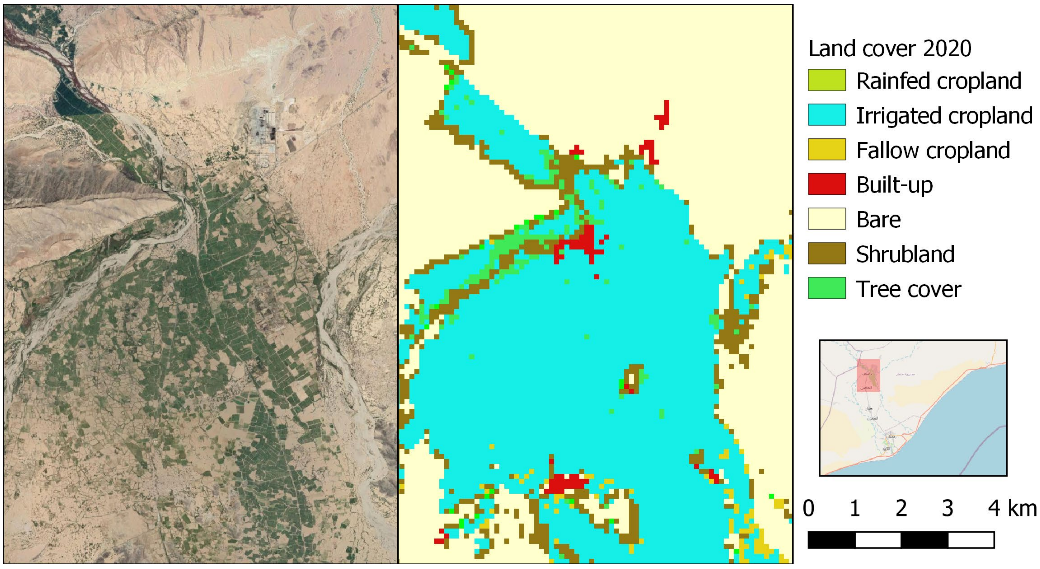


Figure 29. Comparison of irrigated areas based on Google satellite imagery (left) and the land cover map in the WaPOR database (right).

Wadi outflow into the Gulf of Aden, based on FLO1K is less than 1 mm/y, or 5 MCM/y. This estimate is substantially lower than values for literature values reported for Wadi Bana (154 MCM/y) and Wadi Hassan (15-30 MCM/y) entering the Abyan Delta (Riaz et al. n.d.). However, it is expected flow out of the delta is substantially lower than inflow as a result of spate irrigation. Therefore, in the adjusted water balance a higher value of 5 mm/y is assumed.

Within the year, the bulk of rainfall occurs in July and August (Figure 30). Evapotranspiration is highest in the summer months and low in winter. In August, precipitation is higher than evapotranspiration, while in all other months there is a precipitation deficit. This deficit is largest just before and after the rainy season, in the months June, September, and October.

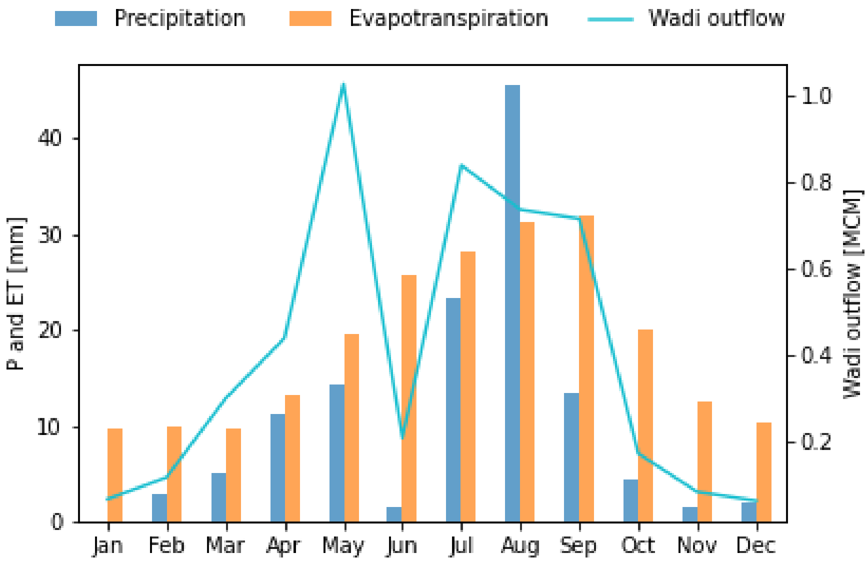


Figure 30. Average monthly water balance for Abyan Delta catchment for the period 2009-2015. P = precipitation, ET = evapotranspiration, Q = wadi outflow.

Both the data-based and adjusted water balance show that the average annual outflow exceeds average annual precipitation (Table 6). It is assumed that the precipitation deficit is compensated by groundwater abstraction. Based on the domestic water demand estimate (Chapter 5.4.2) and the agricultural water demand based on the water balance, more than 80% of abstractions are agricultural. The deficit is smaller in the adjusted water balance than in the data-based water balance, it is by no means unsubstantial, amounting to more than 8% of annual precipitation, or more than seven times annual groundwater recharge. This means that groundwater is being abstracted about ten times faster than it is being replenished. In an analogy to Earth Overshoot Day, the date in which abstraction of groundwater resources exceeds the amount of groundwater that is replenished in that year is February 16th.

5.6.2 Local scale

While catchments are the natural unit to study the water balance, effects of over-abstraction of groundwater can be very local in nature. Therefore, it is important to account for local variability in water availability and water use. There is a strong precipitation gradient, with more precipitation falling in the highlands in the northwest than in the coastal area (Figure 31). Evapotranspiration is highly variable in the catchments, with higher values in the highland areas, in drainage features, and in irrigation areas (Figure 32).

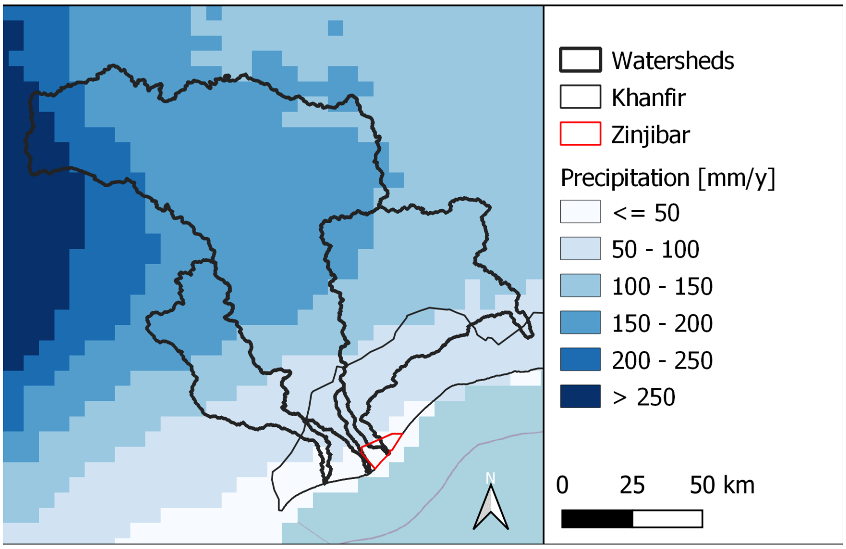


Figure 31. Spatial variability in average annual precipitation.

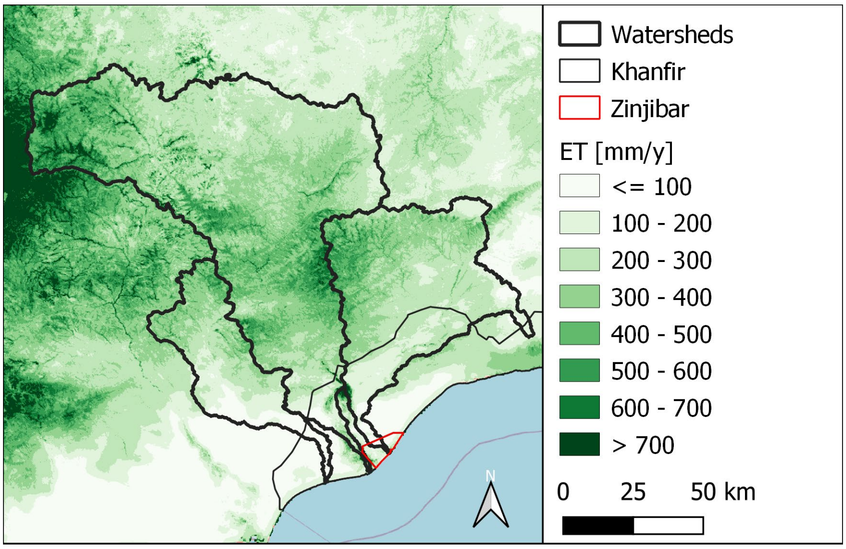


Figure 32. Spatial variability in average annual evapotranspiration.

For the local scale, irrigation areas in the lower part of the Abyan Delta (Figure 28) are used as an example. Average annual evapotranspiration in the upper regions of the irrigation areas is close to 1,000 mm/y, though local maxima are around 1,300 mm/y (Figure 33). These high values are consistent with a crop type requiring year-round irrigation. Based on a land use map of 2006, bananas are cultivated in this area (Annex 6). It is assumed that groundwater resources are used to supply the difference between evapotranspiration and average annual precipitation, a value in the order of 900 mm/y.

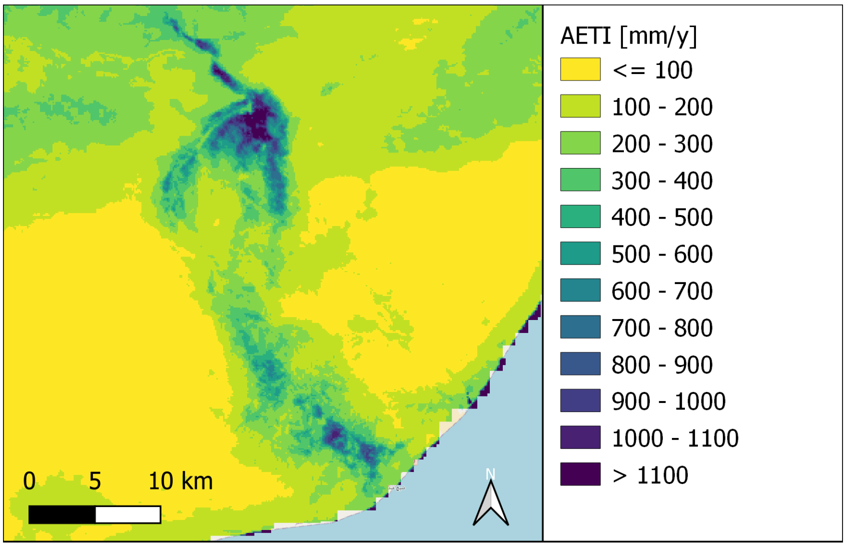


Figure 33. Average annual evapotranspiration in the irrigation areas in the Abyan Delta.

Actual abstraction rates for irrigation are likely to be higher than the estimated 900 mm/y, as part of abstracted water will be routed to surface water or groundwater. If abstraction and return flow are in the same aquifer, this return flow does not need to be taken into consideration. However, it is more likely that abstraction takes place from a deep aquifer, while irrigation losses recharge the shallow aquifer. In this case, local groundwater depletion could lead to local groundwater decline in the order of 1,125 mm/y, assuming the loss to surface water and groundwater is 20% of the total amount of water abstracted for irrigation (Riaz et al. n.d.). Relating the local groundwater abstraction to the natural groundwater recharge rate of 1.3 mm/y shows that irrigation for these crop types has a large area of impact.

5.6.3 Trends

Trends in annual precipitation and evapotranspiration between 2009 and 2020 are presented in Figure 34. It should be mentioned that this period is much too short to reflect any long-term trends that may be due to climate change. The figure shows that precipitation is relatively high in the later part of the study period, with 2020 being an especially wet year. In the same period, evapotranspiration increases with a stronger trend than precipitation. Irrigated areas show the strongest trend of the studied land cover types, while trends in rainfed and non-cropland areas are similar. As a result, the precipitation deficit shows a decreasing trend during the study period (Figure 35). The trend in precipitation deficit can be used as a proxy for trends in groundwater storage, for which direct measurements are not readily available. The direction of the trends using this proxy are more reliable than their magnitude. The trends in precipitation deficit suggest that groundwater availability is decreasing at catchment scale.

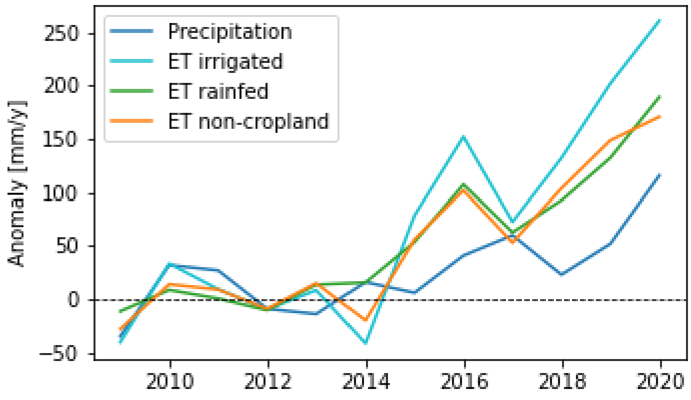


Figure 34. Anomalies of annual precipitation and evapotranspiration from different land cover types compared to the average annual value between 2009 and 2013.

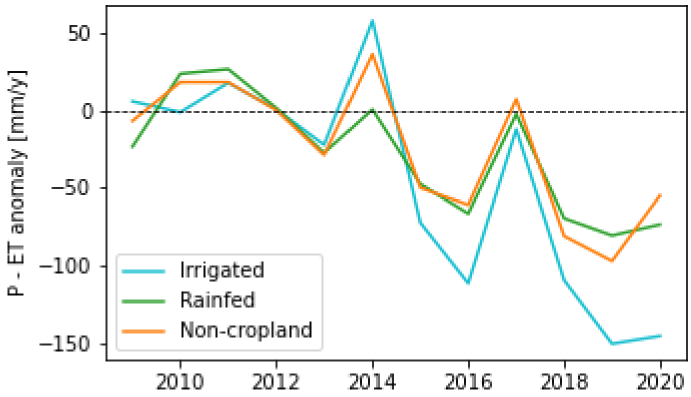


Figure 35. Anomalies of precipitation deficit for different land cover types compared to the average annual precipitation deficit between 2009 and 2013.

A second approach focuses on regional groundwater availability and is based on GRACE observations. The total water storage estimates are converted into groundwater storage anomalies through correction with trends soil moisture and plant canopy water (see Chapter 3). Trends in groundwater storage based on this approach are compared to annual precipitation in Figure 36. The figure shows a decreasing trend in groundwater availability between 2003 and 2015. Between 2015 and 2020, groundwater availability increased. This is likely related to higher rainfall in those years, with 2020 being particularly wet. However, it is also possible that irrigation abstractions decreased as a result of the conflict in this region starting around that time (Annex 2). The results suggest that until 2015, regional groundwater stores were being depleted, while after this time groundwater use was sustainable on a regional scale.

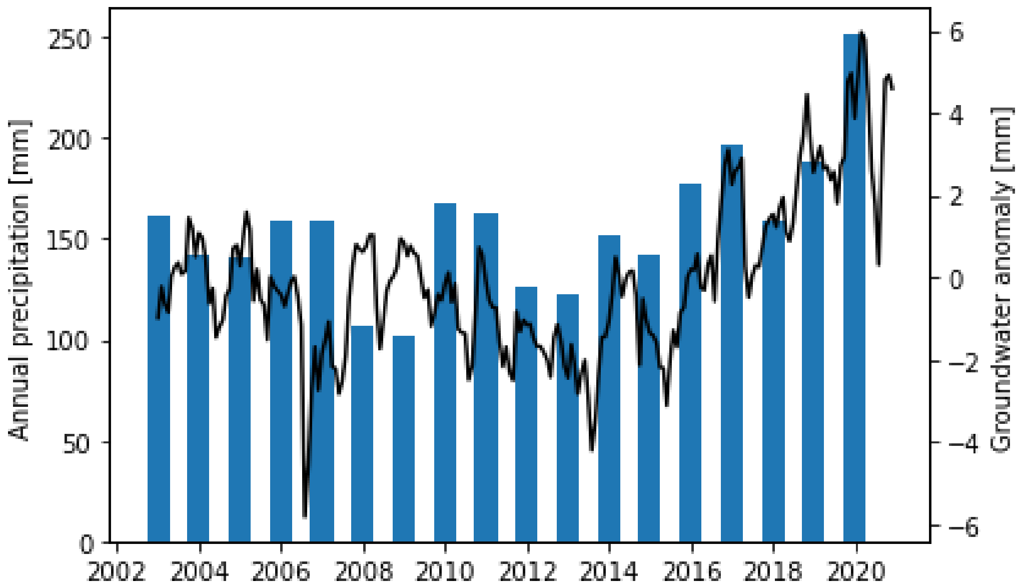


Figure 36. Groundwater anomalies based on GRACE and GLDAS compared to annual precipitation totals in the Abyan Delta region.

It is important to note that the GRACE-based values are sensitive to storage in all aquifers. It is likely that groundwater replenishment is limited to the shallow, renewable aquifer. Replenishment of deeper aquifers, however, is assumed to be negligible. There is anecdotal evidence that groundwater is increasingly being abstracted from these deeper, non-renewable aquifers. Therefore, while the balance of shallow aquifers could be positive in the recent, relatively wet years, the balance of deeper aquifers is most likely negative.

5.7 Conclusions and recommendations

A combination of literature study and remote sensing datasets have been consulted to gain insight into water availability in the Abyan Delta catchment. Previously published reports often contain direct measurements and provide context, but may be outdated and information availability can vary within a given study area. Remote sensing data, on the other hand, provide insight into spatial and temporal patterns and trends in physical variables in a consistent manner for a study area, though the absolute values can be uncertain. In this way, the two data sources are complementary and allow for optimal use of existing data.

5.7.1 Conclusions

The literature study shows that:

- The total volume of groundwater abstraction from Abyan aquifer was estimated to be 86 MCM/y in the 1990s decade, and it increased to 107 MCM/y in 2006;
- Water demand is exceeding sustainable water availability in Abyan Delta. Various literature sources report declining groundwater levels by up to 1 m/y due to the over-abstraction and suggest groundwater abstractions have been increasing in recent decades;
- Sea water intrusion has heavily impacted well fields and private wells in Abyan deltas (KOMEX 2003; abstract), and could continue to the extent that groundwater resources become unusable (Komex 2002);

- Moreover, continued use of poor-quality water for irrigation would also lead to salination of soils, decline in productivity, and eventually possibly even disappearance of agriculture in southern zone (Komex 2002);
- The flow of Wadi Bana and Wadi Hassan is characterised by flood fluctuation, with flood occurring in both summer and autumn seasons;
- Spate irrigation infrastructures are reported to divert the high intensity floods of short duration. To date, it is not clear what is the extent of the use of the network, as infrastructures have suffered damages following flash flood events;
- Groundwater is the main source of drinking water, and it accounts for an increasing proportion of the irrigation water supplies;
- According to Komex (2002), urban contamination resulting from fuel and oil spills, sewage leakages pose a risk to local potable water supplies.

Based on the water balance using remote sensing and satellite data:
- Groundwater is being abstracted more than seven times faster than natural groundwater recharge rates;
- Trend analysis suggests that agricultural water demand has increased in the past 10–20 years;
- Agriculture is the main water user (>80% of groundwater abstractions), with local water demand for irrigation up to nine times higher than average annual precipitation. Irrigation water demand is especially high for crops which are irrigated year-round, such as banana plantations;
- Proxies for groundwater availability suggest that over-abstraction has taken place in the past 10–20 years, though the proxies for catchment and regional scale groundwater availability do not always agree on its timing and duration.

5.7.2 Recommendations

The following key recommendations are suggested for Abyan Delta (Table 7).

Table 7. Key Abyan Delta recommendations.

Water demand management action	Explanation
Spate irrigation infrastructure performance assessment and targeted rehabilitation	Spate water irrigation infrastructure used to play a major role in the Abyan Delta. Literature points towards poor maintenance, high leakages, and inefficient irrigation. By conducting performance assessments at scheme level, one can identify key infrastructure points requiring rehabilitation. Improving spate water irrigation infrastructure may lower reliance on groundwater resources.
Pilot water allocation planning, using bottom-up approach (starting from and together with the users)	Water allocation is important in order to prioritize the use of the scarce available water, especially since agricultural water use is high and at the same time domestic water demands are far from being met. Implement a pilot on water allocation on a small-scale using bottom-up approach (starting from and together with the users) determining i) who is using water (monitoring), ii) who is prescribed for using the water, iii) how to reallocate and prioritize the scarce water use among the various users and along which line of reasoning (e.g. economic or social point of view).

Suggested further research should focus on efforts to:

- More precise delineation of irrigated areas to improve groundwater abstraction and water availability estimates based on remote sensing data. Higher (*i.e.* 30 m) resolution estimates of evapotranspiration can contribute to this;
- Validate proxies for groundwater availability trends based on remote sensing datasets with local data on groundwater abstractions and/or groundwater levels;
- Investigate groundwater availability (storage, abstraction rates, groundwater recharge rates) through (geophysical) surveys;
- Update the existing sea water intrusion mapping to gain insight into changes in salinity over time;
- Study the potential for more efficient irrigation techniques and technologies, especially for crop types receiving irrigation year-round;
- Approximate the current area irrigated under spate irrigation and groundwater irrigation techniques to inform groundwater availability studies;
- Perform feasibility studies for techniques to increase water availability, including water harvesting and artificial recharge.

6 Water availability in Wadi Rima/Siham upstream catchment

This chapter takes a closer look at the water availability for agricultural activities and food production in Jabal Al Sharq District in Dhamar Governorate (confusingly named "Wadi Dhamar" in the ToR,). This focus area is selected as it is one of the implementation areas of the FAO Resilience Programme in the Irrigation and Agricultural Sector (FAO & UNDP, 2020). To carry out the water balance analysis, the study area must take account of the drainage area where lie the districts. Thus, this study analyses the water availability of Wadi Siham and Wadi Rima upstream catchment more specifically.

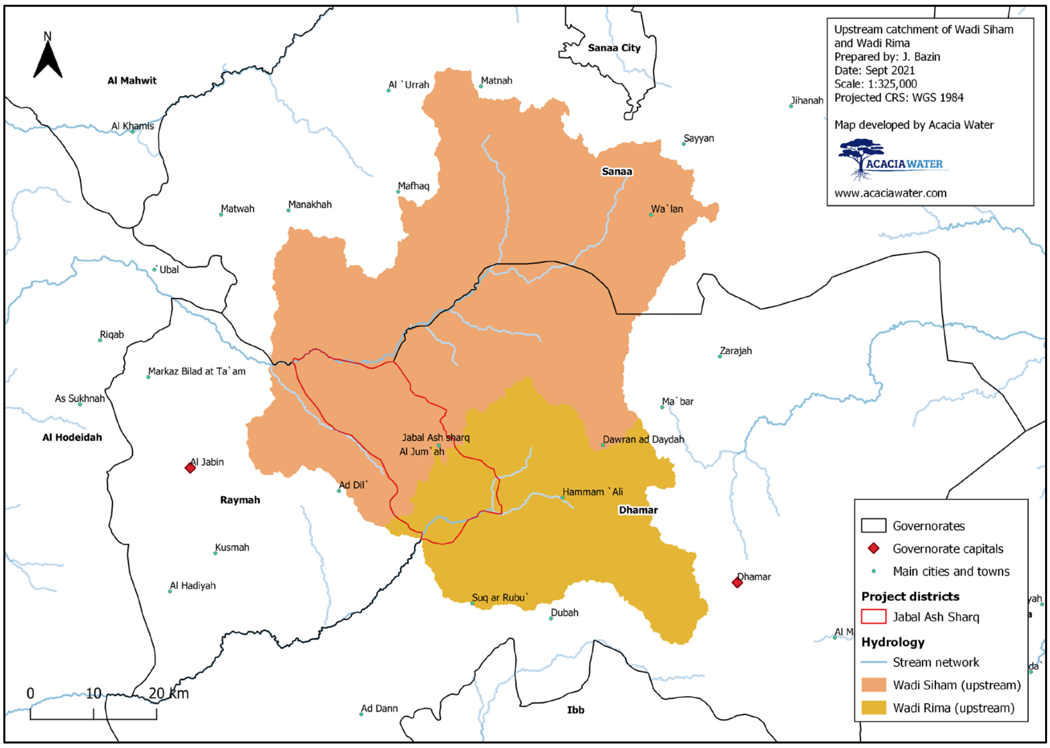


Figure 37: Drainage basin of upstream Wadi Siham and Wadi Rima, derived from DEM data of the SRTMGL1 dataset (NASA-JPL, 2013)

The combination of the available literature with recent remote sensing and satellite data analyses techniques using digital elevation data from SRTMGL1 dataset (NASA-JPL, 2013), precipitation data for the period 2009–2015 and land cover data from ESA Land Cover Maps v2.0.7 dataset (ESA, 2017) results in unique updated insights into the water balance of upper Wadi Rima and Wadi Siham.

6.1 Overview of the wadi catchments

As shown in Figure 37, **the focus area is located in the western highlands of the Yemen Mountain Massif**, bounded by the cities of Sana'a on the north and Dharma on the east. It lies within the upper catchment of two wadis, namely Wadi Siham and Wadi Rima (also spelled Rima).

Wadi Siham is part of the Siham Basin in the north, while Wadi Rima is part of the Rima Basin in the south. Both basins originate in the western highlands and drain the Tihama Plain until the wadis reach the Red Sea (Al Ward & Ismail, 2019). The Wadi Siham Basin covers an area of 4,900 km2; however, **this study focuses on the 2,800 km2 that form Wadi Siham upper catchment area. Wadi Rima sub-catchment covers an area of 1,200 km2 approximately.** The total area of the sub-catchment considered in this study amounts to nearly 4,000 km2.

Administratively the sub-catchment area is situated (partially) in three governorates: Dhamar, Raymah and Sana'a Governorates. It encompasses 12 other districts beside Jabal Ash Sharq District, notably Dawran Anis District.

6.2 Socio-economic characteristics

6.2.1 Population

Based on the census of WASH Cluster (2021), **the population of the entire catchment area is estimated at approximately 700,000 of which 5% are IDPs for a total of 34,000**. Regarding the district of Jabal Al Sharq , its population was evaluated to be 89,000 in 2019 (Alsabri, 2021).

6.2.2 Land use

This remote-sensing study shows that **the focus area is mainly comprised of shrubland (>50%) and grassland (35%)**, as described in Table 8. There is little occurrence of open tree cover, that accounts for less than 3% of the total LULC of the catchment. Wadi Siham is also characterized by the presence of bare or sparsely vegetated areas on 3% of its surface.

Table 8. Main land use and land cover (LULC) in Wadi Rima/Siham upstream catchment, obtained from the land cover data of the ESA Land Cover Maps v2.0.7 dataset (ESA, 2017).

Major Land use / Land cover type	Wadi Rima		Wadi Siham		Wadi Rima/Siham	
	Surface area (km2)	Coverage (%)	Surface area (km2)	Coverage (%)	Surface area (km2)	Coverage (%)
Shrubland	667	57.2	1,470	52.9	2,136	54.1
Grassland	323	27.7	1,064	38.3	1,387	35.1
Cropland, irrigated	73	6.3	57	2.0	130	3.3
Cropland, rainfed	50	4.3	37	1.3	86	2.2
Tree cover, open	49	4.2	59	2.1	108	2.7
Bare / sparse vegetation	2	0.2	90	3.2	92	2.3
TOTAL Surface area	**1,170**	/	**2,780**	/	**3,950**	/

Wadi Siham and, even more, Wadi Rima both support significant agricultural activities. **Irrigated cropland account for 3.3% of the total LULC while 2.2% of the land is earmarked for rainfed agriculture**. The rainfall in the highland plains is adequate to produce rain-fed crops, consisting largely of cereal grains. On the slopes the cultivated land is terraced by a complex system of stone reinforced dykes. These terraces are often many centuries old and highly effective methods of harvesting rainwater.
Looking at Figure 38, **cropland is very localized. Three major production areas can be identified near the towns of Al Jum ah and Dawran ad Daydah, and Dhamar city**. Overall, the catchment barely contains any built-up areas beside the major towns identified.

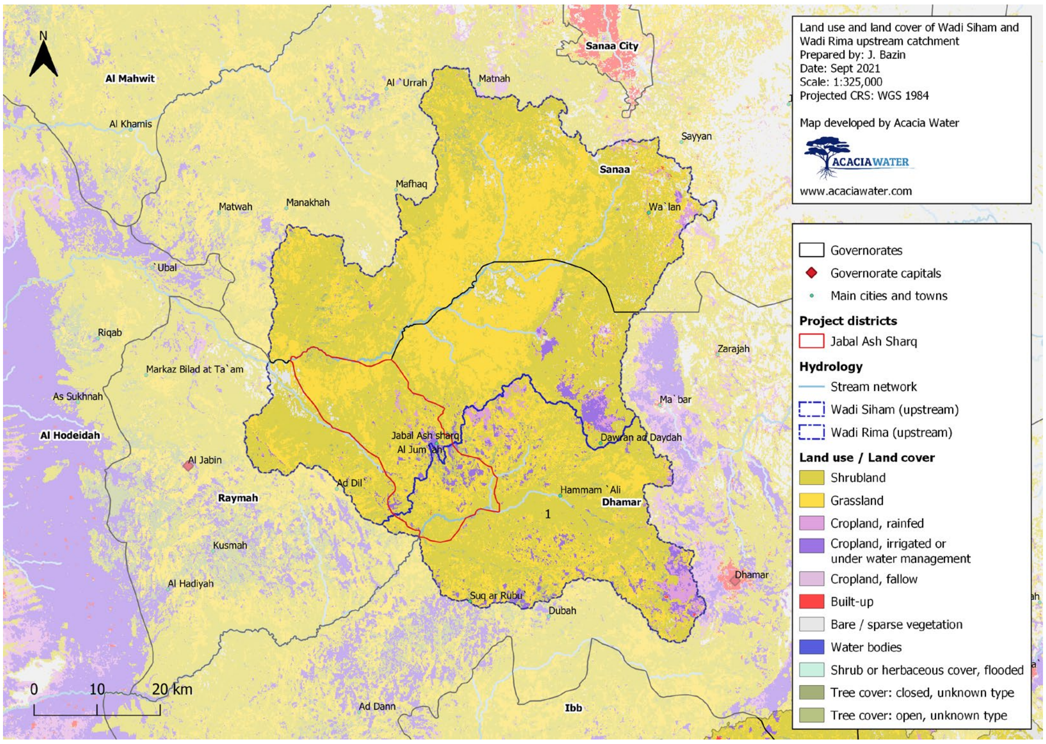


Figure 38: Wadi Siham and Wadi Rima upstream catchment and land use, derived from land cover data of the ESA Land Cover Maps v2.0.7 dataset (ESA, 2017)

6.2.3 Livelihood and conflicts

In view of the sparsely urbanised areas and of the signs of agricultural activities, the population of the catchment is assumed to be predominantly rural.

6.3 Water availability

6.3.1 Surface water

Hydrology and sub-catchments

The upper catchment of the wadis is composed of rocky-rugged mountains and hills with an altitude of 2,000 to 2,400 m a.s.l. in Wadi Rima, and of 2,400 to 3,200 m a.s.l in Wadi Siham. The valley plain of Wadi Siham extends to the western part at an altitude of 800 to 1,100 m a.s.l.. In comparison, the valley of Wadi Rima is limited to the riverbed at 1,200 m altitude. This sub catchment area has a relatively dry climate (Van der Gun & Ahmed, 1995), with an annual rainfall comprised between 100 and 400 mm as indicated by the remote-sensing study. It contributes mainly to the base flow and floods for the wadis. The wadis consist of naturally shaped tributaries that contain and absorb the high though rare floods. Indeed, the water supply to the wadis is irregular.

Overall, the annual runoff volume in the Wadi Siham Basin is very low at 83 MCM/y, which is about 5% of the total rainfall volume, indicating that the total water loss was 95%. Most of the times the place is dry throughout the year; the water supply to the wadi occurs after rainstorms fall during the rainy season. Floods in Wadi Siham Basin were investigated within 20 years period from 1990 to 2009, showing a sporadic pattern with increased variability in duration of floods and total amount of water. There were 570 flood events within 20 years, with a total volume of 53 MCM that is about 3% of the rainfall. Some are considered as mega-flood due to high discharges to the basin. The highest peak discharges of floods occurred in 2005 (about 2,000 m3/s) and 2007 (about 1,800 m3/s and surface water runoff nearly 6,000 m3) (Al Wrd & Ismail, 2019). Overall, Wadi Siham is characterized by an average of 15 floods per year in its upper catchment. Some occur during the *seif* season, from March to July, but the majority during the *kharif* season, from July to November (Bonzanigo & Borgia, 2009).

Similar observations can be made in Wadi Rima, where the mean annual runoff was estimated at 90 MCM/y (Van der Gun & Ahmed, 1995). Surface water flows are extremely variable. Long period of low flows may be alternated by the occurrence of floods with a short duration but a high discharge. Based on records for the period of 1978-1990, it was found that 70-90% of the annual runoff volumes resulted from flows of 0-15 m3/s; the contribution of the flows exceeding 100 m3/s was only 3-7%. During the floods the discharges may rise to several thousand m3/s. High flood peaks occur in the months of April, July and August. The wettest season is usually July to October where the surface flow discharge volumes reach 67% of the total annual flow volumes (NWRA, 2009).

Surface water infrastructures

Wadi Siham offers a large variety of irrigation structures in the Tihama plain and in the upstream catchment, between controlled and uncontrolled artefacts. The latter category conceals various types, including earthen canals, small spurs, large sandy bunds, permanent dams, lined canals, and gates (Bonzanigo & Borgia, 2009).

6.3.2 Groundwater

Geology and groundwater occurrence

The Yemen Volcanics are predominant and almost continuous in the Yemen Mountain, south of Sana’a. The volcanism activity was associated with the Red Sea and Gulf of Aden rift systems. The thickness of the volcanics may exceed 2,500 m in some places. The rock types are alternating lava flows (Van der Gun, 2015, Van der Gun & Ahmed, 1995).

The thick and stratified Yemen Volcanics constitute a generally poor, fissured regional aquifer system, except in the Central Higher Plains area (proximity of Dawran ad Daydah) where it forms rather favourable groundwater zones due to the tectonic activity that probably enhanced the hydraulic properties of the rocks flows (Van der Gun, 2015, Van der Gun & Ahmed, 1995).

Groundwater recharge

According to the study of CEOBS (2021), the recharge of the complex hydrogeological structure found in the Yemen Mountain can be qualified as low to very low.

Groundwater abstraction

Depth to groundwater is highly variable, and many drilling attempts have resulted in dry or poorly productive wells. Based on map of water levels in Wadi Rima/Siham (NWRA, 2009b), assuming the lateral continuity of the geological formations, the water levels in the southern eastern part of Wadi Rima- seem to range between 50-100 m below the surface. In the northern eastern part of Wadi Siham, the water levels can be estimated between 100-150 m below surface levels. To our knowledge, groundwater levels and abstraction have not been monitored and assessed in the focus area.

6.4 Water demand

6.4.1 Agriculture water demand

Food production and farming systems

The remote sensing study identified that the cultivated area accounts for 5.5% of the total surface area of the sub-catchments of Wadi Siham and Wadi Rima, for a total of 21,700 ha in 2020. Wadi Rima is the most productive region with 11% of the land used for agriculture that is a total of 12,300 ha. In Wadi Siham, agricultural land covers 9,400 ha, equivalent to 3% of the total surface area. Based on Alsabri (2021), about 16% of cropland is found in the Jabal Al Sharq District which amounts to 3,400 ha.
In both sub-catchments, 60% of cropland is irrigated (13,000 ha) and 40% is rainfed (8,600 ha); fallow agriculture is not practiced in the area.

Based on the livelihood zones identified and defined by FEWS NET (2010), the sub-catchment includes three main farming systems:

- **YE13, in the North of Wadi Siham: wheat, sorghum, qat, livestock**;
- **YE12, in the West, mainly in Wadi Siham: coffee, qat, sorghum, livestock**;
- **YE05, in the East, mainly in Wadi Rima: potato, vegetable and livestock**.

The recent study carried out by CEOBS (2021) reports the expansion and intensification of qat production in the Western mountains since 2007, with a sharp increase in yields in 2018. However, the cultivated area to produce cereals and vegetables has severely declined since 2014. The cropping calendar can be found in Annex 5.

Irrigated agriculture water demand and practices

As a general comment, irrigation practices have been poorly documented and described in the upper catchment of Wadi Siham and Wadi Rima.

- In the Jabal Al Sharq District at least, Alsabri (2021) reported that 70% of the total cropland is rainfed; the rest is irrigated by springs (20%) and wells (5%) while very little water is diverted from floods or dams. Looking at Figure 38, the land cover obtained from the remote-sensing study indicates a bigger presence of irrigated cropland;
- Most of the agricultural land around the town of Dawran and Daydah is irrigated, based on the remote-sensing study (see Figure 38). As it is located in a favourable groundwater zone (see Section 6.3.2), it may be suspected that irrigation water supply for this cultivated area relies on groundwater;
- The cultivated area near Dhamar city is mainly rainfed as the level of rainfall is more favourable.

6.4.2 Domestic water demand

Estimated domestic water demand

Based on the census of WASH Cluster (2021), the population of the entire catchment area is estimated at approximately 700,000. Assuming that the average water use per capita is 30 l/c/d (see Chapter 7), the total domestic water demand of the Abyan Delta catchment is approximately 7.7 MCM/y.

Domestic water supplies

The literature study has not been able to find any information on the water supply for domestic use in the upper catchment area of Wadi Siham and Wadi Rima.

6.4.3 Overview of groundwater abstraction

Specific information and figures on groundwater use and drilling activities are lacking for the upper catchment of Wadi Siham and Wadi Rima. In the latest well inventory from 1984, 960 wells were reported in the whole Wadi Siham for a total abstraction of 125 MCM/y, noting that the most part was located downstream in the Tihama Plain. For Wadi Rima/Zabi, the number of pumped wells amounted to 1983 for a total of abstracted groundwater of 260 MCM/y (Van der Gun & Ahmed, 1995).

Overall, in the highland plains, the fresh groundwater stored amounts to 50,000 MCM, the approximate abstraction is estimated at 500 MCM/y and the approximate average recharge is 100 MCM/y (Van der Gun & Ahmed, 1995).

6.5 Water balance evaluations

The water balance is based on the upper reaches of two sub-catchments: Wadi Siham and Wadi Rima. In this way, the water balance follows the physical, hydrological boundaries rather than administrative boundaries of the district. The different components of the water balance have been estimated using the methodology and datasets outlined in Chapter 3 and provide insight in the availability of water resources.

6.5.1 Catchment water balance

The combined water balance of the two sub-catchments is presented in Table 9. Since inflow from qanats is assumed to be negligible, precipitation is the dominant source of water in the catchment. The total annual evapotranspiration estimate based on the WaPOR database is 305 mm/y. Evapotranspiration in irrigated areas (335 mm/y) is relatively high compared to rainfed cropland (180 mm/y) and other land cover types (305 mm/y).

There are, however, a few important side notes regarding these results. First, it is unlikely that evapotranspiration non-cropland land cover types exceeds average annual rainfall. Remote sensing datasets such as those used for precipitation and evapotranspiration are reliable in terms of relative spatial and temporal patterns, though the absolute value may contain bias. To avoid differences in absolute values between the datasets having a large impact on the water balance, in an adjusted water balance, evapotranspiration in natural areas is assumed to be 98% of catchment average rainfall (Table 9). Second, the disaggregation of evapotranspiration by land cover type was based on land cover datasets obtained from the WaPOR database. While these are considered to be the most consistent land cover dataset with the other datasets used, visual inspection has proved that reported irrigated areas tend to be larger than expected based on satellite imagery. Therefore, if a more precise delineation of irrigated areas were available, it is likely that the evapotranspiration estimates would be substantially higher.

Table 9. Water balance of focus area in Wadi Rima/Siham upstream catchment (average of 2009-2015) based on open data and an adjusted balance incorporating expert judgement

Water balance term		Value [mm/y]	Source	Adjusted value [mm/y]
In	**Precipitation**	195	CHIRPS	195
	Qanats	0	Assumption	0
Out	**Evapotranspiration (average)**	305	WaPOR	192*
	Irrigated cropland	335	WaPOR	335
	Rainfed cropland	180	WaPOR	180
	Other	305	WaPOR	185*
	Wadi outflow	5	FLO1k	12*
	Groundwater recharge	10	Assumption	10
Balance		**-125**		**-19**

* Value adjusted based on expert judgment, see text for details.

Wadi outflow based on FlO1k is 5 mm/y, or 19 MCM/y. This corresponds to 3% of annual rainfall, which is lower than the 5–7% reported in literature for the two subbasins (Saleh, n.d.). Therefore, in the adjusted water balance a higher value of 12 mm/y is assumed.

Within the year, the bulk of rainfall occurs in July and August, with a smaller rainy season in April and May (Figure 39). Evapotranspiration is highest in the summer months and relatively low in winter. In August and April, precipitation exceeds evapotranspiration. During these months, soil moisture and groundwater storages are replenished to sustain evapotranspiration in drier months and for the generation of wadi flow. In May and July, precipitation and evapotranspiration are balanced, while in the remaining months there is a precipitation deficit. This deficit is largest just after the rainy seasons, in June, September, and October. On average, wadi flow is highest in the rainy seasons.

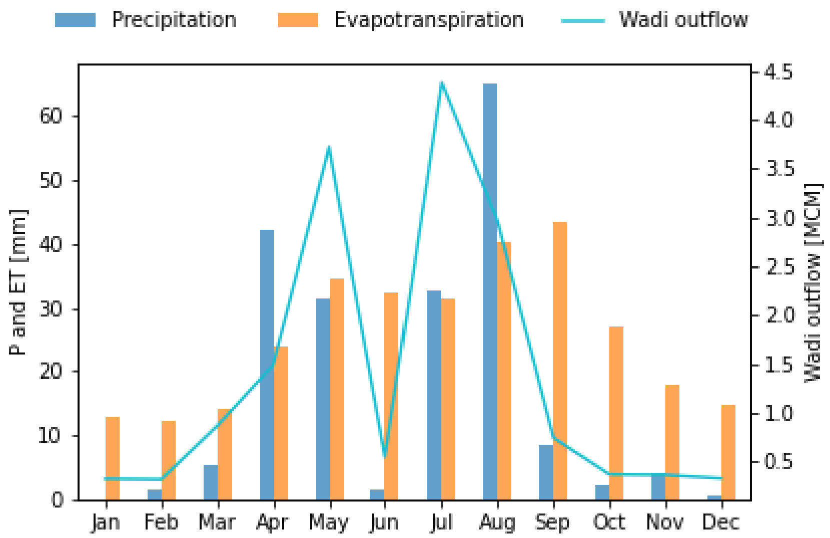


Figure 39. Average monthly water balance for Wadi Rima/Siham upstream catchment for the period 2009-2015. P = precipitation, ET = evapotranspiration, Q = wadi outflow

Both the data-based and adjusted water balance show that the average annual outflow exceeds average annual precipitation (Table 9). It is assumed that the precipitation deficit is compensated by groundwater abstraction. The deficit is smaller in the adjusted water balance than in the data-based water balance, it nevertheless amounts to about 5% of annual precipitation and twice the natural groundwater recharge rate. In an analogy to Earth Overshoot Day, the date in which abstraction of groundwater resources exceeds the amount of groundwater that is replenished in that year is July 11th.

6.5.2 Local scale

While catchments are the natural unit to study the water balance, effects of over-abstraction of groundwater can be very local in nature. Therefore, it is important to account for local variability in water availability and water use. Evapotranspiration is highly variable in the catchments, ranging from lower than 150 mm/y to higher than 1,000 mm/y (Figure 40). Overall, evapotranspiration is higher in Wadi Rima than in Wadi Siham. Variability in precipitation is lower than evapotranspiration, varying between 200 mm/y in the east and more than 300 mm/y in the southwest (Figure 41).

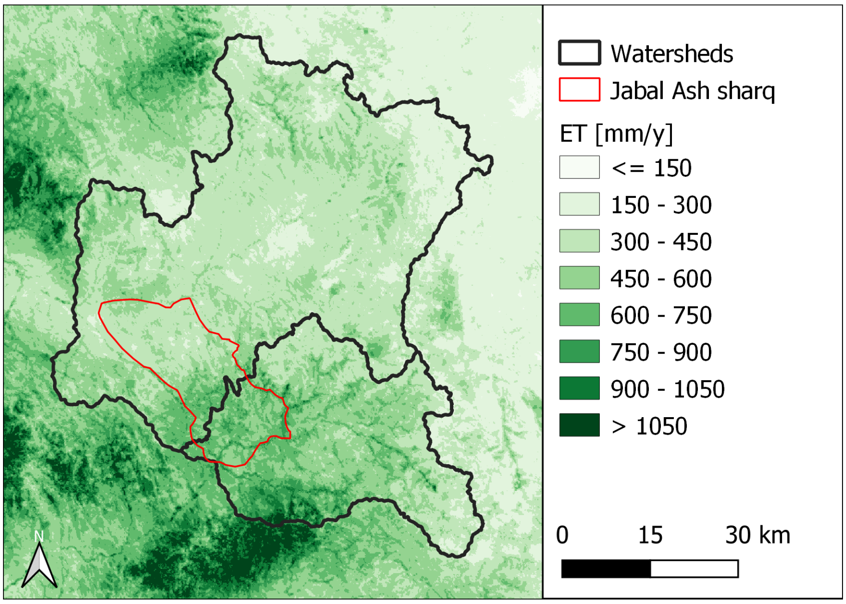


Figure 40. Spatial variability in average annual evapotranspiration.

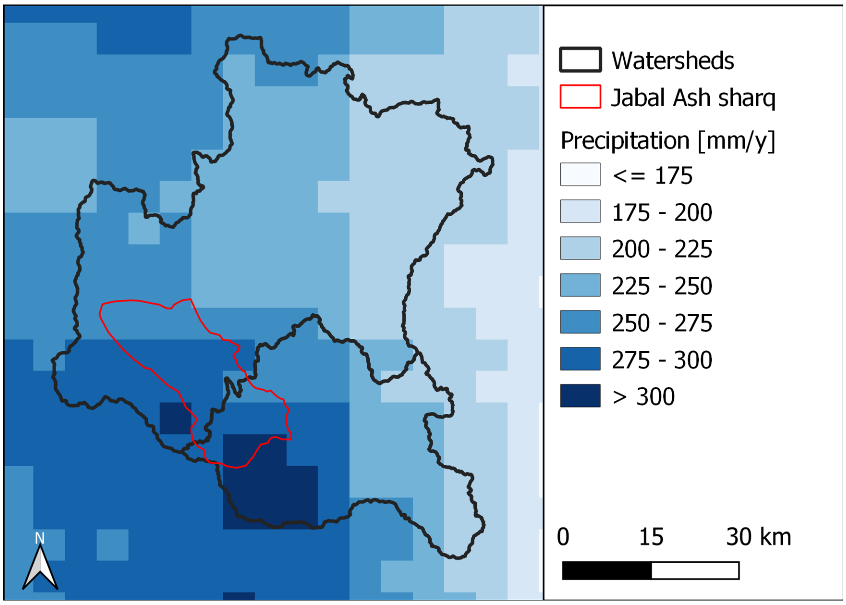


Figure 41. Spatial variability in average annual precipitation.

For the local scale, irrigation areas in the Wadi Rima/Siham upstream catchment are used as an example. Average annual evapotranspiration in selected irrigation areas vary between 500 and 800 mm/y. These values are consistent with irrigation for a single crop season annually. It is assumed that groundwater resources are used to supply the difference between evapotranspiration and average annual precipitation, a value in the order of 400 mm/y. This is substantially higher than the estimated natural recharge rate of 10 mm/y to shallow aquifers.

Actual abstraction rates for irrigation are likely to be higher than the estimate based on evapotranspiration, as part of the abstracted water will return to groundwater or run off as surface water. If abstraction and return flow are in the same aquifer, this return flow does not need to be taken into consideration. However, it is more likely that abstraction takes place from a deep aquifer, while irrigation losses recharge the shallow aquifer. In this case, local groundwater depletion could lead to local groundwater decline in the order of 500 mm/y, assuming that the losses to groundwater and surface water are 20%.

6.5.3 Trends

Trends in annual precipitation and evapotranspiration between 2009 and 2020 are presented in Figure 42. It should be mentioned that this period is much too short to reflect any long-term trends that may be due to climate change. The figure again shows that precipitation increases during the study period, especially in the latter years. The trend in evapotranspiration from rainfed cropland and non-cropland land cover types is similar in magnitude, while the trend in irrigated areas is somewhat stronger. As a result, there is a slight decreasing trend in precipitation deficit (difference between precipitation and evapotranspiration) during the study period (Figure 43). The trend in precipitation deficit can be used as a proxy for trends in groundwater storage, for which direct measurements are not readily available. The direction of the trends using this proxy are more reliable than their magnitude. The trends in precipitation deficit suggest that groundwater availability is decreasing at catchment scale.

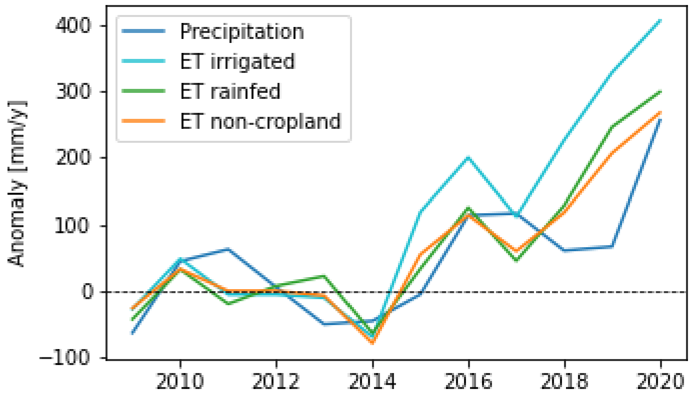


Figure 42. Anomalies of annual precipitation and evapotranspiration from different land cover types compared to the average annual value between 2009 and 2013.

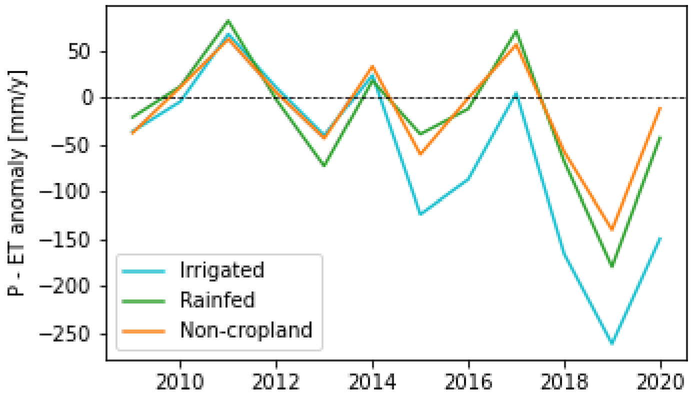


Figure 43. Anomalies of precipitation deficit for different land cover types compared to the average annual precipitation deficit between 2009 and 2013.

A second approach focuses on regional groundwater availability and is based on GRACE observations. The total water storage estimates are converted into groundwater storage anomalies through correction with trends soil moisture and plant canopy water (see Chapter 3).

Trends in groundwater storage based on this method are compared to annual precipitation in Figure 44. The figure shows an overall decreasing trend during the study period, though groundwater anomalies appear to stabilize after 2016. The results suggest that overall, groundwater availability decreased, most likely due to over-abstraction. It is unclear whether the higher precipitation alone is responsible for the change in trend at the end of the study period, or whether groundwater abstractions may have decreased due to the conflict in the country (Annex 2).

It is important to note that the GRACE-based values are sensitive to storage in all aquifers. It is likely that groundwater replenishment is limited to the shallow, renewable aquifer. Replenishment of deeper aquifers, however, is assumed to be negligible. Therefore, abstraction of groundwater from these aquifers will directly result in decreasing aquifer storage.

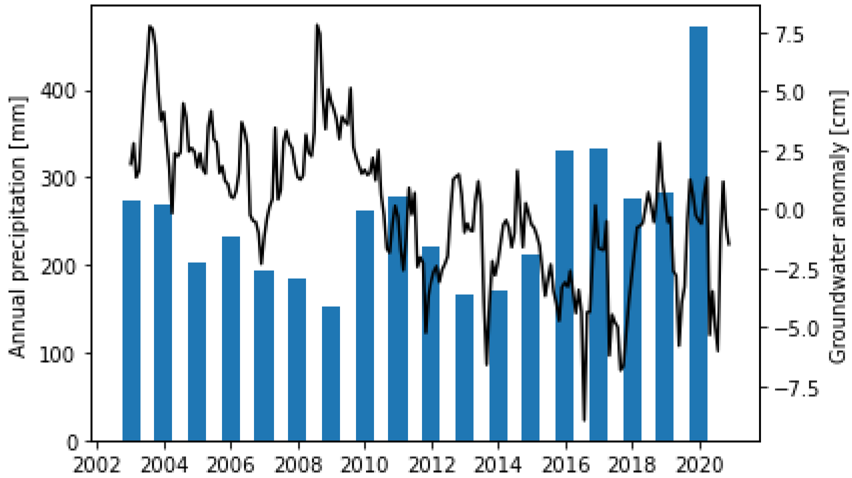


Figure 44. Groundwater anomalies based on GRACE and GLDAS compared to annual precipitation totals in the Dhamar region.

6.6 Conclusions and recommendations

A combination of literature study and remote sensing datasets have been consulted to gain insight into water availability in the Wadi Rima/Siham upstream catchment. Previously published reports often contain direct measurements and provide context, but may be outdated and information availability can vary within a given study area. Remote sensing data, on the other hand, provide insight into spatial and temporal patterns and trends in physical variables in a consistent manner for a study area, though the absolute values can be uncertain. In this way, the two data sources are complementary and allow for optimal use of existing data.

6.6.1 Conclusions

The scarce available literature suggests:

- Water demand and use exceed water availability in Wadi Rima/Siham,upstream catchment which goes at the expense of groundwater abstraction;
- The annual runoff volume in the Wadi Siham Basin and the Wadi Rima Basin is very low. The water supply to the wadis is extremely variable, between long period of low flows and the occurrence of floods with a short duration but a high discharge during the rainy season;
- The sources of water supply for domestic use and agricultural purposes in the Rima/Siham upstream catchment remain unclear to this day, as the upper catchments are very limited covered in available literature;
- Depth to groundwater is highly variable, and many drilling attempts have resulted in dry or poorly productive wells.

The remote sensing and satellite data analysis shows:

- Agriculture is the main water user, with local water demand up to 2.5 times higher than average precipitation;
- Trend analysis suggests that agricultural water demand is increasing;
- Groundwater is being abstracted about twice as fast as natural groundwater recharge rates;
- Proxies for groundwater availability support the conclusion of the water balance, showing decreasing overall trends in the past 10–20 years.

6.6.2 Recommendations

The following key recommendations are suggested for Wadi Rima / Wadi Siham upstream catchments (Table 10):

Table 10. Key Wadi Rima/Siham upper catchment recommendations.

Water supply management action	Water demand management action	Explanation
	Feasibility and pilot study on less-water intensive cropping patterns with focus on rainfed agriculture	Create awareness among farmers on impact of water intensive cultivation. The priority focus in the near-future should lie on shifting towards sustainable agricultural practices relying on rainfed crops, combined with rainwater harvesting techniques. A feasibility study should assess and identify suited alternatives to current water-intensive cropping patterns (involving vegetables, fruits, qat etc.), presenting a positive business case. Subsequent piloting together with farmers helps in awareness raising as well as to showcase vital alternatives. The pilots are advised to also involve varietal research, to identify crop varieties most suited to this specific area.
Feasibility mapping and pilot study on application 3R (recharge, retention, reuse) techniques, with special focus on rehabilitation of traditional RWH structures and terrace rehabilitation		Many traditional RWH techniques are present in Yemen. Knowledge on these systems is often available with local communities and experts. Adopting a community approach may help identify most suited techniques and/or indicate where existing structures can be rehabilitated/improved. Within the hilly landscape of Wadi Rima/Siham upstream catchments, terrace cultivation is practiced. Capturing and retaining (more) water in the system, may reduce flood peaks and increase prolong baseflow for the downstream Tihama plain. In the upstream catchments it favours water availability and reduces pressure on groundwater resources.

Suggested further research should focus on:

- Investigate groundwater availability (storage, abstraction rates, groundwater recharge rates) through (geophysical) surveys;

- Survey applied irrigation water sources and techniques in the study area;
- More precise delineation of irrigated areas to improve groundwater abstraction and water availability estimates based on remote sensing data. Higher (*i.e.* 30 m) resolution estimates of evapotranspiration can contribute to this;
- Validate proxies for groundwater availability trends based on remote sensing datasets with local data;
- Perform feasibility studies for techniques to increase water availability, including water harvesting and artificial recharge.

7 Water supply in the major urban centres

The current humanitarian crisis in Yemen has resulted in population numbers to increase in the major urban areas. Both the crises itself, as well as the increasing demands, have an impact on the water supply. The following paragraphs will highlight water supply dynamics and trends in five major urban areas of Yemen: Sanaa, Aden, Taiz, Hodeidah and Marib. The urban areas form the capital city of the respective governorates in which they are located.

> "It may well be assumed that population numbers in Aden city have doubled since the start of the humanitarian crises. At the same time, water supply has almost halved, either due to a lack of maintenance on the aged system or because of damage related to the ongoing conflict."
> Mr. Fantahun Tefera – UNDP Yemen Project Manager Solid Waste and WASH
> (p.c. 23-08-2021)

7.1 Sanaa

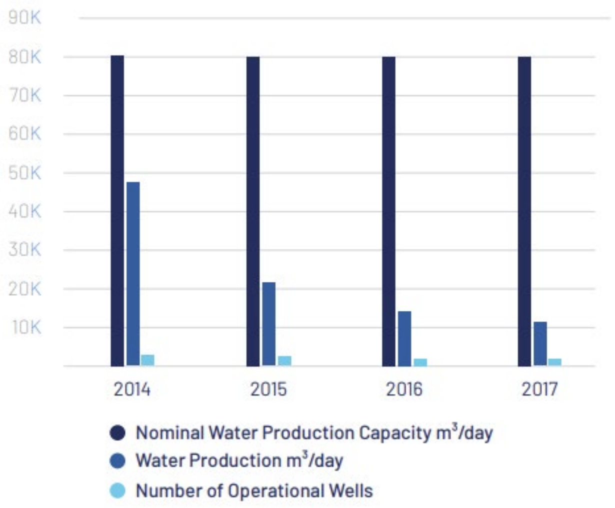
Table 11. Sanaa city key facts (Population numbers from UN Habitat, 2020a)

Population Sanaa Governorate	**1.47 mln**
Population Amanat Al Asimah Governorate	**3.52 mln**
Coordinates:	**15°20′54″N 44°12′23″E**
Elevation:	**2250 m**
Avg. annual rainfall:	**256 mm/y (PET = 2391 mm/y)**

Sanaa (also known as Sana'a or Sana) is the largest city of Yemen, located in the centre of Sanaa Governorate. The city itself forms a separate administrative governorate 'Amanat Al-Asemah'. Although Sanaa is considered the capital city of the country, the Yemeni government is currently seated in the city of Aden. As of 2020, the Sanaa basin is home to approximately nine percent of the total population in Yemen. Currently the population of Sanaa and Amanat Al Asimah governorates are estimated respectively at 1.47 and 3.52 million (UN Habitat, 2020a).

7.1.1 Water supply and distribution

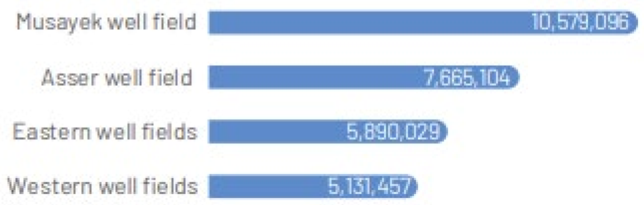
Sanaa city has faced water scarcity issues for years. The water supply grid and management in Sanaa city is considered the worst across Yemen. The conflict in Yemen has led to a drop in water production from 16.5 MCM in 2014 to 6.5 MCM in 2015 (Figure 45). Major problems include damage to water and sanitation infrastructure, lack of stable electricity supply, decreased revenues and fuel shortages. Estimates of non-revenue water due to system leakages range from 40 to 60%. UN Habitat (2020a) reports that water consumption decreased by half last year due to the restrained operational capacity of the system. At the same time, large numbers of IDPs further increase pressure on Sanaa city water supply. Capacity problems result in households only having access to water for less than one full day per week (UN Habitat, 2020a). By 2000, the public water supply only served 40-50% of Sanaa residents (Al-Hamdi, 2000). The percentage has decreased in recent years: in 2009, it was estimated that 55% of residents were connected to the public water supply; in 2018, only 43% did (UN Habitat, 2020a).



Source: GIZ, Technical Assessment Report for Local Corporatuion Sana'a, 2018.

Figure 45. Average water production for Sanaa city per year.

There are Six Water and Sanitation Operational Areas in Sana'a City. The Water and Sanitation Local Corporation is the main body responsible for the provision of water and sanitation services in Sanaa city. It was established by the Republican Decree No. (21) in 2001 and it is the second largest in the country. The Division comprises headquarters and two sub-structures: the water sub-structure, responsible for water distribution and the Wastewater Treatment Plant (WWTP) substructure. The Local Corporation divided the city into six areas and has a local office in each of them. The main building of the local corporation sustained extensive damage (UN Habitat, 2020a).
The city water supply primarily depends on groundwater aquifers, 80 percent of which comes from the Sanaa geological basin (an area of 70x40 km northwest of the city) (UN Habitat, 2020a). Sanaa city is located on the Tawilah aquifer. The aquifer has a natural annual recharge rate estimated between 27 and 63 MCM, mainly coming from the periodic outflow of surrounding wadis. In 1995, water extraction from the aquifer exceeded the natural recharge rate by around 300% (Al-Hamdi, 1997). Recent estimates are higher, suggesting the level of water abstraction to be four to five times higher than the level of replenishment. This has caused groundwater levels to drop by six to eight meters yearly and projections estimate basin depletion to occur within the coming 10 years (UN Habitat, 2020a).



Source: GIZ, Technical Assessment Report for Local Corporatuion Sana'a, 2018.

Figure 46. Nominal water production among the different well fields in Sanaa basin.

The main water supply is coming from about 120 water wells located in four well fields: western well fields, eastern well fields, Musayek well field and Asser well field (Figure 46). Out of 120 boreholes, 83 were operational in 2014, operating 14-16 hours per day and able to produce 46,051 m^3 per day. In the first quarter of 2017 this number further decreased to 10,689 m^3 per day, mainly because of lack of fuel (Table 12). The rapidly dwindling underground reserves and the insufficient replenishment rates have caused many to drill deeper into the ground, with some wells reaching well into 100m in depth (UN Habitat, 2020a).

Table 12. Overview of available water infrastructure.

Description/Facility	Unit	2014	1st Quarter 2017
Public Water Distribution points	Number	12	0
Main Source of Water Supply (SW or GW)		GW	GW
Number of Distinct Supply Zones	Number	6	6
Total Number of Boreholes	Number	120	120
Boreholes in Operation (=borehole pump no)	Number	83	44
Reservoirs	No/m^3	10/40,400	9/34,600
Elevated Tanks	No/m^3	20/2,260	20/2,261
Nominal Water Production Capacity	Well/m^3/d	81,799	81,799
Water Supply Booster & Pumpin Stations	Number	6	5
Water Sterilization Facilities	Number	6	5
Current Water Production Capacity	m^3/d	46,051	10,689
Total Number of Water Meters Installed	Number	94,120	88,497
Total Number of Functioning Water Meters	Meters	68,217	64,119
Number of Zero Reading Water Meters	Number	26,345	58,485
Number of New/Functional Water Meters in Stock	Number	N/A	N/A
Length of Water Supply Network	km	1,035	1,035
Total Number of Bulk Water Meter	Number	106	106
Water Laboratory	Number	1	1

Source: GIZ Yemen Water Sector Annex 17 - Technical Assessment Report for LC Sana'a, 2018

7.1.2 Water demand

Operation capacity of the water and sanitation infrastructure in Sanaa city has been affected by damage, intermittent electricity supply, and lack of finances. The average consumption of water in Sanaa city is 20 litres per person per day and 15 litres per person per day for IDPs (UN Habitat, 2020a).

As of 2018, residents reportedly had access to public water 1-3 hours a day. Consequently, residents rely on private water trucking (subject to affordability), public water distributed using trucks by Sanaa LWSC in local parks, or from philanthropists-sponsored water deliveries (Sabeel). Reportedly, two-thirds (60-70 percent) of the population relied on private water infrastructure in 2018 (UN Habitat, 2020a).

Water demand in the Sanaa area has also increased by the expansion of the agricultural sector, mainly boosted by the introduction of deep tube wells. By 1995, there were over 5,000 wells in the Sanaa area (Al-Hamdi, 2000); as of 2010 this has increased to approximately 13,500 (Lichtenthaeler, 2010). At the same time, traditionally grown, drought-resistant and rainfed crops have been largely replaced by more water-intensive cash crops such as citrus, bananas, grapes, vegetables, and especially qat (Lichtenthaeler, 2010 and Al-Hamdi, 2000). In 2000 about 27% of all farmland in the Sanaa area was dedicated to growing qat (Al-Hamdi, 2000), by 2010, the number had increased to around 50% (Lichtenthaeler, 2010).

An extensive study of JICA (2007a & 2007b) drafted future water demand projections for the Sanaa basin up to the year of 2020. The high population growth scenario considered in the study estimated a population of 3.7 mln in 2020, which is currently far exceeded by the total population number in Sanaa Governorate of 5 mln. The projected water demand by JICA (2007a) of 78,6 MCM might therefore well be outdated. As population estimates turned out 35% higher, most probably water demand is also substantially higher.

This water consumption does not yet consider the expansion in irrigated areas. Estimated irrigated areas in Sanaa in 2018 are reported to be 58,552 ha, of which 36,302 ha depend on groundwater wells (MAI, 2019). JICA (2007a) in their baseline of 2005 considered total irrigated area of about 18,000 ha and a water consumption of 209 MCM, which could well be increased given the changes towards more water-intensive cultivation and expansion of total irrigated areas.

Given the higher population growth rate and expansion of irrigated areas, it can well be assumed that the estimated imbalance for the year 2020 by JICA (2007a) of -298.9 MCM between renewable resources and water demand in Sanaa basin, has got even worse. At the same time, the projections of groundwater resources to run dry (projected 'day zero') and not being able to meet the current 2021 demand, has not been reported so far.

7.2 Aden

Table 13. Aden city key facts (Population numbers from UN Habitat, 2020b)

Population Aden city	**1.14 mln**
Coordinates:	**12˚48′N 45˚02′E**
Elevation:	**6 m**
Avg. annual rainfall:	**50 mm/y (PET = 2560 mm/y)**

Aden is the largest city of southern Yemen. It is also the administrative centre of the Aden governorate. Since 2015, Aden is the temporary (internationally recognized) capital of Yemen, near the eastern approach to the Red Sea (the Gulf of Aden). It is the second most populous city of Yemen, with approximately 1.14 million residents, of which 650 thousand are non-displaced, 290 thousand are returnees from displacement, 60 thousand are IDPs, and nearly 140 thousand are migrants and refugees (UN Habitat, 2020b).

7.2.1 Water supply and distribution

The water supply grid in Aden city connects 138,605 water houses (January 2020). This follows a distribution grid of approximately 1,111 km, comprising 34 reservoirs, three water sterilization facilities, eight pumping stations and 116 water wells. According to Dorsch International Consultants GmbH (2018) the per capita daily water consumption for Aden city in 2016 was 70 litres (Figure 47). The sanitation system consists of a 391 km long piping network, three waste water treatment plants (WWTP) with a total design capacity of 100,000 m^3 per day (Table 14). The WWTP performs well below the design capacity as actual flow in 2018 is reported to be about 40,000 m^3 per day (UN Habitat, 2020b).

The water and sanitation sectors were seriously affected following the eruption of hostilities in 2015. Water coverage for Aden local corporation fell from 92% in 2014 to 86% in 2017, while the sewage coverage for the same years decreased from 79% to 69%. Non-revenue water (water losses) increased from 41% in 2014 to 55% in 2017 (UN Habitat, 2020b).

In the private sector, water is distributed from private wells via water tankers. The price is determined based on the market perception. As of 2018, the tankers were buying water from private wells for YER 112/m^3 and selling it to the households for YER 1,832/m^3. Some of the water requires desalination, which the tanker truck can provide as an additional service (UN Habitat, 2020b).

Table 14. Wastewater treatment plant details in Aden City, 2019 (Source: UN Habitat, 2020b).

WWTP Name	Al-Arish WWTP	Ash-Shaab WWTP	Salah Aldien WWTP
Put in service	2,000	1,979	
Design Flow	70,000 m^3 per day	20,000 m^3 per day	5,000 m^3 per day
Actual Flow, (2014)	over 30,000 m^3 per day	15,000 m^3 per day	
Actual Flow, (2018)	0 m^3 per day*	35,000 m^3 per day	5,000 m^3 per day
Disposal method of treated primary effluent	Sea disposal and irrigation	Sea disposal and irrigation	
Disposal method of treated primary effluent sludge	Sludge is dried under the sun in a primitive and used as a fertilizer	Sludge is dried under the sun in a primitive and used as a fertilizer	
Coverage	Craiter, Attawahi, Al Mualla and Khur Maksar districts	Ash Shaab, Ash Shaikh Outhman, Dar Sad and Al Mansura	Salah Aldainis area in Al Buraiqeh district (sewage from the rest of the district is discharged through the sea outfall pipeline)

Source: Adel A. S. Al-Gheethi et al., "Effectiveness of Selected Wastewater Treatment Plants in Yemen for Reduction of Faecal Indicators and Pathogenic Bacteria in Secondary Effluents and Sludge," Water Practice and Technology 9, no. 3 (2014): pp. 293-306 and Dorsch International Consultants GmbH, Damage Assessment Report of Twelve Water Supply and Sanitation Local Corporations (LCs) and their Affiliated Branch Offices and Utilities. Bonn and Eschborn: GIZ, September 2018.

**According to the MWE, this is because the main pump station in Khur Maksar is nonfunctional and the damaged network pipes from Attawahi, Craiter and Al Mualla.*

Aden city water supply relies primarily on water from groundwater wells. Only 0.3 percent of the water comes from desalination plants (Dorsch international consultants GmbH, 2018). Majority of the water comes from three main well fields:

- El Manasra (13°01'06.0"N 45°00'15.0"E) well field consists of 29 wells, of which 18 are functioning. It supplies 20% of WSLC Aden's command area and serves about 48,000 households. The currently produced water quantity is approximately 450-550 m^3/h, non-revenue water in field and along the main pipes line estimated at 25%. The productivity could reach more than 1,000 m^3/h, if all the wells are operational and there are no problems in overhead line (ZOA Yemen, unpublished);

- Bir Nasser (12°58'08.2"N 44°56'40.7"E; located in Lahj governorate, but under administration of Aden governorate) well field counts 46 wells, of which 38 are functioning. It supplies 40% of WSLC Aden's command area and serves about 97,000 households. The produced water is approximately 1,200 - 1,400 m^3/h, while non-revenue water in field is estimated at 30%, which is distributed to some villages around wellfield (ZOA Yemen, unpublished). Following the conflict, the Bir Nasser well field is reported to still be damaged and not rehabilitated;
- Bir Ahmed (12°52'23.0"N 44°54'22.0"E, Aden governorate) well field consists of 30 functioning wells out of a total of 40. It supplies 40% of WSLC Aden's command area.

Both El Manasra and Bir Nasser well fields either transport water to the collection point in Bir Nasser and then to the distribution network of Dar Sad, Ash Shaikh Outhman and partly Al Mansura, or directly to the Albarzake pump station. From the pump station it is pumped to Khur Maksar, Craiter, Al Mualla and Attawahi (UN Habitat, 2020b). The water from the Bir Ahmed well field is distributed to the network, covering parts of Al Mansura or to the Slaughter House pump station, and pumped to Madinat Ashaab and Al Buraiqeh or to the Albarzake pump station (UN Habitat, 2020b).

Al-Ruwa well field (located in Abyan governorate) used to be part of the WSLC of Aden. However, since 2008 this well field was transferred to be under WSLC of Abyan governorate instead (Al-Maqaleh, UNDP; p.c. 04-09-2021).

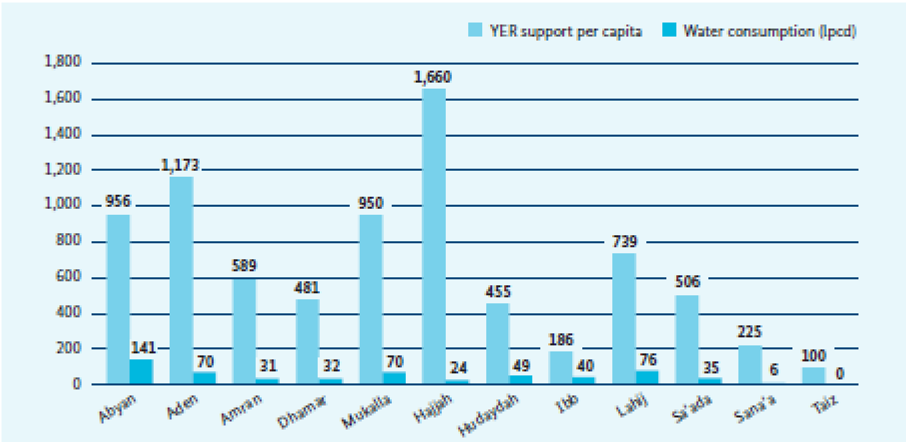


Figure 47. Support versus water supply per capita in 2016 (Source: Dorsch International Consultants GmbH, 2018).

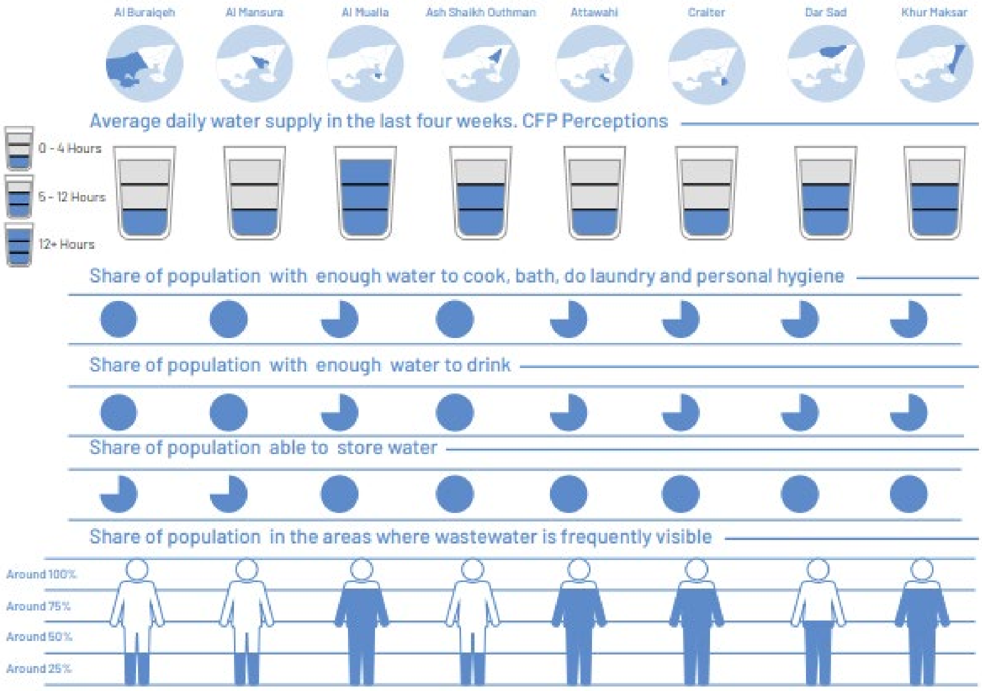
ZOA Yemen in collaboration with the local corporation (LC) of Aden currently run a rehabilitation project to increase the well field and water supply capacity of Bir Nasser and El Manasra well fields (p.c. Pennings, G.; 31-08-2021).

According to Mrs. Duaa Kasida (Project manager Al Naseer Solar Pumping Trading; p.c. 17-09-2021) the Al Nasser well field supplying water to Aden city, which is currently fuel/generator driven, is transformed into a hybrid system. Solar power will in the end supply 70% of the well field's energy demand. This project is funded by Kuwait society for relief. The Al Naseer company at the same time plans to design small desalination factories and water purification and bottling facilities for four cities in Yemen using hybrid solar system.

7.2.2 Water demand

According to Abu-Lohom, et al. (2018) average water consumption in Aden governorate is 8.2 m3 per month per household, for an average household of nine. Almost half (44%) of the households in Aden have already reduced water consumption either because of unavailability or because of high prices (Figure 48). As of April 2020, Aden local council provided 30 MCM of water per year, while the estimated demand was 39 MCM (UN Habitat, 2020b). Majority of the households in Aden rely on piped water as the primary source for drinking and other household functions. However, the unreliability of the supply system has led to new forms of water supply, include trucking, boreholes, and storage tanks (Abu-Lohom, et al., 2018).

> "The crises in Aden city resulted in some areas where water consumption is less than three litres per capita per day (lcpd). This is even well below the bare minimum standard of SPHERE by which people at least require 15 l/c/d."
> Mrs. Gerrianne Pennings – ZOA Yemen Manager of Programme Quality
> (p.c. 31-08-2021)



Source: CFP and KI Surveys, June/July 2019.[174]

Figure 48. Availability of WASH Services in Aden city (per district), 2019.

7.3 Taiz

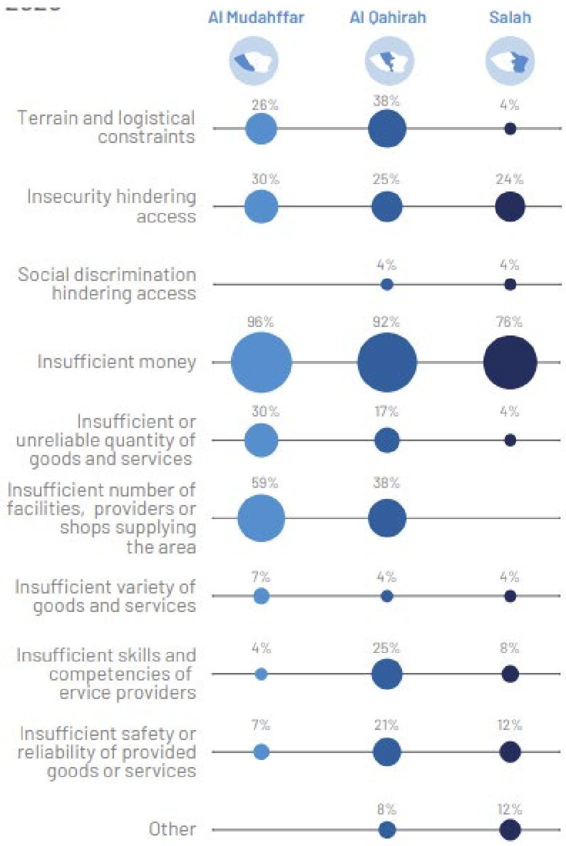
Table 15. Taiz city key facts (Population numbers from UN Habitat, 2020c)

Population Taiz city	**372,854**
Coordinates:	**13˚34′44″N 44˚01′19″E**
Elevation:	**1400 m**
Avg. annual rainfall:	**406 mm/y (PET = 2430 mm/y)**

Taiz (also known as Ta'iz or Ta'izz) is located in the Yemeni highlands, near the port of Mocha on the Red Sea. In 2019, Humanitarian Needs Overview (HNO) data estimated the Taiz city population at 372,854, a drop of more than 280,000 inhabitants due to the ongoing conflict. At the same time, the International Organization for Migration (IOM) reports an inflow of IDPs into Taiz city of more than 50,000 (UN Habitat, 2020c).

7.3.1 Water supply and distribution

Taiz city has been facing water scarcity issues since the 1970s due to rapid population growth. In the mid-1990s, 40 percent of the city's households received water once every forty days from the public supply system. This then increased to once every fifteen days in the 2000s due to the projects implemented at the time, before dropping again to once every fifty to sixty days after 2010. Media reporting from 2015 also suggests that water from the public network supply is only available once a month, while purchasing water from trucks is very costly (Figure 49). Due to such scarcity, most people have to rely on purchasing water from water tankers and using recycled wastewater (UN Habitat, 2020d).

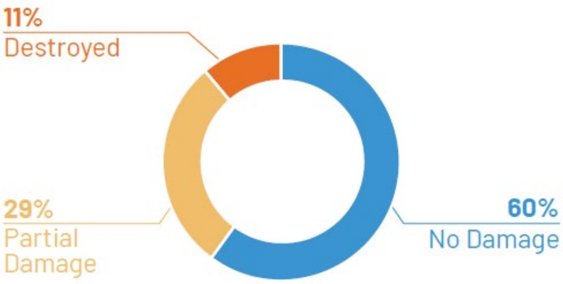


Source: CFP Survey, March 2020.

Figure 49. Main barriers to meet/secure water for drinking purposes needs in Taiz city (per district), 2020.

The water scarcity in Taiz city also led to the exploration of water sources in nearby areas starting from the 1970s, hence impacting the urban-rural relationship. There were several attempts to bring water from the rural areas close to the city, most of which were unsuccessful, due to either limited compensation to the rural communities, which led to their impoverishment, or consequent halt of the projects altogether, due to conflicts with rural communities (UN Habitat, 2020d).

The ongoing conflict has further deteriorated the water- and sanitation situation in Taiz city, and the coverage of water and sanitation services significantly decreased since 2014. Due to the chronic water scarcity, lack of diesel for generators, and damage to various parts of the water supply network, most of the residents of Taiz city rely on purchasing water from vendors, which is often costly (UN Habitat, 2020d).

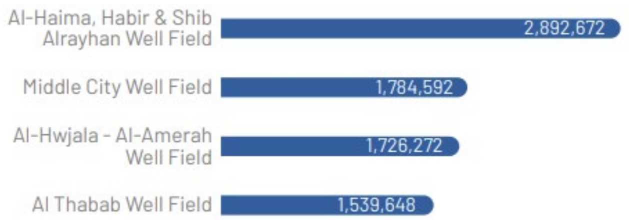


Source: The World Bank Group, DNA: Phase 3, (Washington DC: World Bank, 2018).

Figure 50. Damage status of the WASH infrastructure in Taiz city (2018).

The water and sanitation sector in Taiz WSLC area of operations sustained considerable damage. As of 2018, around 40 percent of the WASH infrastructure in Taiz city has reportedly sustained some degree of damage, while the city-level damage cost is estimated between 26.6 and 32.5 million USD (Figure 50). This includes either partial or total damage to the Head Office building, laboratory, several administrative buildings, iron reservoir, construction of the five pumping stations, several booster pumps, water sterilization units, several generators, three sewage pumping stations, and the walls and the security room building of the WWTP. In addition, parts of the water supply system, including the main pipes and parts of the distribution network, as well as some equipment have also sustained partial damage. The operational capacity of the Taiz WSLC has also been affected by the wider security situation, lack of fuel and limited revenue collection. Currently, 36 percent of the water and sanitation infrastructure in Taiz city is partially functioning, while 4 percent is not functioning at all. Al Mudhaffar and Salah districts are affected the most, with critical infrastructure, such as sewage treatment plant, water pumping stations, and water intake structures, either not functioning at all or operating at a reduced capacity (UN Habitat, 2020c).

Taiz Water and Sanitation Local Corporation (WSLC) coverage area receives water from 86 wells, 39 of which are located within the city boundaries, 23 in Al-Haima, Habir & Shib Alrayhan areas, 9 in Al Thabab well field and 15 in Al-Hwjala - Al-Amerah. As of November 2017, 32 wells are operational and the actual water production stands at 3,000 m^3 per day. The Taiz WSLC coverage area is divided into 12 distribution zones. Most of the water and sanitation infrastructure in Taiz city is publicly managed, except for the water trucks, most of which are private, and several wells (UN Habitat, 2020c).

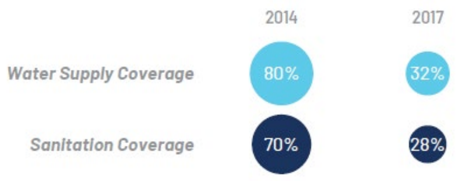


Source: Dorsch International Consultants GmbH, Yemen Water Sector - Damage Assessment Report of Twelve Water Supply and Sanitation Local Corporations (LCs) and their Affiliated Branch Offices and Utilities, May 2018.

Figure 51. Nominal water production (m^3) Taiz city.

The sanitation infrastructure consists of the sewer network, three wastewater pump stations, one Wastewater Treatment Plant (WWTP) and six sewage trucks in Taiz city. The WWTP (stabilization ponds) is located in the Al Burih area, and has a design capacity of the 17,000 m^3 per day. The actual inflow is reported as 5,000- 9,000 m^3 per day, indicating that some wastewater is pumped by farmers to the surrounding areas for agriculture purposes (UN Habitat, 2020c).

Due to widespread water scarcity and low water supply network coverage, most of the households in Ta'iz city obtain water from private vendors, while some get it from wells. Water supply coverage decreased from 80% to 32% between 2014 to 2017 because of the ongoing conflict (Figure 52). Residents also rely on water distribution points. CFPs reported that in all districts of Ta'iz city water obtained from tanker-trucks and carts is the main source of water in the neighbourhood (UN Habitat, 2020c).



Source: Dorsch International Consultants GmbH, Yemen Water Sector – Damage Assessment Report of Twelve Water Supply and Sanitation Local Corporations (LCs) and their Affiliated Branch Offices and Utilities, May 2018.

Figure 52. Water supply and sanitation coverage in Taiz city.

Several reports indicate concerns over the water quality in Ta'iz city. In 2015, 75 percent of respondents were reporting that available water is unsafe for drinking purposes. However, no household purifications methods were reportedly used. Consequently, many households have to separately buy water for drinking purposes, which is often expensive; prior to the outbreak of the conflict in 2015, households were spending between 5 percent and 20 percent of their income on purchasing water.

7.3.2 Water demand

Several humanitarian organizations provide support to improve the WASH situation in Taiz. In June 2017, a rehabilitation project, funded by UNICEF, was completed which reportedly increased the capacity of the water network from 3,000 m³ per day to 5,000 m³ per day. The demand is, however, estimated to stand at 34,000 m³ per day, highlighting chronic water shortage within the city (UN Habitat, 2020c).

7.4 Al Hodeidah

Table 16. Al Hodeidah city key facts (Population numbers from UN Habitat, 2020d)

Population Al Hodeidah Governorate	**2,985,122**	
Population Al Hodeidah City	**178,344**	
Coordinates:	**14˚48′08″N 42˚57′04″E**	
Elevation:	**17 m**	
Avg. annual rainfall:	**54 mm/y (PET = 2394 mm/y)**	

Al Hodeidah (also known as Hodeda, Hodeida, Hudaydah, or Hudaida) is the fourth-largest city in Yemen and its principal port on the Red Sea. It is located on the Tihamah coastal plain which extends from Midi in the north to Bab Al-Mandeb in the south. Population estimates, especially of the old city centre vary, though clearly have decreased in the last years (Table 17; UN Habitat, 2020d).

Table 17. Total estimated population in Al Hodeidah city.

Year	Estimated population	Source
1994	302,600	Population and housing census[28]
2004	416,000	Population and housing census
2017	604,439	CSO Projection
2019	176,344[29]	Rectification 2017 projection with IOM DTM Round 37 displacement figures

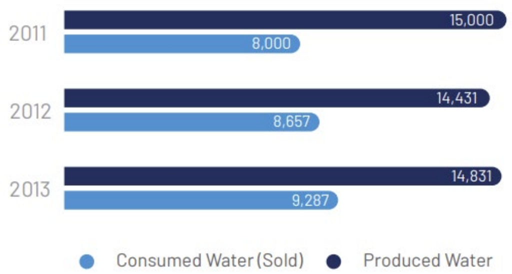
Source: Population and Housing Censuses 1994, 2004, CSO 2017, IOM DTM Round 37, HNO Data 2019."

7.4.1 Water supply and distribution

The provision of urban water and sanitation services is the responsibility of the Al Hodeidah's Water and Sanitation Local Corporation (WSLC), established in 2001. Al Baydda well field, located 12 km north of the city, is the primary source for municipal water hosting 22 water wells. Water from this well field is transported to the water storage ground reservoirs with a capacity of 10,000 m^3, located at the Zabaria pumping station at the WSLC main yard. From there, the water is pumped to five distribution zones (out of eight), covering around 70 percent of all customers. As of September 2015, there were 66,200 water and sanitation connections (UN Habitat, 2020d).

Al Baydda well field mainly feeds Al-Mina district in the city, while Al-Hali district is dependent on eight wells in Al-Qutai'e well field in Al Marawi'ah district. From there, the water is pumped to the collection ground reservoir with a capacity of 5,000 m^3, located in the well field, and then by gravity to the collection reservoirs with a capacity of 10,000 m^3, located at the July 7 pumping station. This serves the remaining 30 percent of the customers.

Furthermore, UNICEF provides diesel to operate water pumps at the three water reservoirs. Urban water supply coverage stood at about 75 percent throughout 2014 – 2017, before damages incurred in 2018. However, the quantity of urban water supply decreased by almost half a million m^3 within the same period, from 14,015,800 in 2014 to 13,542,100 m^3 in 2015 (Figure 53).



Source: CSO Statistical Yearbook, 2017.

Figure 53. Quantity of water production and consumption in m^3 in Al Hodeidah Governorate (2011-2013).

Pre-crisis (2013 – 2014), almost 90 percent of the governorate's population had access to improved water sources, and as of 2016 – 2017, the percentage remained the same, with the water network being the main source of water supply. The sanitation coverage for Al Hodeidah WSLC stood at 49 percent in 2015, and slightly decreased to 46 percent in 2017 (UN Habitat, 2020d).

The amount of non-revenue water was already high pre-conflict (37 percent in 2014) and increased significantly following the escalation (55 percent in 2015). Furthermore, the lack of electricity and increased fuel prices severely affected the operational capacity of the water supply and sanitation services. In 2017, it was reported that the water and sanitation system completely halted its operations due to the lack of these commodities. Overall, petrol prices saw a 131 percent increase from 158 YER pre-crisis to 365 YER in July and August 2019, while diesel prices increased from 150 YER to 450 YER during the same period.201 Accordingly, it was reported in 2018 that prices for commercial water trucking can be four times higher compared to pre-crisis numbers (UN habitat, 2020d).

The water systems were heavily affected by the escalation of the conflict. Since December 2017, 18 incidents were reported to have impacted water facilities infrastructure in Al Hodeidah Governorate. In the summer and autumn of 2018, water supply systems sustained damages on multiple occasions. For instance, in June 2018, water shortages were reported across the city as water supply pipes sustained damage. Repairment works were completed during the same month and access to water substantially improved within the city. However, the following month, water and sewage networks sustained damage again as a result of the digging of trenches for defence purposes, leaving several neighbourhoods in the city without water supply, including Al Shuhada, and Al Salakhana in the Al Hali district and Rabssa and Galil in the Al Hawak district. In summer 2018, airstrikes hit water facilities in Al Hodeidah city and sanitation facilities south of the city. The water supply system in Al Hodeidah depends on pumps and therefore is reliant on electricity. As a result, intermittent supply of electricity throughout the conflict caused parts of the city to be cut off from the water supply, while water trucking services were affected by the increase of fuel prices. Concerns were also raised about the quality of the drinking water (UN Habitat, 2020d).

7.4.2 Water demand

According to a 2019 assessment in Al Mina and Al Hali districts, 90 percent of the households reported that they rely on the public water network as a primary source of water, followed by humanitarian aid (6 percent), and purchasing it from the supermarket/shop (3 percent). Only 1 percent of respondents indicated that they purchase water from water trucks, as a primary source. More than half (57 percent) of the households consume 80 – 120 liters per day, while more than a third (37 percent) consume more than 120 liters, 5 percent consume 40 – 80 liters and 1 percent consumes 20 – 40 liters per day (UN Habitat, 2020d).

From January to October 2019, there were nine WASH cluster partners operating in the three districts of Al Hodeidah city, including three UN Agencies, three INGOs, and three NNGOs. They provided a number of activities to support cholera and WASH Emergency Response, such as provision of spare parts and maintenance of water supply systems, hygiene promotion and community engagement, distribution of basic and consumable hygiene kits, water quality surveillance, provision of access to safe water through water trucking, repairment, rehabilitation or augmentation of water supply and sanitation systems. Also, UNDP supported the rehabilitation of manholes and inspection chambers at Al Mina district. The project targeted rehabilitation of manholes, as many of them have collapsed, while other ones were filled with garbage. In November 2019, Tamdeen Youth Foundation signed a partnership agreement with the Local Water and Sanitation Foundation to maintain and clean the sewage system in several neighbourhoods in Al Hawak district, Al Hodeidah city. The same month, the Deputy Prime Minister for Services Affairs and Development and Minister of Water and Environment opened several water projects in Al Hodeidah governorate, which cost 6.3 billion YER (UN Habitat, 2020d).

7.5 Marib

Table 18. Marib city key facts (Population numbers from UN Habitat, 2020e).

Population Marib city	**630,000**
Coordinates:	**15°27′38″N 45°19′34″E**
Elevation:	**1090 m**
Avg. annual rainfall:	**102 mm/y (PET = 3373 mm/y)**

Marib city (also known as Ma'areb), located about 120 km east of Sanaa, shows a vast increase in population in the recent years. Marib city accounts for a 12-fold increase in population and has become a central hosting destination for communities primarily displaced by conflicts. Current population estimates for Marib city vary between 630,000 (of which 577,000 IDPs) and 1.5 million (Table 19, UN Habitat, 2020e). According to ACAPS (2021), recent conflicts in Marib city and Marib Al Wadi, however, may lead to an estimated 500,000 people leaving Marib area.

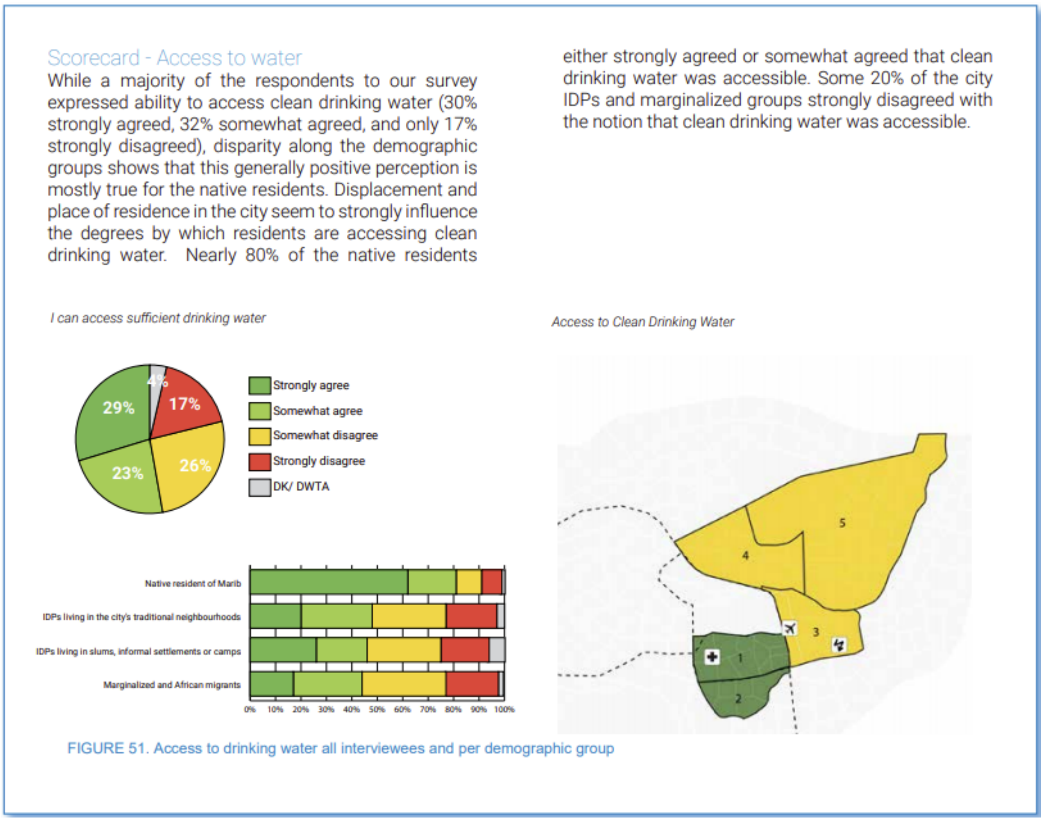
Table 19. Population growth in Marib city and governorate (UN Habitat, 2020e).

Key indicators	Marib city	Marib governorate
Estimated pre-crisis population (2014)	40,000	360,000
Currently international community estimate (2019)	630,000	1.5 million
Official government estimate (2020)	1.5 million	3 million

7.5.1 Water supply and distribution

The background of water and sanitation service provision in Marib is particularly complex and fragmented involving multiple authorities with blurred boundaries between government, tribal customary law (Urf), and International Humanitarian Organizations. Marib's recent history of being neglected by the government prior to the current conflict had left it outside of any central system without a local water corporation or autonomous utility or local National Water and Sanitation Authority (NWSA). Instead, the activities that would usually be executed under NWSA's planning capacity was transitioned to independent water authorities such as the local water corporation that was established in Marib (UN Habitat, 2020e).

Marib's government provides municipal services such as water, sanitation, health, electricity, and education. Marib's basic service provision has been transformed in the past six years by its increased financial resources and investment budget enabling the governorate to pay salaries and staff to operate independently of central government support since late 2015. The influx of IDPs into Marib has put pressure on these services. The variable flows of the population count has led to an unpredictable demand for basic service provision (Figure 54; UN Habitat, 2020e).


Scorecard - Access to water

While a majority of the respondents to our survey expressed ability to access clean drinking water (30% strongly agreed, 32% somewhat agreed, and only 17% strongly disagreed), disparity along the demographic groups shows that this generally positive perception is mostly true for the native residents. Displacement and place of residence in the city seem to strongly influence the degrees by which residents are accessing clean drinking water. Nearly 80% of the native residents either strongly agreed or somewhat agreed that clean drinking water was accessible. Some 20% of the city IDPs and marginalized groups strongly disagreed with the notion that clean drinking water was accessible.

FIGURE 51. Access to drinking water all interviewees and per demographic group

Figure 54. Perceived access to drinking water in Marib city (UN Habitat, 2020e).

Prior to 2015, Marib did not have infrastructure for a piped potable water network. Furthermore, local institutions did not have a role in the provision, monitoring or quality control of the drinking water, and could not collect taxes or fees on water supply and distribution. As of late 2016, approximately 69% of households in Marib had access to potable water in Marib. Now, the local authority is actively working with donors to provide drinking water for the population, expand the sanitation treatment plant in the city of Marib, and provide sanitation projects for IDP camps, such as Al-Khaniq and Al-Jafinah. The current coverage rate for water services is 24.7%, of which 19% is a governmental network. However, as the city's rapid growth has increased the demand for drinking water, the municipality has become dependent on privately supplied delivery trucks (UN Habitat, 2020e).

Marib depends on groundwater wells as the prime and sole source of drinking water. There are currently eight operating wells in Marib. Water is transported to various distribution networks and small tanks via five pumping lines, out of which three are operational. Currently, only around 196,600 people are connected to Marib's water network - or 13% of the Governorate's population. The remainder population relies on private water sources, many of them purchasing their water from 'water tankers'. In case people are connected to the water network, they have access to 10-17 l/c/d (Faruqui, 2021). According to Faruqui (2021), some people are only getting public water once every two weeks.

Faruqui (2021) refers to a water supply rehabilitation project in collaboration with UNICEF to replace existing pumping lines to increase current water supply capacity. Besides, the project focuses on increasing the capacity of water distribution tanks, as a means of additional storage.

7.5.2 Water demand

The main reason for the water shortage in Marib is that demand well exceeds the water production by the eight operating wells. The wells produce about 4,594 m^3 per day enough to supply 15 l/c/d to about 300,000 people. This is well short to the 1.5 million people reported to live in Marib city (Faruqui, 2021).

8 Challenges in effective IWRM implementation

All sectors in Yemen compete, in a weakly regulated setting, for the scarce groundwater resources available. If remained unchecked, groundwater over-exploitation poses a serious threat to the water resources base of many areas in Yemen by depleting aquifers. The literature review and the various key stakeholder interviews provided a thorough view on the challenging arena in Yemen in which water resources are to be integrated and effectively managed, both on a local and national level. Below paragraphs highlight some of the key challenges identified.

8.1 Lack of fact-based knowledge base

Key and basic requirement for effective IWRM is a commonly understood and accepted knowledge base. A solid knowledge base ensures transparency and accountability and guides discussions on policies, regulations and participatory planning based on facts.

With respect to Yemen, actual data on the current state of water resources is lacking, which hampers the development of a sound knowledge base. Actual data, especially since the start of the conflict, cannot be derived due to a general lack of monitoring of for example:

- Wadi flow using staff gauges;
- Wadi flow diversions;
- Groundwater levels; and
- Groundwater abstraction.

> "Most of the existing monitoring points of the NWRA, majority of which automatic data logging stations, have stopped since the crises started or have been looted. The latest thorough studies using the monitoring data from this network go back to 2006-2009 and older. Since the latest recordings, uncontrolled (illegal) drillings and abstractions have continued, most probably resulting in changing water resources availability."
> Mr. Salem Bashuaib - Former chairman NWRA (p.c. 31-08-2021)

Historic data on water resource use and availability is repeatedly published and over time estimates or forecasts are presented as being actually measured (as is done with the estimates presented by Yehya & Al-Asbahi, 2005). It all reflects the uncertainty and lack of knowledge on the actual condition of (ground)water resources, which makes effective IWRM management, planning and discussions difficult, irrespective of whether laws and regulations are in place. Giving these limited data, prospects on the future water availability or an upcoming 'day zero' in terms of water availability are void and often unverified. At the same time, using remote sensing technologies applied in this study, one can support historic data with valuable recent indicates showing wide groundwater over abstraction in Yemen. When supporting these new technologies by strategically located monitoring networks, the desired knowledge base can be developed.

8.2 Conflicts in water allocation

Although one can question the accuracy and recency of the figures of annual recharge, water use and extraction, this report once again supports the exacerbating imbalance between water supply and water demand in Yemen. Continuation of this imbalance inevitably results in further deterioration of the current water and food crises. The ongoing imbalance reflects the inability to set priorities in water allocation. At the same time, prioritization requires knowledge on how much water is available. This again stresses the importance of accurate monitoring of the various components of the water balance (see 8.2.1).

Mr. Job Kleijn, strategic advisor, in Sept 2020: “If all present needs have to be met, the quantity of water in Yemen is insufficient for todays and future needs (domestic, agriculture, industry and nature).”

8.2.1 Competing demands

Looking at the currently available data, Yemen potentially has sufficient annual renewable water resources to fulfil the drinking water demand for its population. Currently these water resources are allocated for 90% to agricultural use and 10% to domestic and industrial use. Reallocating the water resources to meet domestic demands requires a shift in focus towards principal food production and sectoral diversification (*e.g.* other than agricultural focus only). In this, a variety of authors point towards qat as main water consuming crop in the agricultural sector. In the NWSSIP, the MWE argues that it is not only qat to blame, and suggests targeting the entire agricultural sector:

> *The reality is that between 1970 and 2000 the area under other crops, particularly grapes and coffee, has also expanded annually at nearly 3% and 5%, respectively. However, the area under qat expanded at a much faster rate at 9% per year because it is more profitable. Even if increase in qat area levels off, other crops will take up some of the slack and reduction in total area would be smaller. Therefore it is prudent to target expansion in total well-irrigated area, which expanded about ten folds (from 37 thousand to 368 thousand hectares) between 1970 and 1996 (this expansion is equivalent to about 9% per year).* ***By the same logic, most effective agriculture policy instruments would be those that target the entire agricultural sector (such as agricultural trade policy liberalization and removing input price distortions, especially the under-pricing of water) rather than single crops*** *(MWE, 2004).*

Shifting to water efficient technologies is often named as one of the solutions to reduce water consumption in the agricultural sector. However, without carefull planning and reallocation strategies, this may well lead to horizontal expansion of agricultural areas instead of the desired reallocation of water to other sectors.

Hellegers et al. (2008) point out that although the range of possible incentives to reduce water scarcity is wide (water pricing, metering, water rights, water markets, taxes, subsidies, information, participatory management etc.), the range of potentially effective incentives in the Yemeni political context is more limited due to difficulties of implementing and enforcing change. Reducing water consumption will substantially reduce the benefits from qat production and consequently farm income, which is a politically sensitive way of bringing about a balance between supply and demand of water (Hellegers et al., 2008). In general, this will also apply to the remainder of the agricultural sector, and especially the growth of cash crops.

To date, water reallocation thus seems politically too sensitive and therefore hard to realise and most probably requires the sectoral development of sectors other than agriculture to provide competing income generation.

8.2.2 Conflicting interests and powers

Although the MWE and its subordinate NWRA are, according to the Water Law of 2002, the sole authority for implementation of IWRM, in practice this is not the case. MWE and NWRA are hampered by the fact that they are only in charge of about 5% of the water consumed in Yemen. The MAI (and its department for irrigation and dams) is in practice responsible for the main share of water, which is allocated to agriculture and irrigation. This fragmentation of responsibilities is problematic as both institutions have different interests and pursue opposing water policies (Huntjens et al., 2014). Figure 55 clearly shows these conflicting interests between MWE/NWRA and MAI.

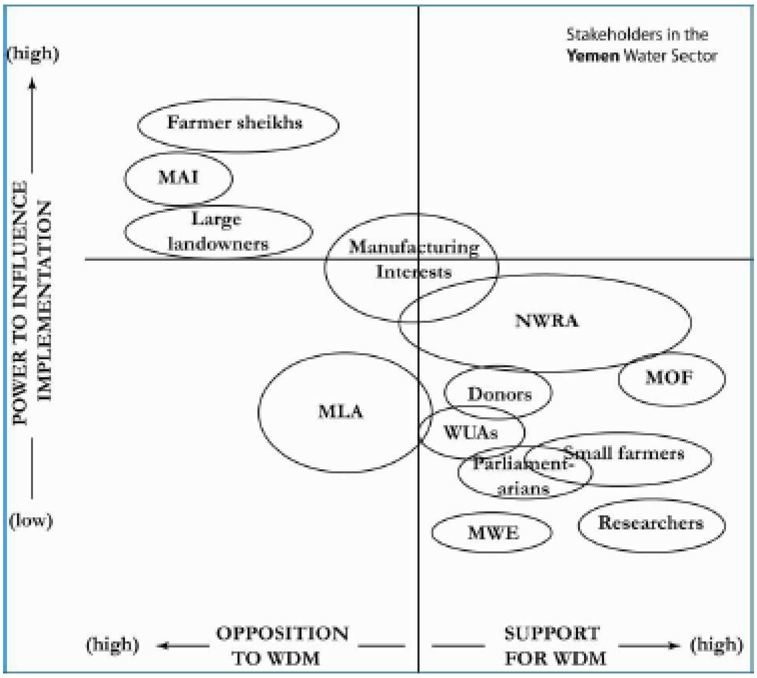


Figure 55. Stakeholder analysis Yemen (irrigation) water sector in relation to Water Demand Management (WDM) (Source: Huntjens et al., 2014).

The conflicting powers and interest are further expressed in the disconnection that seems to exist between the national and local levels. Historically, Yemeni communities were self-moderated and regulated. Given the fact that about 10% of the boreholes are government-owned, against 90% privately owned wells (Morris-Iveson and Alderwish, 2018), makes enforcement of national/central water legislation on a local level difficult. This requires a strong local governance structure which currently lies with the under-resourced NWRA branches. Additionally, a basin management approach is hardly fully implemented in any of the water catchments mainly due to National Water Resources Authority (NWRA)'s weak linkages with local councils that have strong links with local management organizations such as Water User Associations (WUA) which could potentially be delegated many of the water management functions (UNDP & FAO, 2020).

For effective IWRM implementation, ensuring to include and capacitate on the seven main IWRM dimensions may help to properly capacitate the local and national institutional level (Table 20).

Table 20. The seven main dimensions of IWRM (Acacia Water, 2017).

Dimension	Description	Specification
D1	Inclusion of multiple stakeholders	Integration of water users, organizations, everyone having interest in water resources;
D2	Protection of the environment	Sustainable use of natural resources; water quality;
D3	Economic and social welfare	Development promotion; the project has to protect and/or enhance economic and social benefits;
D4	Equity	Needs-driven approach (including future needs); inclusive process;
D5	Participatory and coordinated process	Open and inclusive partnership;
D6	Evidence-based process	Link between research and policy; analytical perspectives (*e.g.* socio economic, hydrology);
D7	Integration of temporal and spatial scales	Up-stream/down-stream; short vs long-term outcomes; spatial dependencies;

8.2.3 Challenges in groundwater resources management

Groundwater resources management has to deal with balancing the exploitation of a complex resource (in terms of quantity, quality and surface water interactions) with the increasing demands of water and land users (who can pose a threat to resource availability and quality). Calls for groundwater management do not usually arise until a decline in well yields and/or quality affects one of the stakeholder groups. If further uncontrolled pumping is allowed, a 'vicious circle' may develop (Figure 56) and damage to the resource as a whole may result (with serious groundwater level decline, and in some cases aquifer saline intrusion or even land subsidence) as is the case in Yemen.

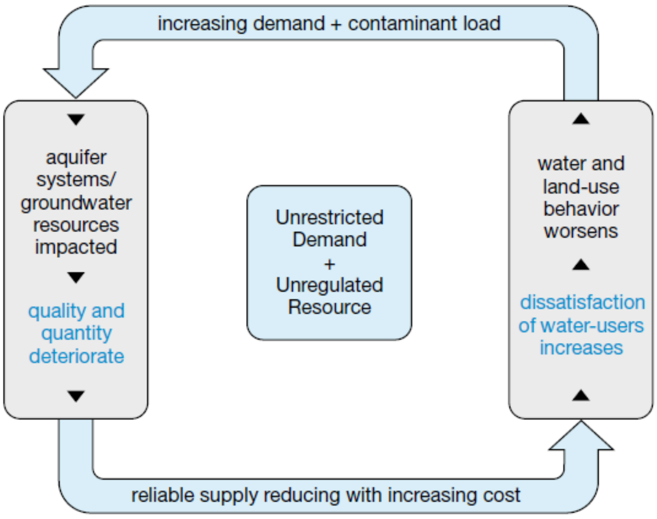


Figure 56. Supply-driven groundwater development – leading to a vicious circle (Source: Tuinhof et al., 2002).

To transform this 'vicious circle' into a 'virtuous circle' (Figure 57) it is essential to recognize that managing groundwater is as much about managing people (water and land users) as it is about managing water (aquifer resources). Or, in other words, that the socio-economic dimension (demand-side management) is as important as the hydrogeological dimension (supply-side management) and integration of both is always required.

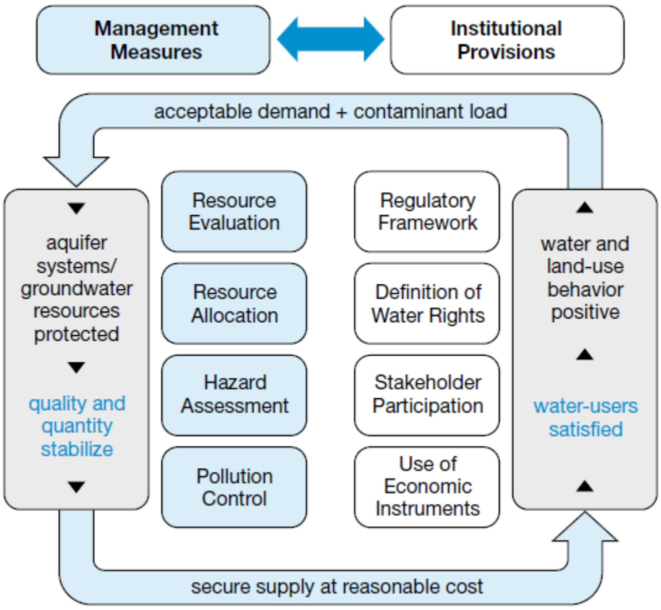


Figure 57. Integrated groundwater resources management – leading to a virtuous circle (Source: Tuinhof et al., 2002).

Key issues for groundwater *supply management* are the need to understand:

- aquifer systems and their specific susceptibilities to negative impacts under abstraction stress;
- interactions between groundwater and surface water, such as abstraction effects (on river baseflow and some wetlands) and recharge reduction effects (due to surface-water modification).

Operational monitoring is a vital tool to develop the understanding needed for effective resource management.

On the groundwater *demand management* side, it will be essential to bear in mind that:

- social development goals greatly influence water use, especially where agricultural irrigation and food production are concerned, thus management can only be fully effective if cross-sector coordination occurs;
- regulatory interventions (such as water rights or permits) and economic tools (such as abstraction tariffs and tradable water rights) become more effective if they are not only encoded in water law but implemented with a high level of user participation;
- regulatory provisions should not go beyond government capacity to enforce and user capacity to comply (Tuinhof et al., 2002).

9 Recommendations and follow up

Based on the available literature data, this study shows there is insufficient water available to adequately serve all present water demand functions, causing an imbalance which is currently bridged by excessive groundwater abstraction. This is additionally supported by insights from recent satellite and remote sensing data. At the same time, the analysis of data shows ample opportunities for implementing a catchment-based approach. **The study provides several key recommendations for each wadi catchment (within respective wadi chapters) as well as a list of short-, mid- and long-term options** (Table 21) to invest in improved knowledge base, mitigate water scarcity, use non-conventional water resources, adapt to climate change and adopt IWRM at all levels. Many of the outlined recommendations are suited for the whole of Yemen, though, where possible, they are specifically attached to one or more of the wadi catchment areas. The recommendations include both (ground)water supply and demand driven management options (Ch. 8.2.3). Implementation may well follow a step-wise approach, using one wadi as a start and multiplying the blueprint approach in other wadi catchments. Part of the suggested recommendations require follow-up study in the form of feasibility or potential mapping before it can be decided if and where pilot studies can best be implemented. Other recommendations require structural implementation, meaning this measure is to be well embedded within a local institute or organization to ensure sustainability and continuation of the activity after initial support by for example a development agency.

Following the conducted study, it is advised to start the structural implementation of water allocation planning and related development of a sound knowledge base in Abyan Delta first, through a pilot study. This can be used as an example to implement in all wadi catchments. Water allocation planning is required to curb the trends of groundwater over abstraction and securing the future prospects of sectoral water use in Yemen. Controlling uncontrolled abstraction and proper water allocation planning, based on annual available renewable water, should therefore be given utmost priority. Decentralization in water governance is an upcoming concept as it promotes awareness at local levels (*e.g.* basin and WUA level). This implies for example the monitoring of groundwater, analysis and interpretation of data, and to a lesser extent decision making. The latter depends on the interplay between the available capacity at lower levels and national or regional institutional arrangements. It is therefore recommended to focus on enhancing capacity building (*i.e.* monitoring, data and information management, analysis, decision making) at WUA, NWRA and basin level and to subsequently agree on tasks and responsibilities.

As indicated in the different wadi analyses, current analyses can be deepened by including more detailed figures on sectoral water use and trends, especially for agricultural use. **In-depth figures on agricultural use can be derived from detailed remote-sensing studies, combined with the necessary field inventory and**

verification. This could well encompass an update of the NWRA studies referred to in this report, combined with the approach adopted in this study. Detailed numbers on domestic, industrial and non-conventional water use are to be derived through (development) organizations and government institutions active in a specific area. The resulting in-depth view helps to show the impact on water availability, inform water allocation and strategic planning as well as re-generating the 'state of urgency' for improved water management across Yemen. Water demand estimates can be improved by consulting the relevant institutions (*e.g.* WSLCs) and development agencies active in WASH or agriculture (*e.g.* NWRA branches, MAI).

Table 21. Recommended measures to take in each wadi catchment, including prioritization, type of implementation and responsible agencies.

Adaptation option	Suggested measures	To be initiated (short, medium-term, long-term)	Agencies	Suited for Dhamar (D), Hadhramaut (H), Abyan (A)	Explanation
Adoption of IWRM at all levels	Water allocation (basin level) planning	Short-term, pilot study, structural implementation	All stakeholders	D, H, A	Water allocation planning is necessary to come to a sustainable balance between supply and demand at basin level. Key in water allocation planning is involvement of all relevant water users and stakeholders and adopting of participatory approach. This ensures water allocation plan is mutually agreed and valued by all water users. Requires monitoring network data to generate insight on catchment/aquifer water balances for successful implementation.
Adoption of IWRM at all levels	Water use(rs) inventory (registration, licensing/water rights, regulation)	Short-term, structural implementation	National and regional authorities, development agencies, all major water well and borehole operators/ owners	D, H, A	To improve water resource management, all water use types and users are to be identified. This inventory helps to develop water allocation strategies, by which it is important to register each water user, establish licenses/(tradable) water rights and allow for regulation. This step requires good local governance/community institutions, which could well be developed from the water users' inventory.
Adoption of IWRM at all levels	Support/Establish WUAs to manage local water resources/ promote user involvement	Short-term, structural implementation	National and regional authorities, development agencies, local communities	D, H, A	Incorporate informal and traditional (often unwritten) laws and regulations on local level and use community strength to shape local IWRM (*e.g.* by WUAs). Promote user involvement as this increases engagement to sustainably use available water resources. Focus on enhancing capacity building (*i.e.*

					monitoring, data and information management, analysis, decision making) at WUA, NWRA and basin level and subsequently agree on tasks and responsibilities.
Investment in improved knowledge base	Monitoring network (groundwater wells, wadi flow, meteorology)	Short-term, pilot study/structural implementation	National and regional authorities, humanitarian and development agencies, all major water well and borehole operators/ owners	D, H, A	Generate insight in wadi flow measurements (how much water is diverted for spate irrigation, how much is flowing to sea and left unused), groundwater trends, abstraction rates, level decline and water quality monitoring (salination of GW wells/soils), and flood forecasting. Helps to inform water allocation and strategic planning as well as re-generate 'state of urgency'.
Investment in improved knowledge base	Data collection, analyses, and information sharing among key institutions	Short-term, pilot study/structural implementation	National and regional authorities, humanitarian and development agencies, all major water well and borehole operators/ owners	D, H, A	Creates awareness on current state of water resources (water demand and supply) in order to take collective action. Ensure to show trends of sectoral water use (domestic, industrial, agriculture) and show impact on water availability. Ensure all institutions have access to and work with same data/knowledge level

Mitigation of water scarcity	In-stream rainwater and runoff harvesting	Short-term, feasibility or mapping study / pilot study	Local authorities, communities, development agencies, national and international experts	**D**, H, A	In-stream interventions consist of structures placed in the stream bed itself to break the power of the stream, reduce the flow downstream, increase groundwater recharge or provide storage for reuse. Examples are sand dams, sub-surface dams, check dams and valley dams etc
Mitigation of water scarcity	Off-stream rainwater and runoff harvesting	Short-term, feasibility or mapping study / pilot study	Local authorities, communities, development agencies, national and international experts	D, **H**, A	Reduce power and velocity of storm water. Interventions in areas with high runoff, steep slopes and loos, sandy soils will be most effective. In areas with (some) soil development, storm water can be retained on-site. In areas with developed calcisols and low slopes, water could be stored in unlined ponds or hafirs. For other soil types, unlined retention structures will enhance groundwater recharge. Lined ponds or underground cisterns (birkads) are good alternatives when the retained water is for meant for immediate reuse (Helder et al., 2020).
Mitigation of water scarcity	Rehabilitating traditional RWH techniques	Short-term, structural implementation	Local authorities, communities, development agencies, regional experts	**D**, H, A	Many traditional RWH techniques present in Yemen, knowledge available with local communities and experts. Community approach may help identify most suited techniques and/or indicate where existing structures can be rehabilitated/improved
Mitigation of water scarcity	Water efficient technologies	Short-term, pilot study	Regional authorities, large farms, development agencies, national and	D, **H**, A	Improved irrigation management may limit on-farm water losses by introducing efficient technologies (sprinkler, drip, piped conveyance) and improved practices (irrigation scheduling, irrigating using CWR, or remote sensed irrigation advice. Key is to ensure that water savings do not lead to expansion of

			international experts		irrigated areas but are allocated to domestic use (to be combined with water allocation planning).
Mitigation of water scarcity	Rehabilitating existing water infrastructure	Short-term, pilot study	National and regional authorities, development agencies, WASH cluster	A, H	Map condition of spate water irrigation structure and limit off-farm water losses by rehabilitating/maintaining existing spate water infrastructure. Also pay attention to existing water supply infrastructure facing same problems. Functional spate water structures will reduce pressure on groundwater resources.
Use of non-conventional water sources	Wastewater reuse	Short-term, feasibility or mapping study / pilot study	Regional authorities, development agencies, local communities and farms, WASH cluster, national and international experts	D, H, A	Currently wastewater is left unused, whereas it could be a valuable resource for irrigation. Investigate feasibility of waste stabilization ponds (WSP) or similar techniques
Climate change adaptation	Flood early warning system to decrease damage	Short-term, structural implementation	Regional authorities, development agencies, local communities, national and international experts	D	Setting up of a flood early warning system in upper catchments for providing timely warning so that harm to people and economic assets can be minimized. In case of Wadi Siham/Wadi Rima, this may provide insight to the population downstream in Tihama plain
Climate change adaptation	Application 3R (recharge, retention, reuse) techniques	Short-term, feasibility or	Regional authorities, development agencies, local	D, H, A	Capture and retain (more) water in the system and reduce flood peaks and increase prolong baseflow. Helps also to improve water availability to spate

		mapping study / pilot study	communities, national and international experts		irrigation systems and reduce pressure on groundwater resources.
Adoption of IWRM at all levels	Strengthen national-local level interactions in implementing IWRM	Medium-term, structural implementation	National and regional authorities, development agencies	D, H, A	Implementation of effective IWRM requires strong national-local level interaction, in which one pays attention to the inclusion of multiple stakeholders, protection of the environment, economic and social welfare, equity, participatory and coordinated process, and the integration of temporal and spatial scales. Strong linkages help to combat uncontrolled drilling and unpermitted abstraction, implement groundwater protection zones and to promote water conservation in agriculture.
Investment in improved knowledge base	Yemen groundwater knowledge hub	Medium-term, structural implementation	International organizations, Yemeni academia	Country-wide	Available international expertise is used to bring together historic relevant investigations with recent local data collection to enhance overall groundwater management practices. A country groundwater knowledge hub as such does not yet exist for any country in the world, though given the many different national and international experts and organizations having worked and studied the groundwater regime of Yemen, this could be of major added value in developing IWRM in Yemen.
Mitigation of water scarcity	Artificial recharge techniques	Medium-term, feasibility or mapping study / pilot study	Development agencies, national and	D, H, A	Artificial infiltration into underground aquifer to recharge depleted shallow groundwater reserves, especially suited with respect to the high

			international experts		evapotranspiration rates in Yemen and good alternative to surface water reservoirs or dams.
Mitigation of water scarcity	Less water-intensive cropping patterns (incl. business case)	Medium-term, feasibility or mapping study / pilot study	Large/small farms, development agencies, national and international experts	A, **D**	Create awareness among farmers on impact of water intensive cultivation. Develop business case with alternative cropping patterns combined with varietal research, using less water-intensive crops. When business case ready, start pilot projects.
Use of non-conventional water sources	Brackish water agriculture: Salt tolerant cropping systems	Medium-term, feasibility or mapping study / pilot study	Large/small farms, development agencies, national and international experts	A, H	Offer alternatives to areas suffering from salt water (GW quality) or sea water intrusion to overcome income losses and low yields. Investigate salt tolerant varieties of well-known crops or introduce new salt tolerant crops.
Climate change adaptation	Flood forecast system to support agricultural practices	Medium-term, pilot study	Regional authorities, development agencies, local communities, national and international experts	A, **H**	Spate flood forecasting to provide advance information on incoming spate flows could help farmers to better plan agricultural activities and take good planting decisions. Investigate possibilities of mobile warning, either or not combined with irrigation advice
Adoption of IWRM at all levels	Incentive structure to encourage efficient and sustainable use	Long-term, structural implementation	National and regional authorities, development agencies	D, H, A	Initiate review and revision of policy and subsidy structure to promote wise-water use. Provide 'prove of concept' with above introduced measures.

Investment in improved knowledge base	Hydrogeological surveys mapping aquifer storage and depletion	Long-term, pilot study	National and regional authorities, development agencies, national and international groundwater experts	D, H, A	Undertake full geophysical surveys to map the characteristics of Yemen's (critical basin) aquifers and extent of current groundwater exploitation, provide estimates on sustainable abstraction rates and volumes. Provides necessary backing to enforce and regulate abstraction and irrigated area development
Use of non-conventional water sources	Desalination of water	Long-term, feasibility or mapping study / pilot study	Regional authorities, development agencies, local communities and farms, WASH cluster, national and international experts	A	Only few initiatives are currently employed regarding desalination of water. Major constraints are in high cost of investments. On long-term innovation may bring down costs, offering a valuable non-conventional water resource.

10 Bibliography

Full list of reviewed literature available in Annex 7.

Abu-Lohom. N.M., et al. (2018). Water Supply in a War Zone, A Preliminary Analysis of Two Urban Water Tanker Supply Systems in the Republic of Yemen. Washington DC: The World Bank.

Acacia Water (2017). IWRM at Acacia Water: a short guideline on the application of IWRM within Acacia Water.

ACAPS. (2021). Conflict escalation in marib and potential humanitarian and economic impacts: Scenario. Reliefweb. https://reliefweb.int/sites/reliefweb.int/files/resources/20210726_acaps_yemen_analysis_hub_marib_scenario.pdf.

Ajami, H. 2021. Geohydrology: Groundwater. Encyclopedia of Geology (Second Edition). D. Alderton and A. Scott (Eds.). Academic Press, Oxford, p. 408-415.

Aklan, M. M., de Fraiture, C., & Hayde, L. G. (2019). Which Water Sources Do People Revert to in Times of War? Evidence from the Sana'a Basin, Yemen. *International Journal of Environmental Research*, *13*(4), 623-638.

Aklan, M. M. (2011). The potential of rooftop rainwater harvesting for Sana'a, Yemen. *MSc thesis*. University of Jordan and the Institute of Technology and Resources Management in the Tropics and Subtropics (ITT), University of Applied Sciences-Cologne.

Almohsen, R. A. (2015). Thousands die in Yemen in fights over water. *SciDevNet*. 24 June 2015. https://www.scidev.net/global/news/water-death-yemen-conflict/

Alsabri, A. (2021). Water resources in Yemen, Overview about the targeted Districts in Three Governorates in Yemen. *Prepared on behalf of FAO as input to this literature study.*

Arab Countries Water Utillity Association (ACWUA). (2010). Wastewater Reuse in Arab Countries: Comparative compilation of information and reference list. Amman, Jordan. https://www.ais.unwater.org/ais/pluginfile.php/356/mod_page/content/128/Jordan_Summary-Report-CountryCasestudies_final.pdf

Alderwish, A., & Al-Eryani, M. (1999). An approach for assessing the vulnerability of the water resources of Yemen to climate change. Climate Research, 12(2-3), 85-89.

Alderwish, A. M., Al-Khirbash, B., & Mushied, H. (2014). Review of Yemen's control of groundwater extraction regime: situation and options. *International Research Journal of Earth Sciences*, *2*(3), 7-16.

Al-Eshlah, A., Al-Rubaidi, H., & Al-Sabri, A. (2013). National Conference for the Management and Development of Water Resources in Yemen: Paper 2-B Agriculture's contribution to solving the water crises.

Al-Hamdi, M.I. (1997). Case Study XIII – Sana'a, Yemen. In Helmer, R., & Hespanhol, I. (1997). *Water pollution control: a guide to the use of water quality management principles* (pp. 483-495). WHO/UNEP.

Al-Hamdi, M.I. (2000). *Competition for scarce groundwater in the Sana'a Plain, Yemen: A study on the incentive systems for urban and agricultural water use.* CRC Press.

Almhab, A. (2009). Estimation of regional evapotranspiration using remote sensing data in arid area. Doctoral dissertation, Ph. D Thesis, January 2009, Department of Remote Sensing, Faculty of Engineering and GIS, UTM, Malaysia.

Al-Mashreki, M. H., Atroosh, K. B., Muflahi, A. A., Obaid, N. A., & Caoline, K. (2015). GIS-based assessment of land suitability for industrial crops (cotton, sesame and groundnut) in the Abyan Delta, Yemen. *Journal of Experimental Agriculture International*, 384-405.

Al-Maswari, A. A., Saleh, S. A., Al-Nozaily, F. A., & Al-Abyadh, M. A. (2020). Potential of Road Rainwater Harvesting in Yemen–Its Social, Environmental and Economic Benefits: A Case Study of Sana› a–Hodeida Road, Yemen. *Journal of Science and Technology*, *25*(1), 23-64.

Al-Sabri, A., & Halim, M. K. (2012). Status and New Developments on the Use of Brackish Water for Agricultural Production in the Near East: Yemen country report. Cairo, Egypt. FAO.

Al Ward, M. A., & Ismail, W. R. (2019). Precipitation analysis and water resource of Wadi Siham Basin, Yemen. Geografi, 7(2), 36-63.

Ali, W., & Al-Kadasi, F. (2011). Change: Policy Implications – The Case of NWSSIP II. A Policy Note. National Sector Strategy and Climate Change. UNDP Publications

Atroosh, K. B. (2006). Agricultural water use efficiency in Yemen. *Proceedings of the expert consultation meeting.* AARINENA Water Use Efficiency Network. ICARDA, Aleppo, Syria.

Atroosh, K. B., & Moustafa, A. T. (2012). An estimation of the probability distribution of Wadi Bana flow in the Abyan Delta of Yemen. *Journal of Agricultural Science*, *4*(6), 80.

Baquhaizel, S. A., Saeed, I. A., & Bin Ghouth, M. S. (2011). Documentary study on models of traditional irrigation systems and methods of water harvesting in Hadramout and Shabwah governorates. Water and Environment Center, Sana'a, Yemen.

Barbarossa, V., Huijbregts, M.A.J., Beusen, A.H.W., Beck, H.E., King, H., Schipper, A.M., 2018. FLO1K, global maps of mean, maximum and minimum annual streamflow at 1 km resolution from 1960 through 2015. Sci. Data 5, 180052. https://doi.org/10.1038/sdata.2018.52

Bauman, P., Kellett, R., Steensma, G., Cadman, C., Hardisty, P., Dottridge, J. (2003) Two case studies of Geophysical Delineation of Salt Water Intrusion in Yemen: Wadi Hadramaut and the Tuban and Abyan Deltas, In: *The Second International Conference on Saltwater Intrusion and Coastal Aquifers – Monitoring, Modeling, and Management*, Mérida, Yucatan, Mexico, March 30 – April 2, 2003.

Breisinger, C., Ecker, O., Al-Riffai, P., Robertson, R., Thiele, R., & Wiebelt, M. (2011). Climate change, agricultural production and food security: evidence from Yemen (No. 1747). Kiel Working Paper.

Buchhorn, M. ; Smets, B. ; Bertels, L. ; De Roo, B. ; Lesiv, M. ; Tsendbazar, N. - E. ; Herold, M. ; Fritz, S. Copernicus Global Land Service: Land Cover 100m: collection 3: epoch 2015: Globe 2020. DOI 10.5281/zenodo.3939038

Chevalking, S. (2010). A technical-institutional analysis of small dams in the Sana'a Basin, Yemen. Metameta.

Climate Diplomacy (2021). Local Violence over Water Resources in Yemen. Adelphy and German Federal Foreign Office. https://climate-diplomacy.org/case-studies/local-violence-over-water-resources-yemen

Conflict and Environment Observatory (CEOBS). (2021). Groundwater depletion clouds Yemen's solar energy revolution. CEOBS. https://ceobs.org/groundwater-depletion-clouds-yemens-solar-energy-revolution/

Clifford, B. and Triebert, C. (2016). Yemen's Bombed water infrastructure: an OSINT investigation. Bellingcat. https://www.bellingcat.com/news/mena/2016/02/05/yemens-bombed-water-infrastructure/

Dorsch International Consultants GmbH (2018) Yemen Water Sector: Damage assessment report of twelve water supply and sanitation local corporations (LCs) and their affiliated branch offices and utilities. Part 1: Resilience Strategy Report. Bonn and Eschborn: GIZ.

EAI. (2007). Advice on Terms of Reference for EAI for Wadi Bana Dam Project – Yemen. Netherlands Commission for Environmental Assessment.

ESA. (2017). Land Cover CCI Product User Guide Version 2. Tech. Rep.. Available at: maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf

Ewea, H. A. R. S. A. (2007). Assessment of potential water resources in Abyan area-southern Yemen. Civil Engineering Research Magazine, 23(5), 785-795.

FAO. (2008). AQUASTAT Country Profile – Yemen. Food and Agriculture Organization of the United Nations (FAO). Rome, Italy

FAO. (2018). Yemen Plan of Action 2018-2020 – Strengthening resilient agricultural livelihoods. Rome, Italy.

Farquharson, F. A. K., Plinston, D. T., & Sutcliffe, J. V. (1996). Rainfall and runoff in Yemen. *Hydrological sciences journal*, *41*(5), 797-811.

Faruqui, S. (2021, August 05). Explained: Rehabilitating water infrastructure in marib. Muslimhands. https://muslimhands.org.uk/latest/2021/08/yemen-water-solutions-rehabilitating-infrastructure-in-marib.

FEWS NET. (2010). Livelihoods Zoning "plus"Activity in Yemen. USAID.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelson, J. (2015) The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Sci Data 2, 150066. https://doi.org/10.1038/sdata.2015.66

Van der Gun, J. A., & Ahmed, A. A. (1995). The water resources of Yemen: a summary and digest of available information. *Report WRAY-35.* TNO, Netherlands

Glass, Nicole. "The water crisis in Yemen: causes, consequences and solutions." *Global Majority E-Journal* 1, no. 1 (2010): 17-30. https://www.american.edu/cas/economics/ejournal/upload/glass_accessible.pdf

Haidera, M., Alhakimi, S. A., Noaman, A., Al Kebsi, A., Noaman, A., Fencl, A., ... & Swartz, C. (2011). Water scarcity and climate change adaptation for Yemen's vulnerable communities. *Local Environment*, *16*(5), 473-488.

Haidera, M., & Noaman, A. (2008). Application of Decision Support Tools for Water Resources Management in Coastal Arid Areas (Case study: Aden, Yemen).

Helder, J., Jungermann, N., Rozing, A., Kleinendorst, T., & Teklesadik, A. (2020). DSS water mission report: Yemen Marib Dam Flooding.

Hellegers, P. J. G. J., Perry, J. N., Al-Aulaqi, N., Al-Eryani, A. R., & Al-Hebshi, M. (2008). *Incentives to reduce groundwater extraction in Yemen.* LEI Wageningen UR.

Huntjens, P. et al. (2014). The Political Economy of Water Management in Yemen: Conflict Analysis and Recommendations. The Hague Institute for Global Justice, the Netherlands.

Hydrosult, WEC & TNO. (2010). Assessment of Water Resources of the Sana'a Basin & Strategic Options for the Sustainable Development of the Basin's Water Resources. MWE, Yemen.

Hydrosult, WEC & TNO (2008). Sana'a Basin Water Management Project: Hydro-geological and water resources monitoring and investigations in Sana'a Basin. World Bank. MWE, Yemen.

IPCC (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Available at https://www.ipcc.ch/report/ar5/wg1/ .

Japan International Cooperation Agency (JICA). (2007a). The study for the water resources management and rural water supply improvement in the republic of Yemen – Water Resources Management Action Plan for Sana'a Basin. *Final Report – Main Report.* NWRA & MWE.

Japan International Cooperation Agency (JICA). (2007b). The study for the water resources management and rural water supply improvement in the republic of Yemen – Water Resources Management Action Plan for Sana'a Basin. *Final Report – Supporting Report.* NWRA & MWE.

Lichtenthaeler, G. (2010). Water conflict and cooperation in Yemen. *Middle East Report*, *254*, 30-36.

Mannaerts, C.M., Blatchford, M.L., Njuki, S.M., Zeng, Y., Nouri, H., Maathuis, B.H.P., 2020. WaPOR quality assessment: Technical report on the data quality of the WaPOR FAO database version 2. Food and Agriculture Organization of the United Nations (FAO).

Marchant, D. J. U., García Peña, A., Tamas, M., & Harou, J. J. (2018). Simulating Water Allocation and Cropping Decisions in Yemen's Abyan Delta Spate Irrigation System. Water, 10(2), 121.

McCracken, M. (2012). The impact of the water footprint of qat on Yemen's water resources. *MSc Thesis*. University of East Anglia.

MetaMeta Research, and PAN Yemen Consult. (2013). Study on strategic orientation and reorganization of the irrigation sector. 62/CS/IRR/WSSP/11. Diagnostic Report. 's Hertogenbosch, the Netherlands, Metamata research.

Metameta and WEC. (2014). CoCooN-Integrated Project: Groundwater in the Political Domain. *1st and 2nd reports.* NWO.

Ministry of Agriculture & Irrigation (MAI). (2019). Agricultural statistics – Year Book 2018. Dept. of statistics and agricultural information.

Ministry of Water and Environment (MWE). (2004). National Water Sector Strategy and Investment Program (NWSSIP). Republic of Yemen.

Morris-Iveson, L. and Alderwish, A. 2018. Experiences with local water governance and outcomes for vulnerable communities in the Tihama region of Yemen. *Water Alternatives* 11(3): 684-698. https://www.water-alternatives.org/index.php/alldoc/articles/vol11/v11issue3/460-a11-3-13/file

Moyer, J. D., Bohl, D., Hanna, T., Mapes, B. R., Rafa, M. (2019). Assessing the Impact of War on Development in Yemen. UNDP. Sanaa, Yemen.

Murgham, A.A., Hulaibi, A.Y., Abdulaziz, A.S., Al-Marhabi, A., Al-Kubati, E.M., Al-Maga'ali, A.A., Nasser, N.H., Nasher, F.M., Al-Absi, S.A.H., Salem, M.S., Al-Jalal, S. (2013). Conflict-Livelihood Interaction In Yemen: Participatory assessment conducted in Abyan, Taiz, Hajja, and Amran Governorates. "

NASA-JPL. (2013). NASA Shuttle Radar Topography Mission Global 1 arc second. NASA EOSDIS Land Processes DAAC.

National Water Resources Authority (NWRA). (2009). Groundwater management and agricultural development in Yemen. Ministry of Water and Enviroment.

Noaman, A., Al-Nozaily, F.A. and Al-Mashreki, M.H. (2021). Yemen country file. Fanack Water. https://water.fanack.com/yemen/.

Noaman, A., & Al-Washali, T. (2019). The Yemen Experience on Water Harvesting. *Nairobi Knowledge and Experience Exchange Symposium*. Nairobi, Kenya. https://floodbased.org/wp-content/uploads/2021/05/Water-Harvesting-in-Yemen_Abdulla-Noaman.pdf

Noaman,. A. (2004) Indigenous knowledge for using and managing water harvesting techniques in Yemen. Civil Engineering Department, Water and Environment Center (WEC), Sana'a University, Yemen.

NWRA. (2011). Wadi Hadramawt. Changes in groundwater chemistry between 2001 and 2011. National Program Integrated Water Resources Management (NPIWRM), National Water Resources Authority (NWRA).

NWRA. (2009). Tihama Water Resources Management, Wadi Zabid & Wadi Rema'a Water Quality. Final Report. National Water Resources Authority, Ministry of Water and Environment, Yemen.

NWRA (2009b). Preparation of Water Resources Assessment Plan for Dhamar Plain, Final Report. National Water Resources Authority, Ministry of Water and Environment, Yemen.

NWRA. (n.d.). Water Resources Management Plan for Tuban-Abyan Delta Region. National Water Resources Authority, Ministry of Water and Environment, Yemen.

REACH (2018) Wash Household Assessment – Water, Sanitation, and Hygiene household level needs assessment in Yemen.

Republic of Yemen. (2016). Yemen National Report. *Third United Nations Conference on Housing and Sustainable Urban Development (Habitat III)*. Quito, Ecuador. https://uploads.habitat3.org/hb3/Yemen-National-Report-September-2016.pdf

Rodell, M., P.R. Houser, U. Jambor, J. Gottschalck, K. Mitchell, C.-J. Meng, K. Arsenault, B. Cosgrove, J. Radakovich, M. Bosilovich, J.K. Entin, J.P. Walker, D. Lohmann, and D. Toll, The Global Land Data Assimilation System, Bull. Amer. Meteor. Soc., 85(3), 381-394, 2004.

RTI International (2011). The Sana'a Water Issues and Options Study. World Bank.

Saleh, S.A. (n.d.) "Spate Irrigation in Yemen".

Van der Salm, S., Bastiaanssen, W., Voogt, M., Kassies, R., Pelgrum, H., Al-Shaybani, S., Al-Hemiary, A. (2012). Final report: Satellite Imagery follow-up study. WaterWatch & Hydro-Yemen.

Soliman, M. M., El Tahan, A. H. M., Taher, A. H., & Khadr, W. M. (2015). Hydrological analysis and flood mitigation at Wadi Hadramawt, Yemen. Arabian Journal of Geosciences, 8(11), 10169-10180.

Steenbergen, F. V., Lawrence, P., Haile, A. M., Salman, M., Faurès, J. M., Anderson, I. M., Nawaz, K. & Ratsey, J. (2010). Guidelines on spate irrigation. *FAO irrigation and drainage paper*, (65).

Taher, T., Ward, C., Fadl, N., Saleh, A., & Sultan, M. (2013). Planning for integrated water resources management: case study Sana'a Basin Yemen. *Int Water Technol J (IWTJ)*, *3*(4), 232-248.

Tuinhof, A., Dumars, C., Foster, S., Kemper, K., Garduno, H., Nanni, M.(2002). Groundwater resources management: an introduction to its scope and practice. *Brief Note Series – Note 1.* GW-Mate Core Group, World Bank. https://www.yumpu.com/en/document/read/46704012/groundwater-resource-management

UNDP & FAO. (2020). Joint (UNDP and FAO) Project Proposal - Decentralised Cooperative Water Governance for Food Security and Peace in Yemen (CoWaGo).

UNDP (2013). Manakha Rainwater and Fog harvesting – Final report. National Foundation for Watershed Management. *Final Project Report.* National Foundation for Watershed Management & Services.

UNDP-NWRA. (2009). Water Resources Management for the Wadi Hadramawt Region (Updated and Revised). National Water Resources Authority (NWRA) Sana'a, UNDP/UNDESA/Government of The Netherlands.

UN-Habitat (United Nations Human Settlements Programme in Yemen). (2020a). Sanaa City Profile (PDF). Retrieved 08 July 2021 from https://yemenportal.unhabitat.org/.

UN-Habitat (United Nations Human Settlements Programme in Yemen). (2020b). Aden City Profile (PDF). Retrieved 08 July 2021 from https://yemenportal.unhabitat.org/.

UN-Habitat (United Nations Human Settlements Programme in Yemen). (2020c). Taiz City Profile (PDF). Retrieved 08 July 2021 from https://yemenportal.unhabitat.org/.

UN-Habitat (United Nations Human Settlements Programme in Yemen). (2020d). Hodeidah City Profile (PDF). Retrieved 08 July 2021 from https://yemenportal.unhabitat.org/.

UN-Habitat (United Nations Human Settlements Programme in Yemen). (2020e). Marib City Profile (PDF). Retrieved 08 July 2021 from https://yemenportal.unhabitat.org/.

UNOCHA. (2012). Community Profiling, Governorate of Abyan, Zijnjibar & Khanfar Districts. United Nations Office for the Coordination of Humanitarian Affairs.

Veenstra, S., Al-Nozaily, F. A., & Alaerts, G. J. (1995). Purple non-sulfur bacteria and their influence on waste stabilisation pond performance in the Yemen Republic. *Water Science and Technology*, *31*(12), 141-149.

WASH Cluster. (2021). District census data of Yemen. *Shared with Acacia Water by UNDP Yemen on 29-08-2021.*

Ward, C., Saif, A. S., Sultan, M., Fadl., N., Al-Sakaf, O., Taher, T., & Basuhay, S. (2010). Sana'a Basin Integrated Water Resources management – Action Oriented Policy Paper. Republic of Yemen.

Water and Environment Centre (WEC). (2005). Well inventory maps and figures Sana'a Basin. https://www.yemenwater.org/s/Sanaa-well-inventory-Figures-Maps.pdf

Water and Environment Centre (WEC). (2001). Sana'a Basin Water Management Report II – Technical Report. Sanaa University. https://static1.squarespace.com/static/5eb18d627d53aa0e85b60c65/t/5f00cc6eebaa0d2e0cb8bae2/1593887859545/The-Sanaa-Basin-Water-Management-Report-II-Technical-report.pdf

Watkins, M.M., Wiese, D.N., Yuan, D.-N., Boening, C., Landerer, F.W. (2015). Improved methods for observing Earth's time variable mass distribution with GRACE using spherical cap mascons, *J. Geophys. Res.*, 120, doi:10.1002/2014JB011547.

Wiese, D.N., Landerer, F.W., Watkins, M.M. (2016) Quantifying and reducing leakage errors in the JPL RL05M GRACE mascon solution, *Water Resour. Res.*, 52, doi:10.1002/2016WR019344.

Whitehead, F. (2015). Water scarcity in Yemen: the country's forgotten conflict. *The Guardian*, 2 April 2015. https://www.theguardian.com/global-development-professionals-network/2015/apr/02/water-scarcity-yemen-conflict

World Bank. (2010). Yemen Assessing the Impacts of Climate Change and Variability on the Water and Agricultural Sectors and the Policy Implications. *Report No. 54196-YE.*

World Bank. (2015). The Republic of Yemen – Unlocking the potential for Economic Growth – A country economic Memorandum. *Report No. 102151-YE.*

World Bank, 2020. United Nations Population Division. World Urbanization Prospects: 2018 Revision. And OECD National accounts data files. https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS?locations=YE & https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG?locations=YE

Yehya, Q., & Al-Asbahi, A. M. (2005). Water resources information in Yemen. *(IWG-ENV), International Work Session on Water Statistics, Vienna (June 20-22).* https://millenniumindicators.un.org/unsd/ENVIRONMENT/envpdf/pap_wasess3a3yemen.pdf

Zeitoun, M. (2009). The political Economy of Water Demand management in Yemen and Jordan: A synthesis of findings. Water Demand Management Research Series 5, WaDImena, International Development Research Center (IDRC).

Websites:
https://www.yemenwater.org/

Annexes

Annex 1 – Stakeholders in the Yemen Water Sector

Overview of the Stakeholders in the Yemen Water sector from Huntjens et al. (2014).

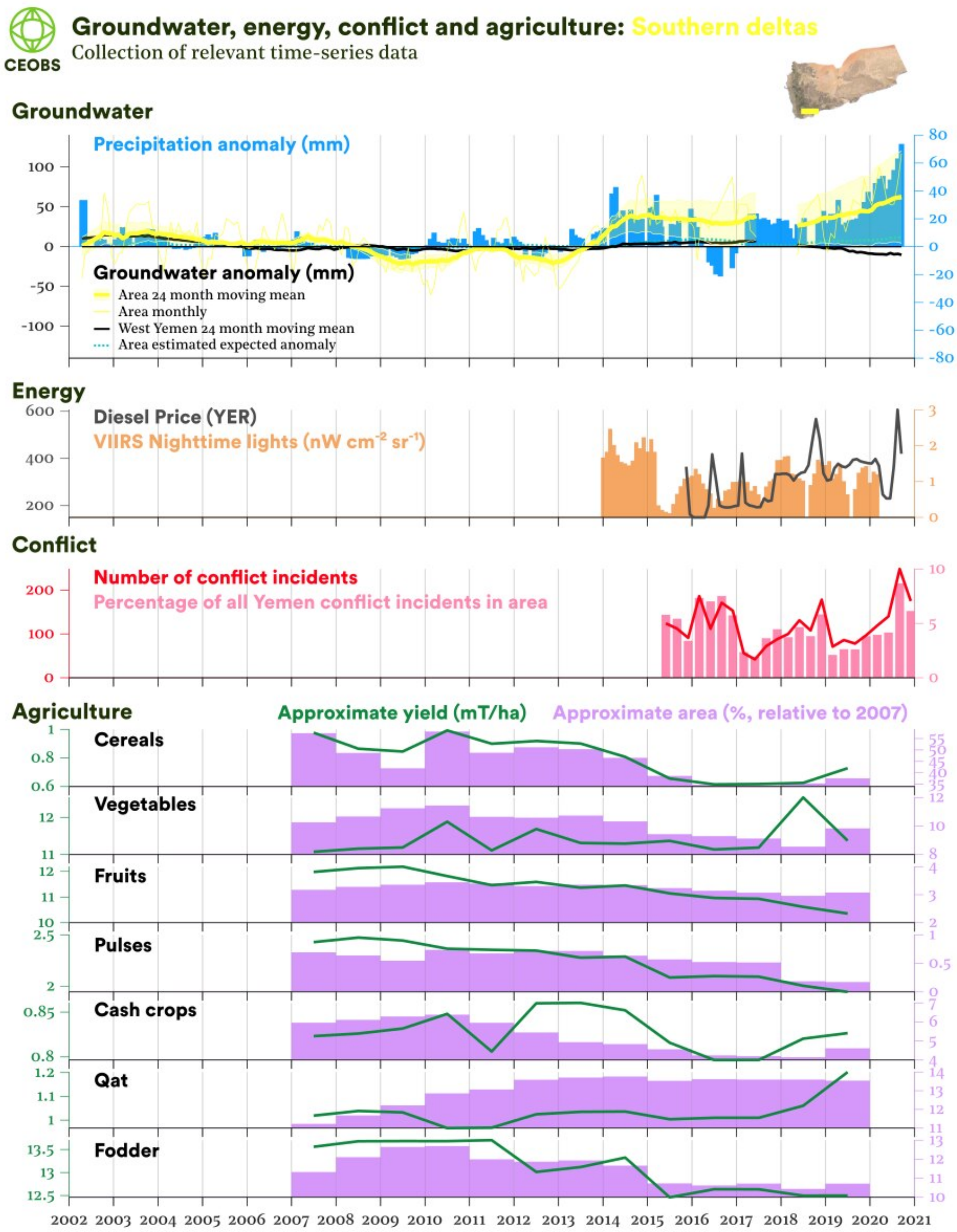
Institution / Organization	Responsibility and interest	Influence/power
Ministries		
Ministry of Water and Environment	Founded in 2003 and supervises water resources management through the NWRA. Developing water resources on the basis of IWRM; providing clean drinking water and sanitation services, allocating water for other uses; and protecting the environment from pollution and desertification, conserving natural resources and rationalizing their exploitation	The ministry has low implementation capacity resulting in low bargaining power (Zeitoun, 2009)
Ministry of Agriculture and Irrigation	Responsible for formulating policies for water resources, for food security and for crops, livestock, and forestry production, and for coordinating public investment and services in the sector. Have an interest to maintain water allocations for Irrigation and	Better bargaining power than MWE due to vested networks (Zeitoun, 2009) and is responsible for the lion's share of (agricultural) water resources (Hübschen, 2011)

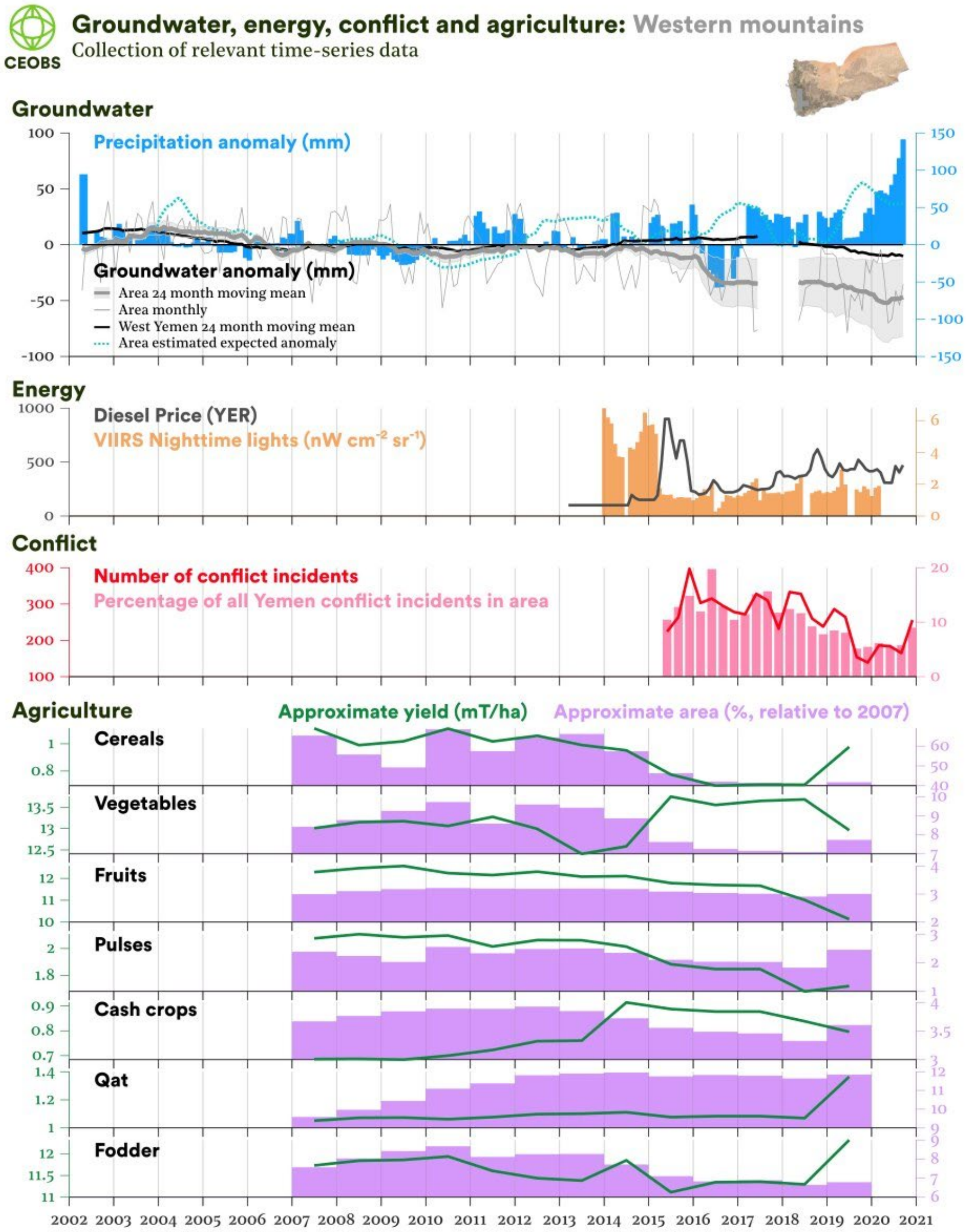
	Agriculture rather than other water users	
Ministry of Local Administration (MLA)	Enforcing *Law No.4 Regarding Local Authority* (Hübschen, 2011)	Plays a decisive role in the process of decentralization and the establishment of the Local Corporations (Hübschen, 2011)
Ministry of Planning and International Cooperation (MPIC)	Responsible for sustainable development and poverty reduction, and investment planning and programming (Hübschen, 2011)	MPIC headed the high-level Inter-Ministerial Steering Committee in 2007 to coordinate and integrate the actions of ministries engaged in water management and prepare the 2008 National Water Sector Strategy (Hübschen, 2011)
Ministry of Finances	Responsible for allocating financial and investment resources. It also sets the diesel prices	Has the power to tax, and allocates financial resources to other ministries. The ministry has therefore relevant bargaining power in investments in water resources development (Hübschen, 2011)
Departments / District authorities		
National Water Resources Authority	Statutory body with autonomous financial administration, responsible for water resources planning, groundwater monitoring, legislation and licensing, water extraction regulation, property rights control, and public awareness. The develop and implement the National Water Sector Strategy NWSSIP (Hübschen, 2011)	Although the Water Law (2002) identifies NWRA as the sole authority for WRM and law enforcement, the authority is not supplied with more resources, power and autonomy. It has therefore limited implementation capacity, therefore donor dependent (Ward et al. 2007; Hübschen, 2011).
National Water and Sanitation Authority	Responsible for water supply and sanitation service delivery, O&M, and collecting revenues in communities with more than 30,000 citizens	Under influence of international donor community to increase effectiveness and efficiency. It is gradually replaced by decentralized LCs (Hübschen, 2011)
General Authority for Rural Water Supply Projects (GARWSP)	Responsible for planning, design and construction of water and electricity schemes for rural settlements with less than 30,000 residents	In the process of decentralization. 20 branches have been opened in all governates. Until 2008, 11 branches were empowered to carry out the full range of activities. Capacity in personnel, facilities, finances, and administration is limiting the power of the local offices (Hübschen, 2011).
Local Corporations (LC)	15 LCs (in 2011) were responsible for app. 95% of the urban drinking water	Increasing in influence as LCs are replacing the centralized authority of

	supply (Hübschen, 2011)	the NWSA (Hübschen, 2011)
Water Supply department	Implementing department under the MWE for coordinating rural water supplies	Limited power due to limited capacity
Regional development agencies (RDA)	Providing field services to farmers The division of responsibility between AREA and the RDAs with respect to water management is unclear (EOEARTH, 2008)	Limited power in relation to water resources management, also due to unclear responsibilities (EOEARTH, 2008)
Agricultural Research Extension Authority (AREA)	Providing farmers extension services	Limited power in relation to water resources management, also due to unclear responsibilities (EOEARTH, 2008)
Environmental Protection Authority	Reports environmental issues to MWE	Does not have real enforcement power
Knowledge institutes		
Universities	To develop knowledge about water resources and sustainable management of the available natural resources	Low influence (Zeitoun, 2009)
Vocational training centres	To educate professionals in sustainable water resources management, engineering and technology.	Low influence (Zeitoun, 2009)
International donors		
International donors	Financing and investing in improved water resources management, providing technical assistance in development and implementation of programs Promoting principles of IWRM (incl. decentralization) and Water Demand Management Developing the Rada'a supporting decentralization of water resources management and principles of IWRM (Hübschen, 2011)	Due to competition rather than the promoted cooperation among each other, donors are susceptible to be "divided and conquered" by local leaders (Zeitoun, 2009) The Yemeni water sector is heavily dependent on foreign donor support; donors are more powerful than the MWE (Zeitoun, 2009).
Political stakeholders		
Parliamentarians	Political parties and individual parliamentarians have been supporting the irrigation water supply reform (Ward et al., 2007) Personal interest in remaining in seat, which can result in an interest to remain the status quo or in reducing rural poverty. It depends on the constituency (Ward et al.. 2007)	Legitimacy granted by the people provides bargaining power (Zeitoun, 2009) The position of parliamentarians is strongly linked to patronage systems (Zeitoun, 2009)
Army and security officials	Can have personal interests in the conflict (land and water, financial interests), but also can have an interest to settle conflicts.	Force power, networks to parliamentarians, high officials, can be powerful in the local context

Local stakeholders		
Sheiks / tribal leaders / large landowners	Water users, local leaders, influential in legitimizing customary rules or legal rules, monopolizing water rights Contextual dependent Accuser, respondent, or mediator	Non-compliance to legislation, bargaining power in development of infrastructure, force (gun power) (Zeitoun, 2009) Influence and power is related to networks with security officials, parliamentarians, etc. (Anon, 2009) and legitimacy granted by the people
Large (irrigation) farmers	Local water users, interest in resources development for irrigation, domestic water supply, and water for animals Responsible for daily water management and operation of irrigation systems	Have a true implementation power in water resources management. Are strongly supported by the MAI. As most water in Yemen is consumed by irrigation, this group has real power in influencing water use. ((Zeitoun, 2009; Hübschen, 2011)
Small farmers	Local water users, interest in resources development for irrigation, domestic water supply, and water for animals Responsible for daily water management and operation of irrigation systems	Provide authority to sheiks / tribal leaders. Limited bargaining power, because of limited resources. Poverty and wealth are important for the level of power and influence (Zeitoun, 2009)
Religious leaders	Securing socio-cultural values and norms Contextual dependent, but involved in conflict settlement in the light of customary and Islamic rules	Legitimacy granted by the people, and based on the personal social network (security officials, parliamentarians, sheiks, tribal leaders)
The very poor	The very poor have limited access to (irrigation) water resources, the bit more prosperous can have access to shared water resources/tube wells/water conservation technologies (Zeitoun 2009) Improved access to water resources, costs of water are very high because dependent on water vendors,	Very limited, very dependent on more powerful stakeholders (sheiks, tribal leaders)
Women and girls	Women and girls spent in some cases many hours each day for water fetching and are therefore water managers	Women have the same water rights as men according to customary rights, but have very limited voice in decision-making over water resources management.

Annex 2 – CEOBS groundwater trends using GRACE





CEOBS
Groundwater, energy, conflict and agriculture: Western mountains
Collection of relevant time-series data
Groundwater
Precipitation anomaly (mm)
Groundwater anomaly (mm)
Area 24 month moving mean
Area monthly
West Yemen 24 month moving mean
Area estimated expected anomaly
Energy
Diesel Price (YER)
VIIRS Nighttime lights (nW cm-2 sr-1)
Conflict
Number of conflict incidents
Percentage of all Yemen conflict incidents in area
Agriculture
Approximate yield (mT/ha)
Approximate area (%, relative to 2007)
Cereals
Vegetables
Fruits
Pulses
Cash crops
Qat
Fodder
2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021

Annex 3 – Wadi Hadhramaut cropping calendar

Food and Agriculture Organization of the United Nations

Yemen Food Security Information System (FSIS) Development Programme

Programme Funded by the European Union and Implemented by FAO and MOPIC/Food Security Technical Secretariat

Yemen Seasonal Calendar (Desert – Dry and Hadramout Eastern Plateau Agro-Ecological Zones –Crop Production)

Seasonal events	January	February	March	April	May	June	July	August	September	October	November	December	Remarks
Rainy Seasons				1st Season				Pick of the Season		2nd Season			
Dry Season	Dry Season										2nd Season		
▪ Cereals & Legumes:													
Wheat			Harvest					Land Preparation		Planting	Ag. Op. (including Urea application 1 &2)		
Barley	Harvest							Land Preparation		Planting	Ag. Op. (including Urea application 1 &2)		
Sorghum Grain – Spring Season		Land Preparation	Planting	Ag. Op. (Urea application1)	Agriculture Operation (including Urea application 2)		Harvest						Land preparation includes: plowing - leveling – applying Organic Fertilization (Manure) and in some cases Chemical Super Phosphate
Sorghum Grain – Autumn Season							Land P. Planting	Ag. Op. Urea 1			Harvest		
Maize Grain – Spring Season		Land Preparation	Planting	Agriculture Operation (Urea application1)	Ag. Op. Nitrogen Fertilization 2	Harvest							
Maize Grain – Autumn Season									Land P. Planting	Ag. Op. Urea 2	Ag. Op. Urea 1	Harvest	
Fenugreek		Harvest							Land Preparation	Planting			
Peas	Harvest								Land Preparation	Planting			
Beans	Harvest								Land P. Planting			Harvest	
Cowpea			Land P. Planting			Harvest							
▪ Fodder:													
Alfa- alfa – Spring Season	Land Preparation	Planting						Harvest					
Alfa- alfa – Autumn Season					Harvest				Land Preparation		Planting		
Sorghum – Spring Season		Land Preparation	Planting	Ag. Op. (including Urea application)	Harvest								
Sorghum – Autumn Season					Land P.	Planting Ag. Op. Urea 1	Ag. Op. (including Urea application2)				Harvest		
Maize		Land Preparation	Planting	Ag. Op. (including Urea application)							Harvest		

Food and Agriculture Organization of the United Nations

Yemen Food Security Information System (FSIS) Development Programme/ Funded By European Union`

Produced: August, 2018

Contact: FAO-FSIS programme:FAOYE-FSIS@fao.org, FSTS/Ministry of planning & International Cooperation (MoPIC): abdulwahedmukred@gmail.com /awmukred@yemen.net.

Food and Agriculture Organization of the United Nations

Yemen Food Security Information System (FSIS) Development Programme

Programme Funded by the European Union and Implemented by FAO and MOPIC/Food Security Technical Secretariat

Yemen Seasonal Calendar (Desert – Dry and Hadramout Eastern Plateau Agro-Ecological Zones –Crop Production)

Seasonal events		January	February	March	April	May	June	July	August	September	October	November	December	Remarks
▪ Cash Crops														
Sesame	Spring Season		Land Prep.; Planting		Ag. Op. Urea 1	Ag. Op. Urea 2	Harvest							
Sesame	Autumn Season						Land Prep.	Planting	Ag. Op. Urea 1	Ag. Op. Urea 2		Harvest		
Black Bean									Land Preparation	Planting		Ag. Op. Urea app.1	Harvest	
Henna		Planting				Harvest							Land Preparation	
Coriander Seeds	Spring Season	Land Prep.	Planting	Ag. Op. Urea 1; Harvest										
Coriander Seeds	Autumn Season								Land Prep.	Planting		Harvest		
▪ Horticulture (Fruits):														
Palm				Land Prep.; Planting				Harvest - Monaseef	Harvest-Dates; Land Prep.	Planting	Ag. Op. (Urea application1)		Ag. Op. (Urea application 2)	
Citrus		Harvest; Land Prep.	Planting; Ag. Op. (Urea application1)	Ag. Op. Urea 2		Harvest		Ag. Op. Urea application1					Harvest	
Mango		Land Preparation; Ag. Op. (Urea application1)	Planting	Ag. Op. (Urea application 2)		Harvest								
▪ Vegetables:														
Tomatoes	Spring Season	Planting	Ag. Op. Urea 1	Ag. Op. Urea 2	Harvest								Land Preparation	
Tomatoes	Autumn Season	Harvest						Land Prep.; Planting		Agriculture Operation (including Urea application 2)			Harvest	
Potatoes		Ag. Op. (Urea application 1)	Harvest							Land Preparation	Planting		Ag. Op. (Urea application2)	
Onion	Spring Season	Harvest			Land Preparation	Planting								
Onion	Autumn Season	Harvest						Agriculture Operation (Urea application 1 &2)				Harvest		
Squash	Spring Season	Planting	Ag. Op. (Urea application 1 &2)	Harvest				Agriculture Operation (Urea application 1 &2)				Harvest		
Squash	Autumn Season	Harvest							Land Preparation	Planting		Ag. Op. (Urea application 1)	Harvest	
Egg Plant	Spring Season	Land Prep.; Planting	Ag. Op. (Urea application 1 &2)		Harvest									
Egg Plant	Autumn Season	Harvest						Land Preparation	Planting		Ag. Op. (Urea application 1 &2)		Harvest	
Garlic	Spring Season	Ag. Op. (Urea application 1 &2)		Harvest						Land Preparation	Planting	Ag. Op. (Urea application 1 &2)		
Garlic	Autumn Season													
Chilly	Spring Season	Land P.; Planting	Urea applicatio		Harvest									
Chilly	Autumn Season	Harvest						Land Preparation	Planting				Harvest	
Okra	Spring Season	Planting	Ag. Op. (Urea application 1)		Ag. Op. (Urea application2); Harvest								Land Preparation	
Okra	Autumn Season						Land Preparation	Planting	Agriculture Operation (Urea application 1 &2)			Harvest		
Watermelon		Land P.; Planting	Ag. Op. Urea 1	Ag. Op. Urea 2	Harvest									
Sweet melon		Land P.; Planting	Ag. Op. Urea 1	Ag. Op. Urea 2	Harvest									
Watermelon (Local)		Land P.; Planting	Ag. Op. Urea 1	Ag. Op. Urea 2	Harvest									Mainly in Hadramout (Seayoun), it called "Baladi"

Food and Agriculture Organization of the United Nations

Yemen Food Security Information System (FSIS) Development Programme/ Funded By European Union

Produced: August, 2018
Contact: FAO-FSIS programme:FAOYE-FSIS@fao.org, FSTS/Ministry of planning & International Cooperation (MoPIC): abdulwahedmukred@gmail.com /awmukred@yemen.net.

Annex 4 – Gulf of Aden cropping calendar

Food and Agriculture Organization of the United Nations

Yemen Food Security Information System (FSIS) Development Programme

Programme Funded by the European Union and Implemented by FAO and MOPIC/Food Security Technical Secretariat

Yemen Seasonal Calendar (Arabian Sea Coast & Gulf of Aden Agro- ecological zone–Crop Production)

Seasonal events	January	February	March	April	May	June	July	August	September	October	November	December	Remarks
Rainy Seasons				1st Season						2nd Season			
Flow of torrents(Floods)				Torrents Flow		Pick of Torrents Flow			Torrents Flow				
Dry Season	Dry Season										Dry Season		
▪ Cereals:													
Sorghum - Grains	Land Preparation including Manure application	Planting				Land Preparation including Manure	Harvest		Planting			Harvest	
Sorghum - Fodder		Land Preparation including Manure	Planting			Harvest			Planting			Harvest	
Maize	Harvest								Land Preparation including Manure	Planting			
Millet	Harvest			Land Preparation including Manure	Planting		Harvest		Land Preparation including Manure	Planting			
▪ Fruits:													
Papaya						1st Harvest after seedling	Harvest Cont.	Planting seedling In Nursery	Land preparation including Manure &Phosphates	Planting Seedling in Permanent Land			
Banana - Production	Harvest -Industrial Ripening-Marketing and Remove moles that Harvest have been harvested –in addition of Agriculture Operation including Urea application in April & August												
Banana – New planting										Land preparation including Manure &Phosphates	Planting		
Palm Production		Ag. Operations Artificial Pollination			Harvest -Balah	Harvest- Monasef		Harvest- Dates			Ag. Operations Leaves Removal		
Palm – New Planting						Land Preparation including Manure	Planting						
Mangoes- Production		Harvest						Ag. Operations (Dead branches pruning &plow around the trees)		Ag. Operations (Urea application)			
Mango - New Planting	Planting Cont.								Land preparation, Seedling beds & Fertilizations		Planting (grafted seedlings)		
Citrus (Limon) - Production		Ag. Operations (Urea application)		Harvest				Ag. Operations (Dead branches pruning and remove the growths below the plants)		Ag. Operations Urea application	Harvest		
Citrus (Limon) - New Planting									Land Preparation including Manure	Planting Seedling			
Coconut – Production	Harvest		Ag. Operations Manure application	Harvest					Ag. Operations Manure application	Harvest Cont.			
Cream				Harvest	Ag. Operations (Dead branches Pruning + Fertilization			Land Preparation including Manure	Planting Seedling				
Guava				Harvest	Ag. Operations (Dead branches Pruning + Fertilization			Land Preparation including Manure	Planting Seedling				
The Abbasi (sputa)					Harvest	Ag. Operations (Dead branches Pruning + Fertilization		Land Preparation including Manure	Planting Seedling				

Food and Agriculture Organization of the United Nations

Yemen Food Security Information System (FSIS) Development Programme/ Funded By European Union`

Produced: August, 2018
Contact: FAO-FSIS programme:FAOYE-FSIS@fao.org, FSTS/Ministry of planning & International Cooperation (MoPIC): abdulwahedmukred@gmail.com /awmukred@yemen.net.

Food and Agriculture Organization of the United Nations

Yemen Food Security Information System (FSIS) Development Programme

Programme Funded by the European Union and Implemented by FAO and MOPIC/Food Security Technical Secretariat

Yemen Seasonal Calendar (Arabian Sea Coast & Gulf of Aden Agro- ecological zone–Crop Production)

Seasonal events	January	February	March	April	May	June	July	August	September	October	November	December	Remarks
▪ Cash Crops													
Tuhef	**Land Preparation** including Manure	**Planting**					**Harvest**						
Cotton	**Harvest**				**Land Preparation** including Manure			**Planting**		**Agriculture Operations** (Almond worms control)			
Sesame	**Land Preparation** including Manure	**Planting**			**Harvest & Threshing**	**Land Preparation** including Manure	**Planting**				**Harvest & Threshing**		
Tobacco	**Harvest** (of October Planting)		**Harvest** (of December Planting)				**Land Preparation** (including Manure)			**Planting**		**Planting**	
Flowers (Fol)				**Harvest**						**Planting**			
Henna		**Harvest**							**Planting**				
Ground Nuts					**Land Preparation** (including Manure)			**Planting**			**Harvest**		
▪ Vegetables:													
Tomatoes in Permanent Land	**Harvest & Marketing**							**Land Preparation** (including Manure & Phosphates application	**Planting**	**Re-Planting & Fertilization**	**Agriculture Operations** (Irrigation – weeding & Fertilization)		
Tomatoes in Nurseries	**Harvest & Marketing**						**Nursery Preparation**	**Land preparation** (including Manure	**Planting**		**Agriculture Operations**		
Chilly	**Harvest** (Red Fruits) for Drying **Harvest** (Green Fruits) for consumption							**Nursery Preparation** **Planting Seedling**	**Land Preparation** (including Manure & Phosphates application	**Planting Seedling in Permanent Land**	**Ag. Application** Urea1 Application	**Agriculture Operations** (Urea2 \ weeding and control)	
Onions		**Harvest (Processing & Marketing)**						**Nursery Preparation** **Planting Seedling**	**Land Preparation** (including Manure & Phosphates application	**Planting Seedling in Permanent Land**	**Ag. Application** Urea1 Application	**Agriculture Operations** (Urea2 / weeding and control)	
Egg plant	**Harvest & Marketing**							**Nursery Preparation** **Planting Seedling**	**Land Preparation** (including Manure & Phosphates application	**Planting Seedling in Permanent Land**	**Ag. Application** Urea1 Application	**Agriculture Operations** (Urea2 / weeding and control)	
Okra		**Land Preparation** (including Manure & Phosphates application	**Planting** (Summer Season)		**Summer Harvest**		**Land Preparation** (including Manure & Phosphates application)	**Planting** (Winter Season)		**Winter Harvest**			
Watermelon , sweet melon and squash	**Land Preparation** (including Manure & Phosphates **Planting** (Squash)	**Planting** (Water and Sweet melon)	**Ag. Operations** (Urea application and control)	**Harvest & Marketing**			**Land Preparation** (including Manure & Phosphates	**Planting** (Water and Sweet melon)	**Planting** (Squash) **Ag. Operations** (Urea/ weeding and control)	**Harvest**			
Sweet Potato	**Harvest**							**Land Preparation** (including Manure)	**Planting Seedling**				

Annex 5 – Central Highland cropping calendar

Food and Agriculture Organization of the United Nations

Yemen Food Security Information System (FSIS) Development Programme

Programme Funded by the European Union and Implemented by FAO and MOPIC/Food Security Technical Secretariat

Yemen Seasonal Calendar (Central highland Agro- ecological zone–Crop Production)

Activities \Monthly \Seasonal events	January	February	March	April	May	June	July	August	September	October	November	December	Remarks
Rainy Seasons		1st Rainy Season			Dry Season(Jahr)	2nd Rainy Season							Jahr: Interval period between the rainy seasons
▪ **Cereals:**													
Sorghum	**Land Preparation** Ploughing, including Manure application			**Planting**/ Sowing	**Agricultural Operations** (Thinning , weeding, Leaves removal (Sharf))					**Harvest & Threshing**		**Land preparation**	
Zea maize	**Land preparation** Ploughing , including Manure application		**Planting**/ Sowing	**Agricultural Operations** (Thinning , Urea application ,silk cutting ,weeding and Leaves removal (Sharf))					**Harvest & Threshing**			**Land preparation**	
Wheat	**Land preparation**	**Agricultural Operations** (manure application)			**Harvest & Threshing**	**Planting** – summer season	Agricultural Operations (Urea application)			**Harvest & Threshing**		**Land preparat ion** **Planting winter season**	
Barley	**Land preparation**	**Planting** – Winter season	**Ag. Operations** (manure application)		**Harvest & Threshing**	**Agricultural Operations** (Ploughing)	**Planting** – summer	Agricultural Operations (Urea application)		**Harvest & Threshing**		**Land preparat ion** **Planting winter season**	
Millet	**Land preparation**	**Ag. Operations** (Ploughing & Manure application)			**Planting**	**Agricultural Operations** (Thinning)			**Harvest & Threshing**			**Land preparation**	Cowpea is usually grown intercropped with sorghum after one month of planting
Pulse: Faba bean	**Land Preparation** **Planting**	**Agricultural Operations** (Ploughing ,Weeding, Fertilization)			**Harvest & Threshing**							**Land preparation**	
Lentil	**Planting continued**	**Agricultural Operations** (Ploughing ,Weeding)			**Harvest & Threshing**	**Ag. Operations** (Ploughing ,Weeding)	**Planting –** summer season	**Agricultural Operations** continued (weeding)		**Harvest & Threshing**		**Planting winter season**	**Ag. Operations**- Agricultural Operations
▪ **Horticulture (Fruits):**													
Citrus Trees ((*Oranges, Mandarins, and Lemon*)	**Ag. Operations** (Pruning \ Control)		**New Planting**/ \seedlings **Ag. Operations** (Holes ploughing , Organic fertilization , Irrigation)		**Agricultural Operations** (Irrigation & Fertilization)		**Ag. Operations** (Irrigation only)		**Harvest** **Agricultural Operations** (Irrigation only)		**Agricultural Operations** (Irrigation & Pest Control) (Pruning \ Control)		
Almonds \stone fruits (Peach and apricot)Trees	**Land preparation** **Agricultural Operations** (Organic Fertilization)	**New Planting**/ Fruits formation	**Ag. Operations** (Irrigation during Fruits formation & Green fertilization)	**Harvest**		**Ag. Operations** (Pest Control)	**Ag. Operations** (irrigation only)	**Local – early matured -Varieties**		**Agricultural Operation** (Glaucoma control)		**Agricultural Operations** (Pruning\ management)	• Planting in plastic bags takes long the whole year; • Apricot local varieties starts harvesting in August –September
Pomegranate-Perennial trees/(Al-Hadah & Rada'a)	**Ag. Operations** (Pruning)	**Ag. Operations** (Organic Fertilization & heavy irrigation)	**Agricultural Operations** (Irrigation)		**Agricultural Operations** (Irrigation & fertilization)		**Ag. Operations** (Irrigation)	**Harvest**				**Land preparation** **Ag. Operations** (Pruning\management)	
Figs -Perennial trees	**Agricultural Operations** (Pruning)		**Ag. Operations** (Fertilization) (Irrigation) (Spiders Control)		**Harvest**							**Land preparation**	
Cactus					**Harvest**			**Harvest**					
▪ **Cash Crops:**													
Coffee	**Planting** (seedlings) with fertilizers in the Nursery		**Planting**/ Transplanted to the permanent plantation		**Agricultural Operations Including:** Pests control (spraying , smoking)			**Flowering**	**Harvest**		**Post- Harvest** (Drying ,Sorting &Grading)	**Land preparation**	
Qat	**Land preparation**		**Planting** with fertilization		**Agricultural Operations** (Fertilizing \irrigation , pest control & growth catalyst fertilizer)			**First & Second Harvest**		**Harvesting continued over the year**			
Sesame	**L.P**					**Planting**		**Harvest**					**L.P.- Land preparation**
Ground Nuts	**L.P**		**Planting**		**Agricultural Operations** (weeding & urea application)		**Harvest & Threshing**						

**** Agricultural Operations (Ag.Op.) includes :** cultural practices followed during the growing seasons as: sowing/planting, irrigation , weeding, fertilization, leaf-removal , pest control ,pruning, and harvesting, Drying and threshing as post-harvest operations also included;
**** Land Preparation:** Cultural practices followed before the growing seasons to start

Food and Agriculture Organization of the United Nations

Yemen Food Security Information System (FSIS) Development Programme/ Funded By: European Union`

Produced: March, 2018
Contact: FAO-FSIS programme:FAOYE-FSIS@fao.org, FSTS/Ministry of planning & International Cooperation (MoPIC): awmukred@yemen.net.

Food and Agriculture Organization of the United Nations

Yemen Food Security Information System (FSIS) Development Programme

Programme Funded by the European Union and Implemented by FAO and MOPIC/Food Security Technical Secretariat

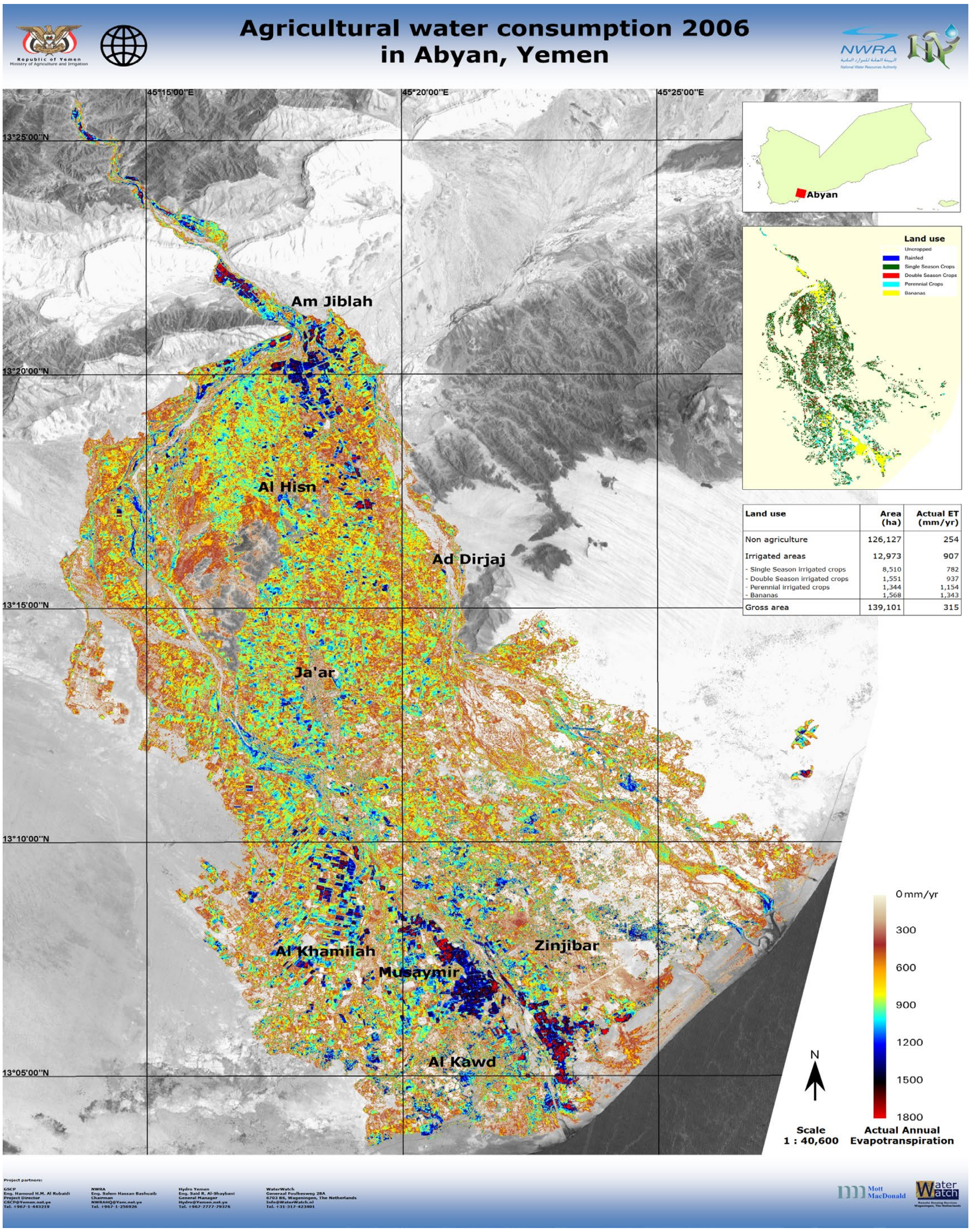
Yemen Seasonal Calendar (Central highland Agro- ecological zone– Crop Production)

Activities \Monthly \Seasonal events			January	February	March	April	May	June	July	August	September	October	November	December	Remarks
▪ **Vegetables:**															
Tomatoes (Irrigated & Open filed)		Spring season		**Land preparation** **Ago. Op.** (Organic & phosphate fertilization)	**Planting** (seedlings in nursery) **Ago. Op** (irrigation, replanting, protective spray)	**Ago. Op.** (Irrigation, Weeding, Fertilization (1) & spray)	**Ago. Op** (Irrigation Weeding, Growing, monitoring Spray)	**Ago. Op** (Fertilization (2)& Damaged fruits removal)	**Harvest** **Agricultural Operations** (Irrigation)						In the spring and autumn seasons, the control operations taken place for the early blight during the second month after planting, while in case of the late blight, the control taken place in the third month. In the winter season , it is rarely the blight to occur
		Autumn season							**Land preparation** **Ago. Op.** (Organic & phosphate fertilization)	**Planting** (seedlings in nursery) **Ago. Op** (irrigation, replanting, protective spray)	**Ago. Op.** (Irrigation, Weeding, Fertilization urea (1) & spray)	**Ago. Op** (Irrigation Weeding, Growing, monitoring Spray)	**Ago. Op** (Fertilization (2)& Damaged fruits removal)	**Harvesting** **Agricultural Operations** (Irrigation)	
Potatoes	Qa'a Bakil , Anes & Jbhan	Spring season	**Land preparation** **Ago. Op.** (Organic & phosphate fertilization)	**Planting**	**Ago. Op** (Irrigation, Weeding, Fertilization (1), Spray)	**Ago. Op** (Irrigation, Soil Filling & Control)	**Harvest** **Agricultural Operations** (Irrigation& Drying)								
		Summer Season					**Land preparation** **Ago. Op.** (Organic & phosphate fertilization)	**Planting**	**Ago. Op.** (Irrigation, Weeding, Fertilization Urea (1) &spray)	**Ago. Op.** (Irrigation, Soil Filling & Control	**Harvest** **Agricultural Operations** (Irrigation& Drying)				
		Winter season	**Ago. Op** (Irrigation, Soil Filling & Control)	**Harvest** **Agricultural Operations** (Irrigation& Drying)							**Land preparation** **Ago. Op.** (Organic & phosphate fertilization)		**Planting**	**Ago. Op.** (Irrigation, Weeding, Fertilization(1)& Spray	
	Plateau	Spring season		**Land preparation** **Ago. Op.** (Organic & phosphate fertilization)	**Planting**	**Ago. Op.** (.Irrigation, Weeding, Fertilization ,Spray)	**Ago. Op** (Irrigation, Soil Filling & Control)	**Harvest** **Agricultural Operations** (Irrigation& Drying)							
		Summer Season					**Land preparation** **Ago. Op.** (Organic & phosphate	**Planting**	**Ago. Op.** (.Irrigation, Weeding, Fertilization ,Spray)	**Ago. Op** (Irrigation, Soil Filling & Control)	**Harvest** **Agricultural Operations** (Irrigation& Drying)				
	Al Baidha, Rada'a & Mukairous	Spring season		**Land preparation** **Ago. Op.** (Organic & phosphate fertilization)		**Planting**	**Ago. Op.** (.Irrigation, Weeding, Fertilization ,Spray)	**Ago. Op** (Irrigation, Soil Filling & Control)	**Harvest** **Agricultural Operations** (Irrigation& Drying)						
		Autumn season								**Land preparation** **Planting** **Ago. Op.** (Organic & phosphate fertilization)	**Ago. Op.** (.Irrigation, Weeding, Fertilization ,Spray)	**Ago. Op** (Irrigation, Soil Filling)	**Harvest** **Agricultural Operations** (Irrigation& Drying)		
Onion		Spring season		**Land preparation** **Ago. Op.** (Organic & phosphate fertilization)	**Planting** (seedlings) **Ago. Op** (Irrigation, Soil Filling)	**Ago. Op.** (.Irrigation, Weeding, Urea Fertilization 1)	**Ago. Op.** (.Irrigation, Weeding)	**Ago. Op.** (.Irrigation, Fertilization)		**Harvest** **Agricultural Operations** (Take off & Drying)					
		Winter season	**Ago. Op.** (Irrigation, Fertilization)		**Harvest** **Agricultural Operations** (Take off & Drying)						**Land preparation** **Ago. Op.** (Organic & phosphate fertilization)	**Planting** (seedlings) **Ago. Op** (Irrigation, Soil Filling)	**Ago. Op.** (.Irrigation, Weeding, Urea Fertilization 1)	**Ago. Op.** (.Irrigation, Weeding)	
Chilly- **Spring season**				**Land preparation** **Ago. Op.** (Organic & phosphate	**Planting** (seedlings) **Ago. Op** (Irrigation, Monitoring Spray)	**Ago. Op.** (.Irrigation, Weeding, Urea Fertilization-1& Spray)	**Ago. Op.** (.Irrigation, Weeding)	**Ago. Op.** (.Irrigation, Fertilization-2)	**Harvest** **Agricultural Operations** (Irrigation& Drying)						
Cucumber		Spring/Summer season	**Land preparation** **Ago. Op.** (Organic & phosphate fertilization)	**Planting & Replanting**	**Ago. Op.**(Irrigation, Weeding, Fertilization Urea , hanging, pruning)	**Harvest**									n the green houses
		Spring season						**Land preparation** **Ago. Op.** (Organic & phosphate fertilization)	**Planting & Replanting**	**Ago. Op.**(Irrigation, Weeding, Fertilization Urea , hanging, pruning)	**Harvest**				
		Winter season	**Harvest**									**Land preparation** **Ago. Op.** (Irrigation, protective spray, Organic &phosphate fertilization)	**Planting /Seedling& Replanting**	**Ago. Op.**(Irrigation, Weeding, Fertilization Urea , hanging, pruning)	

Yemen Food Security Information System (FSIS) Development Programme/ Funded By: European Union

Produced: March, 2018
Contact: FAO-FSIS programme:FAOYE-FSIS@fao.org, FSTS/Ministry of planning & International Cooperation (MoPIC): awmukred@yemen.net.

Annex 6 – Agricultural water consumption 2006 in Abyan, Yemen



Agricultural water consumption 2006
in Abyan, Yemen
Republic of Yemen
Ministry of Agriculture and Irrigation
NWRA
45°15'00"E
45°20'00"E
45°25'00"E
13°25'00"N
13°20'00"N
13°15'00"N
13°10'00"N
13°05'00"N
Am Jiblah
Al Hisn
Ad Dirjaj
Ja'ar
Al Khamilah
Musaymir
Zinjibar
Al Kawd
Abyan
Land use
Uncropped
Rainfed
Single Season Crops
Double Season Crops
Perennial Crops
Bananas

Land use	Area (ha)	Actual ET (mm/yr)
Non agriculture	126,127	254
Irrigated areas	12,973	907
- Single Season irrigated crops	8,510	782
- Double Season irrigated crops	1,551	937
- Perennial irrigated crops	1,344	1,154
- Bananas	1,568	1,343
Gross area	139,101	315

0 mm/yr
300
600
900
1200
1500
1800
N
Scale
1 : 40,600
Actual Annual
Evapotranspiration
Project partners:
GSCP
Eng. Hamoud H.M. Al Rubaidi
Project Director
GSCP@Yemen.net.ye
Tel. +967-1-443219
NWRA
Eng. Salem Hassan Bashuaib
Chairman
NWRAHQ@Yem.net.ye
Tel. +967-1-256926
Hydro Yemen
Eng. Said R. Al-Shaybani
General Manager
Hydro@Yemen.net.ye
Tel. +967-7777-79376
WaterWatch
Generaal Foulkesweg 28A
6703 BS, Wageningen, The Netherlands
Info@WaterWatch.nl
Tel. +31-317-423401
Mott MacDonald
WaterWatch

Annex 7 – List of reviewed literature sources

Reviewed literature files as part of water resources desk study Yemen									
Name file	**Type**	**Titel**	**Year**	**By**	**For**	**Pages**	**Focus Area**	**Topics**	**Folder**
High importance									
Literature from https://www.yemenwater.org/o-water-resources									
Water Crisis Yemen causes consequences solutions	PDF	The Water Crisis in Yemen: Causes, Consequences and Solutions	2010	Nicole Glass		14	Yemen	Brief literature overview on Yemen's water crisis. Discussing causes, consequences and solutions	Water governance & policies
Overview NWSSIP Update	PDF	Overview of the NWSSIP Update	2008?	?		17	Yemen	Briefly outlines the govt structure on watermanagement and description of National Water Sector Strategy and Investment Program 2005-9 (NWSSIP) and its updated strategy 2008-15.	Water governance & policies
Water-Scarcity-in-the-Arab-World	PDF	Water Scarcity in the arab world	?	?		8	Arab countries	Presents figures on annual renewable freshwater per capita (1970, 2000 and 2030 [projected]) as well as water demand by sector in percentage of total water use (2002-2003)	Water demand
Evaluation of WRM in Amran Governate	PDF	Evaluation of the Water Resources Management Situation in Selected Districts of Amran Governorate	2008	GFA, Ghayth Aquatech, OtterWasser	Gtz	26	Amran Governorate: Sawdah, Khamer, Kharef and Theibin	Hydrological baseline and discussion of sectoral water use and WRM issues	Water recources management
Annex-1-Yemens-Water-Cycle	PDF	Yemen's Water Cycle	2007	KfW		1	Yemen	Simplified and schematic overview of Yemen's water cycle	Water Supply
Annex-6-Progress-Water-Resource-Management	PDF	Progress on Key Water Resources Management Actions	2007	KfW		1	Yemen	Tabular national overview of no. Wells, licensing and water resources monitoring	Groundwater resources
Sana Basin IWRM	PDF	Sana'a Basin Integrated Water Resources management - Action oriented policy paper	2010	AOPP		112	Sana'a Basin	Summary of water management challenges in Sana'a Basin, evaluation of water governance & IWRM + improvements. Check water balance for each sub-basin, incl. clear maps from p. 38 onwards	Water governance & policies
Chevalking_smalldams-SanaaBasin_2010	PDF	A technical-institutional analysis of small dams in the Sana’a Basin, Yemen	2010	MetaMeta		67	Sana'a Basin, case study on wadi Al Kharid	Overview of recharge and water distribution Sana'a Basin	Groundwater resources
CountryWRAssistanceStratey_Irrigation_2004	PDF	Country Water Resources Assistance Strategy (CWRAS) - Irrigation Thematic Group	2004	Mukred		19	Yemen	Overview of laws and regulations in irrigation management and ways forward	Water governance & policies
D1.-Water-resources-in-the-GCC-countries-An-overview	PDF	Water Resources in the GCC Countries: An Overview	2000	Al-Rashed & Sherif		17	Gulf Countries	Discussion of general geology (incl. useful maps) of Arabian Peninsula and aquifer recharge estimates. Unclear whether it also covers Yemen aquifers, because Yemen is not part of the GCC countries.	Groundwater resources
Deraft-Report-Wadi-Harad-and-Al-Jar	PDF	TIHAMA WATER RESOURCES MANAGEMENT Wadi Harad and Al Jar Water Quality	?	NWRA			Sana'a Basin: Wadi Al Jar and Wadi Harad	Hydrochemical study on water quality in Wadi Harad and Wadi Al Jar	Groundwater quality
Deraft-Report-Wadi-Mawr1	PDF	TIHAMA WATER RESOURCES MANAGEMENT Wadi Mawr Water Quality	?	NWRA			Al Hudaydah: Wadir Mawr	Hydrochemical study on water quality in Wadi Mwar	Groundwater quality
WRM action plan Taiz region 2004	PDF	Water Resources Management Action Plan for the Ta'iz region (Upper Wadi Rasyan)	2004	NWRA			Ta'iz region: upper wadi rasyan	Overview of water supply and demand and subsequent required water governance actions in Ta'iz region with water balance figures of 1999.	Water resources management
Negenman-T.-2000	PDF	Evolution of water resources management in Yemen	1997	Negenman			Yemen	Hydrogeological map of yemen (p.4 black&white), Abstraction figures of 1995 for several aquifer complexes (p.3).	Groundwater resources
Options-Analyses-for-Sana_final-draft_FINAL	PDF	The Sana'a Water Issues and Options Study	2011	RTI	World BANK	61	Sana'a Basin	WEAP Model development and results, including different scenario analyses. Includes sub-basin maps of sana'a basin on page 5 and aquifer characteristics from page 11 onwards	Water infrastructure developments

Paper-2-A	PDF	National Conference for the Management and Development of Water Resources in Yemen: Managing water for social equity, economic efficiency and environmental stability: governing spate-flood Irrigation for social equity, environmental sustainability and economic output.	2011	Kuster et al		29	Yemen	Water governance directions on water rights and use in irrigated agriculture	Water governance & policies
Paper-2-B	PDF	National Conference for the Management and Development of Water Resources in Yemen: Agriculture's contribution to solving the water crisis	2013	Al-Eshlah et al		15	Yemen	Presents figures on irrigated areas and qat cultuvation 1970-2008, rate of depletion of aquifers and sectoral water demand from 1990-2010. Also lists an overview of MAI interventions	Water governance & policies
The+study+for+the+water+resources+management+and+rural+water+suppl y+improv	PDF	THE STUDY FOR THE WATER RESOURCES MANAGEMENT AND RURAL WATER SUPPLY IMPROVEMENT IN THE REPUBLIC OF YEMEN WATER RESOURCES MANAGEMENT ACTION PLAN FOR SANA'A BASIN - Main report	2007	JICA	NWRA, MWE	117	Sana'a Basin	Projections of water demand from 2005-2020 based on various scenarios. Extensive hydrological baseline data for Sana'a basin, including maps of dam and spring locations (p.31), estimates of GW recharge in sub-basins (p.32), list of alternative water sources (p.34), overview of sectoral water uses and detailed water balances.	Water resources management
JICA-Final-report-complete-supporting-report	PDF	THE STUDY FOR THE WATER RESOURCES MANAGEMENT AND RURAL WATER SUPPLY IMPROVEMENT IN THE REPUBLIC OF YEMEN WATER RESOURCES MANAGEMENT ACTION PLAN FOR SANA'A BASIN - Supporting report	2007	JICA	NWRA, MWE	358	Ta'iz region and Sa'dah basin, Sana'a basin	More in-depth maps of water resources, geology, aquifer yields and water quality etc. of Sana'a Basin. Policy overview and WRM plans for Tai'z region and Sa'dah Basin	Water resources management
Report-II-v2	PDF	Unknown	2001	WEC		85	Sana'a basin	Useful geological maps Sana'a Basin with extensive description of geological formations and aquifer systems.	Groundwater resources
incentives_to_reduce_groundwater_e xtraction_in_ye-wageningen_university_and	PDF	Incentives to reduce groundwater extraction in Yemen	2008	LEI, WUR		133	Yemen: Sana'a basin, Taiz Basin and Wadi Hadramout	Includes literature review on water prices and use (water balance of 2005) and policy analysis	Water governance & policies
SANAA-CITY-WATER-SITUATION	PDF	Sana'a city water situation	2005	Prof. Sufian	Renewable energy conference	26	City of Sana'a	Present and new sources of water for Sana city are discussed. Incl. map of well density	Water supply
Summary_Draft-Final-_Formatted-JonY	PDF	Assessment of Water Resources of the Sana'a Basin Strategic Options for the Sustainable Development of the Basin's Water Resources	2010	HYDROSULT/WEC/TNO		67	Sana'a Basin	Aquifer storage investigations and assessment, aquifer modeling studies of Sana'a basin	Groundwater resources
Thesis-Defence-Musaed	PDF	The Potential Of Rooftop Rainwater Harvesting For Sana'a, Yemen	2011	Aklan		38	Sana'a basin	Thesis presentation for potential of rooftop water harvesting and storage in Sana'a basin	Water supply
TheWaterResourcesOfYemen1 (wray-35.pdf for high resolution text)	PDF	The Water Resources of Yemen - a summary and digest of available information	1995	van der Gun		267	Yemen	Large document with a vast amount of baseline information on geology, water resources, climate, surface water, groundwater and management. Although some might be dated, report includes lots of maps and figures. E.g. aquifer map on p. 85 or geology map p.18	Water resources management
Volume1-0-MainReport_Jan-_Final-12th-jan_editeddoc	PDF	IRRIGATION IMPROVEMENT PROJECT: WATER RESOURCES ASSESSMENT AND DETAIL DESIGN OF DIFFERENT COMPONENTS OF WADI AHWAR- ABYAN	2008	HYDROSULT/WEC/TNO	MAI	92	Sana'a: Wadi Ahwar-Abyan	Water resource assessment of Wadi Ahwar-Abyan and suggested irrigation system design.	Water infrastructure developments
Wadi_Zabid_Remaa_water_quality_R eport1	PDF	TIHAMA WATER RESOURCES MANAGEMENT Wadi Zabid & Wadi Rima water quality	2009	NWRA		96	Sana'a Basin: Wadi Zabid & Wadi Rima	Hydrochemical study on water quality in Wadi Zabid & Wadi Rima	Groundwater quality
Water-Quality_-Wadi-Surdud	PDF	TIHAMA WATER RESOURCES MANAGEMENT Wadi Surdud water quality	2009	NWRA		87	Sana'a Basin: Wadi Surdud	Hydrochemical study on water quality in Wadi Surdud	Groundwater quality
YE-Qat	PDF	YEMEN: CDR Building Block Qat	?	Ward		28	Yemen	Discusses use, cultivation of Qat in Yemen	Water demand

Yemen_CWRAS	PDF	REPUBLIC OF YEMEN COUNTRY WATER RESOURCES ASSISTANCE STRATEGY	2005	World Bank		103	Yemen	Overview of water sectoral problems, challenges and Yemen's strategic respons through the NWSSIP program	Water governance & policies
YemenWater	PDF	Yemen s Water Resources And Treated Wastewater	?	Abdul-Malik		8	Yemen	Overview of water resource institutions existing in yemen (p.5 & p.6) and waste water quality in various regions of Yemen	Water resources management
List+of+Technical+Reports+and+Publications+Related+to+the+Water+Resources+o	PDF	List of technical reports and publications related to the water resources of Yemen	?	WRAY		115	Yemen	Vast list of technical reports and publications related to water resources of Yemen.	General
Study+into+Water+resources+in+AlBayda+province+part1	PDF	Rada Integrated rural development project: Study into water resources in Al Bayda Province	1984	Ilaco		112	Al Bayda: Rada basin	Hydrogeolocial baseline data of Al Bayda region.	Water resources management
Study+into+Water+resources+in+AlNayda+province+Part2	PDF	Rada Integrated rural development project: Study into water resources in Al Bayda Province - Annexes	1984	Ilaco		215	Al Bayda: Rada basin	Background data including extensive geological data of Al Bayda region	Water resources management
Water+resources+of+the+SADAH+Area+main+report+	PDF	Water Resources of the Sadah Area	1985	van der Gun		53	Sadah Area	Hydrogeolocial baseline data of Sadah area	Water resources management
Water+Resources+Wadi+Adhanah+and+Marib+area	PDF	Water resources of Wadi Adhanah and Marib area	1990	Uil and Dufour		148	Wadi Adhanah and Marib area	Hydrogeolocial baseline data of Wadi Adhanah and Marib area	Water resources management

Literature from https://www.yemenwater.org/o-special-topic-groundwater

Review-of-Yemens-control-of-groundwater-extraction-regime-situation-and-opt	PDF	Review of Yemen's control of groundwater extraction regime: situation and options	2014	Alderwish et al		18	Yemen	The paper assess and examines the alternative options that exist in Yemen to prevent overexploitation of groundwater resources and shows lessons from experience and future directions. It discusses present interventions and functioning.	Water governance & policies
Salient_Features_Spate_GSCP	PDF	Groundwater & Soil Conservation Project: SALIENT FEATURES OF SPATE SCHEMES UNDER GSCP	2011	MIA		47	Yemen	Tabular overview of major spate irrigation schemes across the country, including catchment areas, design discharge and locations	Water demand
Wadi-Hadhramowt-WQ-Report	PDF	Wadi Hadhramawt: Changes in groundwater chemistry between 2001 and 2011	2011	NWRA		79	Wadi Hadhramawt (same as Hadramut?)	Hydrochemical study on water quality in Wadi Hadhramawt	Groundwater quality
Wahib-Al-Qubatees-Thesis	PDF	ARTIFICIAL RECHARGE ASSESSMENT OF GROUNDWATER THROUGH MEKHTAN DAM BANI HUSHEISH , SANA'A BASIN – YEMEN	2009	Al-Qubatee		150	Sana'a basin: Wadi Sa'wan	Hydrogeological baseline of Sana'a basin including geoelectrical surveys and groundwater artifical recharge eveluations in Wadi Sa'Wan region. Report includes maps with dam locations in Sana'a basin.	Groundwater resources
Groundwater+in+the+BAQIM+plain+final+report	PDF	GROUNDWATER RESOURCES IN THE BAOIM PLAIN	1993	DHV		83	Hajjah and Sa'dah	Well inventory of the Baqim plain, including geological setting, aquifer system, and water balance.	Groundwater resources
Groundwater+in+the+Nothern+TIHAMA+region+Final+report	PDF	Groundwater resources and use in the northern tihama region (Hajjah)	1993	DHV		138	Sa'dah	Well inventory of the Tihama region, including geological setting, aquifer system, and water balance.	Groundwater resources
Groundwater+resources+and+use+in+the+Al+HAMRA+plain+Final+report	PDF	GROUNDWATER RESOURCES AND USE IN THE AL HAMRA PLAIN	1993	DHV		80	Sa'dah, Amran	Well inventory of the Al hamra plain, including geological setting, aquifer system, and water balance.	Groundwater resources
Groundwater+resources+and+use+in+the+Al+HARF+plain+Final+report	PDF	GROUNDWATER RESOURCES IN THE AL HARF PLAIN	1993	DHV		79	Hajjah, Sa'dah	Well inventory of the Al harf plain, including geological setting, aquifer system, and water balance.	Groundwater resources
Groundwater+resources+and+use+in+the+ALSHSHAH+plain+Final+report	PDF	GROUNDWATER RESOURCES IN THE AL ASHSHAH PLAIN	1993	DHV		82	Hajjah, Sa'dah	Well inventory of the al ashshah plain, including geological setting, aquifer system, and water balance.	Groundwater resources
Groundwater+resources+and+use+in+the+ATTAF+plain+Final+report	PDF	GROUNDWATER RESOURCES AND USE IN THE ATTAF PLAIN	1993	DHV		82	Hajjah, Sa'dah	Well inventory of the attaf plain, including geological setting, aquifer system, and water balance.	Groundwater resources
Groundwater+resources+investigation+in+the+AMRAN+valley+_compressed	PDF	Ground-water resources investigation in the amran valley, yemen	1980	Tibbitts and aubel (USGS)		147	Amran	Well inventory and geological overview of sub-districts in amran valley	Groundwater resources

1st-2nd-Reports	PDF	Groundwater in the policital domain	2014	WEC & metameta		43	Yemen	Clear overview of institutional setup of water sector and all relevant organisations at national, regional and field level (p.5) and further elaborated from p.19 onwards	Water governance & policies
Al-Hebshi-M.-A-Economics_of_Water	PDF	Economic incentive structures for groundwater extraction in Yemen	?	Al-Hebshi		27	Yemen	Provides basic overview of water tariffing options and price of water in Sana'a in 2008	Water governance & policies
Al-Mujaylis_Paper-	PDF	Collaborative Research To Assess the Degradation of Groundwater Resources in Al-Mujaylis, Tihama Coastal Plain, Yemen	?	Al-Qubatee et al			Tihama coastal plain (south of Hudaydah)	Qualitative analysis of groundwater degradation in Wadi Zabid and Wadi Rima. Geological map of Zabid region.	Groundwater resources
Al-Mujaylis-Final-Draft-Report-with-Appendixes_2	PDF	Groundwater in the political domain: Al-Mujaylis case study	?	Al-Qubatee et al		47	Tihama coastal plain (south of Hudaydah)	Overview of hydrologic and socio-economic problems in Al-Mujaylis area and water governance analysis on water rights in Wadi Zabid and Wadi Rima.	Water governance & policies
Redistribution+of+Groundwater+Abstraction+in+Wadi+As+Ssirr	PDF	Redistribution of Groundwater Abstraction in Wadi As Ssirr: A Task for the Local Water User Associations	2005	Al-Sakkaf et al		8	Sana'a Basin: Wadi As Ssirr	Map with location of wells in Wadi As Sirr and estimate on groundwater abstraction.	Groundwater resources
Environmental+Management+in+Sana'a+Basin+Urbanization+and+Degradation+of+Groundwater+Qual	PDF	Environmental Management in Sana'a Basin: Urbanization and Degradation of Groundwater Quality	2006	Al-Sakkaf et al		8	Sana'a Basin	Paper discusses groundwater polution in Sana'a basin and management instruments to control it.	Groundwater quality
Aquifer-System-in-Yemen	PDF	Principals of groundwater	?	?		42	Yemen	Provides a useful overview of existing aquifer types in Yemen, especially from p. 8 onwards	Groundwater resources
CP03.-Rationalizing-groundwater-resource-utilization-in-the-sanaa-basin-Yemen	PDF	RATIONALIZING GROUNDWATER RESOURCE UTILIZATION IN THE SANA'A BASIN – YEMEN	2003	Foster	Worldbank	10	Sana'a Basin	Overview of groundwater resource balance in Sana'a Basin and possible interventions that may reduce aquifer depletion	Groundwater resources
Dieselpaperdraft4	PDF	Politics Impact, Diesel Availability, Groundwater Accessibility Nexus In Yemen Implications of 2011 Diesel Crisis	?	?	?	31	Yemen	Discusses elaborately the impact of 2011 diesel crises on groundwater accessibility	Groundwater resources
Fact-sheet-1	PDF	Management of Groundwater by Local Organizations	?	WEC & metameta	CoCoon project	4	Wadi Sana'ah (Dhamar city) & Khrabat Muuhyab (Sana'a)	Two examples of organization over water management are discussed, together with recommendations on how to improve	Water governance & policies
Farrag-A.A.-A.S.-Al-Gabiri-and-A.-Abdulgader	PDF	SURFACE WATER POLLUTION AND ITS EFFECT ON GROUNDWATER IN TAIZ WATER BASIN	?	Farrag et al		8	Ta'iz basin	Paper discussing groundwater quality analysis in Taiz basin area. Includes description of surface water system, groundwater system. Water sample analysis seems to be missing.	Groundwater resources
Groundwater-Security-in-Yemen-MetaMeta	PDF	GROUNDWATER SECURITY IN YEMEN Role and Responsibilities of Local Communities in Conserving Groundwater		Steenbergen		34	Sana'a and Taiz basin	Discusses local groundwater management at different locations in Sana'a and Taiz region. Provides lessons and recommendations how to improve gw management.	Water governance & policies
Groundwater01	PDF	A Strategy for Controlling Groundwater Depletion in the Sa'dah Plain, Yemen	1999	Al-sakkaf et al		17	Sa' dah plain (northwest yemen)	Discusses hydrogeology of Sa'dah plain and groundwater depletion. Provides strategies for better management	Groundwater resources
Hellegers-P.J.G.J.-Perry-C.J.-and-Al-Aulaqi-N.-2008	PDF	Paper: Incentives to reduce groundwater consumption in Yemen	2008	Hellegers et al	NWRA	13	Yemen	In this paper options for changing the incentive structure to reduce unsustainable groundwater consumption in Yemen are evaluated. Includes different tables on Value/cost ratio of major crops in Sana'a, Taiz and Hadramaut (p.5)	Water demand
Problems+of+Groundwater+Development+in+the+Sana'a+Basin+Yemen	PDF	Problems of groundwater development in the Sana'a basin, Yemen Arab Republic	1982	Charalambous		10	Sana'a basin	Discusses groundwater recharge and aquifers in Sana'a basin	Groundwater resources
Ideas-for-Groundwater-Management-Digital	PDF	IDEAS FOR GROUNDWATER MANAGEMENT	2008	Metameta IUCN		144	oa Yemen	Discusses several ideas for groundwater management and uses examples of Yemen.	Water resources management
Interim_report	PDF	Satellite Imagery follow-up study	2012	Waterwatch & Hydro-yemen	MAI	48	Siham, Dhamar, Rada & Abyan	Study identifies changes in land use and water consumption between 2006 and 2010. Presents map with major wadi catchments	Water demand

Literature from https://www.yemenwater.org/o-water-for-agriculture

how-Yemen-chewed-itself-dry-Adam-Heffez-Foreign-Affairs	PDF	How Yemen Chewed itself Dry: Farming Qat, Wasting water	2013	Heffez		5	Yemen	Opinion paper on qat and possible management interventions Yemen government could take	Water governance & policies
Effect-of-Modern-Agricultural-Techniques-on-Sustainability-of-Groundwater-	PDF	Effect of Modern Agricultural Techniques on Sustainability of Groundwater and Enhancing Field Crops Production in Dhamar	?	Al washali et al		3	Dhamar region	Paper discusses results of trial with improved irrigation methods in Dhamar region, suggesting drip irrigation in greenhouses could lead to substantial savings of water in tomato cultivation.	Water demand
Draft_AlternativeAgriculturalVision-2025	PDF	How Yemen Chewed itself Dry: Farming Qat, Wasting water	?	?		4	Yemen	Opinion article suggesting alternative options to improve agriculture and cope with challegens in the agricultural sector regarding water shortages. No scientific basis, and rather standard options (water conservation, improved irrigation, enhancing agri. marketing and alternative crop growth to replace qat	Water governance & policies
DIPMSC-presentation	PDF	Water harvesting	?	Tahir		58	Yemen	Discussion of water harvesting in Yemen. Nice topographic map of yemen on p. 34. Calculations on water harvesting potential are limited	Water Supply
Water+charging+in+irrigated+agriculture	PDF	Water charging in irrigated agriculture: an analysis of international experience	2004	FAO		98	General	Discusses water tariffing and presents right table on the need for adjustments in water tariffing strategy in Yemen	Water governance & policies
Annex-8-Water-Savings-Potentials-in-Agriculture	PDF	Water savings potentials in agricultural use	2007	Redecker		1	Yemen	Nice and clear flow chart on options to reduce irrigation GW use and GW abstraction	Water demand
Annex-7-Water-Savings-Potentials-in-Domestic-Use	PDF	Water saving potentials in domestic use	2007	Redecker		1	Yemen	Nice and clear flow chart on options to reduce domestic water use	Water demand
Annex-5-List-of-PIP-Projects-Agriculture	PDF	List of PIP project proposals for agriclture/irrigation	2007	Redecker		1	Yemen	Overview of development projects in period 2007-2013. Unknown whether overview is complete.	Water infrastructure developments
Annex-3-Matrix-Joint-Elements-of-Water-and-Agriculture	PDF	Matrix of joint elements of IRR and WRM objectives, policies and approaches	2007	Redecker		1	Yemen	Overview of overlapping elements in the NWSSIP program regarding IRR and WRM. Might be useful for section on policies regarding water management	Water governance & policies
AdenAgendafull_frameworkforstructuraladjustment-MAI_1998	PDF	Framework of the Structural Adjustments For Reform of the Agriculture and Irrigation Sector	2000		MAI	67	Yemen	Report with suggestions to structurally reform the MAI. Discusses yemeni agricultural sector, challenges and modernization/development prospects. Though dated, it might be useful as a comparison to current situation	Water governance & policies
Yemen1Use+of+Brackish+water+for+agriculture+production+in+the+Near+East+No	PDF	Use of Brackish Water for Agricultural Production in the Near East and North Africa: Case study of Yemen	2013	Al-sabri		18	Yemen	Presentation discussing the posibilities for brackish water use in agriculture	Water Supply

Yemen-Country-Report_Brackish-Water-Use	PDF	Status and New Developments on the Use of Brackish Water for Agricultural Production in the Near East: Yemen country report	2012	Al-Sabri		39	Yemen	Discusses water quality in yemen and status of brackish water use in various wadi's across the country (oa Wadi Mawr, Zabid, Abyan delta). Clear maps on EC values of water. Overview of existing and planned WWTPs in Yemen	Groundwater quality
Ward-Gatter-2000-Qat-in-Yemen-PDF	PDF	Qat in Yemen Towards a Policy and Action Plan	2000	Ward and Gatter		108	Yemen	Thorough overview of qat in yemen: socio-economic aspects, requirements and impact on agriculture and water, impact on health. Is often referred to document.	Water demand
Tihama-Environment-Protection-Project	PDF	Tihama Environment Protection Project Interim Evaluation Report	2003	IFAD		99	Tihama region (hodeidah and south)	Useful maps on page 9 and 11 and 13 on dune progression and settlment locations in project area within tihama plain (hodeidah and south)	General
Tehama-refer	PDF	Tehama-refer	?	?		12	Taiz reigon (Wadi Tuban, Zabid)	Seems to be an overview of literature findings on Taiz reigon (Wadi Tuban, Zabid). Description of Zabid alluvial aquifer system and productiivity (p.8/9). Rainfal map of Wadi Zabid and Rima (p.10)	Groundwater resources
MAI_Qat_Workshop_2008Report	PDF	Qat Policy Review Workshop "Towards practical Policies for Limiting the Expansion of Qat Cultivation"	2008	Gatter & Williams	MAI, Worldbank	46	Yemen	Qat policy review and outcomes of group discussions. Oa overview of actions taken to combat qat development. Might be interesting to go through the outcomes of the working groups p.11-14. Presents conditions to be met by alternative crops	Water demand
Assessment+study+of+the+impact+of+agriculture+demonstration+program+in+production+and+inc	PDF	Assessment Study of the Impact of Agricultural Demonstrations Program on Production and Income in Zabid and Tuban Valleys	2007	Qaid	MAI		Zabid and Tuban	Discusses irrigated agriculture in Zabid and Tuban valleys, presenting figures on agr. Production area and yield	Water demand
IFAD-PDR-Yemen-EOP-Main-report-and-annexes	PDF	The International Fund for Agricultural Development REPUBLIC OF YEMEN ECONOMIC OPPORTUNITIES PROGRAMME Programme Final Design Report	2010	IFAD			Yemen	P.9-14 present a consice country profile with high amount of statistics on demography, poverty, agriculture. Might be useful as country introduction	General

Literature from https://www.yemenwater.org/o-hydrology

mapping+and+evaluation+of+GW+Sa'dah+Region+	PDF	MAPPING AND EVALUATION OF GROUNDWATER IN THE WAJID SANDSTONE OF THE SA'DAH REGION	1993	DHV		38	Sa'dah	Presents mapping and description of Wajid Sandstone complex and aquifer system.	Groundwater resources
Geology-of-Yemen	PDF	Geology of yemen	?	?		48	Yemen	Presentation discussing the geology of Yemen, highlighting major rifts and formations. Contains useful maps (e.g. p.46). Useful to have a general idea of geological builtup!	Groundwater resources
Yemen-fig5.1	PDF	Main surface water systems in Yemen	1995	Van der Gun		1	Yemen	High resolution map showing the major surface water systems in Yemen (incl. names of major rivers).	Water resources management
Yemen-fig2.3	PDF	Geological map of Yemen	1995	Van der Gun		1	Yemen	High resolution map showing the general geological formations in Yemen.	Water resources management
Varisco1983HumanEcology	PDF	Sayl and Ghayl: The Ecology of Water Allocation in Yemen	1983	Varisco		20	Yemen	Paper discussing the two major types of water allocation systems in yemen: seasonal flood (sayl) and highland spring flow (ghayl). Especially the elaborate definition/characterisation of both systems may be interesting for the seciton on surface water systems	Water Supply
Traditional-Water-Rights-in-the-Wadi-Zabid-Tuban	PDF	Legal Survey of Existing Traditional Water Rights in the Spate Irrigation Systems in Wadi Zabid and Wadi Tuban.	2004	Bahamish		60	Wadi Zabid & Wadi Tuban	Overview of water rights existing in spate irrigation systems of Wadi Zabid & Wadi Tuban	Water governance & policies

TDA_DesignManual_Volume2_14Dec	PDF	Design manual: GUIDELINES FOR WADI DIVERSION AND PROTECTION WORKS	2008	Ratsey		36	Yemen	Design manual for wadi diversion & protection works. Presents some nice pictures, which we might include in recommendations section. Also this manual might be of use when providing follow-up advise on detailes wadi catchments.	Water resources management
TDA_DesignManual_Volume1_14Dec	PDF	Design manual: technical design criteria	2008	Ratsey		28	Yemen	Presentation of design criteria for wadi diversion and protection works	Water resources management
second-draft-samary-for-wadi-zabeed	PDF	Remote Sensing for Assessment of Water budget in Wadies Zabid &Rima	2011	Almhab		76	Wadi Zabid & Wadi Rima	Remote sensing analysis to draft a water balance for Wadi Zabid & Wadi Rima. Doubt on the quality of results presented in this report.	Groundwater resources
SATELLITE-ANALYSIS-OF-CROPPING-AND-IRRIGATION-WATER-USE	PDF	Satelite analysis of cropping and irrigation water use	?	WEC, ITC Twente		51	Sana'a Basin	Presents remote sensing analysis of land use changes and water use between 1985-1998. Dated figures and numbers, but approach might be replicable if necessary	Water demand
Sanaa-well-inventory-Figures-Maps	PDF	Sana'a well inventory Figures	2005	WEC		39	Sana'a Basin	High resolution maps of sana'a basin showing all types of well inventories (e.g. annual groundater abstraction per km2, source and quality of water etc.)	Groundwater resources
Poster_Rada_Yemen	PDF	Agricultural water consumption 2006 in Rada, Yemen	2006	NWRA		1	Rada	Low resolution map showing agricultural water consumption in rada, incl. tabular information on area and actual ET	Water demand
Poster_Dhamar_Yemen	PDF	Agricultural water consumption 2006 in Dhamar, Yemen	2006	NWRA		1	Dhamar	Low resolution map showing agricultural water consumption in Dhamar, incl. tabular information on area and actual ET	Water demand
Poster_Siham_Yemen_Left	PDF	Agricultural water consumption 2006	2006	NWRA		1	Al hudaydah region	Low resolution map showing agricultural water consumption in Al hudaydah region,	Water demand
Poster_Thema_Yemen	PDF	Agricultural Water Management Yemen	2006	NWRA		1	Dhamar	Low resolution maps showing dams and faults, water stress coefficients, agricultural water consumption in Dhamar, incl. tabular information on area and actual ET	Water demand
Poster_Abyan_Yemen	PDF	Agricultural water consumption 2006 in Abyan, Yemen	2006	NWRA		1	Abyan	Low resolution map showing agricultural water consumption in Abyan, incl. tabular information on area and actual ET	Water demand
part-IV-water-quality-report-edited-milli	PDF	HYDROLOGICAL MONITORING AND ANALYSES IN SANA'A BASIN DRAFT FINAL REPORT (Part IV: Water Quality Report)	2008	HYDROSULT/WEC/TNO		1	Sana'a basin	Extensive water quality report on Sana'a basin with comparisons between 1986 and 2007. All presented in tabular and maps form per aquifer comples.	Groundwater quality
part-II-Surface-water-edited-milli	PDF	HYDROLOGICAL MONITORING AND ANALYSES IN SANA'A BASIN DRAFT FINAL REPORT (Part II: Surface Water Report)	2008	HYDROSULT/WEC/TNO		160	Sana'a basin	Extensive list of dam locations incl. coordinates in Sana'a basin (p.9). Discusses potential locations for surface water runoff stations.	Water resources management
part-I-Rainfall-weather-Stations-April-15-2008-milli	PDF	HYDROLOGICAL MONITORING AND ANALYSES IN SANA'A BASIN DRAFT FINAL REPORT (Part I: Rainfall and Meteorological Network)	2009	HYDROSULT/WEC/TNO		46	Sana'a basin	Report showing rainfall monitoring stations in sana'a basin, including their recording period and maps of isohyetale lines (1972-2005).	Water resources management
Hydrology-of-Yemen	PDF	Hydrology of Yemen	2006	Abdulla Noman (WEC)		72	Yemen	Useful report discussing hydrology of yemen, from topography to geology, hydrogeology, soils, agroecological systems, climatic zones (incl. tabular and areal info p.10), tabular information on runoff in main catchments (p. 36), main rain water harvesting techniques used in yemen (p. 57 onwards)	Water resources management
Graphics-ed2-rev1	PDF	Hydrological analysis - Irrigation improvement project	2003	?		34	Wadi Zabid	Elaborate rainfall and runoff statistics of Wadi Zabid.	Water supply
geolmap_100	PDF	Sana'a basin water management project - Compiled geological map	?	GAFag	MWE	1	Sana'a basin	High resolution 1:100 000 geological map of sana'a basin	Groundwater resources
geolmap_50_d	PDF	Sana'a basin water management project - Compiled geological map Sheet D	?	GAFag	MWE	1	Sana'a basin	High resolution 1:50 000 geological map of southeast of sana'a basin	Groundwater resources

geolmap_50_c	PDF	Sana'a basin water management project - Compiled geological map Sheet C	?	GAFag	MWE	1	Sana'a basin	High resolution 1:50 000 geological map of northeast of sana'a basin	Groundwater resources
geolmap_50_b	PDF	Sana'a basin water management project - Compiled geological map Sheet B	?	GAFag	MWE	1	Sana'a basin	High resolution 1:50 000 geological map of northwest of sana'a basin	Groundwater resources
geolmap_50_a	PDF	Sana'a basin water management project - Compiled geological map Sheet A	?	GAFag	MWE	1	Sana'a basin	High resolution 1:50 000 geological map of southwest of sana'a basin	Groundwater resources
AyoubAlmhabPG053005d09ttt	PDF	ESTIMATION OF REGIONAL EVAPOTRANSPIRATION USING REMOTE SENSING DATA IN ARID AREAS	2009	Almhad		346	Sana'a basin, Wadi Tuban, Wadi Hadramout	Thesis presenting Evapotranspiration analysis for Sana'a basin , Wadi Tuban, and Wadi Hadramout using remote sensing. Unfortunate not many in-depth/useful analyses relevant for our report	Water resources management
Act-1-Ch-10-Hydrogeological-findings-sep2008-milli-completed	PDF	Sana’a Basin Water Management Project - Hydro-geological and Water Resources Monitoring and Investigations - Ch 10	2008	HYDROSULT/WEC/TNO		24	Sana'a basin	Hydrogeologic findings in sana'a basin incl. water quality data for the different aquifers in Sana'a basin and maps/tables on lineaments in the basin	Groundwater quality
Act-1-Ch-9-Groundwater-storage-sep2008-milli-completed	PDF	Sana’a Basin Water Management Project - Hydro-geological and Water Resources Monitoring and Investigations - Ch 9	2008	HYDROSULT/WEC/TNO		38	Sana'a basin	Maps on recoverable groundwater storage in Sana'a basin aquifers	Groundwater resources
Act-1-Ch-8-Groundwater-Depletion-milli-completed	PDF	Sana’a Basin Water Management Project - Hydro-geological and Water Resources Monitoring and Investigations - Ch 8	2008	HYDROSULT/WEC/TNO		32	Sana'a basin	Maps showing groundwater depletion in Sana'a basin aquifers	Groundwater resources
Act-1-Ch-7-Hydrogeochemical-Setting-milli-completed	PDF	Sana’a Basin Water Management Project - Hydro-geological and Water Resources Monitoring and Investigations - Ch 7	2008	HYDROSULT/WEC/TNO		110	Sana'a basin	Hydrogeochemical setting of Sana'a basin, discussing major hydrochemicals in the different aquifer systems. Very useful when considering water quality	Groundwater quality
Act-1-Ch-6-Groundwater-Occurrence-milli-completed	PDF	Sana’a Basin Water Management Project - Hydro-geological and Water Resources Monitoring and Investigations - Ch 6	2008	HYDROSULT/WEC/TNO		56	Sana'a basin	Groundwater occurence in sana'a basin incl. groundwater level data, groundwater flow in the various aquifers, groundwater recharge and discharge. Discusses public/private/rural water supply and agricultural water use (2004-2006)	Groundwater resources
Act-1-Ch-5-Aquifer-Capacity-milli-completed	PDF	Sana’a Basin Water Management Project - Hydro-geological and Water Resources Monitoring and Investigations - Ch 5	2008	HYDROSULT/WEC/TNO		64	Sana'a basin	Aquifer capacity in sana'a basin, incl. pumping tests of the various aquifer systems	Groundwater resources
Act-1-Ch-4-Aquifer-Geometry-milli-completed	PDF	Sana’a Basin Water Management Project - Hydro-geological and Water Resources Monitoring and Investigations - Ch 4	2008	HYDROSULT/WEC/TNO			Sana'a basin	Aquifer geometry in sana'a basin, discussing surface water system, groundwater zones and elaborately describes aquifer geometry	Groundwater resources
Act-1-Ch-3-Geological-Setting-milli-completed	PDF	Sana’a Basin Water Management Project - Hydro-geological and Water Resources Monitoring and Investigations - Ch 3	2008	HYDROSULT/WEC/TNO		94	Sana'a basin	Geological setting of Sana'a basin incl. results of geological field surveys carried out in Nihm, Bani Hushaish, Hamadan and Arhab area	Groundwater resources
Act-1-Ch-2-Preparatory-activities-milli-completed	PDF	Sana’a Basin Water Management Project - Hydro-geological and Water Resources Monitoring and Investigations - Ch 2	2008	HYDROSULT/WEC/TNO		63	Sana'a basin	Overview of (outputs of) past hydrogeological studies in sana'a basin. Discussion of boundaries of groundwater flow system and aquifer capacity	Groundwater resources
Act-1-Ch-1-Introduction-milli-completed	PDF	Sana’a Basin Water Management Project - Hydro-geological and Water Resources Monitoring and Investigations - Ch 1	2008	HYDROSULT/WEC/TNO		9	Sana'a basin	Introduction on the report on Hydro-geological and Water Resources Monitoring and Investigations in Sana'a basin	Groundwater resources
20120710_Final-report_Satellite-Imagery_follow-up	PDF	Satellite Imagery follow-up study	2012	Waterwatch & Hydro-yemen	MAI	180	Siham, Dhamar, Rada & Abyan	Study identifies changes in land use and water consumption between 2006 and 2010 for Siham, Dhamar, Rada & Abyan using satellite imagery. Especially Abyan might be of interest to this study	Water demand
Literature from https://www.yemenwater.org/new-page-5 (water management)									
Activity-2-Draft-Final-Report-May-2009-last-Word-97-milli	PDF	SANA’A BASIN WATER MANAGEMENT PROJECT - Sub-Component 3(d) Hydro-geological and Water Resources Monitoring and Investigations - ACTIVITY 2: WATER BALANCE ESTIMATION AND SUB-BASIN MONITORING	2009	HYDROSULT/WEC/TNO		173	Sana'a Basin	Water balance and rainfal runoff analysis for six major dams in Sana'a basin.	Water resources management

10-Inegrated-watershed-management-for-recharge-dam-paginaged	PDF	INTEGRATED WATERSHED MANAGEMENT FOR RECHARGE DAMS IN SANA'A BASIN - YEMEN	2010	Alderwish		30	Sana'a Basin	Assessment of environmental, social and economical benefit of 10 constructed dams in small wadis in Sana'a basin.	Water Supply
Water+Buffer+Management+Retentio n,+Recharge+and+Reuse+of+AlSayla+Water+in+Sana'a+Basin+	PDF	Water buffer management retention, recharge and reuse of Al Sayla water in Sana'a Basin	2016	Saleh et al		42	Sana'a Basin	Overview of 3R approach for Wadi Al Saylah in Sana'a basin	Water resources management
Water+Managment+plan+SA'DAH+plain+target+area	PDF	WATER MANAGEMENT PLAN SA'DAH PLAIN TARGET AREA	1994	DHV		186	Sa'dah plain	Large report on water management in sa'dah plain, including maps on well locations, withdrawal figures, agricultural water management and use.	Water resources management
BorgiaBonzanigoFinalThesis8Nov2009 pdf	PDF	Tracing evolutions of water control in Wadi Siham, Yemen	2009	Bonzanigo & Borgia		116	Tihama plain / Hodeidah (Wadi Siham)	Apart from intstitutional and water governance review of three case study areas (Burquqa, Khalifa, Waqir) it contains several maps indicating the irrigation and dam structures in the study area (e.g. p 38) and provides a useful overview of water management institutions playing a role in the area.	Water resources management
032010_Chevalking_SmallDamsPresentation_WEC-Seminar	PDF	A social - technical analysis of small recharge dams and their implications local community and basin	2010	Chevalking		42	Sana'a basin	Presentation on dam development and implementation in Sana'a basin. Covering instutional setting involved at basin level (p. 7)	Water supply
Zeitoun-PE-of-WDM-in-Yemen-and-Jordan-2009	PDF	The Political Economy of Water Demand Management in Yemen and Jordan: A Synthesis of Findings	2009	Zeitoun (IDRC)		52	Yemen	Report addresses power-related obstacles to implementation of water demand management measures. Power analysis is used to assess relative influence of each stakeholder towards implementing water demand management measures (p. 23). Interesting for part on water governance	Water governance & policies
WSSP_2010_SUGGESTIONSFORTHEWUASTRATEGYINWSSP_vs2	PDF	SUGGESTIONS FOR THE WUA STRATEGY IN WSSP	2010			28	Yemen	Report poses strategy for WUA development within the national irrigation project. It presents several cases of local groundwater management in Yemen (Sana'a, Taiz and Dhamar region) (Annex 1) explaining the role of WUAs	Water governance & policies
The-Political-Economy-of-Water-Management	PDF	The Political Economy of Water Management in Yemen: Conflict Analysis and Recommendations	2014	Huntjens et al	EKN	241	Yemen	Extensive analysis of water governance and conflict in Yemen. Several case studies in Sana' Basin (Shahik dam, Arrowdah, Bani Matar), Wadi Siham and Taiz region (Shararah, Bani Yusof, Al Horoor, Qurada)	Water governance & policies
Water-In-The-Arab-World	PDF	Water in the Arab world - management perspectives and innovations	2009	World Bank		554	Arab countries	Various analyes of water governance in Yemen, assessments and engineering view (e.g. Wadi Ahwar) on the integral management of spate irrigation and groundwater irrigation (p. 525 onwards).	Water governance & policies
Taha-Taher-CWMP-Final-Report-2009	PDF	Community Water Management Project	2009	WEC		66	Dhamar, Taiz, Hadramout	Pilot study looking at WUA and WUG formation in three areas in Taiz, Hadramout and Dhamar region. Presents tabular overviews of various groundwater monitoring wells including lat/long data and monitoring graphs	Water resources management
Water+Harvesting+from+Roads+Guidance+Note+Yemen+Final+English+Madiha	PDF	Water from roads in Yemen - A guidance note	2015	Metameta, WEC		30	Yemen	First analysis for water harvesting from roads in yemen under the umbrella of 'roads for water' initiative, includes clear pictural overview of different types of water harvesting in yemen	Water resources management

RTRWH-inManakha-city-ppt-3-.1-27-4-2015-1-1	PDF	Analyzing the potential of Roof Rain water harvesting Systems for water supply in Manakha town and surrounding area	2014	WEC		48	Sana'a (Manakha)	Presentation showing quantitatively the potential of rooftop water harvesting in Manakha region. Includes results of social servey on preferred types of RWH and willingness to invest.	Water Supply
Report-of-comments-RTI-analysis1	PDF	Comments on the practical feasibility of prepared options for revising water management practices in the Sana'a Basin to increase the availability of water supply to Sana'a City.	?	RTI	World BANK	7	Sana'a	Document with comments, pros and cons to options of water availability increase in Sana'a basin. Especially interesting is the viewpoint of various stakeholders on different options (p.3)	Water governance & policies
Livestock+Performances+Depending+More+on+Investment+Level+than+on+Herd+Management	PDF	Livestock performances depending more on investment level than on herd management	2006	ROUX LIONEL THOUILLOT FLORIANE		216	Tihama plain: Wadi Mawr	PhD Thesis focussing on livestock performance in Wadi Mawr. Document provides in-depth overview of the wadi, its irrigation system and built-up	Water resources management
Promotion-of-Indigenous-Knowledge-in-Water-Demand-Management-	PDF	Promotion of Indigenous Knowledge in Water Demand Management for the Historical Old Sana'a City's Gardens (Maqashim)	?	WEC		26	Sana'a City	Paper discusses old grey water harvesting systems called Maqashim. Presents technical drawings how to revive these traditional water gardening systems.	Water supply
npa_yemen_english	PDF	YEMEN'S NATIONAL PROGRAMME OF ACTION FOR THE PROTECTION OF THE MARINE ENVIRONMENT FROM LAND-BASED ACTIVITIES (NPA)	2003	UNEP		114	Yemen	Document highlighting various problems arising in the coastal areas of Yemen and possible measures to take. Might give some useful information regarding Abyan Delta	Water resources management
Master-Thesis-Musaed	PDF	THE POTENTIAL OF ROOFTOP RAINWATER HARVESTING FOR SANA'A, YEMEN	2011	Aklan			Yemen, Sana'a Basin	PhD Thesis on rooftop rainwater harvesting in Sana'a. Thesis presents the current status and methods used of RWH in Yemen and Sana'a basin specifically (Ch 2) and gives a broad overview of hydrogeological setup of the basin (Ch 3). Includes a lot of useful pictures, especially appendix D (p. 151/152)	Water Supply
induced-dam-recharge	PDF	Induced recharge at new dam sites—Sana'a Basin, Yemen	2009	Alderwish		11	Sana'a Basin, Wadi Bahaman	This paper describes the approach and methodology applied to assess the potential recharge of four new proposed dam sites and suitability of cascade (check) dams on minor wadis of the Sana'a basin and estimates its recharge 2007-2026.	Water Supply
Hovden-Eirik-2006	PDF	Rainwater harvesting cisterns and local water management;	2006	Hovden		184	Governorate of Hajja (Hajja, Mabyan and Shiris), Wadi Mawr	qualitative geographical/socio-anthropological case study and ethnographic description of rainwater harvesting cisterns and their role in local water management. Again useful overview of ancient RWH approaches, Ch 2.4 describes typology of different cisterns.	Water Supply
Integrated+Water+Quality+and+its+Impact+on+the+Population+of+Mawyah+District+Final+Thesis	PDF	Integrated Water Quality Management and its Impact on the Population of Mawyah District	2012	Al-thabel		175	Taiz (Mawyah district)	Study identifies and assesses drinking water supply wells on water quality indicators in Mawyah district, Taiz. Study presents hydrogeological baseline of the Mawyah district.	Groundwater quality
Final+Report+Integrated+Watershed+Management+For+small+Catchments+Within+Sana'a+Basin	PDF	Integrated Watershed Management for Small Catchments Within Sana'a Basin, Yemen	2014	WEC		44	Sana'a Basin	Assessment of effectiveness of water supply management in Sana'a basin by evaluating the functioning of 10 dams in the Sana'a basin, estimating their inflow (upstream runoff) and daily discharge.	Water Supply
Final-report-hydrochemsitry-of-Sanaa-basin-new	PDF	HYDRO GEO CHEMISTRY OF SANA'A BASIN	2010	Alderwish		128	Sana'a Basin	Study analyses groundwater quality of various wells in the Sana'a basin. Report provides clear maps of the spatial distribution of various water quality parameters (p. 39 onwards).	Groundwater quality
Farmers-Behaviors-Toward-Better-Irrigation-Water-Management	PDF	Farmers behaviours Toward better irrigation water management	?	Al Thari et al		71	Sana'a Basin	Inventory of irrigation water use in sana'a basin and presentation of qualitative results of interviews among irrigated farmers	Water demand

Fact+sheet+2+Wadi+Zabid+The+Case +For+Managing+Water+in+a+Basin	PDF	Wadi Zabid: the Case for Managing Water in a Basin		WEC, MetaMeta		4	Wadi Zabid	Factsheet presenting a quick overview of water distribution in Wadi Zabid.	Water resources management
Other sources: https://yemenportal.unhabitat.org/									
01-Sanaa-City-Profile	PDF	Sana'a City Profile	2020	UN Habitat		95	Sana'a	Very up to date (2020) numbers and figures on population, water supply and water demand of Sana'a city (chapter 10)	City Profiles
01-Taiz-City-Profile	PDF	Ta'iz City Profile	2020	UN Habitat		115	Ta'iz	Very up to date (2020) numbers and figures on population, water supply and water demand of Ta'iz city (chapter 12)	City Profiles
01-Aden-Final-Online-Final	PDF	Aden City Profile	2020	UN Habitat		121	Aden	Very up to date (2020) numbers and figures on population, water supply and water demand of Aden city (chapter 12)	City Profiles
210408_marib_small	PDF	Marib City Profile	2020	UN Habitat		108	Marib	Very up to date (2020) numbers and figures on population, water supply and water demand of Marib city (chapter 9)	City Profiles
01-Hodeida	PDF	Al Hodeidah City Profile	2020	UN Habitat		89	Al Hodeidah	Very up to date (2020) numbers and figures on population, water supply and water demand of Al Hodeidah city (chapter 12)	City Profiles
FAO									
FAO - Yemen Plan of Action 2018-2020 - Strengthening resilient agricultural livelihoods	PDF	FAO - Yemen Plan of Action 2018-2020 - Strengthening resilient agricultural livelihoods	2018	FAO		68	Yemen	FAO's three-year Plan of Action, improving food security and nutrition and strengthening the resilience of vulnerable rural and peri-urban households while restoring the agriculture sector of the country. With some good water scarcity facts	FAO
FAO - Yemen Famine Prevention Plan Jan-Jun 2019 - Contributing to improved food security and nutrition	PDF	FAO - Yemen Famine Prevention Plan Jan-Jun 2019 - Contributing to improved food security and nutrition	2019	FAO		24	Yemen	The Famine Prevention Plan stipulates key interventions that the FAO will implement between Jan-Jun 2019 to prevent the most vulnerable and at-risk households from sliding into famine, including some water facts	FAO
FAO - Aquastat - Country profile Yemen 2008	PDF	Country profile - Yemen - version 2008	2008	FAO		17	Yemen	FAO - AQUASTAT (2008) The country profile is a summary of key information that gives an overview of the water resources and water use at the national level.	FAO
FAO - Yemen - Computation of long-term annual renewable water resources	PDF	Aquastat - Yemen - RWR	2008	FAO		1	Yemen	Computation of long-term annual renewable water resources (RWR) by country (in km^3/year, average)	FAO
YEM-dams_eng	xlsx	Dams of Yemen	2008	FAO		2	Yemen	Overview of 46 dams located in Yemen, with legend on the second tab sheet (2008)	FAO
FAO - Yemen - Irrigation areas sheet	PDF	Aquastat - Yemen - Irrigation areas sheet	2008	FAO		1	Yemen	Overview of physical areas irrigated (2004)	FAO
AQUASTAT country statistics Yemen	xlsx	Aquastat - Yemen	2021	FAO		1	Yemen	Up to date water statistics of FAO (5 year average with latest 5 year period = 2013-2017)	FAO
Received and to be included UNDP Reports									
CoWaGo Prodoc Final Draft 07.07.20 CLEAN	PDF	Joint (UNDP and FAO) Project Proposal Decentralised Cooperative Water Governance for Food Security and Peace in Yemen (CoWaGo)	2020	UNDP & FAO		83	Yemen, Wadi Hadramout, Wadi Bana and Wadi Dhamar	Project proposal of the CoWaGo project to build nexus between water governance, food security and reconciliation to reinfoce livelihood resilience and recovery of conflict-affected communities. Proposal highlights target areas in Wadi Hadramout, Wadi Bana and Wadi Dhamar (p.23) and presents a profound problem analysis of Yemen irt water governance, food security etc.	UNDP Reports

NWSSIP	PDF	National Water Sector Strategy and Investment Program (NWSSIP)	2004	MWE		91	Yemen	Overview of the NWSSIP, objectives and strategies 2005-2009	UNDP Reports
PlanningofIntegratedWaterResources ManagementcasestudySanaaBasin	PDF	Planning of Integrated Water Resources Management: Case Study Sanaa Basin	2013	Taher and Ward		18	Sana'a basin	The IWRM concept and its application to Sana'a Basin is reviewed in this paper to understand the shortcomings, and try to put forward the necessary parameters to assist in resolving the water crisis with an emphasis on their practical application. Presents tabular sectoral figures of water demand 1990-2010, water balance and overview of IWRM approach for Sana'a basin	UNDP Reports
UNDP-YEM-Manakha Project . final report	PDF	Manakh Rainwater and Fog Harvesting Final Report	2013	National foundation for watershed management & services		20	Sana'a basin (Manakha)	Study describing effectiveness of various (indigenous) water harvesting systems: terraces, fog harvesting, closed rocky-tanks and open-rocky tanks	UNDP Reports
YemenWaterUserAssossiactionStudy	PDF	Yemen Water User Association Study: Findings and Recommendations for a problem-solving approach	2009	Bruns & Taher		77	Yemen	Study covers various experiences with WUAs in Yemen and suggest possible improvements or implementing strategies.	UNDP Reports
PIMS4989_Yemen_LDCF_Water Harvesting ProDoc_for GEF resubmission_3February_FINAL	DOCX	Integrated Water Harvesting Technologies to Adapt to Climate Induced Water Shortages	2014	UNDP		144	Yemen	Project proposal document for enhancing water harvesting technologies accross yemen. Useful climate change scenario description (p.7 onwards) and possibly also useful scene setting in whole of chapter 1.	UNDP Reports
National water sector investment strategy	PPTX	Water Resources Information in Yemen	2005	NWRA	UNDP	21	Yemen	Dated information on water resources, such as annual water level decline, water demand and	UNDP Reports
FAO Project Proposal with Annexes FINAL-GCP YEM 046 GER	PDF	Project Proposal Yemen - FAO Resilience Programme in the Irrigation and Agricultural Sector	2020	FAO, UNDP, KFW		76	Wadi Hadramut; Wadi Bana; Dhamar wadi	Project Proposal. Overall objective: to enhance livelihood resilience and sustainable peace in Yemen through sustainable water management. Specifically, the project aims to i) improve agricultural production and resilience to water scarcity, ii) enhance livelihood opportunities, iii) reduce water related conflict and improve water management through awareness raising and disaster preparedness at local level	UNDP Reports

Specific Wadi Bana literature

10.1.1.828.690	PDF	An Estimation of the Probability Distribution of Wadi Bana Flow in the Abyan Delta of Yemen	2012	Atroosh & Moustafa		10	Wadi Bana	Overview of Wadi Bana Flow 1948-2008 (P.7) and estimated flows for wet, medium and dry years, and extremes. General introduction of Wadi Bana, however, no deliniated map included.	Wadi Bana
076_tor_wbana_advice	PDF	Advice on Terms of Reference for EIA for Wadi Bana Dam Project	2007	NL Commission for Environmental Assessment	MWE	23	Wadi Bana	Chapter 3 gives overview of present situation in Wadi Bana, incl. some insight in Water Balance, irrigation water requirement and impacts of dam development	Wadi Bana
ApplicationofDecisionSupportToolsfor Water	PDF	Application of Decision Support Tools for Water Resources Management in Coastal Arid Areas (Case study: Aden, Yemen)	2008	Haidera & Noaman		21	Wadi Bana	Useful table 2 (p. 9) on flows, irrigation, return flow and GW abstraction for 2006, incl. relative share to different governates.	Wadi Bana
c012p085	PDF	An approach for assessing the vulnerability of the water resources of Yemen to climate change	1999	Alderwish & Al-Eryani		5	Wadi Bana / Abyan Delta	Includes map of various wadis flowing into Abyan delta. Includes modelled estimates of surface water resources per month in Abyan Delta.	Wadi Bana

21 Feasibility_Study_Wadi_Bana_and_Abyan	PDF	Feasibility Study for Wadi Bana and Abyan Delta Development Project - Annex A Hydrology & Water Resources	1984	Ws Atkins & Partners		153	Wadi Bana	Description of geomorphology and geology of Wadi Bana (p.10/11), climatic analysis (p.14-16). And extensive discussions of runoff, discharge etc., though the presented data might be inaccurate for now	Wadi Bana
Ewea2007-AssessmentofPotentialWaterResourcesinAbyanArea	PDF	Assessment of potential water resources in Abyan area-southern Yemen	2007	Civil Engineering Research Magazine, Al-Azhar Univ			Abyan delta		Wadi Bana
AlMahreki2015-GISbasedAssessmentofLandSuitabilityforIndustrialCropsinAbyanDelta	PDF	GIS-based assessment of land suitability for industrial crops (cotton, sesame and groundnut) in the Abyan Delta, Yemen	2015				Abyan delta		Wadi Bana
UNDP-EM-2013-Qualitative Study - Multi-dimensional Livelihoods Assessment in Conflict Affected Areas	PDF	Conflict-Livelihood Interaction In Yemen: Participatory assessment conducted in Abyan, Taiz, Hajja, and Amran Governorates	2013	Interaction in development	UNDP		Abyan governate		Wadi Bana
Marchant2018-Water_Allocation-AbyanDeltaSpateIrrigationSystem	PDF	Simulating Water Allocation and Cropping Decisions in Yemen's Abyan Delta Spate Irrigation System	2018				Abyan Delta		Wadi Bana

Specific Dhamar literature

articl	PDF	Impact of Climate Change on Groundwater in Dhamar Basin (Yemen)	2017	Alaizari et al		8	Dhamar Basin	Questionable whether discussed basin is indeed Dhamar Basin (as it lies completely outside the governorate boundaries). Paper discusses climate change projections on groundwater in the basin and might therefore be useful.	Wadi Dhamar
WadiSIhamBasinLatest2020	PDF	Precipitation Analysis and Water Resource of Wadi Siham Basin, Yemen	2019	Majed & ruslan		29	Wadi Siham Basin	Covers part of Dhamar governorate and discusses rainfall patterns in the area (1979-2008)	Wadi Dhamar
3eb2805eb2b64a550260fadbd4926ef54f5f	PDF	QUALITY ASSESSMENT OF GROUND WATER IN DHAMAR CITY, YEMEN	2017	Al Aizari et al		16	Dhamar City	Chemical and statistical regression analysis on groundwater at five fields (17 sampling wells) located in Dhamar city	Wadi Dhamar
PWM	PDF	PARTICPATORY WATERSHED MANAGEMENT PROJECT DHAMAR PWMP	?	WEC	IUCN	27	Dhamar	Overview of the participatory watershed management project in Dhamar. Includes several useful maps delineating watersheds in Dhamar (p2, 3, 15, 17), including devides in sub-catchments. Might be useful when targetting Dhamar wadi catchments	Wadi Dhamar

Specific Wadi Hadramuth literature

Soliman2015_Article_HydrologicalAnalysisAndFloodMi	PDF	Hydrological analysis and flood mitigation at Wadi Hadramawt, Yemen	2015	Soliman et al		12	Wadi Hadramuth	Study on runoff of wadi Hadramuth in relation to the 2008 flooding. Discusses soil type and land use and different sub-cathcments in the Hadramuth area (incl. data on area, peak discharge, precipitation).	Wadi Hadramuth
FLOODRISKSANDITSMITIGATION	PDF	FLOOD RISKS AND ITS MITIGATION AT EASTERN YEMEN (CASE STUDY: WADI HADRMOUT)	2014	Taher		143	Wadi Hadramuth	Thesis on Wadi Hadramuth flood risk. P.18 onwards gives areal description of Wadi Hadramuth. Chapter 4 gives results of rainfall-runoff modelling and ch 5 on land use/land cover	Wadi Hadramuth

Reports received through former NWRA Chairman

Figure 2.2 Topographical Map of Dhamar Basin	PDF	Figure 2.2 Topographical Map of Dhamar Basin	2009	NWRA		1	Dhamar basin (part of Hadramuth catchment	Figure 2.2 Topographical Map of Dhamar Basin	NWRA Reports
Figure 2.3 Map Showing the locations of eight Qa's including intervening plain areas between Qa's	PDF	Figure 2.3 Map Showing the locations of eight Qa's including intervening plain areas between Qa's	2009	NWRA		1	Dhamar basin (part of Hadramuth catchment	Figure 2.3 Map Showing the locations of eight Qa's including intervening plain areas between Qa's	NWRA Reports

Figure 5.1 Locations of existing monitoring wells within the project area	PDF	Figure 5.1 Locations of existing monitoring wells within the project area	2009	NWRA		1	Dhamar basin (part of Hadramuth catchment	Figure 5.1 Locations of existing monitoring wells within the project area	NWRA Reports
Figure 6.1 Locations of all historic rainfall-meteorological stations in study area	PDF	Figure 6.1 Locations of all historic rainfall-meteorological stations in study area	2009	NWRA		1	Dhamar basin (part of Hadramuth catchment	Figure 6.1 Locations of all historic rainfall-meteorological stations in study area	NWRA Reports
Figure 6.9 Catchment areas of different Qa's in the project area	PDF	Figure 6.9 Catchment areas of different Qa's in the project area	2009	NWRA		1	Dhamar basin (part of Hadramuth catchment	Figure 6.9 Catchment areas of different Qa's in the project area	NWRA Reports
Figure 8.1 Hydrogeological map of the Project Area	PDF	Figure 8.1 Hydrogeological map of the Project Area	2009	NWRA		1	Dhamar basin (part of Hadramuth catchment	Figure 8.1 Hydrogeological map of the Project Area	NWRA Reports
Map 4.1 Locations of all surveyed water points in the entire study area	PDF	Map 4.1 Locations of all surveyed water points in the entire study area	2009	NWRA		1	Dhamar basin (part of Hadramuth catchment	Map 4.1 Locations of all surveyed water points in the entire study area	NWRA Reports
Map 4.12 Depth to the ground water for the entire study area	PDF	Map 4.12 Depth to the ground water for the entire study area	2009	NWRA		1	Dhamar basin (part of Hadramuth catchment	Map 4.12 Depth to the ground water for the entire study area	NWRA Reports
Map 4.46 Total Annual Groundwater Abstraction per Square Kilometer in the Study Area	PDF	Map 4.46 Total Annual Groundwater Abstraction per Square Kilometer in the Study Area	2009	NWRA		1	Dhamar basin (part of Hadramuth catchment	Map 4.46 Total Annual Groundwater Abstraction per Square Kilometer in the Study Area	NWRA Reports
Groundwater Monitoring in Wadi Hadhramawt 2001-2011	PDF	Groundwater Monitoring in Wadi Hadhramawt 2001-2011	2011	NWRA		82	Wadi Hadramuth	Changes in groundwater chemistry between 2001 and 2011. Very useful WQ report of wadi hadramuth including a textual description of tributaries, main aquifer systems and maps of the main WQ constituents along the wadi valley.	NWRA Reports
Other sources									
reach_yem_report_wash_secondary_desk_review_may_2020	PDF	Secondary Desk review on Wash assessments in Yemen	2020	Wash cluster		30	Yemen	Provides useful maps on WASH status categorized in e.g. access to water, vulnerability to floods etc.	Water resources management
pap_wasess3a3yemen	PDF	Water Resources Information in Yemen	2005	Yehya & Al-Asbahi		12	Yemen	Overview of water resources development, uses and quantities.	Water resources management
McCrackenQatWFsImpactonYemen	PDF	THE IMPACT OF THE WATER FOOTPRINT OF QAT ON YEMEN’S WATER RESOURCES	2012	McCracken		63	Yemen	Water footprint assessment assessing the impact of qat on yemen's water resources. Qat consumes 36% of Yemen’s total renewable water resources and 32% of all groundwater withdrawals	Water resources management
agri_stat_2018	PDF	Agricultural statistics 2018	2018	MIA		85	Yemen / data per governorate	Document (unfortunate arabic) with statistics on agricultural production in 2018. Might be valuable, eventually by translating in google…	Water demand
annual_rep_2019	PDF	Annual report of the Ministry of Agriculture and Irrigation 2019	2019	MIA		49	Yemen / data per governorate	Annual report (unfortunate arabic) with statistics on agricultural production and irrigation water use in 2019. Might be valuable, eventually by translating in google…	Water demand
WB - Water Papers - Understanding and improving groundwater governance - 2012	PDF	Managing the invisible - Understanding and improving groundwater governance	2012	WB		174	worldwide incl. Yemen	Groundwater Governance in Yemen (p.51 and beyond), GW conflict examples Ta'iz (Box 22, p90) and Wadi Dahr (Box23, p.91)	water governance & policies

PN_32_GW-recharge-and-saving_Yemen_SF	PDF	Groundwater Recharge and Saving in Spate Irrigation Areas, Case study, Wadi Zabid	2017	Flood Based Livelihoods Network Yemen		12	Wadi Zabid, al Hudayday Governorate	Spate irrigation, water resource management, groundwater recharge	Water resources management
26122013 Sana'a Basin Draft Report_11April_	DOCX	Decentralized management of water use in the Sana'a Basin to sustain water resources and rural livelihoods - Draft Formulation Report	2013	Embassy of the Kingdom of The Netherlands	Republic of Yemen; Ministry of Water & Environment; National Water Resources Authority; Sana'a – Amran Branch	44	Sana'a Basin	Document describing the Bilateral Program (scope, justification, components, output, implementation plan) including a situation analysis of Sana'a Basin (physical and demographic characteristics, water availability and sue, agricultural practices, water resources management, institutional environment) **and interesting water balance calculations**	Water resources management
Sana'a Basin formulation_Annexes 1-4 11 April_ final draft	DOCX	Decentralized management of water use in the Sana'a Basin to sustain water resources and rural livelihoods - Draft Formulation Report	2013	Embassy of the Kingdom of The Netherlands	Republic of Yemen; Ministry of Water & Environment; National Water Resources Authority; Sana'a – Amran Branch	24	Sana'a Basin	Annex of the Draft Formulation Report, inlcuding the ToR, Mission programme, References and background information on the water balance and sub basins	Water resources management
seasonal_calendar_-_centeral_highlands_agro-ecological_zone_-yemen-english-march_2018	PDF	Yemen Food Security Information System (FSIS) Development programme - Yemen Seasonal Calendar	2018	FAO		5	Yemen (Central highland)	Presents a clear cropping calendar for the central highland agro-ecological zone: The geographical areas that falls under this zone are: Amran, Sana'a, Dhamar and highlands of (Sa'dah, Hajjah, Al-Mah weet ,Mareb).	Water demand
IPC_communication_Report Sept 2014	PDF	Yemen Seasonal Calendar (Central highland, Southern uplands, coastal areas and Eastern Plateau)	2014	FAO		1	Yemen (Central Highland, southern uplands, coastal areas and eastern plateau)	Presents a clear cropping calendar for the different agro-ecological zones in yemen	Water demand
seasonal_calendar_southern_uplands_-_yemen-_english-march_2018	PDF	Yemen Seasonal Calendar (Southern Uplands Agro-ecological zone–Crop Production)	2018	FAO		5	Yemen (Southern uplands)	Presents a clear cropping calendar for the southern upland agro-ecological zone: The geographical areas that falls under this zone are Ibb, Al-Beida, Al Dhalaa and highlands of (Taiz, Abyan and Lahj)	Water demand
yemen_seasonal_calendar_-arabian_sea_coast_gulf_of_aden_agro-_ecological_zone_-_october_-_en	PDF	Yemen Seasonal Calendar (Arabian Sea Coast & Gulf of Aden Agro- ecological zone–Crop Production)	2018	FAO		8	Yemen (Arabian Sea Coast, Gulf of Aden)	Presents a clear cropping calendar for the Arabian Sea coast and Gulf of Aden agro-ecological zone: South east coastal zone along the Gulf of Aden and Arabian sea (Aden, lowland and coastal areas of (Lahj, Abyan, Shabwa), and coastal part of Hadramout and Al Mahrah)	Water demand
yemen_seasonal_calendar_-desert_-_dry_and_hadramout_eastern_plateau_agro-ecological_zones_-o	PDF	Yemen Seasonal Calendar (Desert – Dry and Hadramout Eastern Plateau Agro-Ecological Zones –Crop Production)	2018	FAO		8	Yemen (Dry and Hadramout Eastern Plateau)	Presents a clear cropping calendar for the Dry and Hadramout Eastern Plateau agro-ecological zone: includes the eastern plateau and internal desert areas (al Jawf, part of (Mareb, Hadramout, Shabwa and Al Mahrah)	Water demand
red_sea_and_tihamah_plain-seasonal_calendar_-_yemen_-_english-_march_2018	PDF	Yemen Seasonal Calendar (Red sea & Tihamah Plain Agro- ecological zone–Crop Production)	2018	FAO		5	Yemen (Red sea & Tihamah Plain)	Presents a clear cropping calendar for the Red Sea and Tihamah plain agro-ecological zone: Western coastal area along the red sea including Tihamah plateau (Al Hodeidah, and lowland and coastal areas of Hajjah, Al Mahweet, Taiz)	Water demand

seasonal_calendar_-_northern_highland_agro-_ecological_zone_-_yemen_-english_-_march_2018	PDF	Yemen Seasonal Calendar (Northern highland Agro-ecological zone–Crop Production)	2018	FAO		4	Yemen (Northern Highland)	Presents a clear cropping calendar for the Northern highland agro-ecological zone	Water demand
wpccasestudy13	PDF	Case Study XIII – Sana'a, Yemen. In Water pollution control: a guide to the use of water quality management principles	1997	Al-Hamdi		12	Sanaa basin	Case study referring to several aquifer recharge numbers and well abstraction in Sanaa basin	Water demand
giz2018-0319en-yemen-water-1-strategy	PDF	Yemen Water Sector: Damage assessment report of twelve water supply and sanitation local corporations (LCs) and their affiliated branch offices and utilities. Part 1: Resilience Strategy Report.	2018	Dorsch International consultants GmbH	GIZ	64	Yemen	Provides useful graphs on water use per capita in major urban cities and discusses performance of the various local corporations in water supply. Also contains useful parts on the Yemen Water Sector to include in the policy chapter!	Water supply
128907-WP-P165727-Water-Supply-in-a-War-Zone-PUBLIC	PDF	Water Supply in a War Zone, A Preliminary Analysis of Two Urban Water Tanker Supply Systems in the Republic of Yemen.	2018	Abu-Lohom et al	WorldBank	35	Sanaa and Aden	Highlights number of key aspects of yemen urban water supply and sanitation situation in Sanaa and Aden, especially focusing on water tanker supply systems	Water supply
20210726_acaps_yemen_analysis_hub	PDF	CONFLICT ESCALATION IN MARIB AND POTENTIAL HUMANITARIAN AND ECONOMIC IMPACTS: SCENARIO	2021	ACAPS Analysis Hub		14	Marib	Impacts of recent conflict in Marib highlighted	water governance & policies
Traditional_irrigation_systems_water_harvesting	PDF	Documentary study on models of traditional irrigation systems and methods of water harvesting in Hadramout and Shabwah governorates	2011	Baquhaizel, S. A., Saeed, I. A., & Bin Ghouth, M. S.		88	Yemen	Overview of ancient RWH techniques	Water supply
541960ESW0Gray1OFFICIAL0USE0ONLY191	PDF	Yemen Assessing the Impacts of Climate Change and Variability on the Water and Agricultural Sectors and the Policy Implications	2010	Worldbank		102	Yemen	Yemen Assessing the Impacts of Climate Change and Variability on the Water and Agricultural Sectors and the Policy Implications	Water resources management
2_Yemen_Salem. NWRA	PDF	GROUNDWATER MANAGEMENT AND AGRICULTURAL Development in Yemen	2009	NWRA		32	Yemen	Presents summary information in graphs on groundwater depletion in water management regions of NWRA in Yemen	Water resources management
Yemen-National-Report-September-2016	PDF	Yemen National Report	2016	Govt. Of Yemen		68	Yemen		water governance & policies
Aklan2019_Article_WhichWaterSourcesDoPeopleRever	PDF	Which water sources do people revert to in times of war: evidence from the Sana'a basin, yemen	2019	Aklan et al.		16	Sanaa basin		Water resources management
Jordan_Summary-Report-CountryCasestudies_final	PDF	Wastewater Reuse in Arab Countries: Comparative compilation of information and reference list.	2010	ACWUA		34	Arab countries, Yemen		Water resources management
potentialroadRWH	PDF	Potential of Road Rainwater Harvesting in Yemen–Its Social, Environmental and Economic Benefits: A Case Study of Sana› a–Hodeida Road, Yemen	2020	Al-Maswari		42	Sana, Hodeida, Yemen		Water supply
Yemen-Country-Report_Brackish-Water-Use	PDF	Status and New Developments on the Use of Brackish Water for Agricultural Production in the Near East: Yemen country report	2012	Al-Sabri		39	Yemen		Water Supply
UNDP-YEM-CC and water sector VA in Yemen	PDF	Change: Policy Implications – The Case of NWSSIP II. A Policy Note. National Sector Strategy and Climate Change.	2011	Ali		18	Yemen		Water governance & policies
Bauman	PDF	Two case studies of Geophysical Delineation of Salt Water Intrusion in Yemen: Wadi Hadramaut and the Tuban and Abyan Deltas,	2003	Bauman		2	Wadi Hadramuth		Wadi Hadramuth
KAP_1747	PDF	Climate change, agricultural production and food security: evidence from Yemen	2011	Breisinger		36	Yemen		Water resources management

Rainfall and runoff in Yemen	PDF	Rainfall and runoff in Yemen	1996	Farquharson		16	Yemen		Water resources management
ye_zonedescriptions_en	PDF	Livelihoods Zoning "plus"Activity in Yemen	2010	FEWS NET		39	Yemen		Water resources management
sdata201566	PDF	The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes.	2015	Funk et al		21			Water resources management
Water scarcity and climate change adaptation for Yemen s vulnerable communitie	PDF	Water scarcity and climate change adaptation for Yemen's vulnerable communities	2011	Haidera et al		17	Yemen		Water resources management
DSS_Marib_final	PDF	DSS water mission report: Yemen Marib Dam Flooding	2020	Helder et al			Marib		Marib Dam
40660903	PDF	Water Conflict and cooperation in Yemen	2010	Lichtenthaeler		7	Yemen		Water governance & policies
Art11-3-13	PDF	Experiences with local water governance and outcomes for vulnerable communities in the Tihama region of Yemen	2018	Morris-Iveson		15	Yemen		Water governance & policies
ImpactOfWarOnDevelopmentInYemen	PDF	Assessing the Impact of War on Development in Yemen.	2019	Moyer			Yemen		Water governance & policies
Noman	PDF	Indigenous knowledge for using and managing water harvesting techniques in Yemen	2004	Noaman		14	yemen		Water Supply
reach_yem_report_yem1802_november_2018_0	PDF	Wash Household Assessment – Water, Sanitation, and Hygiene household level needs assessment in Yemen.	2018	Reach		41	Yemen		Water resources management
i1680e	PDF	Guidelines on spate irrigation	2010	Steenbergen et al		249			Water resources management
Zinjibar and Khanfar Community Profiles	PDF	Community Profiling, Governorate of Abyan, Zijnjibar & Khanfar Districts.	2012	UNOCHA		59	Abyan		Water resources management

van Hogendorpplein 4
2805 BM Gouda

Telefoon: 0182 – 686 424
Internet: www.acaciawater.com
Email: info@acaciawater.com