REPUBLIC OF YEMEN
MINISTRY OF WATER AND ENVIRONMENT
SANA'A BASIN WATER MANAGEMENT PROJECT

(IDA CREDIT 3774-YEM)

Sub-Component 3(d)

Hydro-geological and Water Resources Monitoring and Investigations

ACTIVITY 2: WATER BALANCE ESTIMATION AND SUB-BASIN MONITORING

DRAFT FINAL REPORT

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ABBREVIATIONS

amsl	above mean sea level
ASCE	American Society of Civil Engineering
CN	Curve Number
CWMU	Central Water Management Unit
ET	Evapotranspiration
FC	Field Capacity
HWC	High Water Council
Kc	Crop coefficient
NEH	National Engineering Hand book USA
NWRA	National Water Resources Authority
PWP	Plant Wilting Point
SCS	Soil Conservation Service
WEC	Water & Environment Center

EXECUTIVE SUMMARY

The Sana'a Basin (3240 km^2) is hydrologically self-contained, with very little outflow, which occurs only in years with heavy rainfall. Sana'a Basin is under high water stress from growing population and irrigation water demand resulting in the decline of groundwater resources.

The objective of Activity 2 as part of Sub-component 3D of the Sana'a Basin Water Management Project is to collect hydrological information on rainfall, evapotranspiration, surface water and groundwater for improvement of the estimation of the water balance of the Sana'a Basin and its sub-basins. The specific objective of Activity 2 is to implement specific monitoring activities in selected experimental sub-basins to study the effect on water resource availability and depletion by measures concerning water recharge and irrigation methods.

The following major activities are performed in order to accomplish the main objectives:

- Selection of four experimental sub-basins for data collection and monitoring;
- Field water balance study at three farms – two modern irrigation farms (Ghadran and Al Hinami) and one traditional farm (Luluah);
- Reservoir monitoring and water balance at six reservoirs;
- Sub-basin water balance for the 22 sub-basins in Sana'a Basin;
- Overall, comprehensive water balance modeling using Water Evaluation and Planning (WEAP) model;
- In addition to the data collection and monitoring under study a lot of data, information and knowledge from previous studies such as WEC (2004), SAWAS (1996), WRAY (1995), HWC (1992), GAF (2007) are inputs to this study.
- Water balance is evaluated under average (long term), Year 2007, and Year 2008 situations.

The major outcomes of the study are:

Six-Reservoir Water Balance

Reservoir water balance components for six dams (Methbel, Mekhtan, Mussaibih, Khalaqa, Arisha, and Al-Hayathem) are estimated based on reservoir water level measured using staff gauges. Stored water between flash floods is estimated from reservoir water level readings and converted to volume of flood using a depth (elevation) – volume curve developed for each dam. Reservoir evaporation is estimated from GAF (2007) potential evapotranspiration data with a multiplication factor of 1.2 to account for open water evaporation rate. Estimation of leakage and direct water abstraction from reservoirs is also performed. The remaining terms become recharge to the aquifer due to the impoundment of water in the reservoir.

Table 1 Summary of the six-reservoir water balances (year 2007-2008)

Elements	Dams					
	Al- Hayathem	Arisha	Khalaqa	Methbel	Mekhtan	Mussaibih
Dam catchment area (km^2)	33.2	6.5	5.5	32.6	5.6	3.6
Reservoir area geology	Limestone	Sandstone	Sandstone (foundation cutoff wall provided)	Tertiary volcanic	Volcanic	Volcanic (foundation cutoff wall provided)
Total balance days	238	189	513	105	513	602
Annual rainfall (mm)	192	221	221	192	221	221
Total measured volume of runoff for balance period (m^3)	439380	197448	203822	9864	122210	44344
Reservoir Evaporation (m^3)	65561	4000	48712	1272	47845	19275
Release (m^3)	88373	122959	65400	1775	11863	2757
Recharge (m^3)	285447	70489	89710	6817	62502	22832
Average reservoir pool area (m^2)	52698	3925	16762	1512	15846	6547
Mean recharge (mm/day)	19	79	9	36	6	5

The reservoirs have different recharge rates depending on permeability of the reservoir area. Seasonal reservoirs are more effective for recharge than those retaining water for longer periods.

Field Water Balance

From the field water balance study conducted, the computed irrigation efficiency at Luluah farm (traditional irrigation farm) is about 56%. Because furrow irrigation is used, the water loss by deep percolation and non-beneficial evapotranspiration is significant. The other farms (Al-Hinami and Ghadran), where water is efficiently applied through implementation of modern irrigation techniques, no loss through deep percolation or non-beneficial evapotranspiration was found. Only if a heavy rain falls after irrigation will deep percolation occur from the Ghadran and Al Hinami farms.

Sub-basin Runoff and Recharge Estimate

Runoff: The average annual runoff generated in the 22 sub-basins of Sana'a Basin is 66 M m^3, about 70% of which is estimated to be groundwater recharge, which is the main form of recharge in Sana'a Basin.

Sana'a Basin WEAP Hydrologic Modeling

Water balance conditions of Sana'a Basin are determined by considering irrigation and water supply demands and recharge and water resource potential of the basin from a long-term average, Year 2007, and Year 2008.

Water Demand: (1) Using the forecast from the 2004 census, the 2010 Sana'a Basin population will be about 2.9 million. The annual water supply demand will be 58 M m^3 for the forecasted population of about 2.9 million people. (2) The total irrigation water demand of 18,953.2 ha irrigated land in Sana'a Basin is 221.1 M m^3; this is equivalent to an annual demand of 11,668 m^3/ha.

Recharge: The WEAP soil moisture accounting model shows that annual average groundwater recharge in Sana'a Basin from all sources, Wadi runoff, Reservoirs, and Return flow, including west water discharge from Sana'a City, is 78 M m^3.

Table 2 Average groundwater recharge (all sources), M m^3

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Reservoir	0.1	0.3	0.9	1.6	0.6	0.2	0.4	1.2	0.1	0.1	0.1	0.1	5.5
Direct rainfall and Wadi Runoff	4.8	5.9	7.5	11.7	5.9	1.1	1.7	5.8	1.9	0.6	1.2	3.0	51.2
Return flow	1.9	2.2	2.5	3.6	2.9	1.1	1.0	2.6	1.2	0.6	0.7	1.2	21.3
Total	6.8	8.3	10.9	16.9	9.3	2.4	3.0	9.6	3.2	1.3	2.0	4.3	78.1

Comparison of the average, Year 2007, and Year 2008 reveals that recharge in Sana'a Basin depends on the rainfall amount and intensity, that is, the ability to generate runoff in the wadis. Recharge in Years 2007 and 2008 is estimated to be 67.8 and 49.8 M m^3 respectively, which is less than average.

Water Balance

The current total annual water demand (irrigation 221 M m^3 and water supply 58 M m^3) is 279 M m^3. The average annual water resources replenishable from groundwater, surface water, and reservoirs are estimated at 86.8 M m^3, with monthly variations shown below.

Table 3 Water supply delivered from replenishable water sources, M m^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
6.8	8.4	10.0	15.0	11.8	5.2	4.3	10.1	5.5	2.5	2.6	4.6	86.8

The average unmet water demand from replenishable water sources mined from the groundwater aquifer is 192.7 M m^3, with a maximum of 19.3 M m^3 in June and minimum of 8.2 M m^3 in February.

Table 4 Unmet demand or supply delivered from non replenishable groundwater sources (mining), M m^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
8.5	8.2	12.6	8.3	19.3	29.1	26.6	19.0	20.6	18.9	12.2	9.3	192.7

Water saving from improved irrigation system

The water saving from the application of modern irrigation techniques is significant; if all existing traditionally irrigated areas are converted to modern farms, the annual total irrigation water demand will be reduced to 133 M m^3 from 221 M m^3. The total annual water balance of Sana'a Basin will be improved from -192.7 M m^3 to -114.2 M m^3.

Table 5 Comparison of average annual water balance with traditional and modern irrigation systems

Sub-basin	Water Balance (M m^3) Traditional System	Water Balance (M m^3) Modern System
1	-0.04	0.0
2	-2.36	-0.5
3	-1.51	-0.3
4	0.00	0.0
5	-0.18	-0.1
6	-0.77	-0.2
7	-2.57	-1.5
8	-13.24	-7.0
9	-52.20	-32.5
10	-0.52	0.0
11	-24.59	-13.6
12	-9.49	-5.7
13	-19.32	-10.7
14	-7.46	-0.9

Sub-basin	Water Balance (M m^3) Traditional System	Water Balance (M m^3) Modern System
15	-2.90	-2.1
16	-34.00	-30.4
17	-10.26	-5.9
18	-3.64	-0.2
19	-2.87	-0.6
20	-2.83	-1.4
21	-1.57	-0.5
22	-0.40	-0.1
	-192.7	-114.2

Though there will be a big improvement in water use efficiency in the modern irrigation system, the overall water balance of Sana'a Basin will continue to decline. Generally, the water resources of Sana'a Basin cannot sustain irrigation development from groundwater resources. Existing water demand on most of the sub-basins can be brought under control through the introduction of modern irrigation techniques; however, sub-basins 9 (Wadi Bani Hwat), 16 (Wadi al Mawrid where Sana'a City is located), 8,11,12,13, and 17 cannot sustain their existing demand for water.

Chapter 1. INTRODUCTION

1.1 Background

The Sana'a Basin, part of Sana'a Governorate, is located in the Central Highlands of Yemen and includes the capital city of Sana'a (Figure 1-1). It covers an area of about 3240 sq. km, accounting for 6.06% of the country's total area. Sana'a City is located in the plain of Sana'a Basin and occupies about 5% of the total area of the basin (160 km^2).

Socio-economic conditions across the Sana'a Basin have changed considerably in recent years. Rapid growth of urban population in the national capital city (Sana'a) has resulted in this change. Expansion of the urban center into rural areas, as well as modernization of life style and infrastructure improvement have increased interaction between the city and its surroundings.

Based on 2004 Census figures, the Consultants have worked out the total population of Sana'a Basin for the year 2004 as 2.0 million, with a 5.5% annual growth rate in urban areas and 3.5% in rural areas. This estimate comes very close to the figure estimated in the Sana'a University WEC Socio-economic Study Report (Oct. 2001) for 2005 as 2.13 million. This study also projected that, by the year 2025, the Sana'a Basin population would rise to 5.85 million. The other human resource parameters for Sana'a Basin are assumed to be the same as that of the Sana'a governorate, which indicate that the gender ratio is 103.2 and that the average number of persons per household is 7.8 *(Statistical Year Book 2004, CSO, ROY).* Sana'a City is growing rapidly. Expansion of the urban center into rural areas, as well as the modernization of life style and improvement of infrastructure have increased the interaction between the city and its surroundings. Figure 1-2 shows the expansion of Sana'a City and population distribution in the basin in 2006.

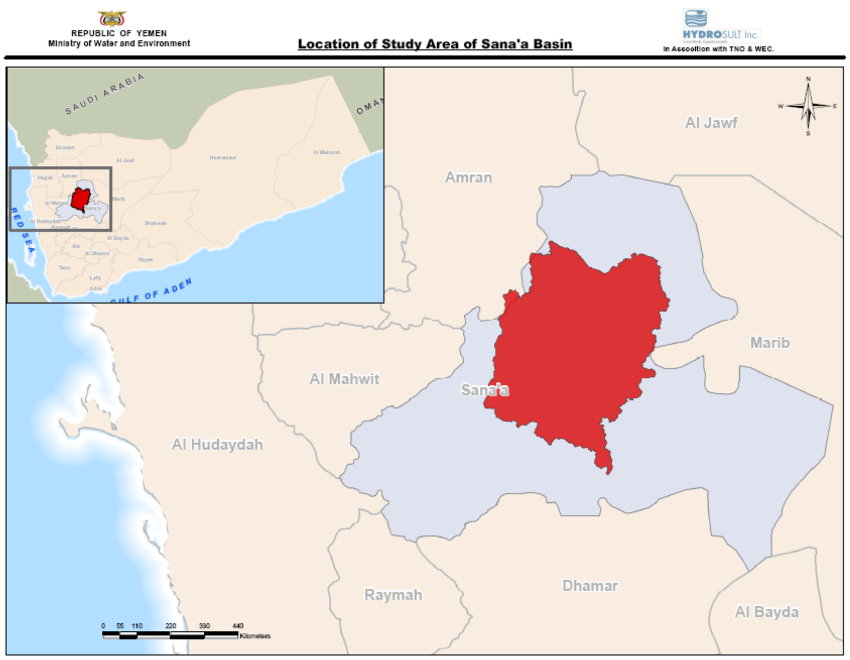


Figure 1-1 Location map

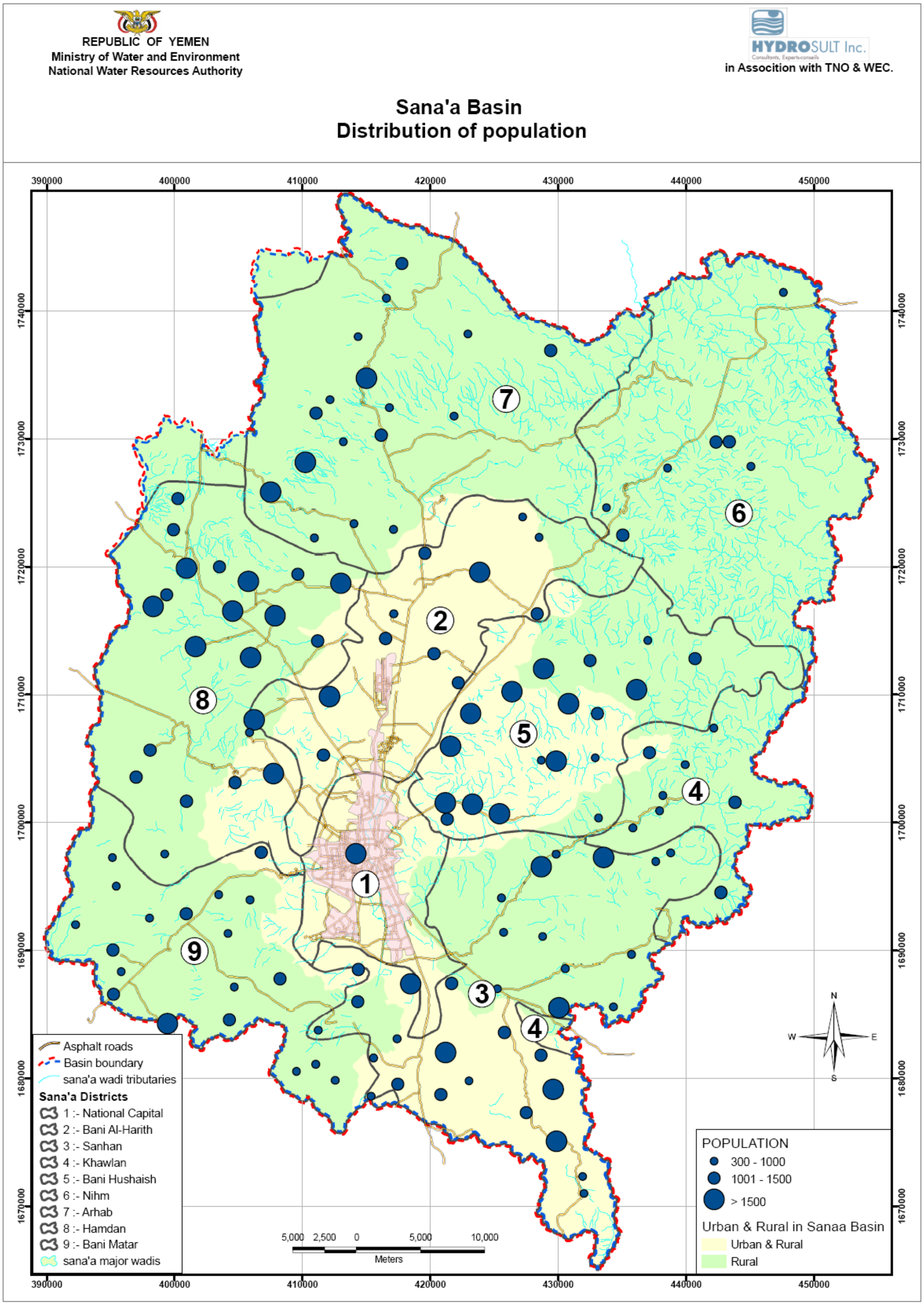


Figure 1-2 Distribution of population in Sana'a Basin in 2006, based on 2004 census

The Sana'a Basin is hydrologically self-contained with very little outflow, only in years with heavy rainfall. The ephemeral mountain stream of wadi Al-Kharid originates approximately 30 km northeast of Sana'a. From its origin, the wadi descends the eastern slopes of the Yemen mountain massif, through the Amran limestone and confluence with the wadi Al-Jauf. The length of wadi Al-Kharid is about 50 km. The bed level of Wadi Al-Kharid varies between 1910 to 3666 m (amsl).

Already a very scarce resource in Yemen, the availability of water for agriculture is decreasing rapidly due to overuse. Sana'a Basin is under high water stress from the growing population and irrigation water demand; by contrast, the groundwater resource is reported to be declining.

1.2 Objective

The general objective of Activity 2 is to collect hydrological information on rainfall, evapotranspiration, surface water and groundwater for an improved evaluation of the water balance of the Sana'a Basin and its sub-basins. The specific objective of Activity 2 is to implement specific monitoring activities in selected experimental sub-basins to study the effect on water resource availability and depletion by measures concerning water recharge and irrigation methods.

1.3 Scope

This Draft Final Report will describe all activities in the 3-year period of the study as well as the findings through sub-basin monitoring activities, including field-level observations and the water balance estimation at field, sub-basin and Sana'a Basin level with specific activities on:

- Selection of 4 experimental sub-basins, data collection and monitoring;
- Field water balance study at three farms – two modern irrigation farms (Ghadran and Al Hinami) and one traditional farm (Luluah);
- Reservoir monitoring and water balance at six reservoirs;
- Sub-basin water balance for the 22 sub-basins in Sana'a Basin;
- Overall, comprehensive water balance modeling using Water Evaluation and Planning (WEAP) model; and
- Water balance is evaluated under long-term average, Year 2007, and Year 2008 situations and with improved irrigation system scenarios.

Chapter 2. EXPERIMENTAL SUB-BASINS AND HYDROLOGICAL MONITORING

The criteria and the process to select four experimental sub-basins in Sana'a Basin were described in Technical Note I. The four experimental sub-basins as shown in Figure 2-1 are:

- Wadi Zahr & Al Ghay (Methbel watershed),
- Wadi as Sirr,
- Wadi Khalaqa, and
- Wadi Sa'Wan.

The sub-basins were selected with the notion that, if hydrological monitoring is successfully conducted, it will be possible to derive parameters for computation of the Sana'a Basin water balance. As described in Technical Note I, the sub-basins have the following major characteristics:

Wadi Zahr & Al Ghay Sub-basin

The Wadi Zahr & Al Ghay sub-basin has a very large catchment area (327 km^2). Part of its tributary catchment is the Methbel watershed, with a catchment area of about 46 km^2. Most of the catchment is agricultural land and has a flatter slope. The Methbel dam is located at coordinates of

398836 E and 1699472 N and its catchment area is about 32.6 km^2. The dam site is located in a gorge where the dam height is about 25 m; geologically, the watershed belongs to the volcanic area.

Wadi As Sirr Sub-basin

Wadi As Sirr sub-basin has a catchment area of 227 km^2. The sub-basin is located in the sandstone area and many irrigation developments exist from groundwater and flood diversion. Grape and Qat are the major crops. It is one of the sub-basins most affected in terms of a declining water table due to over abstraction. Two pilot farms with a drip irrigation system in place exist in the sub-basin.

Wadi Khalaqa Sub-basin

The Wadi Khalaqa sub-basin has a catchment area of 75.6 km^2. There are two major watersheds forming the Wadi Khalaqa sub-basin: the Khalaqa-Al Hayathem and Arisha watersheds. There are three existing dams belonging to the two watersheds of Khalaqa sub-basin. Geologically, it belongs to the sandstone and limestone area. The Khalaqa and Al-Hayathem watersheds cover an area of 33.2 km^2 up to Al-Hayathem dam site. Khalaqa dam is located in the upstream catchment covering about 5.5 km^2. The watershed belongs to the sandstone area. The Arisha watershed has a catchment area of 35 km^2 up to the confluence of Al-Hayathem. Arisha dam is located in the upper catchment, covering about 6.5 km^2. It belongs to the sandstone area.

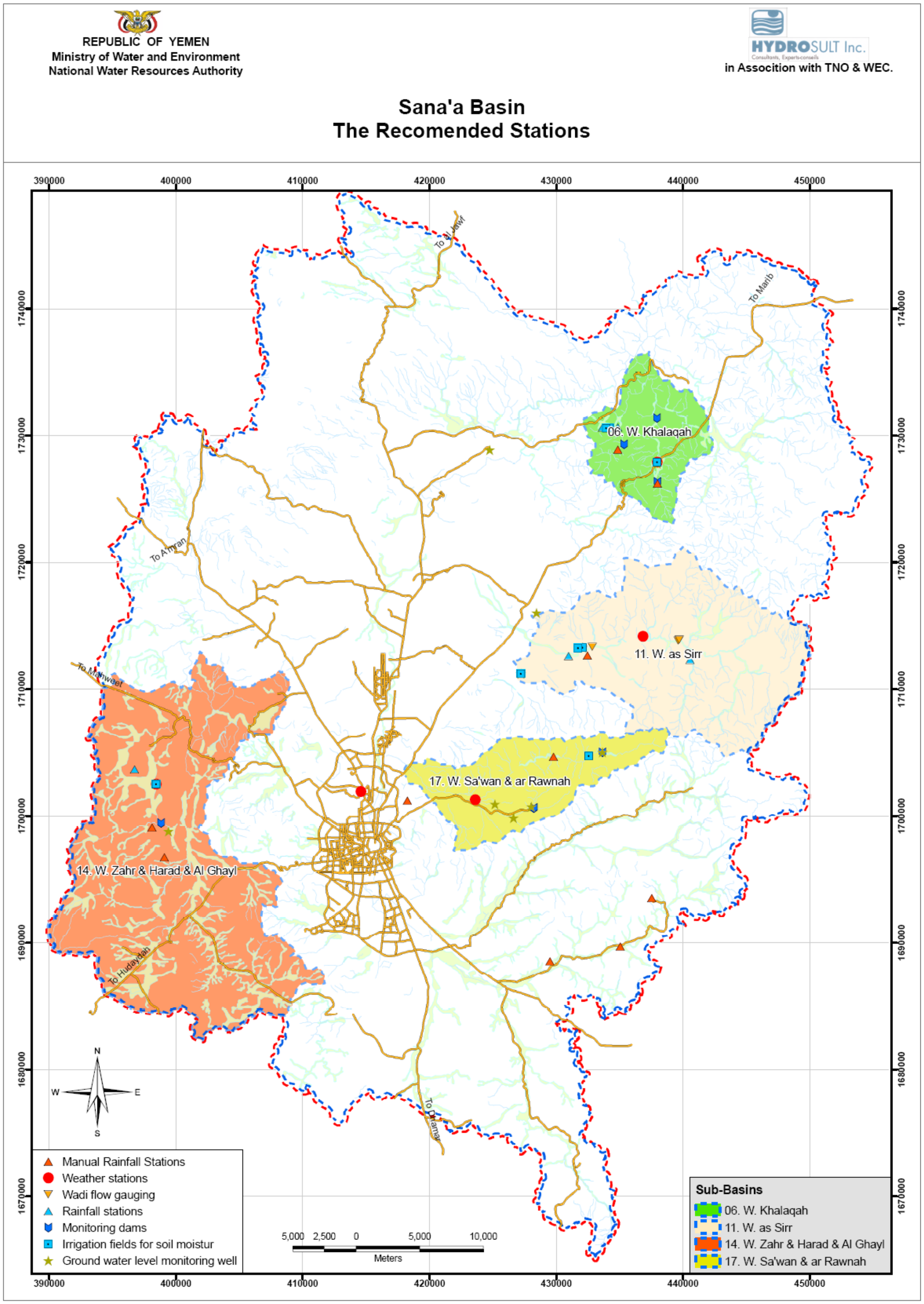


Figure 2-1 Experimental sub-basins and hydrometeorological stations

Wadi Sa'Wan Sub-basin

The total catchment area of Wadi Sa'Wan is 89.7 km^2. The Wadi Sa'Wan sub-basin has two major watersheds: the Barian and Mekhtan-Mussaibih watersheds. The Barian watershed covers about 50 km^2 up to the confluence of the other tributary from Mekhtan-Mussaibih watershed. The Mekhtan-Mussaibih watershed covers an area of about 25 km^2 up to the confluence of the other tributary from Barian watershed. Two small dams are located in the upper catchment, the Mekhtan and Mussaibih dams. The catchment area covered by the two dams is about 9 km^2. The watershed is in volcanic area.

Chapter 3. HYDROLOGICAL MONITORING IN THE EXPERIMENTAL SUB-BASINS

The major objective of Activity 2 is to collect hydrological information which will subsequently be used to determine the water balance of Sana'a Basin and sub-basins. The monitoring elements for data collection are:

- Rainfall,
- Weather,
- Wadi runoff,
- Groundwater level,
- Reservoir water level,
- Soil moisture and,
- Irrigation water abstraction,

Locations of hydrological monitoring stations in the experimental sub-basin are shown in Figure 2-1.

1.4 Rainfall stations

Nine rainfall stations (with six new stations) located in the four experimental sub-basin are shown in Table 3-1.

Table 3-1 Rainfall Stations in the Four Experimental Sub-basins

No	Station	Sub-basin	East Coord. (m)	North Coord. (m)	Remark
1	Qratel Village School	Wadi Zahr & Al Ghay	396728	1703699	New station
2	Mend	Wadi Zahr & Al Ghay	399550	169005	Existing NWRA station
3	Barian Village (School)	Wadi Sa'Wan	433653	1730652	New station
4	Al Kherbah	Wdai Sa'Wan	443606	1701288	Existing NWRA station
5	Al Fetah School	Wadi as Sirr	440553	1712331	New station
6	Ali Bin Abitaleb School	Wadi as Sirr	430971	1712638	New station
7	Bait As Said	Wadi as Sirr	436689	1714095	Existing NWRA station

No	Station	Sub-basin	East Coord. (m)	North Coord. (m)	Remark
8	Bani Kutran School	Wadi Khalaqa	434868	1730652	New station
9	Nasar School	Wadi Khalaqa	437972	1727907	New station

Other important (neighboring) rainfall stations operated by NWRA and WEC are:

Table 3-2 Other Important Rainfall Stations used in this study

No	Station	Sub-basin	East Coord. (m)	North Coord. (m)	Remark
1	Arhab				Existing NWRA station
2	Al Sunaina	Wadi Khalaqa	434868	1730652	Existing NWRA station
3	Shahik	Wadi Khalaqa	437972	1727907	Existing NWRA station
4	Darsalm	Wadi Ghaiman	419887	1689906	Existing NWRA station
5	8985	Sana'a City	417235	1690311	WEC station
6	8986	Sana'a City	415954	1689144	WEC station
7	8987	Sana'a City	415289	1702498	WEC station
8	8988	Sana'a City	412044	1699288	WEC station

In 2007 due to the fact that most of the stations operated by NWRA and CWMU are not successful in getting the data the Consultant established manual rainfall stations and operated by its own staff (Table 3-3).

Table 3-3 Manual Rainfall Stations Operated by the Consultant

St. No.	Station	East Coord. (m)	North Coord. (m)
2008001	Bit Al-Nukhaif Jameaa Bir Al -Na'amy	432473	1712674
2008002	Khalaqa	438002	1726222
2998003	Methbel Omar bin Al-Khatab School	398115	1699113
2008004	Ghayman Al-Sadakah Al-Yamany Al-Almany	429513	1688546
2008005	Sawan-Al-Kherbah Hail House	427744	1700580

St. No.	Station	East Coord. (m)	North Coord. (m)
2008006	Sawan-Barian Al-Housin Bin Ali Al-Rawnah School	429792	1704686
2008012	Al-Qudrah-Ghayman-Al-Shahid Al-Hamasi School	435049	1689713
2008013	Bani Bahlul-Suk Enaqa-Al-Salam School	437529	1693531

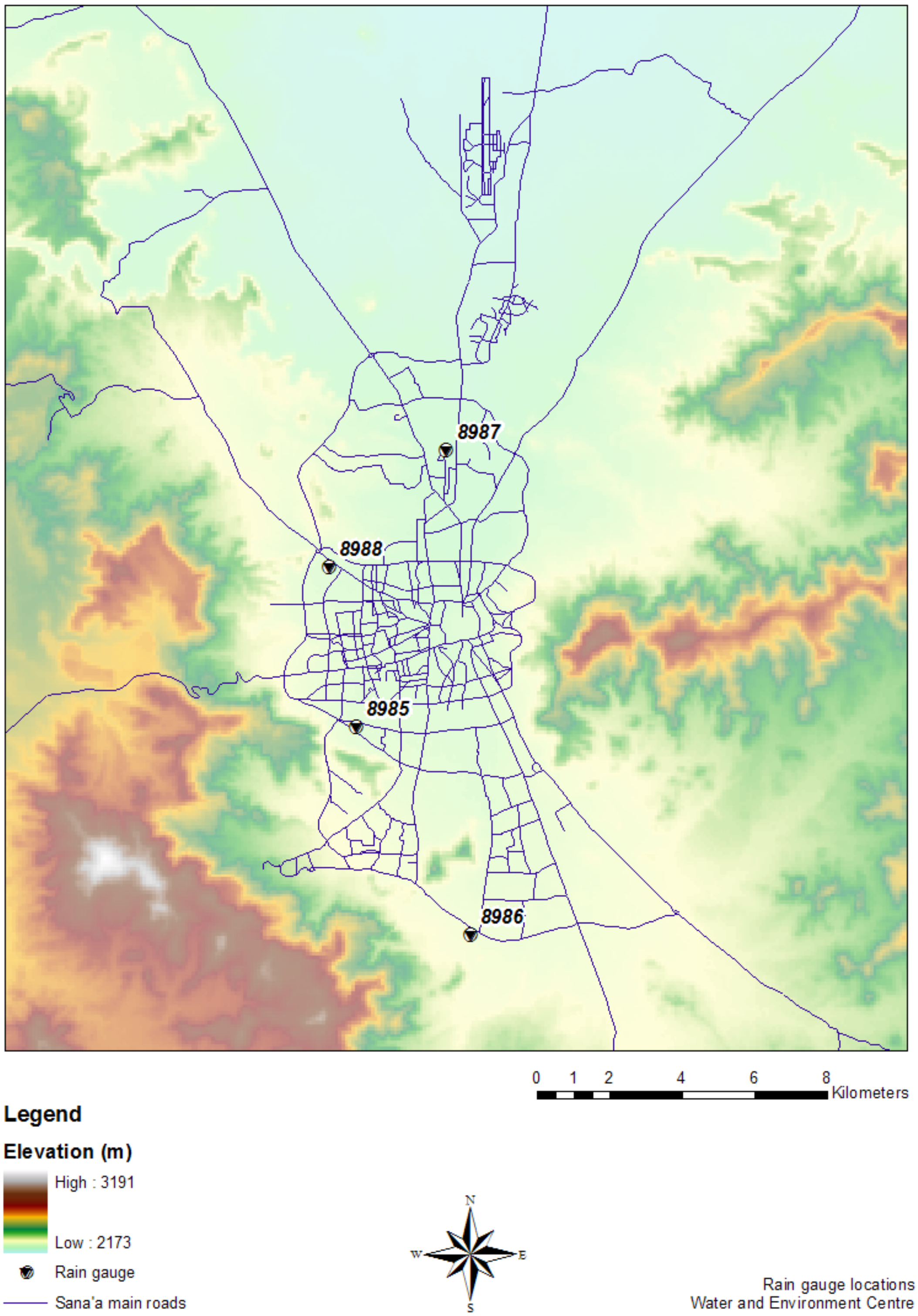


Figure 3-1 WEC Rainfall Stations in Sana'a

1.5 Weather Stations

The following stations (Table 3-4) are part of weather monitoring program:

Table 3-4 Weather Stations in and around Experimental Sub-basins

Station	Sub-basin	East Coordinate	North Coordinate	Remark
Qratel Farm	Wadi Zahr	398441	1702516	New station
Al Kherbah	Wadi SaWan	423606	1701288	New station
Ghdhran	Wadi as Sirr	436844	1714183	New station
Arhab				Existing NWRA station

1.6 Wadi flow gauging stations

Three Wadi flow gauging stations have been established: two in Wadi as Sirr and one in Wadi Barian (Sa'Wan). The stations were established and are operated by NWRA. Staff gauges have been erected and a gauge house for the automatic water level recorder was set up. For water level measurements to be conducted successfully, discharges could be computed by the Slope area method. Unfortunately, due to recent security problems in the area, monitoring of the stations will be difficult and up to now no data have been collected. The locations of the established stations are shown in Table 3-5.

Table 3-5 Wadi Flow gauging locations

Station	Sub-basin	East Coordinate (m)	North Coordinate (m)	Remark
1	Wadi Sirr	430450	1704593	(Staff and gauge house)
2	Wadi Sirr	432830	1713331	(Staff and gauge house)
3	Wadi Barian	439704	1713903	(Staff and gauge house)

1.7 Dam/Reservoir water level stations

Reservoir water levels are being monitored at six dam sites. Staff gauges are erected for water level reading and topographic surveys are performed to establish area capacity curves for each reservoir. With the water level readings from the staff gauge, the amount of water inflows to the reservoir and storage are determined from the area capacity curves. Water balances of each reservoir will be analyzed for recording periods. The locations of the reservoir water level monitoring sites are given in Table 3-6.

Table 3-6 Locations of dam/reservoir water level monitoring stations

Dam	Sub-basin	East Coordinate	North Coordinate
Methbel	Wadi Zahr (Methbel)	398837	1699455
Mekhtan	Wadi SaWan	428224	1700633
Mussaibih	Wadi SaWan	428231	1700655
Khalaqa	Wadi Khalaqa	437986	1726362
Al Hayathem	Wadi Khalaqa	437950	1731391
Arisha	Wadi Khalaqa	435360	1729322

1.8 Groundwater level Monitoring wells

The purpose of groundwater level monitoring in this study is to review the fluctuation of groundwater levels, particularly due to water storage at dam sites.

Table 3-7 Locations of groundwater level monitoring wells

Name of Well	Sub-basin	East Coord. (m)	North Coord. (m)	Remark
HSH40	Wadi Zahr (Methbel)	400033	1698954	Manual
D/S of Mekhtan dam	Wadi SaWan	428044	1700730	Manual (e.Existing NWRA monitoring well)
Well D-25	Wadi SaWan	426640	1699852	Existing NWRA monitoring well
Well C-896 (Matre)	Wadi Sawan (Barian)	433653	1705038	Water level recorder
Ghadran Farm	Wadi as Sirr	427214	1711229	Water level recorder
HS20	Wadi Khalaqa (Arisha)	434860	1729651	Manual
HS172	Wadi Khalaqa	437875	1726662	Manual

1.9 Soil moisture and Irrigation water abstraction measurements

Two farms in Wadi as Sirr sub-basin where modern irrigation techniques are successfully practiced and one farm in Wadi Zahr sub-basin where the traditional furrow irrigation system is used have been selected for soil moisture measurement. Soil water potentials are measured using equipment called an Irrometer. Irrigation water abstractions are taken from meters installed near the farms. The soil moisture monitoring stations are listed in Table 3.8.

Table 3-8 Locations of Soil moisture and water abstraction monitoring stations

Irrigation field	Sub-basin	East Coordinate (m)	North Coordinate (m)
Luluwa Farm	Wadi Zahr (Methbel)	401466	1700871
Ghadran Farm	Wadi As Sirr	427214	1711229
Hinnami Farm	Wadi As Sirr	x	x

Chapter 4. DATA COLLECTION

1.10 Rainfall

The rainfall data collection in 2007 in the experimental sub-basins was not very successful. This is attributed to lack of equipment experience by NWRA and CWMU technicians and to adequate follow up. This applies not only to the newly installed stations, but most of the NWRA operated rainfall stations failed to record rainfall adequately in the 2006-2007 period. The rainfall data records found useful for hydrological analysis are shown in Appendix A. The four WEC stations in Sana'a City have also been found very useful as they had complete daily records in 2007. In 2008, data collection was much better, which includes 13 manual rain gauge stations operated by the consultant and the four WEC rainfall stations.

1.11 Weather

Weather data such as air temperature, relative humidity, wind speed and direction have been recorded at Arhab and the new Qratel stations. Two new stations were established at Ghadran (Wadi Sirr) and Al Kherbah (Wadi Sa'Wan), but no record is available from these stations.

The wind speed data collected at the Arhab and Qratel stations appears to be erroneous and, since there is no sunshine hours record, it is difficult to calculate evapotranspiration with the data available. Therefore, evapotranspiration calculated by GAF will be used for water balance analysis.

1.12 Reservoir Water Level

Water levels in the reservoirs are collected at six dam sites. Water level measurement at the six dam sites was continued in 2008. One dam site on Wadi Ghayiman was included in the monitoring; however, the dam will hold water only in extreme conditions, particularly where heavy rain falls in the downstream catchment. Runoff from moderate rainfall in the upper catchment will be diverted by farmers and infiltrated through Wadi bed before it reaches the dam sites. The dams are:

- Methbel
- Khalaqa
- Arisha
- Al Hayathem
- Mekhtan and
- Mussaibih

Chapter 5. FIELD WATER BALANCE

Soils function as a storehouse for plant nutrients, as habitats for soil organisms and plant roots, and as a reservoir for water to meet the evapotranspiration demands of plant communities. The amount of water that a soil can hold for plant use is determined by its physical and chemical properties. This amount determines the length of time that a plant can be sustained adequately between irrigations or rainfall events. This amount also determines the frequency of irrigation, the amount to be applied, and the capacity of the irrigation system needed for continuous optimum crop growth.

A field water balance from a small irrigation area will be determined using water balance equation:

$$I + P = (S_1 - S_2) - O - ETc - R_e$$

where

R_e = Deep percolation to groundwater storage (possibly recharge)

S_1 and S_2 = Soil moisture at time 1 and 2 respectively at beginning and end of a day

I = Irrigation water applied to the area

P = Precipitation

O = Surface runoff from the field due to rainfall (mm), computed by the SCS method

ET_c = Evapotranspiration

Despite the complicated set of data required, water balance methods are considered by some to be the most accurate way to estimate recharge (Lerner et al. 1990).

The field water balance study is conducted in three farms (Ghadran, Al Hinami, and Luluah). The new irrigation techniques are implemented as water-saving technology in Ghadran and Al Hinami farms, both farms located in Wadi as Sirr sub-basin. The furrow irrigation method is still used on Luluah farm, located in Wadi Zahr sub-basin.

The water mark monitor (Irrometer) is used to measure soil moisture (water potential). Table 5-1 shows the measured soil water potential at Hinami and Ghadran farms in Centi Bars.

Table 5-1 Soil Water Potential in Centi Bars

Date	Al Hinami Farm	Ghadran Farm
	Grape (at 70 cm depth)	Qat (at 70 cm depth)
9-Jul-07	10	7
10-Jul-07		
11-Jul-07		
12-Jul-07		
13-Jul-07		

Date	Al Hinami Farm	Ghadran Farm
	Grape (at 70 cm depth)	Qat (at 70 cm depth)
14-Jul-07		
15-Jul-07		
16-Jul-07		
17-Jul-07		
18-Jul-07		
19-Jul-07		
20-Jul-07		
21-Jul-07		
22-Jul-07	9	
23-Jul-07		
24-Jul-07		
25-Jul-07	43	20
26-Jul-07		
27-Jul-07		
28-Jul-07		
29-Jul-07		
30-Jul-07		20
31-Jul-07	22	
1-Aug-07		
2-Aug-07		
3-Aug-07		
4-Aug-07	16	20
5-Aug-07	30	36
6-Aug-07	41	42

Date	Al Hinami Farm	Ghadran Farm
	Grape (at 70 cm depth)	Qat (at 70 cm depth)
7-Aug-07		
8-Aug-07		36
9-Aug-07		
10-Aug-07		
11-Aug-07	46	51
12-Aug-07	55	56
13-Aug-07		
14-Aug-07		
15-Aug-07		
16-Aug-07		
17-Aug-07		
18-Aug-07		
19-Aug-07		

The following reading classification guide is recommended by the equipment manufacturer.

Table 5-2 Irrometer soil water potential interpretation

No.	Soil water potential (Centi Bar)	Manufacturer recommendation
1	0-10	Saturated soil
2	10-30	Soil is adequately wet (except coarse sands, which are beginning to lose water)
3	30-60	Usual range for irrigation (most soils)
4	60-100	Usual range for irrigation in heavy clay
5	100-200	Soil is becoming dangerously dry for maximum production

Water Available for Plants

In designing an irrigation system, information is needed on how much of the water in soils is available to plants as the soil functions as a reservoir that has a limited capacity. Traditionally, water available to plants has been considered to be the amount of water held by the soil between field capacity (FC) and permanent wilting point (PWP) (NEH 15-1, 1991).

By definition, FC is the amount of water a well-drained soil holds after "free" water has drained off. For coarse-textured soils, drain-off occurs soon after irrigation because of their relatively large pores. In fine-textured soils, drainage takes much longer because of their small pore size. Soil properties that materially affect field capacity are texture and strata within the profile that restrict water movement. Fine-textured soils hold more water than coarse-textured soils. Field capacity for sandy soils is defined as -1/10 bar (10 Centi Bars), for silty soils, -1/5 bar (20 Centi Bars); and for clay soils, -1/3 bar (33 Centi Bars) (NEH 15-1, 1991).

The permanent wilting point (PWP) is the soil-water content at which plants can no longer obtain enough water to meet minimal transpiration requirements, at which time they wilt and, even if watered, will not recover. Plants will wilt if they are not able to take up soil water fast enough to meet the climatic ET demand. Plants continue to absorb water when wilted, but not at a rate sufficient to regain turgor. The water potential commonly used for PWP is -15 bars (NEH 15-1, 1991).

Soil water considered to be available for plant growth lies at a potential energy level between FC and PWP.

Generally, well-drained sandy soils have a low available water capacity. Silty soils have a good available water-holding capacity, as do clay loams and clays. Table 5.3 provides a general guide of available water ranges for given soil texture classifications.

Table 5-3 Ranges in available water content by textural classes (NEH 15-1, 1991) and (ASCE, 1990, Table 2-6, p. 21)

Textural class (NEH 15-1, 1991)	Inches of water per inch of soil depth or cm of water per cm of soil depth
Very coarse sand	0.03 - 0.06
Coarse sand-loamy sand	0.06 - 0.10
Sandy loam - fine sandy loam	0.10 - 0.14
Very fine sandy loam - silt loam	0.12 - 0.19
Sandy clay loam - clay loam	0.14 - 0.21
Sandy clay - clay	0.13 - 0.21
Peat and muck	0.17 - 0.25

Textural Class (ASCE, 1991)	Field Capacity (%)	Wilting Point (%)	Available Capacity (%)
Sand	0.12	0.04	0.08
Loamy sand	0.14	0.06	0.08
Sandy loam	0.23	0.10	0.13
Loam	0.26	0.12	0.15
Silt loam	0.30	0.15	0.15
Silt	0.32	0.15	0.17
Silty clay loam	0.34	0.19	0.15
Silty clay	0.36	0.21	0.15
Clay	0.36	0.21	0.15

Both rainfall and irrigation water are stored in the soil; therefore, the effective plant root zone provides a reservoir for water storage. In order to determine effectively the capacity of the reservoir, information is required for the water retaining properties of the soils and the root development characteristics of individual crops. A reliable estimate of the potential ET or ETo is required, along with the appropriate crop curve so that kc values are known. With ETo and Kc., estimates of ETc are determined from the relation:

ETc = (ETo) (Kc)

Table 5-4 shows the field water balance calculation at Al-Hinami farm, a 1-ha drip irrigation system on loam soil. The crop is all grapes. Rainfall is from nearby Bait Said rainfall station. ETc = (ETo*Kc) is based on the GAF study and soil moisture (water potential) is measured on the field using watermark Irrometer. Irrigation water abstraction is taken from water meter readings installed on the pipe system. The Field capacity of the soil is 0.26% and wilting point is 0.12%. The IWC calculated using a bulk density of 1.35 gm/cc for a 70 cm depth (where moisture is measured) is 132 mm.

Table 5-5 gives field water balance for Ghadran Qat farm on sandy loam soil. A GAF average kc value of 0.84 is taken for all months. The Field capacity of the soil is 0.23% and wilting point is 0.10%. The IWC calculated using a bulk density of 1.7 gm/cc for 70 cm depth is 155 mm. Table 5-4 and Table 5-5 show that, at both Al-Hinami and Ghadran farms during the period of measurement, no excess water was applied from irrigation to result in deep percolation.

Table 5-4 Field water balance at Al-Hinami farm

Date	SM	IWC (mm)	I (mm)	P* (mm)	ETc† (mm)	O (mm)	S_t (mm)	Re (mm)	Remark
9-Jul-07	10	132		11.75	4.93	0.2	138.92	6.62	
10-Jul-07		132		5.5	4.93		132.87	0.57	
11-Jul-07		132		0	4.93		127.37	0	
12-Jul-07		127		0	4.93		122.44	0	
13-Jul-07		122		0	4.93		117.51	0	
14-Jul-07		118		0	4.93		112.58	0	
15-Jul-07		113		0	4.93		107.65	0	
16-Jul-07		108		0	4.93		102.72	0	
17-Jul-07		103		0	4.93		97.79	0	
18-Jul-07		98			4.93		92.86	0	
19-Jul-07		93			4.93		87.93	0	
20-Jul-07		88			4.93		83	0	
21-Jul-07		83			4.93		78.07	0	
22-Jul-07	9	78	8.7		4.93		81.84	0	Rain
23-Jul-07		132			4.93		127.07	0	
24-Jul-07		127			4.93		122.14	0	
25-Jul-07	43	122	7.3		4.93		124.51	0	
26-Jul-07		125			4.93		119.58	0	
27-Jul-07		120			4.93		114.65	0	
28-Jul-07		115			4.93		109.72	0	
29-Jul-07		110			4.93		104.79	0	

* from Bait Said station

† Modified from GAF(2007)

Date	SM	IWC (mm)	I (mm)	P* (mm)	ETc† (mm)	O (mm)	S_t (mm)	Re (mm)	Remark
30-Jul-07		105			4.93		99.86	0	
31-Jul-07	22	100			4.93		94.93	0	Rain‡
1-Aug-07		95			3.87		91.061	0	
2-Aug-07		91			3.87		87.192	0	
3-Aug-07		87			3.87		83.323	0	
4-Aug-07	16	83			3.87		79.454	0	Rain
5-Aug-07	30	79			3.87		75.585	0	
6-Aug-07	41	76			3.87		71.716	0	

Where:
SM = Soil moisture (Water Potential) measured (Centi Bars)
IWC = Available water content (mm)
I = Irrigation water applied (mm) (measured by water meter and divided by area to convert to depth of water)
P = Precipitation (mm) at nearby rainfall station
Etc = Average daily crop evapotranspiration (Kc*ETo)
O = Surface runoff from the field due to rainfall (mm) computed by SCS method
S_t = Soil moisture storage at time t (mm)
Re = Recharge to Groundwater in excess of Field Capacity of soils

The application of irrigation water on July 22 and 25, 2007 (Table 5-4) does not bring the soil to the field capacity. Recharge/deep percolation will occur if rainfall occurred after irrigation water is applied on the field. It is seen that the drip irrigation technique is efficient.

Table 5-5 Field water balance at Ghadran farm

Date	SM	IWC (mm)	I (mm)	P§ (mm)	ETc** (mm)	O (mm)	S_t (mm)	Re (mm)
8-Jul-07		155	24.4	0	4.87		174.23	
9-Jul-07	7	155		11.75	4.87	0.00	161.58	6.878
10-Jul-07		155		5.5	4.87		155.33	0.628

‡ Rainfall improved the soil moisture, although the nearby station did not record it

§ from Bait Said station

** Modified from GAF (2007)

Date	SM	IWC (mm)	I (mm)	$P^{§}$ (mm)	ETc^{**} (mm)	O (mm)	S_t (mm)	Re (mm)
11-Jul-07		155		0	4.87		149.83	0
12-Jul-07		150		0	4.87		144.96	0
13-Jul-07		145		0	4.87		140.08	0
14-Jul-07		140		0	4.87		135.21	0
15-Jul-07		135		0	4.87		130.34	0
16-Jul-07		130		0	4.87		125.47	0
17-Jul-07		125		0.2	4.87		120.80	0
18-Jul-07		121		3.4	4.87		119.32	0
19-Jul-07		119		0.8	4.87		115.25	0
20-Jul-07		115		0	4.87		110.38	0
21-Jul-07		110		0	4.87		105.51	0
22-Jul-07		106	1.2	0	4.87		101.84	0
23-Jul-07		102		0	4.87		96.96	0
24-Jul-07		97		0	4.87		92.09	0
25-Jul-07	20	92		0	4.87		87.22	0
26-Jul-07		87		0.2	4.87		82.55	0
27-Jul-07		83		0	4.87		77.68	0
28-Jul-07		78		0	4.87		72.80	0
29-Jul-07		73		15	4.87		82.93	0
30-Jul-07	20	83		15	4.87		93.06	0
31-Jul-07		93		0	4.87		88.19	0
1-Aug-07		88		0	4.45		83.74	0
2-Aug-07		84		0	4.45		79.28	0
3-Aug-07		79	25.6	0	4.45		100.43	0

Date	SM	IWC (mm)	I (mm)	P§ (mm)	ETc** (mm)	O (mm)	S_t (mm)	Re (mm)
4-Aug-07	20	100		0	4.45		95.98	0
5-Aug-07	36	96		0	4.45		91.53	0
6-Aug-07	42	92		0	4.45		87.08	0
7-Aug-07		87		0	4.45		82.62	0
8-Aug-07	36	83		0	4.45		78.17	0
9-Aug-07		78		0	4.45		73.72	0
10-Aug-07		74		0	4.45		69.27	0
11-Aug-07	51	69		0	4.45		64.82	0
12-Aug-07	56	65		0	4.45		60.36	0

Water Balance at Luluah Farm

Soil water potential is measured at two depths (30 cm and 70 cm) below the ground in Luluah farm. The major objective is to determine field water balance and irrigation efficiency.

To calculate the available water between FC and PWP, the following formula will be used:

$$D = (B.D.)(d)(IWC)/(dw)(100)$$

where:

- D centimeters of water in soil depth (d)
- B.D. soil bulk density (grams oven dry soil/cm^3 volume sampled)
- d soil depth in inches or centimeters
- IWC Actual (measured) water content between FC and PWP in % by weight
- dw density of water taken as 1 g/cm^3

The relationship between IWC and the measured soil water potential is shown in Figure 5.1.

Laboratory analysis was effected by taking samples from the three farms to determine the type of soil and water content. Table 5-6 shows the laboratory analysis results.

Table 5-6 Laboratory Soil Analysis at 3 Farms

Date	Location	Sampling Depth (cm)	Soil moisture content %	Sand %	Silt %	Clay %	Soil type
30-07-02	Ghadran Farm	30	9.8	70	18.8	11.2	Sandy
		50	11.7				
		100	13.5				
31-07-02	Al-Hinami Farm	30	12.2	43.8	37.5	18.7	Loam
		50	9.9				
		100	13.8				
1/8/2007	Luluah	30	19.6	32.5	41.3	26.2	Loam
		50	19.1				
		100	24.9				
5/8/2007	Luluah	30	29.4	32.5	43.1	24.4	

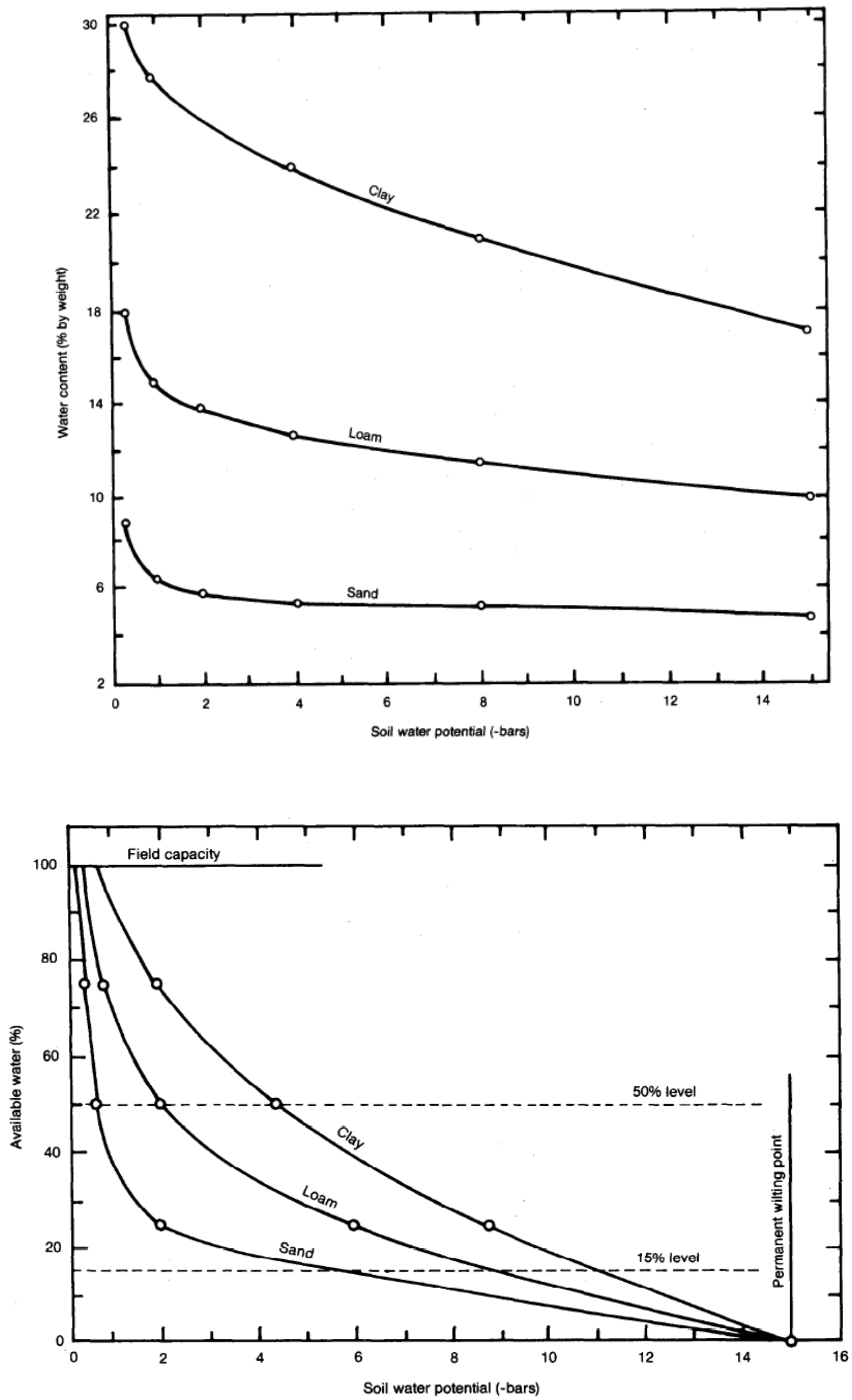


Figure 5-1 Soil Water Characteristic Curves (Source: NEH 15-1. 1991)

The soil bulk density as determined in the laboratory analysis for each farm is shown in Table 5-7.

Table 5-7 Soil Bulk Density at the three Farms

Data	Location	Bulk density g/cm^3
1-09-07	Hinami Farm	1.35
1-09-07	Ghadran Farm	1.7
3-09-07	Luluah Farm	1.62

The soil water potential measured at Luluah farm is shown in Table 5-9.

Table 5-8 Soil moisture measurement (Water Potential) at Luluah Farm

Date	Station	Crop	Water Potential (Centi Bars)		Remark
			Depth 30 cm	Depth 70 cm	
27/02/2008	Luluah	Nill	40	3	Irrigation
01/03/2008	Luluah	Nill	10	6	Irrigation
05/03/2008	Luluah	Nill	18	10	
15\04\2008	Luluah	Potatoes	13	2	Irrigation
19\04\2008	Luluah	Potatoes	14	1	Irrigation
22\04\2008	Luluah	Potatoes	13	1	Irrigation
26\04\2008	Luluah	Potatoes	13	1	Irrigation
29\04\2008	Luluah	Potatoes	13	0	
03\05\2008	Luluah	Potatoes	13	1	
06\05\2008	Luluah	Potatoes	17	2	
8/5/2008	Luluah	Potatoes	15	4	Irrigation
12/5/2008	Luluah	Potatoes	13	3	Rain 11/5/2008 (10pm-10:30)
15/05/2008	Luluah	Potatoes	13	5	
19/05/2008	Luluah	Potatoes	13	1	Irrigation

Date	Station	Crop	Water Potential (Centi Bars)		Remark
			Depth 30 cm	Depth 70 cm	
24/05/2008	Luluah	Potatoes	12	2	
27/05/2008	Luluah	Potatoes	15	4	Irrigation
31/05/2008	Luluah	Potatoes	12	6	Rain 30/05/2008
2/6/2008	Luluah	Potatoes	13	6	Rain (1/6/2008)
4/6/2008	Luluah	Potatoes	14	6	Rain (3/6/2008)
7/6/2008	Luluah	Potatoes	12	4	
10/6/2008	Luluah	Potatoes	13	3	Irrigation
15/6/2008	Luluah	Potatoes	14	2	
18/6/2008	Luluah	Potatoes	13	7	
22/6/2008	Luluah	Potatoes	13	10	

In Luluah Farm, the water is applied for irrigation by pumping water from a well. The furrow irrigation method is used. The well discharge is 8 lit/sec and pumped for four hours i.e. about 115.2 m^3 of water applied to a field of about 3402 m^2 in area. The computed irrigation efficiency at Luluah farm is about 56%. Because furrow irrigation is used, the water loss by deep percolation and non-beneficial evapotranspiration is significant, unlike the other farms (A- Hinami and Ghadran), where water is efficiently applied through implementation of modern irrigation techniques. Only when heavy rain falls after irrigation, percolation from the Ghadran and Al Hinami farms will occur.

Table 5-9 Computation of Water Balance at Luluah Farm

Date	Soil Depth (cm)	Water Potential (C Bars)	IWC (%)	PWP (%)	BD (gm/cc)	Water Depth D (mm)	Total (d =70 cm)	FC. 70 cm (mm)	ETc (mm)	AWE (mm)	WR (mm)	WP (Irr.)	Perc. (mm)	Eff.	Remark
27/02/08	30	40	15.25	10	1.62	25.5									
	70	3	18	10	1.62	51.8	77.4	90.7							
							63.0		14.4	63.0	27.7	33.9	6.1	82%	
1/3/08	30	10	18	10	1.62	38.9									
	70	6	18	10	1.62	51.8	90.7								
							70.7		20	70.7	20.0	33.9	13.9	59%	
5/3/08	30	18	17.3	10	1.62	35.5									
	70	10	18	10	1.62	51.8	87.3								
15\04\08	30	13	17.7	10	1.62	37.4									
	70	2	18	10	1.62	51.8	89.3	90.7							
19\04\08	30	14	17.6	10	1.62	36.9			18	71.3	19.4	33.9	14.5	57%	

Date	Soil Depth (cm)	Water Potential (C Bars)	IWC (%)	PWP (%)	BD (gm/cc)	Water Depth D (mm)	Total (d =70 cm)	FC. 70 cm (mm)	ETc (mm)	AWE (mm)	WR (mm)	WP (Irr.)	Perc. (mm)	Eff.	Remark
	70	1	18	10	1.62	51.8	88.8								
22\04\08	30	13	17.7	10	1.62	37.4			13.5	75.3	15.4	33.9	18.5	45%	
	70	1	18	10	1.62	51.8	89.3								
									18	71.3	19.4	33.9	14.5	57%	
26\04\08	30	13	17.7	10	1.62	37.4									
	70	1	18	10	1.62	51.8	89.3								
29\04\08	30	13	17.7	10	1.62	37.4			13.5	75.8	14.9				Rain
	70	0	18	10	1.62	51.8	89.3								
03\05\08	30	13	17.7	10	1.62	37.4			19.8	69.5	21.2				Rain
	70	1	18	10	1.62	51.8	89.3								

Date	Soil Depth (cm)	Water Potential (C Bars)	IWC (%)	PWP (%)	BD (gm/cc)	Water Depth D (mm)	Total (d =70 cm)	FC. 70 cm (mm)	ETc (mm)	AWE (mm)	WR (mm)	WP (Irr.)	Perc. (mm)	Eff.	Remark
06\05\08	30	17	17.4	10	1.62	36.0			19.8	69.5	21.2				Rain
	70	2	18	10	1.62	51.8	87.8								
8/5/08		15	17.45	10	1.62	36.2			10.8	77.0	13.7	33.9	20.2	40%	
		4	18	10	1.62	51.8	88.0								
12/5/08		13	17.7	10	1.62	37.4			21.6	66.4	24.3				Rain
		3	18	10	1.62	51.8	89.3								
15/05/08		13	17.7	10	1.62	37.4			16.2	73.1	17.6				
		5	18	10	1.62	51.8	89.3								
19/05/08		13	17.7	10	1.62	37.4			16.2	73.1	17.6	33.9	16.3	52%	
		1	18	10	1.62	51.8	89.3								

Date	Soil Depth (cm)	Water Potential (C Bars)	IWC (%)	PWP (%)	BD (gm/cc)	Water Depth D (mm)	Total (d =70 cm)	FC. 70 cm (mm)	ETc (mm)	AWE (mm)	WR (mm)	WP (Irr.)	Perc. (mm)	Eff.	Remark
24/05/08		12	17.8	10	1.62	37.9			27	62.3	28.4				
		2	18	10	1.62	51.8	89.7								
27/05/08		15	17.55	10	1.62	36.7			16.2	73.5	17.2	33.9	16.7	51%	
		4	18	10	1.62	51.8	88.5								
31/05/08		12	17.8	10	1.62	37.9			21.6	66.9	23.8				Rain
		6	18	10	1.62	51.8	89.7								
2/6/08		13	17.7	10	1.62	37.4			12.8	76.9	13.8				Rain
		6	18	10	1.62	51.8	89.3								
4/6/08		14	17.6	10	1.62	36.9			12.8	76.5	14.2				Rain

Date	Soil Depth (cm)	Water Potential (C Bars)	IWC (%)	PWP (%)	BD (gm/cc)	Water Depth D (mm)	Total (d =70 cm)	FC. 70 cm (mm)	ETc (mm)	AWE (mm)	WR (mm)	WP (Irr.)	Perc. (mm)	Eff.	Remark
		6	18	10	1.62	51.8	88.8								
7/6/08		12	17.8	10	1.62	37.9			19.2	69.6	21.1				
		4	18	10	1.62	51.8	89.7								
10/6/08		13	17.7	10	1.62	37.4			19.2	70.5	20.2	33.9	13.7	59%	
		3	18	10	1.62	51.8	89.3								
Average														56%	

d	Soil depth (cm) is the depth of soil at which water potential is measured; it is measured at 30 and 70 cm below the ground
Water Potential	Value of water potential measured in Centi Bars
IWC (%)	Irrometer-measured water content (%) as obtained from chart (Figure 5.1)
BD	The bulk density (gm/cm^3) of soil determined by laboratory analysis (Table 5.6)
D (Water Depth. mm)	Available water depth at two soil horizons (0-30 cm. and 30-70 cm)
Total depth of water	Available water depth at total 70 cm
FC (70 cm)	Field Capacity at 70 cm depth

ET c	Crop evapotranspiration (mm)
AWE	Available water after evapotranspiration (mm)
WR	Water required to bring the 70 cm soil to field capacity (mm)
PWP	Permanent Wilting Point (% by volume). Table 5-3
WPirr	Average irrigation water provided by farmers during irrigation (mm)
Perc.	Excess water above field capacity assumed to be percolated (mm)
Eff.	Irrigation Efficiency computed as Water required divided by water provided (WR/WPirr)

Chapter 6. RESERVOIR RUNOFF AND WATER BALANCE

1.13 Runoff to the Reservoirs

Runoff or inflow to the reservoirs as a result of catchment rainfall upstream of dam sites is computed by the SCS-CN method using daily rainfall of nearby stations. The resulting runoff is compared to the runoff volume from water level measurements by staff gauge. This is done mainly to check the validity of CN values proposed by HWC, HYDROSULT and ARCADIS.

The HWC (1992) study divided the country into eight runoff characteristic zones. This classification was adopted in previous studies such as HYDROSULT (2002) and ARCADIS (2006). The same is adopted in this study to classify runoff characteristics for the six reservoirs and the 22-sub-basins of Sana'a Basin. Table 6.1 shows the runoff characteristic zones.

Table 6-1 Definition of runoff characteristic zones used in Yemen (HWC. 1992)

Zone ID	Description
P1	Steep slopes with bare rock
P2	Low slopes with bare rock or thin soils
P3	Steep slopes with natural vegetation
P4	Flat areas with impermeable soils
P5	Terraces on slopes
A1	Flat and sandy alluvial areas
A2	Terraces in wadi beds or on plains
A3	Low slopes with natural vegetation

The first five of these zones are regarded as runoff producing, the last three as runoff absorbing zones.

The SCS model is used to estimate runoff volume from available rainfall data. The CN values adopted by HWC and the later two studies are shown in Table 6.2. The latest ARCADIS values are adopted in this case, which updated the HWC and HYDROSULT CN estimates.

Estimate of runoff from the six dams (Methbel, Mekhtan, Mussaibih, Arisha, Khalaqa, and Al-Hayathem) are discussed below.

Table 6-2 Runoff computation parameters (SCS-CN method) for different land use groups

	HWC			HYDROSULT			ARCADIS				
Zone	Dry	Average	Wet	Dry	Average	Wet	Dry	Average	Wet	Initial loss factor	Max antecedent moisture mm
P1	78	90	96	87	94	97	85	94	98	0.15	40
P2	70	85	94	74	88	95	75	88	95	0.20	45
P3	51	70	85							0.20	50
P4	57	75	88	65	75	82	57	75	88	0.20	48
P5	45	65	82	60	70	89	51	70	85	0.30	55
A1	35	55	74	35	55	74	35	55	74	0.25	70
A2	45	60	82	45	65	82	46	65	81	0.30	60
A3	40	65	78							0.20	65

(source: ARCADIS. 2006)

1.13.1 Methbel Dam/Reservoir

The dam is at the exit of a wide upstream plain having large low mounds of outcropping basaltic lava flow material surrounded by sedimentary deposits. The dam site consists of layers of Tertiary Volcanic rock (tuff, rhyolite), characterized by horizontal layers interbedded with thin tuff layers.

Methbel dam has a catchment area of 32.6 km^2 (Figure 6-1). Reservoir runoff using the SCS-CN method and runoff classification zones has been determined. The two WEC stations (8985 and 8988) daily rainfall data are used for the computation. The summary of annual rainfall and runoff in 2007 is shown in Table 6-3.

Table 6-3 Summary of annual rainfall-runoff (Methbel reservoir)

	Annual Rainfall (mm)	Annual Runoff (mm)					
		P1	P2	P3	A1	A3	Total
Station 8985	192.0	15.0	0	0.1	0.0	0.0	15.1
Station 8988	81.6	0.4	0	0	0	0	0.4
Mean rainfall (mm)	137.0	7.7	0	0	0	0	7.7

	Annual Rainfall (mm)	Annual Runoff (mm)					Total
		P1	P2	P3	A1	A3	
Area (ha)		191.5	0	45.1	1296.6	1730.3	3263.6
Total (m^3)		14738	0	22	0	0	14761

Runoff calculated[††] using the SCS method is 14761 m^3/year with an average annual runoff coefficient of 5.6%. The total runoff volume in Methbel reservoir measured by staff gauge and converted to volume using rating curve in 2007 is [‡‡]12492 m^3. The runoff calculated and measured is within a difference of 15%.

[††] Daily SCS-CN method is used to estimate daily runoff for each runoff characteristic zone (hydrologic unit) of P1, P2, P3, A1 and A3. The above table gives the annual summary and runoff is then calculated for each hydrologic unit and then summed to get the annual figures. For P1 Runoff (m^3) =Runoff (mm) * generating area (ha) * 10 = 7.7*191.5 = 14738 m^3/year.

[‡‡] Volume of flood estimated between flood events.

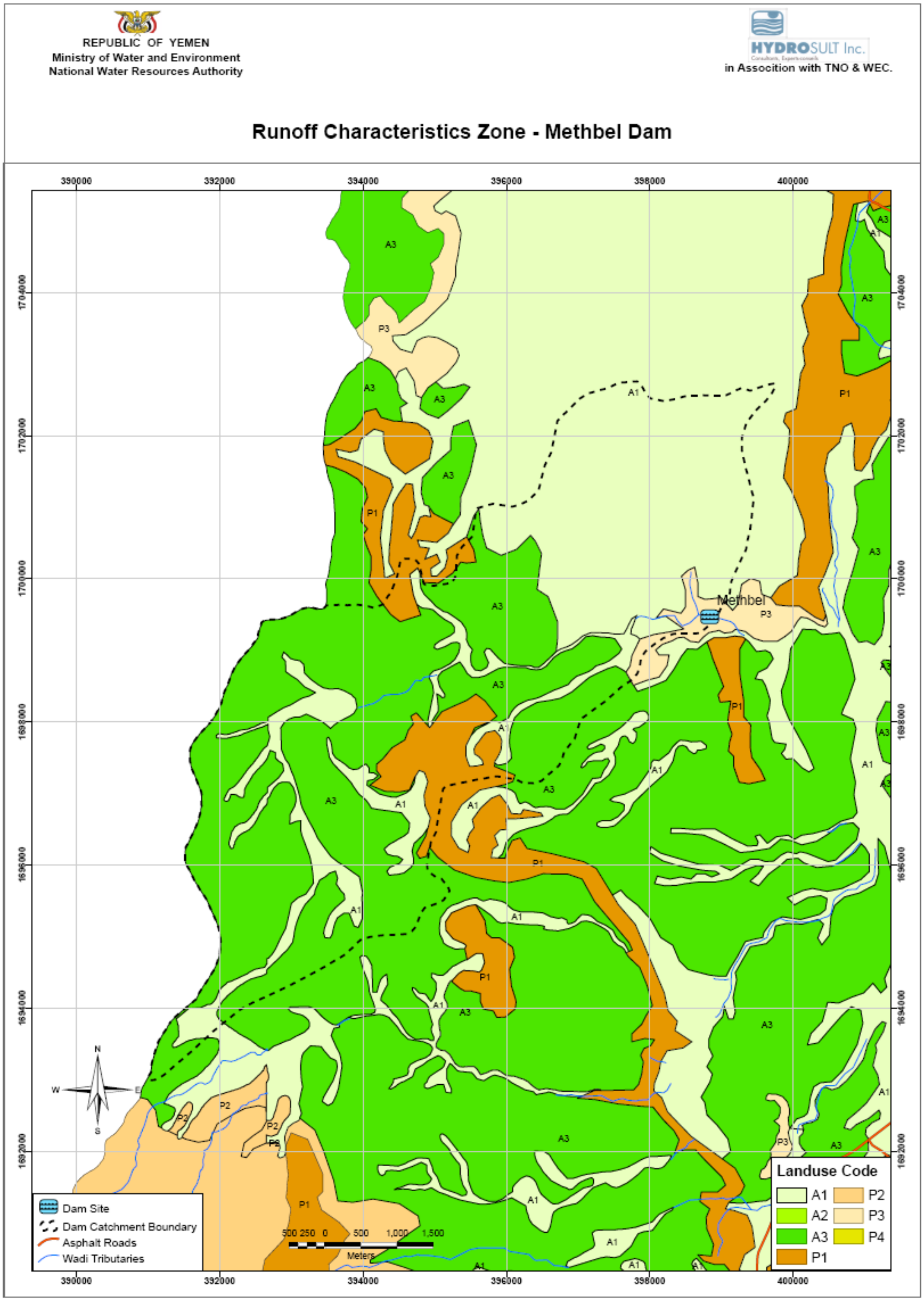


Figure 6-1 Methbel Dam Catchment Runoff Characteristic Zones

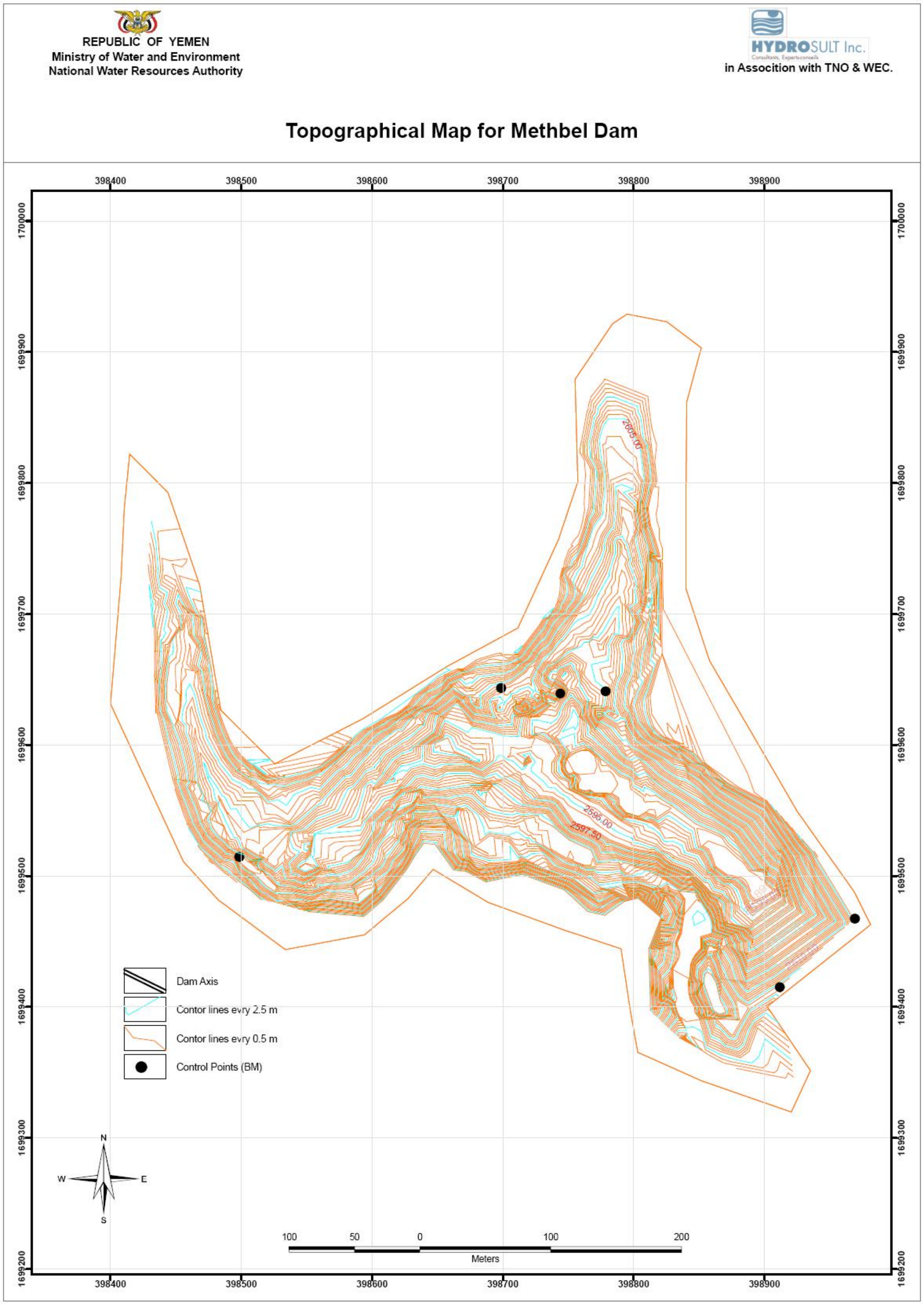

REPUBLIC OF YEMEN
Ministry of Water and Environment
National Water Resources Authority
HYDROSULT Inc.
in Association with TNO & WEC.
Topographical Map for Methbel Dam
398400
398500
398600
398700
398800
398900
1700000
1699900
1699800
1699700
1699600
1699500
1699400
1699300
1699200
2605.00
2595.00
2597.50
Dam Axis
Contor lines evry 2.5 m
Contor lines evry 0.5 m
Control Points (BM)
N
W
E
S
100
50
0
100
200
Meters

Figure 6-2 Methbel Reservoir Topographic Survey Map

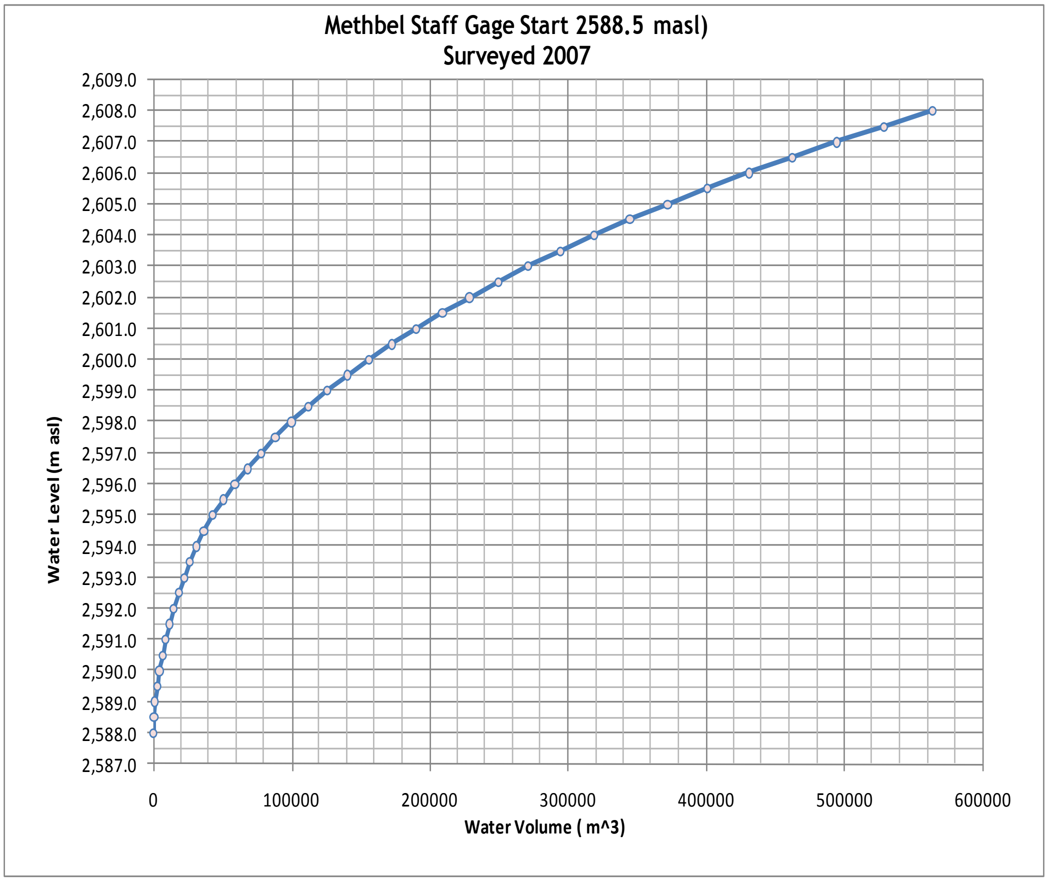


Figure 6-3 Depth-Volume curve for Methbel dam

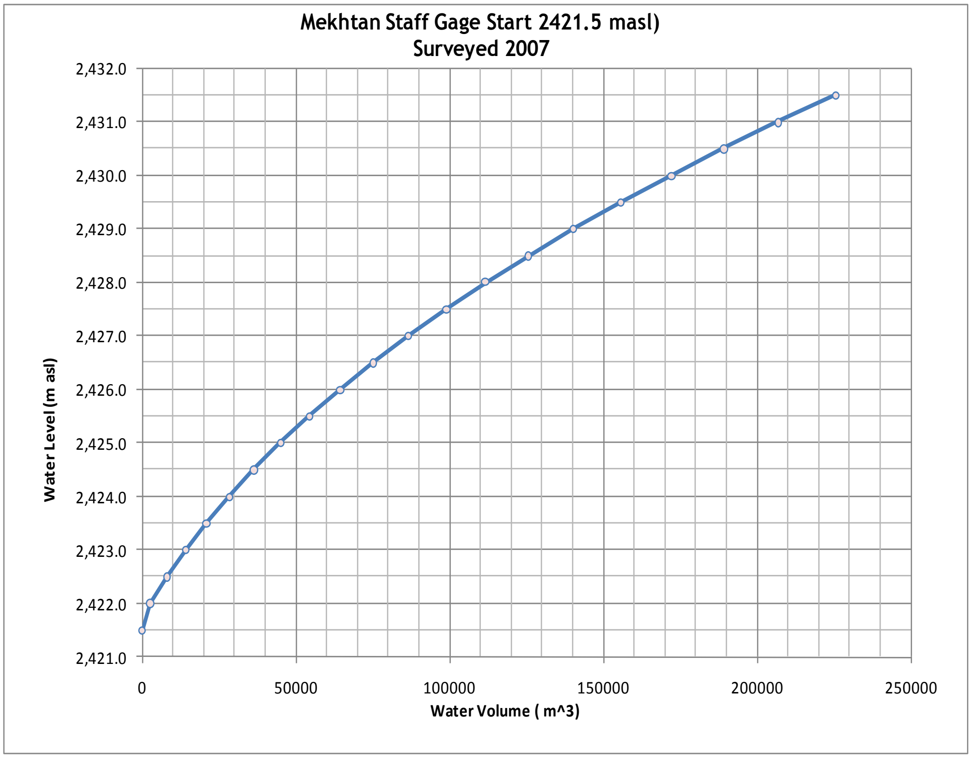
1.13.2 Mekhtan Dam

Reservoir runoff using the SCS-CN method and runoff classification zones has been determined for Mekhtan dam catchment, with a catchment area of 5.68 km^2. The WEC (8986) station daily rainfall data are used for computation. The summary of annual rainfall and runoff in 2007 is shown in Table 6.4. Annual runoff is 110413 m^3 and the annual runoff coefficient is 16%. The total Runoff volume in Mekhtan reservoir measured by staff gauge and converted to volume using the 2007 rating curve (Figure 6-5) is 122210 m^3. The runoff calculated and measured is within a difference of 10%.

Table 6-4 Summary of Annual Rainfall-Runoff (Mekhtan Reservoir)

	Rainfall (mm)	Runoff (mm)		
		P1	P2	Total
Station 8986	221	24.7	9.8	34.5
Area (ha)		367.4	200.7	568.1
Total (m^3)		90729	19684	110413

Figure 6-4 Mekhtan Reservoir Topographic Survey Map


Mekhtan Staff Gage Start 2421.5 masl)
Surveyed 2007
Water Level (m asl)
Water Volume (m^3)

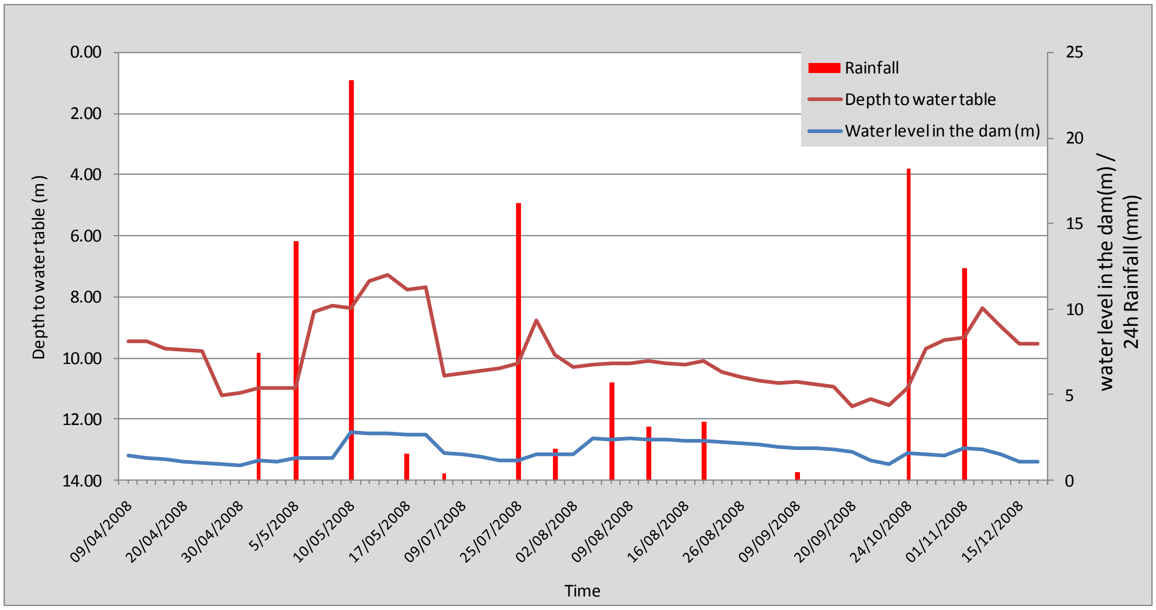

Rainfall
Depth to water table
Water level in the dam (m)
Depth to water table (m)
water level in the dam(m) / 24h Rainfall (mm)
Time

Figure 6-5 Depth-Volume curve for Mekhtan Dam (top) and response of groundwater table and Mekhtan reservoir level to rainfall (bottom)

1.13.3 Mussaibih Dam

Reservoir runoff using the SCS-CN method and runoff classification zones has been determined for Mussaibih dam catchment, with an area of 3.65 km^2. The WEC (8986) station daily rainfall data are used for the computation. The summary of annual rainfall and runoff in 2007 is shown in Table 6-5. Annual runoff is estimated at 67033 m^3, with an annual runoff coefficient of 16%. The total Runoff volume in Mussaibih reservoir measured by staff gauge and converted to volume using the 2007rating curve is 51896 m^3 which shows a 29% difference from the SCS-CN estimate. The response of groundwater table and reservoir to water rainfall is shown in Figure 6-7.

Table 6-5 Summary of Annual Rainfall-Runoff (Mussaibih Reservoir)

	Rainfall (mm)	Runoff (mm)		
		P1	P2	Total
Station 8986	221	24.7	9.8	34.5
Area (ha)		209.3	156.4	365.7
Total (m^3)		51696	15337	67033

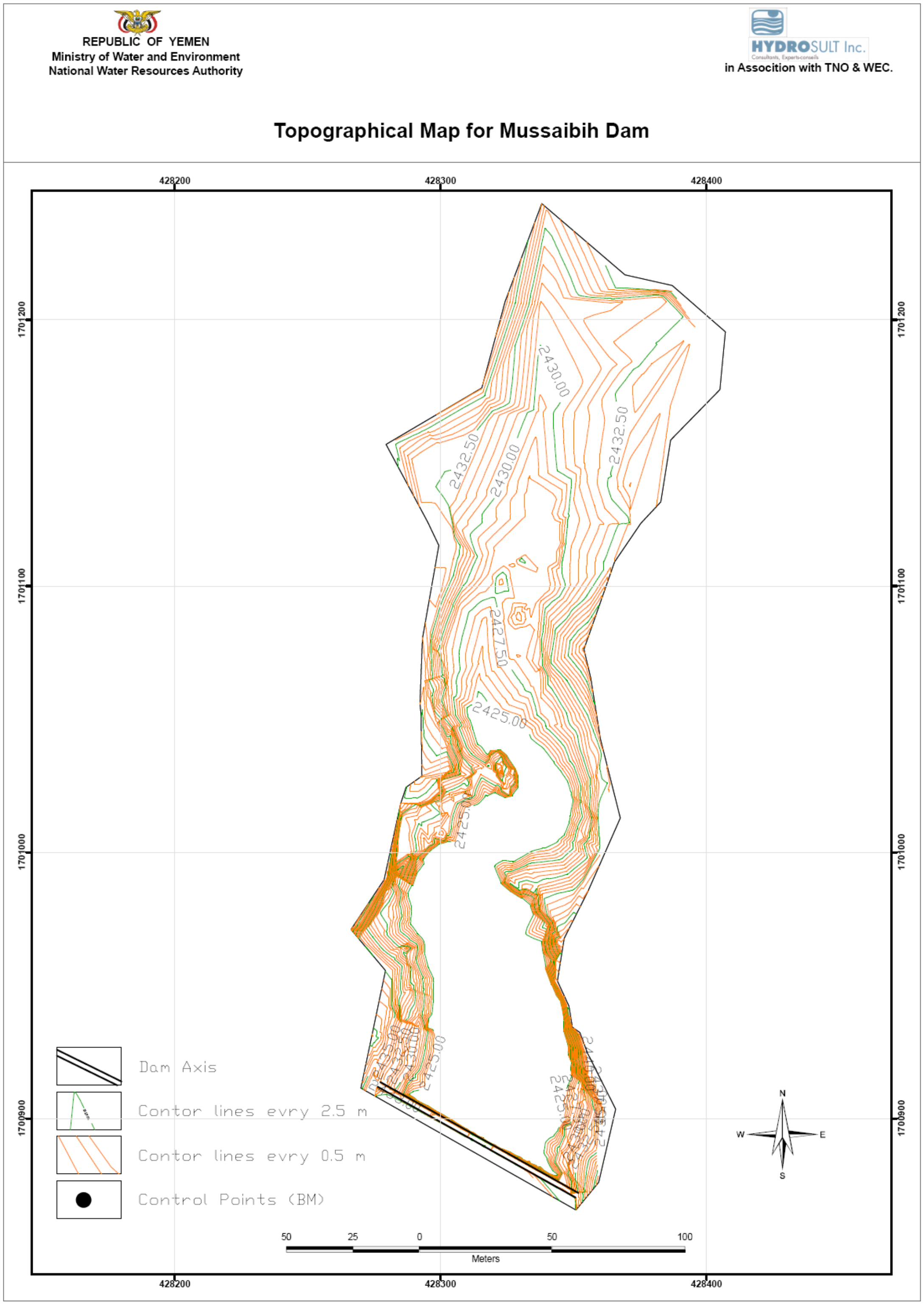
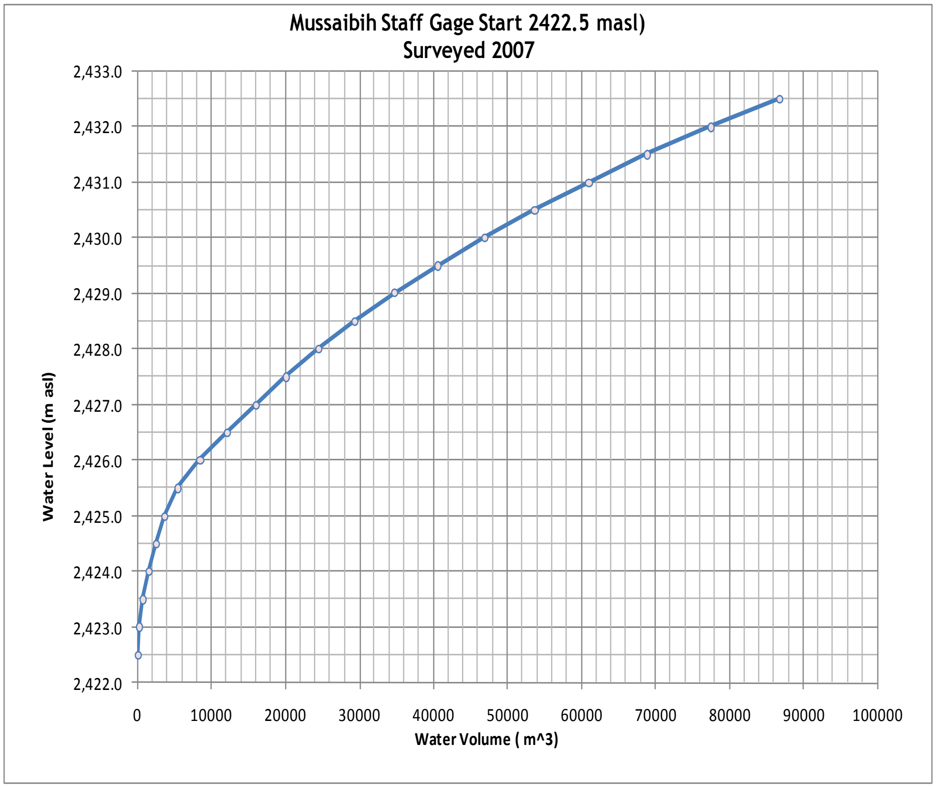


Figure 6-6 Mussaibih Dam Topographic Survey Map



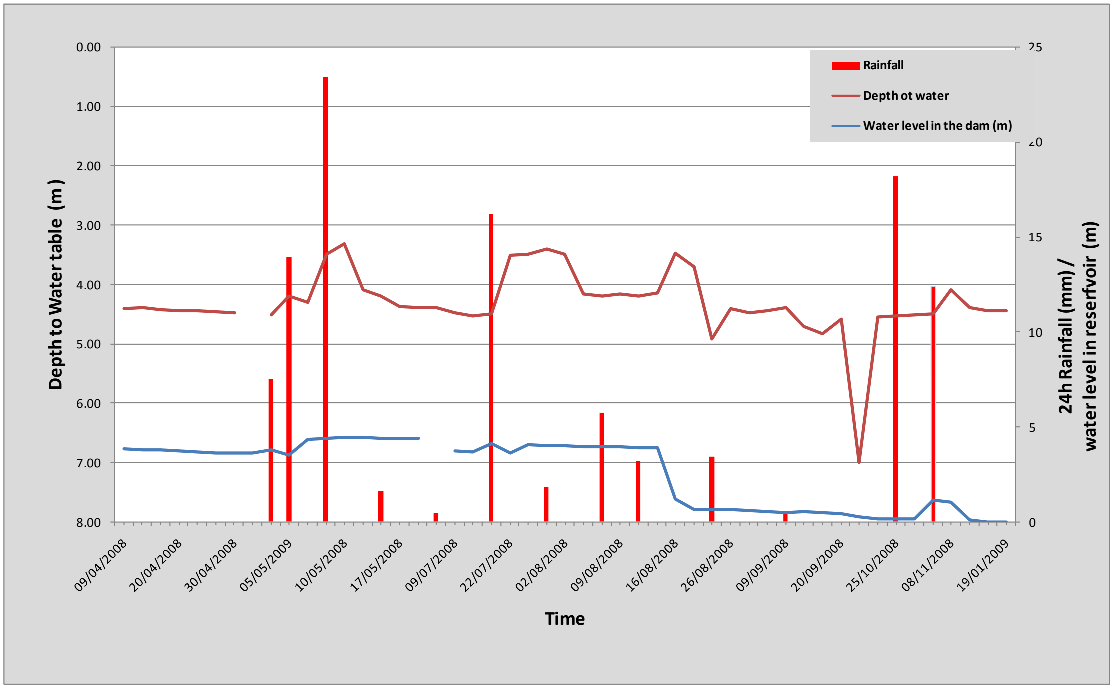


Figure 6-7 Depth-Volume curve for Mussaibih dam response of groundwater table and Mussaibih reservoir level to rainfall (bottom)

1.13.4 Arisha Dam

Arisha dam has a catchment area of 6.33 km^2. Figure 6-8 shows runoff classification zones for Arisha dam catchment. The WEC (8986) station daily rainfall data are used for runoff computation using the SCS-CN method. Table 6-6 shows estimated runoff of 119731 m^3/year in 2007. The annual runoff coefficient is 15%. The runoff measured from reservoir stage measurement (Photo 1 below) is 197448 m^3, which is 40% higher than estimated using the SCS-CN method. Cause for the SCS-CN model under-prediction might be (1) the WEC rainfall station may not represent very well the Arisha catchment and (2) the CN used might underestimate flood volume.

Table 6-6 Summary of Annual Rainfall-Runoff (Arisha Reservoir)

	Rainfall (mm)	Runoff (mm)		
		P1	A3	Total
Station 8986	221	24.7	0	24.7
Area (ha)		484.8	148.4	633.3
Total (m^3)		119731.2	0	119731

Figure 6-8 Staff gauge reading at Arisha dam (photo taken on 05-11-2007)

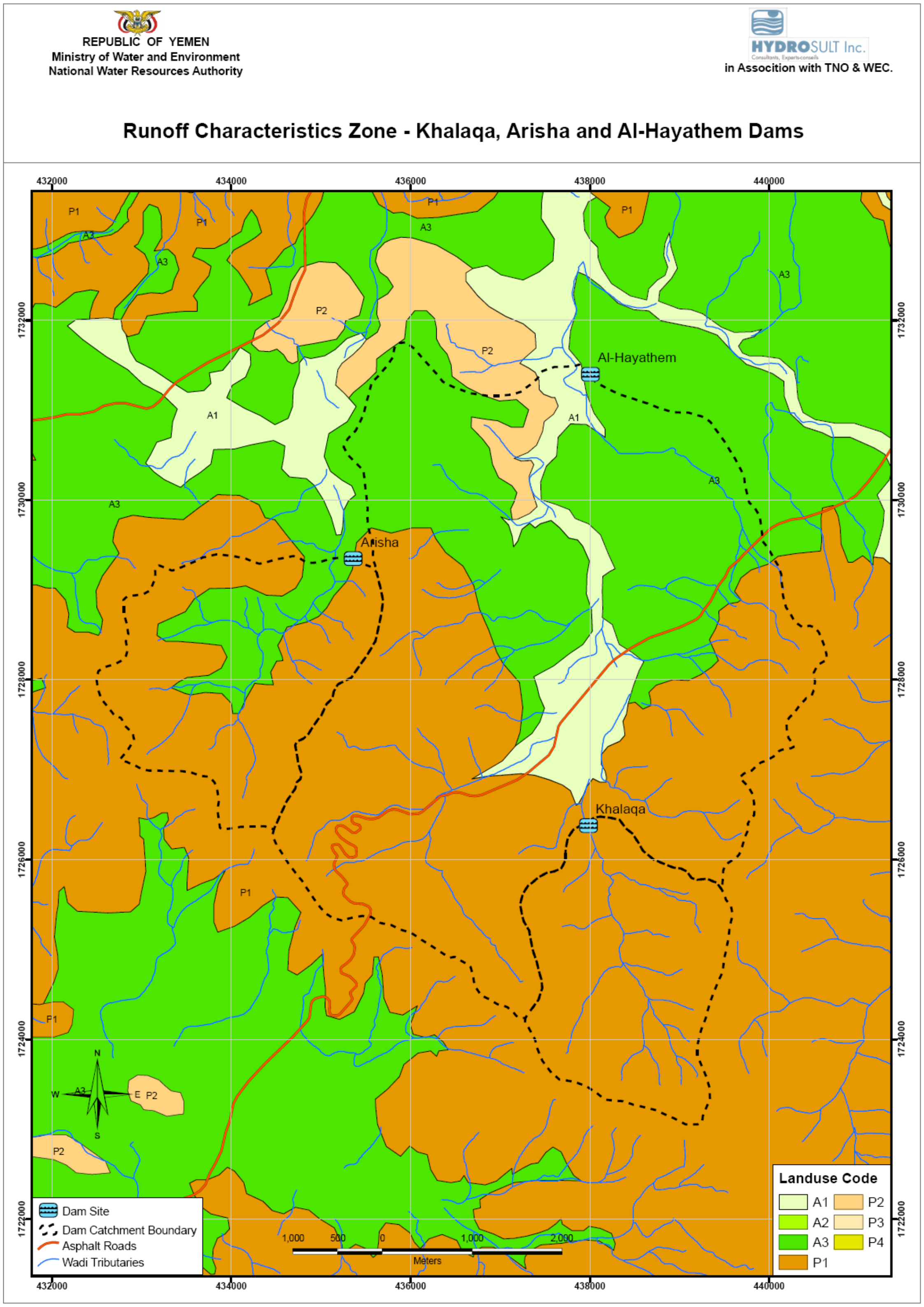


Figure 6-9 Arisha, Khalaqa, and Al Hayathem dam catchments runoff characteristic zones

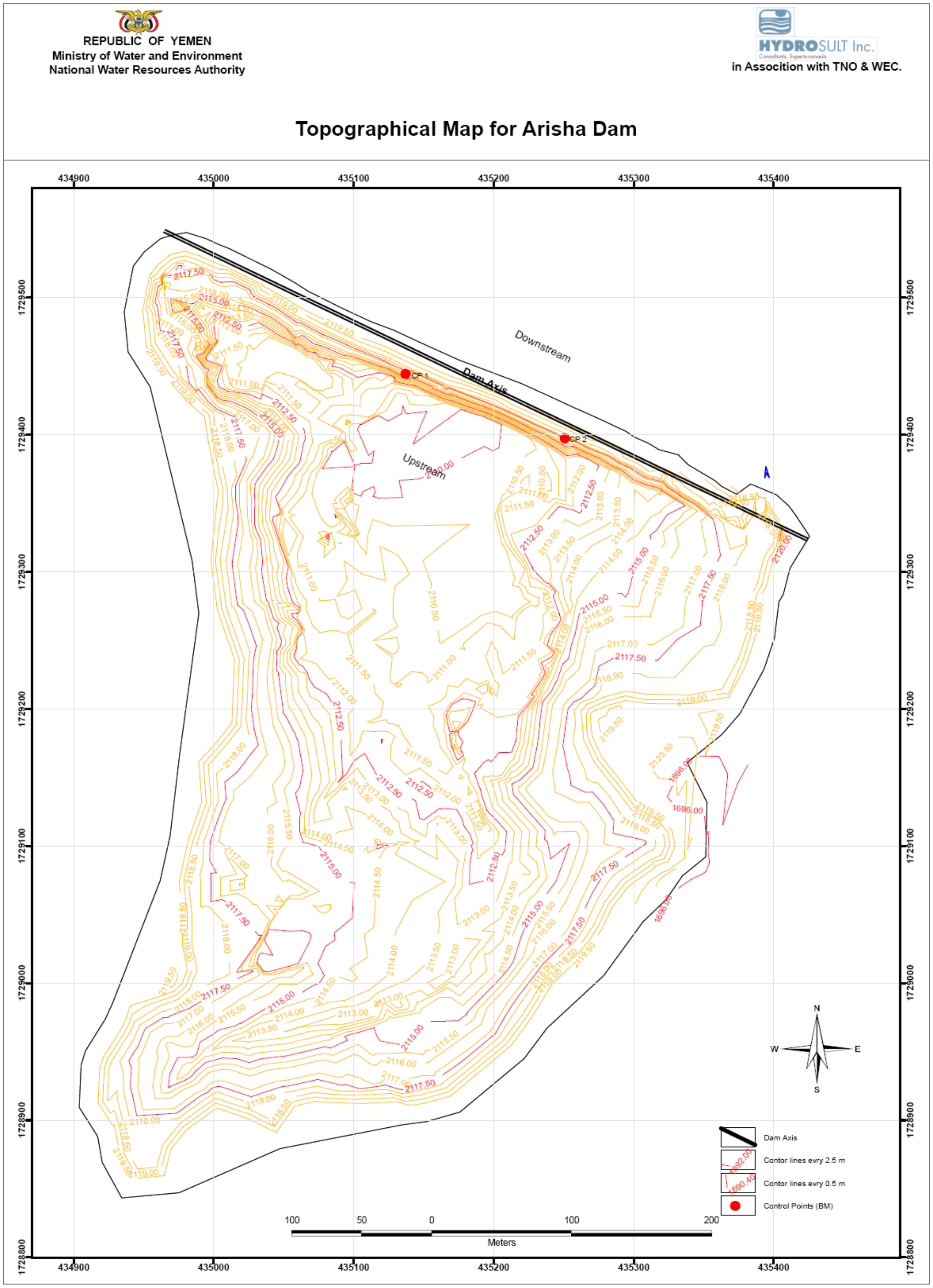


Figure 6-10 Arisha Reservoir Topographic Survey Map

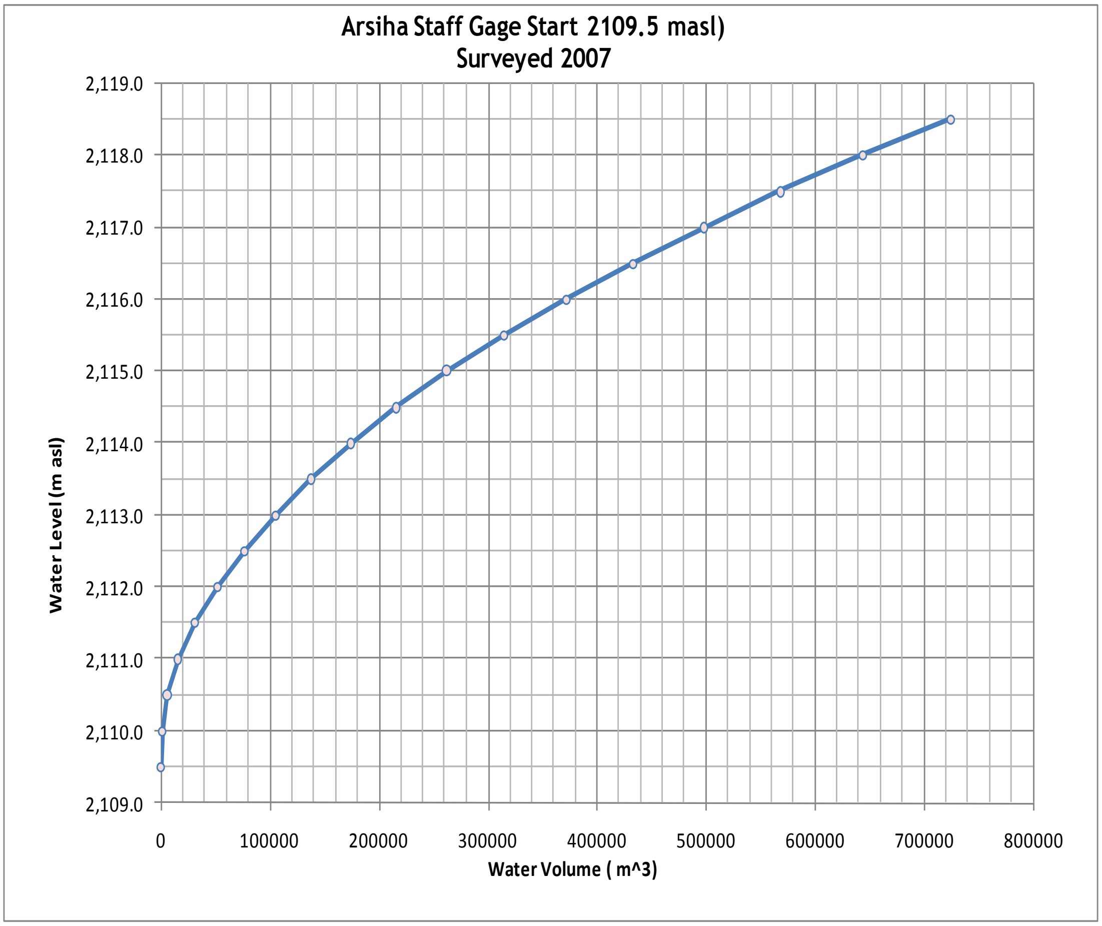


Figure 6-11 Depth-Volume curve for Arisha Dam

1.13.5 Khalaqa Dam

Similarly, reservoir runoff using the SCS-CN method and runoff classification zones has been determined for Khalaqa dam catchment, with an area of 5.6 km^2. The WEC (8986) station daily rainfall data are used for the computation, giving an annual runoff of 138273 m^3 (Table 6-7). The total Runoff volume in Khalaqa reservoir measured by staff gauge and converted to volume using the 2007 rating curve (Figure 6-11) is 203822 m^3, which is much higher than the SCS-CN estimate. The SCS-CN method underestimated flood volume by 32%. 2008 rainfall runoff data estimated by the SCS-method are 75625 m^3, but measured runoff at the dam was 142305 m^3/year.

Table 6-7 Summary of Annual Rainfall-Runoff (Khalaqa Reservoir)

Station	Rainfall (mm)	Runoff (mm)		Total
		P1		
8986	221	24.7		24.7
Area (ha)		559.9		559.9

Station	Rainfall (mm)	Runoff (mm)		Total
		P1		
Total (m^3)		138273.4		138273

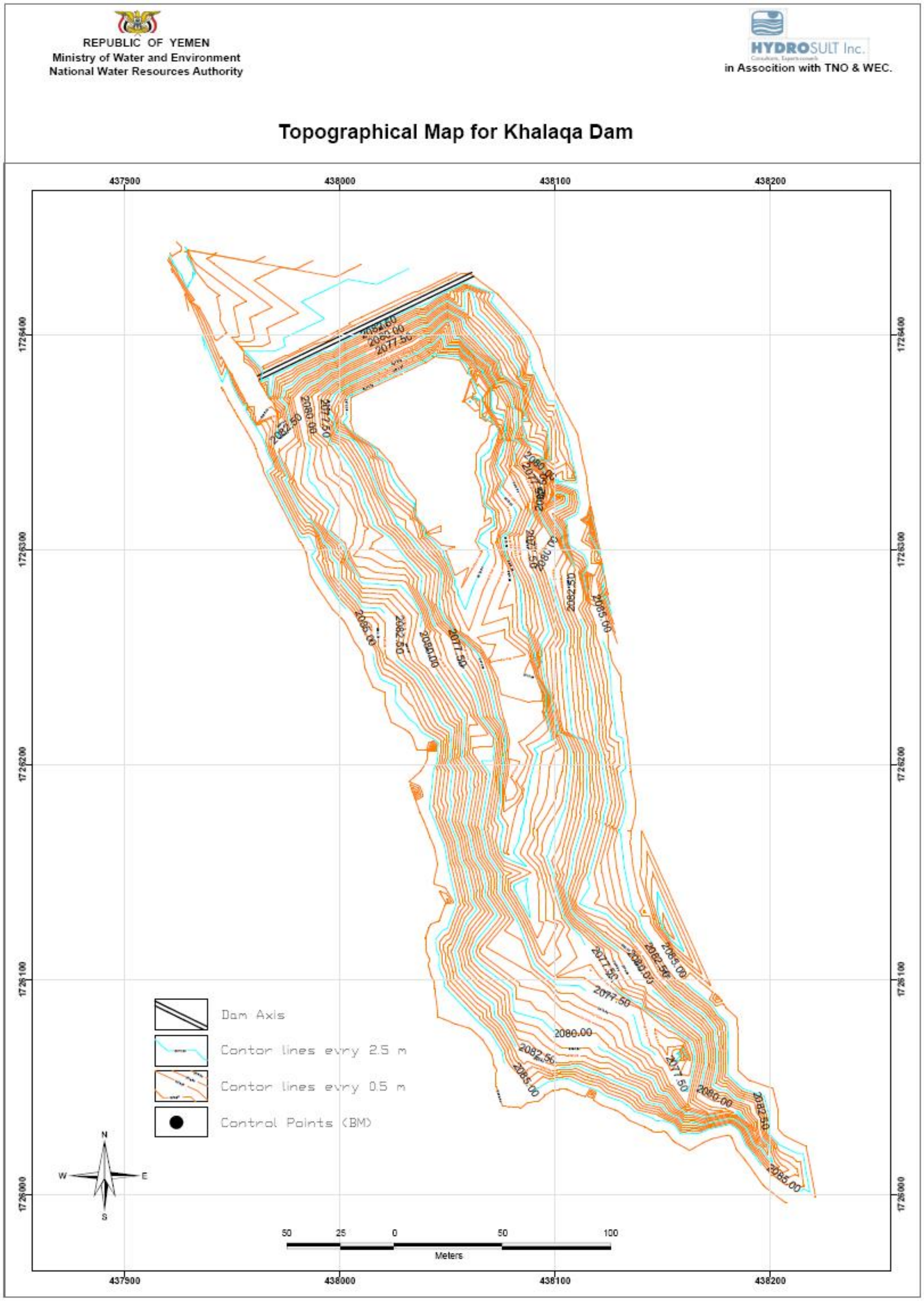
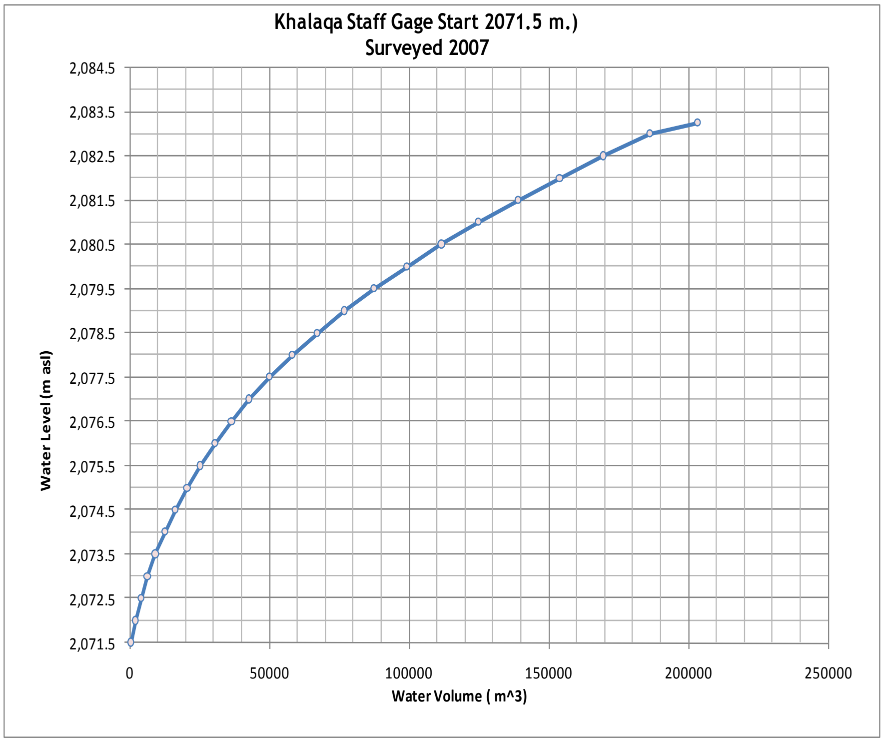

REPUBLIC OF YEMEN
Ministry of Water and Environment
National Water Resources Authority
HYDROSULT Inc.
in Association with TNO & WEC.
Topographical Map for Khalaqa Dam
437900
438000
438100
438200
1726400
1726300
1726200
1726100
1726000
Dam Axis
Contor lines evry 2.5 m
Contor lines evry 0.5 m
Control Points (BM)
N
S
W
E
50
25
0
50
100
Meters
2082.50
2080.00
2077.50
2085.00

Figure 6-12 Khalaqa Reservoir Topographic Map



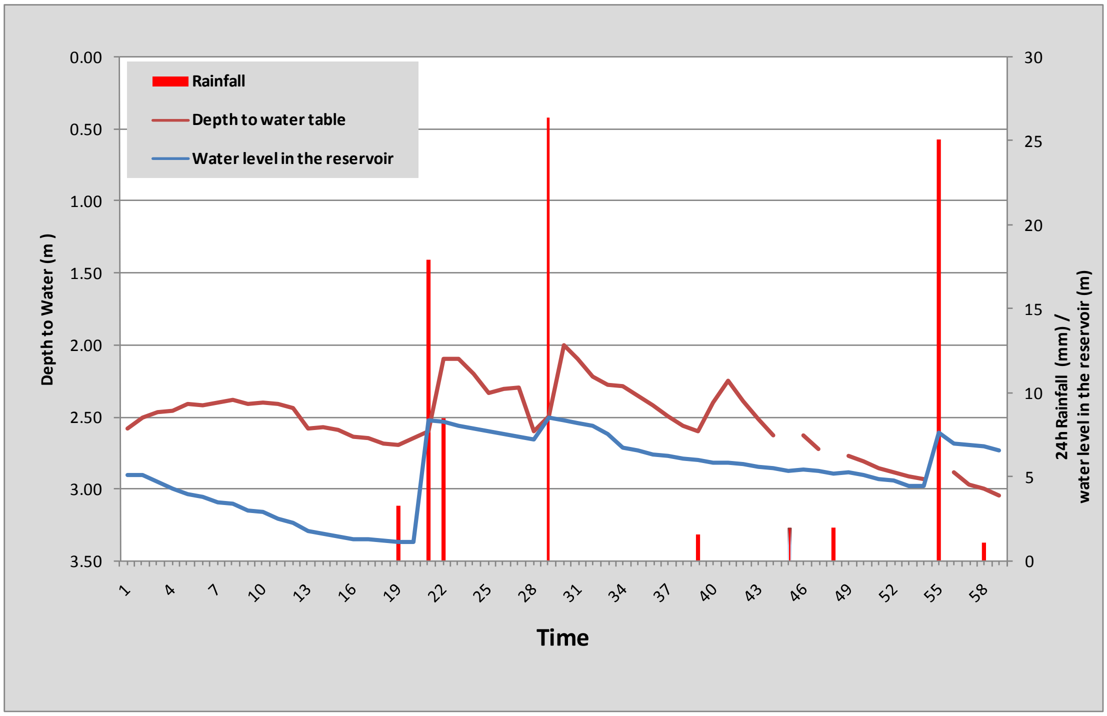


Figure 6-13 Depth-Volume curve for Khalaqa dam (top) dam response of groundwater table and Khalaqa reservoir level to rainfall (bottom)

1.13.6 Al-Hayathem Dam

Geologically, Al-Hayathem site is located entirely within the limestone rocks of the Nayfa and Al-Hajur Formations of the Jurassic Amran Group. The limestone generally displays on a coarse vertical fracture set and a coarse to medium horizontal fracture set. The horizontal set has more open fractures, with up to 30%, and 5% to 10% in the vertical set.

Reservoir runoff using the SCS-CN method and runoff classification zones has been determined for Al-Hayathem catchment, with an area of 27.4 km^2. The WEC (8985) station daily rainfall data are used for the computation. Table 6-8 shows estimated runoff of 219814 m^3/year, giving an annual runoff coefficient of 10%. The runoff measured from reservoir stage measurement is 439380 m^{3,} which is 50% higher than estimated using the SCS-CN method. The WEC Rainfall station doesn't represent very well the Al-Hayathem catchment.

Table 6-8 Summary of Annual Rainfall-Runoff (Al-Hayathem reservoir)

Rainfall Station	Annual Rainfall (mm)	Annual Runoff (mm)					Total
		P1	P2	P3	A1	A3	
8985	192	15	4	0	0	0	19
Area (ha)		1451.12	57.18	0	250.77	977.29	2736.4
Total (m^3)		217526	2287	0	0	0	219814

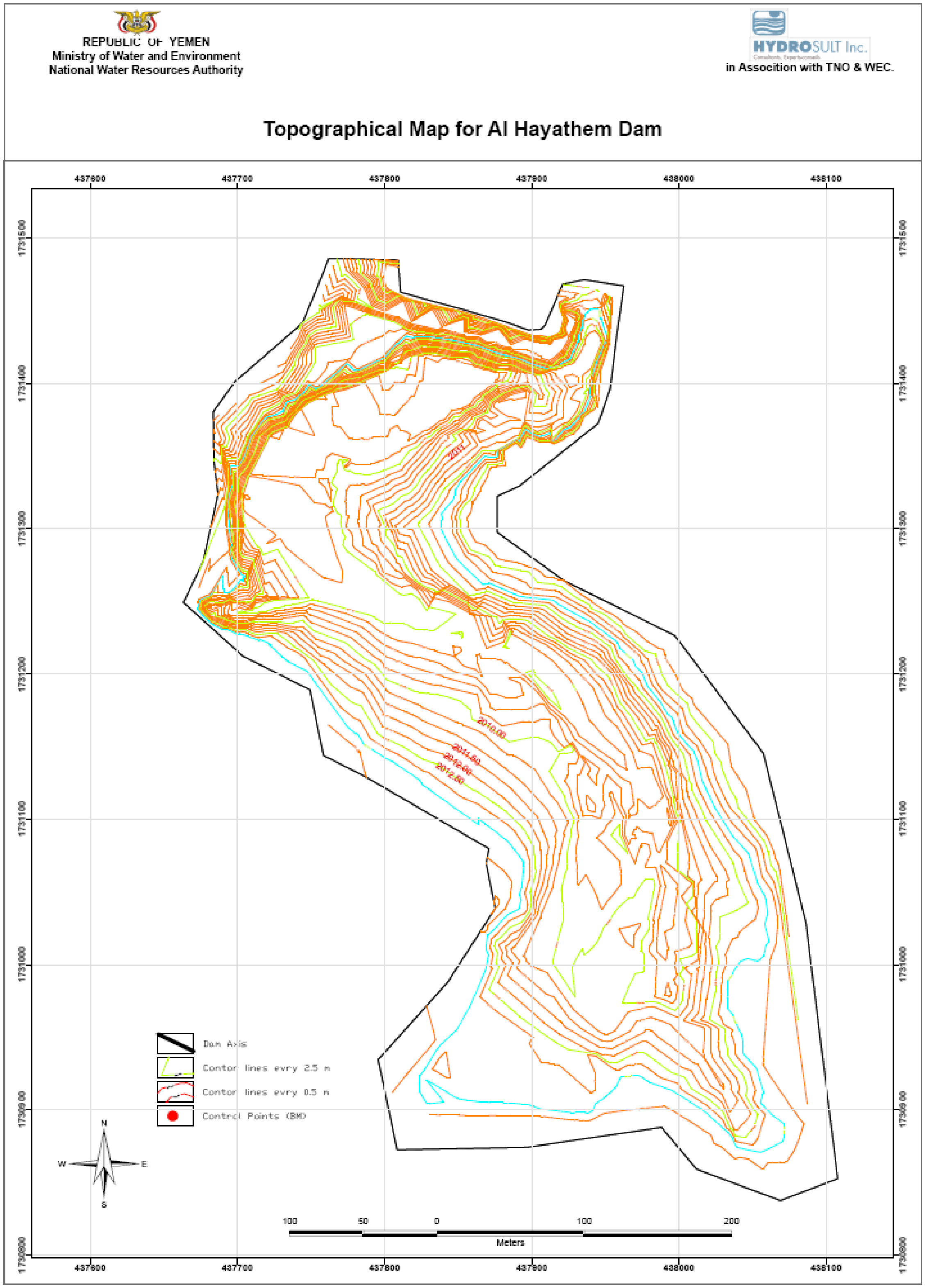


Figure 6-14 Al-Hayathem Reservoir Topographic Survey Map

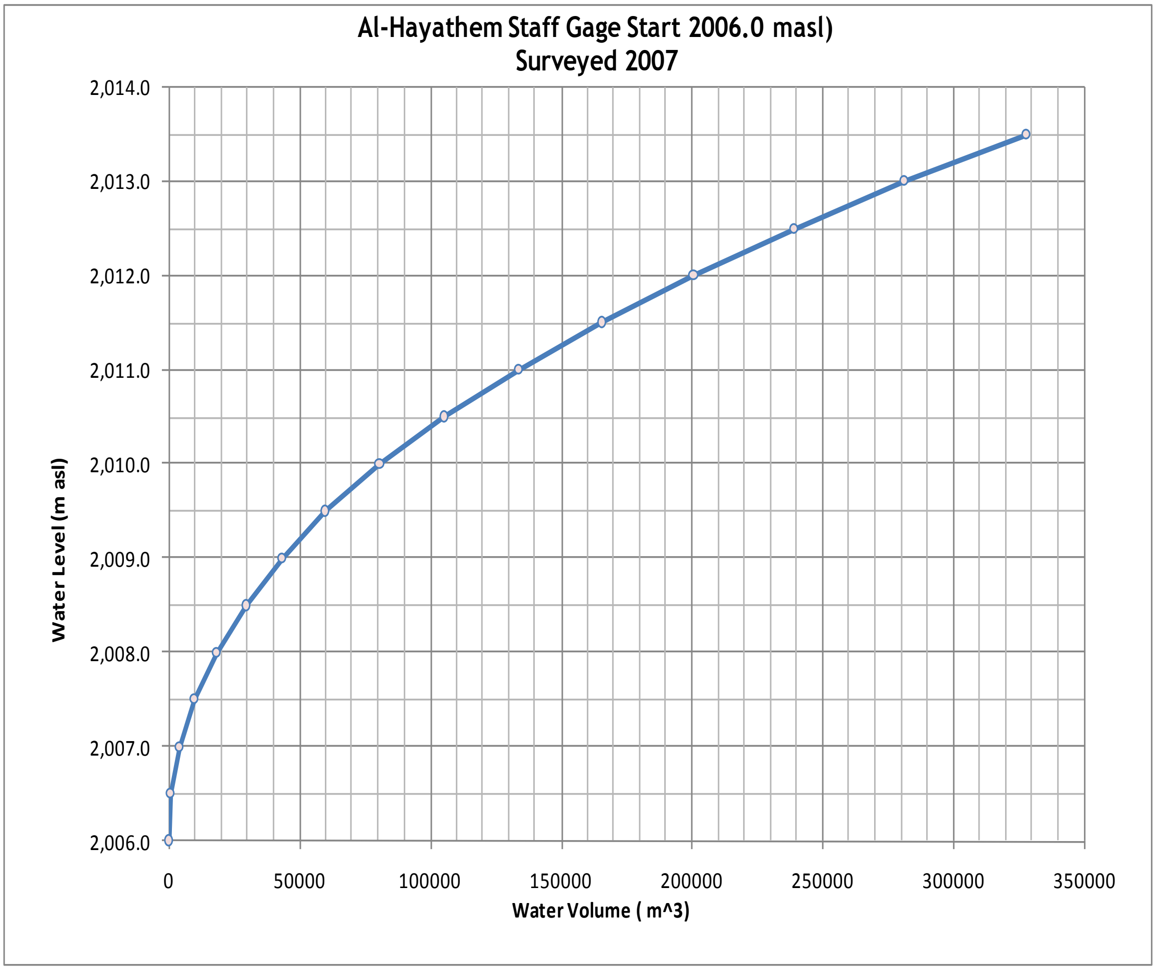


Figure 6-15 Depth-Volume curve for Al-Hayathem Dam

1.14 Reservoir Water Balance

Reservoir water balance components for six dams (Methbel, Mekhtan, Mussaibih, Khalaqa, Arisha, and Al-Hayathem) are estimated based on measured reservoir water level using staff gauge. Stored water between flash floods is estimated from reservoir water level readings and converted to volume of flood using depth (elevation)–volume curves developed for each dam. Reservoir evaporation is estimated from GAF (2007) potential evapotranspiration data with a multiplication factor of 1.2 to account for open water evaporation rate. Very rough estimates of leakage and direct water abstraction from reservoir are also made. Remaining terms become recharge to the aquifer due to the impoundment of water in the reservoir.

Table 6-9 shows a summary of estimated water balance components for the six dams. Figure 6-15 to Figure 6-21 show storage, evaporation, release and recharge variations in time for the six dams. Annex C gives detailed calculations. The recharge from the reservoir varies according to the geology and the shape of the reservoir. Reservoir sites located on sandstone (Arisha dam), limestone (Al-Hayathem dam) and tertiary volcanic (Methbel dam) areas have significant recharge (> 10 mm/day i.e. twice the average evaporation rate). Recharge in Khalaqa reservoir (sandstone area) is expected to be higher than 9 mm/day. Dam grouting and a cutoff wall provided at the dam foundation might, however, contribute to the reduction of recharge. Methbel reservoir, located in a tertiary volcanic area, shows a recharge rate (9 mm/day) that is nearly twice the evaporation rate (~5 mm/day). Minimum recharge of 5 mm/day (about the same as the evaporation rate) is observed at Mekhtan and Mussaibih reservoirs in a rocky volcanic reservoir area.

Table 6-9 Summary of the six-reservoir water balance (year 2007-2008)

Elements	Dams					
	Al-Hayathem	**Arisha**	**Khalaqa**	**Methbel**	**Mekhtan**	**Mussaibih**
Dam catchment area (km^2)	33.2	6.5	5.5	32.6	5.6	3.6
Reservoir area geology	Limestone	Sandstone	Sandstone (foundation cutoff wall provided)	Tertiary volcanic	Volcanic	Volcanic (foundation cutoff wall provided)
Total balance days	238	189	513	105	513	602
Annual rainfall (mm)	192	221	221	192	221	221
Total measured volume of runoff; balance period (m^3)	439380	197448	203822	9864	122210	44344
Reservoir Evaporation (m^3)	65561	4000	48712	1272	47845	19275
Release (m^3)	88373	122959	65400	1775	11863	2757
Recharge (m^3)	285447	70489	89710	6817	62502	22832
Average reservoir pool area (m^2)	52698	3925	16762	1512	15846	6547
Mean recharge (mm/day)	19	79	9	36	6	5

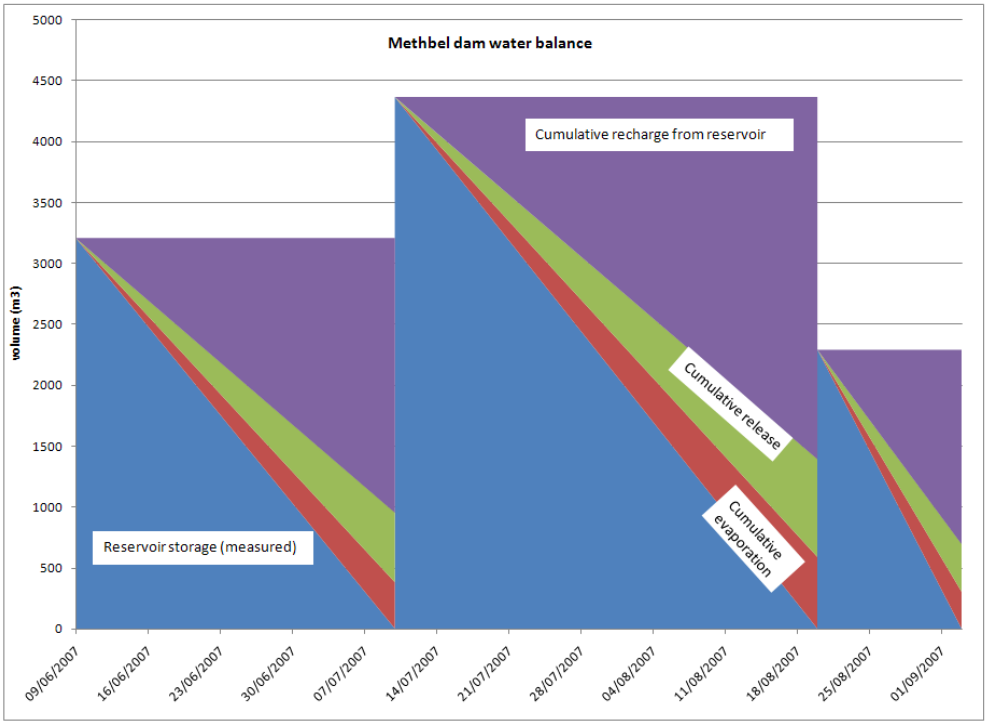


Figure 6-16 Water balance Methbel Reservoir

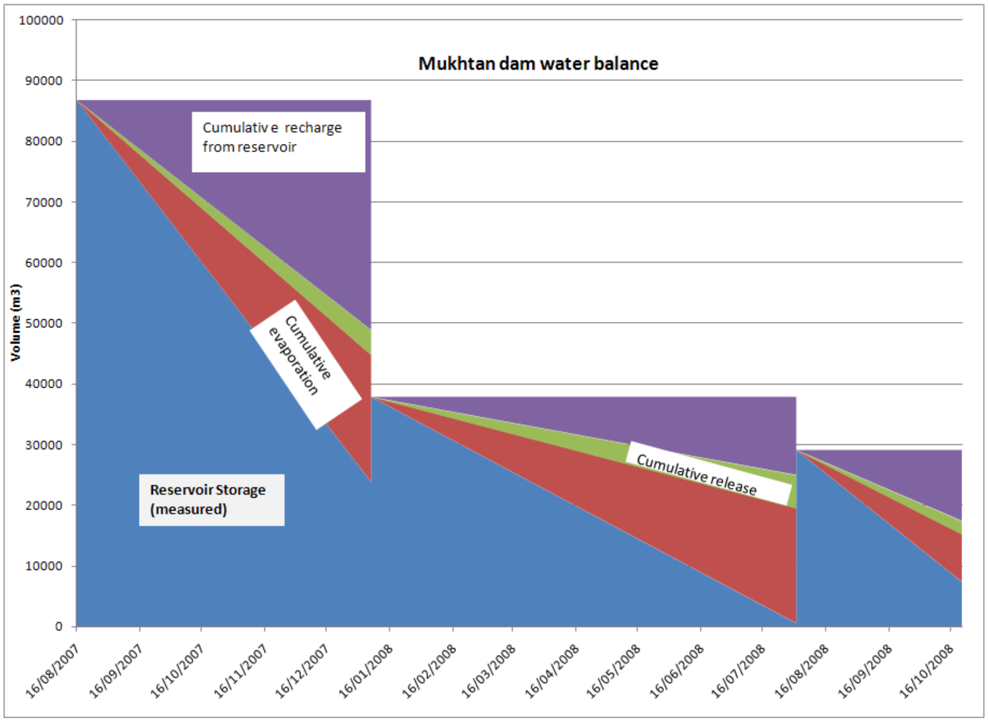


Figure 6-17 Water balance Mekhtan reservoir

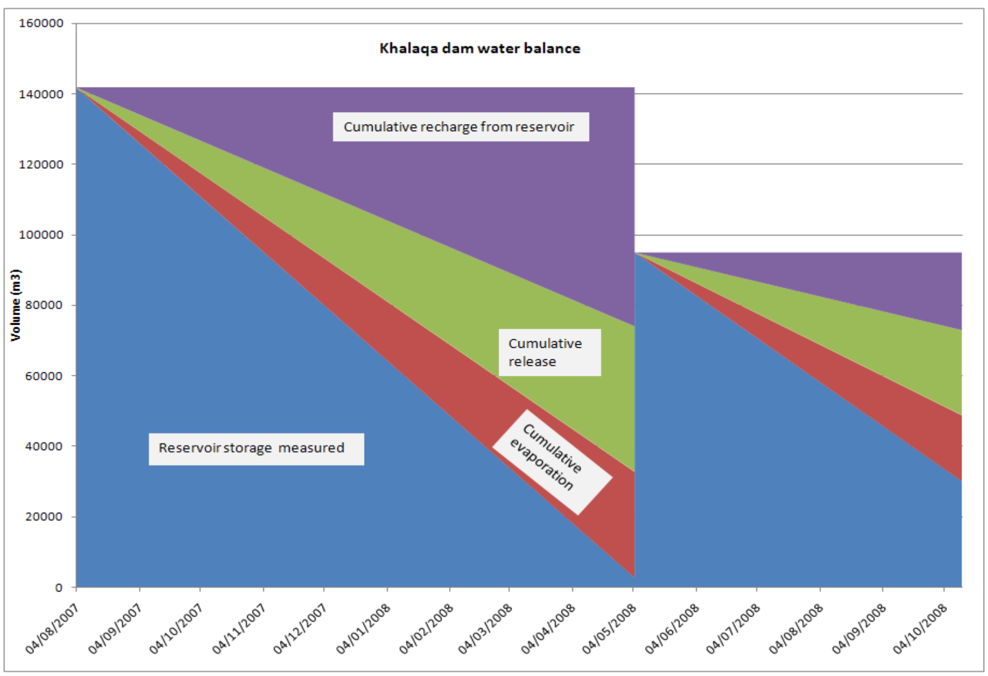


Figure 6-18 Khalaqa reservoir water balance

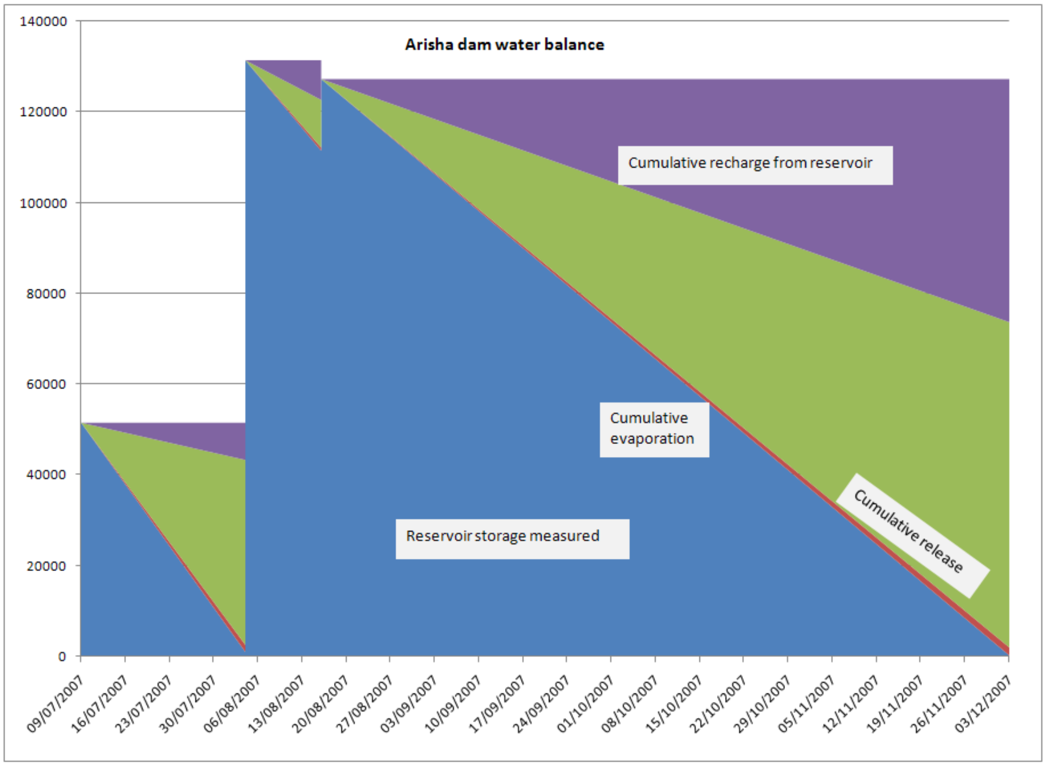


Figure 6-19 Arisha reservoir water balance

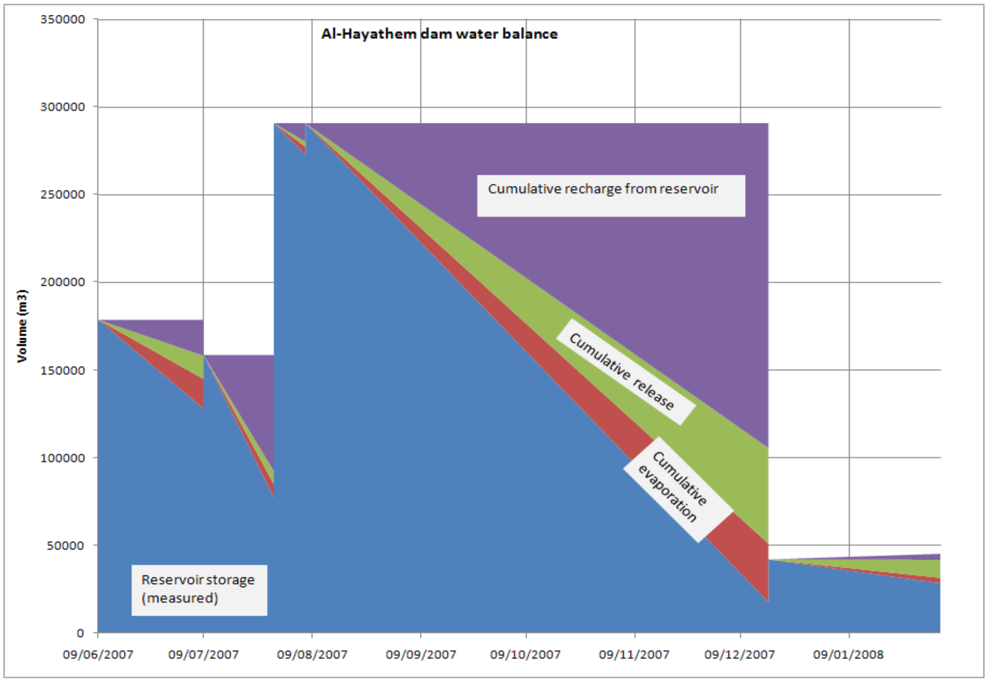


Figure 6-20 Al Hayathem reservoir water balance

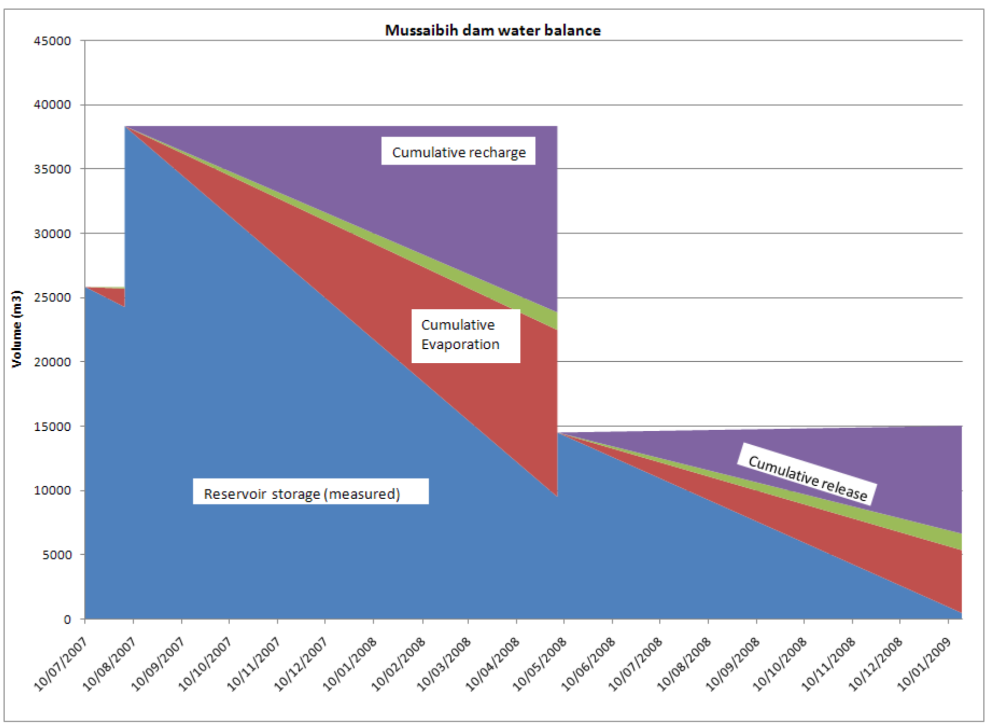


Figure 6-21 Mussaibih reservoir water balance

Chapter 7. RAINFALL – RUNOFF AND GROUNDWATER RECHARGE

To assess wadi runoff and possible groundwater recharge, an estimate of catchment wide long term daily water balance for the 22 sub-basin is made. Thirteen rainfall stations (Table 7-1) which have relatively long-term rainfall data are used in the modeling. Methodology used and input data are discussed below.

1.15 Methodology

The soil moisture balance method was applied to estimate groundwater recharge from direct rainfall. The main hydrological variables used are precipitation (daily rainfall), evapotranspiration and runoff.

The soil moisture balance is one of most commonly used water balance methods. It is used to estimate a component of water balance, usually groundwater recharge, as the residual of all other fluxes that can be measured or estimated more easily (Lerner et al. 1990). The general relation fluxes (i.e. precipitation (P), surface runoff (Q), evapotranspiration (ET) groundwater recharge (R) and change in water storage in the saturated and unsaturated zones (∂S)) consists of:

$$P = Q + ET + R \pm \partial S$$

The basis of the soil moisture balance method for estimating recharge is that the soil becomes free-draining when the moisture content of the soil reaches a limiting value called the field capacity; excess water then generates infiltration towards the aquifer.

The water balance calculation is made for an average field capacity of 102 mm taken for an average 50 cm soil depth in the Sana'a basin.

1.16 Inputs

1.16.1 Precipitation

The precipitation (P) values used are the daily rainfalls of 13 stations distributed in Sana'a Basin. Table 7.1 shows the rainfall stations used in the analysis.

Table 7-1 Rainfall Stations in and around Sana'a Basin used for Rainfall-runoff and Water balance

No	Station	Period of Record		Number of years	UTM east	UTM north	Altitude (m)	MAR (mm)
1	Astan-A	1991	1997	7	427250	1743500	2350	177
2	Samnah-A	1991	1997	7	426600	1730200	2050	150
3	Ma'adi-A	1992	1996	5	442250	1737750	2050	188
4	Birbasil-A	1991	2001	9	443750	1729350	2080	210
5	Darwan	1972	2005	10	401000	1719800	2450	207

No	Station	Period of Record		Number of years	UTM east	UTM north	Altitude (m)	MAR (mm)
6	CAMA	1974	1979	6	415100	1697100	2250	237
7	Adabat	1972	1979	7	432250	1698700	2450	197
8	Mind	1972	1979	7	399650	1690250	2750	279
9	NWRA-A	1989	2004	13	414581	1701935	2400	219
10	Darsalm	2001	2007	4	420400	1689600	2280	150
11	Shu'ub	1975	1987	9	417500	1701000	2270	245
12	Wallan	1979	1992	10	421199	1671381	2350	248
13	Sana'a Airport	1974	1993	20	416700	1711150	2190	170

1.16.2 Evapotranspiration

The monthly evapotranspiration estimate by GAF (2007) is adopted as daily input in mm/day for water balance computation. A factor (beta) is applied to convert potential to actual evapotranspiration. Table 7.2 shows the monthly potential evapotranspiration data.

Table 7-2 Potential Evapotranspiration (mm/day) (Vistaa Sana'a Airport, 2004, as in GAF 2007)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
3.7	4.8	5	4.5	5.4	6.4	5.8	5.3	5.2	4.3	3.7	3.2

To estimate the actual evapotranspiration, many investigators used a soil-moisture extraction function or coefficient of evapotranspiration beta which relates the actual rate of evapotranspiration to the potential rate of evapotranspiration based on some function of the current soil moisture content and moisture retention properties of the soil.

$$E = beta * PE$$

Dyck (1983), Mintz and Walker (1993) also illustrate several moisture extraction functions. Many researchers agree that soils show the general pattern of behavior that moisture is extracted from the soil at the potential rate until some critical moisture content is reached, at which time evapotranspiration is no longer controlled by meteorological conditions. Below this critical point, there is a linear decline in soil moisture extraction until the wilting point is reached. This type of behavior is illustrated by Shuttleworth (1993) and Dingman (1994). Shuttleworth (1993) notes that the critical moisture content divided by the field capacity is typically between 0.5 and 0.8. The type of moisture extraction function just described is commonly applied to daily potential evaporation values. In this case, a beta value of 0.5 is adopted.

1.16.3 Runoff

The HWC (1992) study divided the country into eight runoff characteristic zones. This classification is adapted in previous studies such as HYDROSULT (2002) and ARCADIS (2006). The same is adopted in this study to classify runoff characteristics of the 22-sub-basins of Sana'a Basin. The runoff characteristic zones are shown previously in Table 6.1.

The SCS model is used to estimate runoff volume from the available rainfall data. The CN values adopted by HWC and the later two studies are shown previously in Table 6.2. The last ARCADIS values are adopted in this case. The CN values are found to be in agreement with the reservoir runoffs measured at six dam sites in this study.

Rainfall runoff calculations are made for all 22 sub-basins of Sana'a Basin. The summary results are shown in Table 7-3. The theoretical background of the SCS model is given in Appendix B.

1.16.4 Recharge

Recharge is calculated as two components: direct recharge from rainfall by the soil moisture water balance method as described above and Wadi bed recharge. Results as shown in Table 7.3 indicate that recharge from direct rainfall is a rare phenomenon occurring only during intense rainfall when soil field capacity is exceeded by the amount of water percolating. The mean annual value of direct recharge for an average s-b-basin wide field capacity of 102 mm is only 3.9 M m^3. The major recharge in Sana'a Basin is assumed to occur from surface runoff in the Wadi beds. As WRAY (1995) put it, the main form of natural groundwater recharge in Yemen is by infiltration of surface water from wadis, which is estimated herein at 49.5 M m^3/year (8% of the annual rainfall). The remaining 92% of the 199 mm annual rainfall is estimated to be consumed by evapotranspiration.

If wadis disappear completely, without being diverted for surface water irrigation, then it may be assumed that some 95% of the flow will be converted to recharge. If it is actively used for spate irrigation, then, in general, some 20-30% will be effectively lost to evapotranspiration (WRAY, 1995). Accordingly, in most cases in Sana'a Basin Wadi, runoff is diverted for spate irrigation. Hence, it is reasonable to assume that 70% of the runoff in the Wadis ends up in groundwater recharge and this will be the major form of recharge in the basin. This percentage will be checked later by WEAP model analysis.

Table 7-3 Summary of Rainfall-Runoff-Recharge calculation

					Recharge					Recharge		
			Rainfall	Runoff	Rainfall	Runoff	Total	Catchment Area	Runoff	Rainfall	Runoff	Total
No	Sub-basin	Rainfall Station	mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	Km^2	$M\ m^3$	$M\ m^3$	$M\ m^3$	$M\ m^3$
1	Wadi al Mashamini	Astan-a	177	12.4	0.0	9.3	9.3	76.5	1.0	0.0	0.7	0.7
2	Wadi al Madini	Samnah-a	150	12.6	0.0	9.5	9.5	211.5	2.7	0.0	2.0	2.0
3	Wadi al Kharid	Samnah-a	150	14.6	0.0	11.0	11.0	136.7	2.0	0.0	1.5	1.5
4	Wadi al Ma'adi	Maadia-a	188	21.5	0.0	16.1	16.1	111.5	2.4	0.0	1.8	1.8
5	Wadi A'sir	Birbasl-a	210	40.8	0.8	30.6	31.4	210.2	8.6	0.2	6.4	6.6
6	Wadi Khalaqa	Birbasl-a	231	24.1	2.9	18.1	20.9	75.9	1.8	0.2	1.4	1.6
7	Wadi Qasabah	Samnah-a	150	11.7	0.0	8.8	8.7	64.6	0.8	0.0	0.6	0.6
8	Wadi al Huqqah	Darwan	194	19.5	0.0	14.7	14.6	120.7	2.4	0.0	1.8	1.8
9	Wadi Bani Hwat	Sana'a Airport	170	11.3	0.0	8.5	8.5	322.4	3.6	0.0	2.7	2.7
10	Wadi Thumah	Samnah-a	150	14.1	0.0	10.6	10.6	77.6	1.1	0.0	0.8	0.8
11	Wadi as Sirr	Sana'a Airport	170	17.5	0.0	13.1	13.1	219.1	3.8	0.0	2.9	2.9

No	Sub-basin	Rainfall Station	Rainfall	Runoff	Recharge Rainfall	Recharge Runoff	Recharge Total	Catchment Area	Runoff	Recharge Rainfall	Recharge Runoff	Recharge Total
			mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	Km^2	$M\ m^3$	$M\ m^3$	$M\ m^3$	$M\ m^3$
12	Wadi al Furs	Sana'a Airport	170	20.3	0.0	15.2	15.2	45.8	0.9	0.0	0.7	0.7
13	Wadi al Iqbal	Darwan	194	17.6	0.3	13.2	13.5	204.4	3.6	0.1	2.7	2.8
14	Wadi Zahr & al Ghay	Mind	279	15.8	4.8	11.9	16.6	364.8	5.8	1.7	4.3	6.1
15	Wadi Hamdan	NWRA-A. CAMA	228	24.2	0.0	18.2	18.2	63.7	1.5	0.0	1.2	1.2
16	Wadi al Mawrid	Darsalm. NWRA'A. CAMA	202	35.6	0.0	26.7	26.7	179.6	6.4	0.0	4.8	4.8
17	Wadi Sa'Wan	Shoub	245	30.9	0.3	23.2	23.5	95.4	3.0	0.0	2.2	2.2
18	Wadi Shahik	Adabat	197	29.6	2.4	22.2	24.6	236.9	7.0	0.6	5.3	5.8
19	Wadi Ghayman	Adabat. Darsalm	173	16.4	1.5	12.3	13.8	143.8	2.4	0.2	1.8	2.0
20	Wadi al Mulakhy	Wallan	248	17.7	3.1	13.3	16.4	69.8	1.2	0.2	0.9	1.1
21	Wadi Hizyaz	Wallan	248	21.5	3.3	16.1	19.4	80.5	1.7	0.3	1.3	1.6
22	Wadi Akhwar	Wallan	248	19.3	2.8	14.5	17.3	125.4	2.4	0.4	1.8	2.2

No	Sub-basin	Rainfall Station	Rainfall	Runoff	Recharge			Catchment Area	Runoff	Recharge		
					Rainfall	Runoff	Total			Rainfall	Runoff	Total
			mm/yr	mm/yr	mm/yr	mm/yr	mm/yr	Km^2	$M m^3$	$M m^3$	$M m^3$	$M m^3$
Total			199	20.0	1.0	15.3	16.3	3236.8	66.0	3.9	49.5	53.4

Chapter 8. SANA’A BASIN AND SUB-BASIN WATER BALANCE

Water Evaluation and Planning (WEAP) software of Stockholm Environmental Institute (SEI), Boston will be used for water balance analysis. The WEAP System model was developed by the SEI to enable evaluation of planning and management issues associated with water resource development. The WEAP model can be applied to both municipal and agricultural systems and can address a wide range of issues including sectoral demand analyses, water conservation, water rights and allocation priorities, streamflow simulation, reservoir operation, ecosystem requirements and project cost-benefit analyses (SEI 2001).

The WEAP model has two primary functions (Sieber et al. 2004):

- Simulation of natural hydrological processes (e.g. evapotranspiration, runoff and infiltration) to enable assessment of the availability of water within a catchment,
- Simulation of anthropogenic activities superimposed on the natural system to influence water resources and their allocation (i.e. consumptive and non-consumptive water demands) to enable evaluation of the impact of human water use.

To allow simulation of water allocation, the elements that comprise the water demand-supply system and their spatial relationship are characterized for the catchment. The system is represented in terms of its various water sources (e.g. surface water, groundwater); withdrawal, transmission, reservoirs, and wastewater treatment facilities, and water demands (i.e. irrigation, domestic water supply, etc.).

The WEAP model essentially performs a mass balance of flow sequentially down a river system, making allowance for abstractions and inflows. To simulate the system, the river is divided into reaches. The reach boundaries are determined by points in the river where there is a change in flow as a consequence of confluence with a tributary, or an abstraction or return flow, or where there is a dam or a flow gauging structure.

Sana’a Basin is schematized according to WEC 2001 sub-basin classification from its upper catchment downstream to its exit at Wadi Al Kharid. Irrigation abstraction sites and water supply demand at sub-basin level and dams/reservoirs in the basin are all taken into consideration. The schematic diagram is shown in Figure 8.4.

The analysis will be performed for average conditions, considering the long term mean annual rainfall in Sana’a Basin and for years 2007 and 2008 conditions.

1.17 Water Balance Data

Population, water supply demand, irrigation areas, types of crops, climate and rainfall data are some of the inputs required in the WEAP model.

1.17.1 Water Supply

Total water demand is estimated at 54.6 lit/cap/day, composed of an average of 35 lit/cap/day of domestic demand, taking 30% percent of domestic demand as non domestic demand and 20% system loss. Figure 8.1 shows the population of Sana’a Basin according to 2004 census data. Future population growth is assumed at 5.5% annual growth rate in the urban area and 3.5% in rural area.

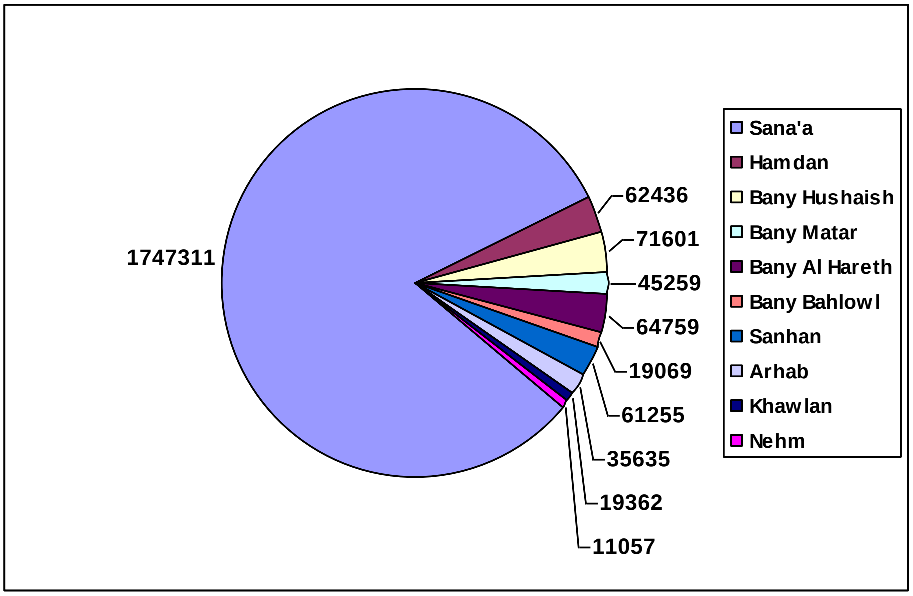


Figure 8-1 Population distribution in Sana'a Basin by district based on 2004 Census (in thousands)

Table 8-1 Summary of Annual Water Supply Demand

Demand type	Water demand (lit/cap/day)	
Domestic	35.0	
Non domestic	10.5	30% of domestic demand
Sub Total	45.5	
System losses	9.1	20% of Production
Total demand	54.6	lit/cap/day
	19.9	m^3/cap/year

1.17.2 Irrigation water demand

Table 8-2 Irrigated areas in Sana'a Basin by sub-basins (source GAF. 2007)

Sub-Catchment Name	ID No.	Catchment Area		Irrigated Area	
		(ha)	(%)	(ha)	(%)
Wadi al Mashamini	1	7777.9	2.4	69.0	0.9
Wadi al Madini	2	21330.0	6.6	351.6	1.6

Sub-Catchment Name	ID No.	Catchment Area		Irrigated Area	
		(ha)	(%)	(ha)	(%)
Wadi al Ma'adi	4	11133.0	3.4	100.2	0.9
Wadi al Kharid	3	13821.0	4.3	237.5	1.7
Wadi A'sir	5	20875.0	6.4	593.2	2.8
Wadi Khalaqa	6	7567.7	2.3	180.5	2.4
Wadi Qasabah	7	6451.7	2.0	186.1	2.9
Wadi al Huqqah	8	12027.0	3.7	1176.1	9.8
Wadi al Iqbal	13	20294.0	6.3	1538.1	7.6
Wadi Thumah	10	7704.6	2.4	125.5	1.6
Wadi bani Huwat	9	32703.0	10.1	4825.5	14.8
Wadi as Sirr	11	21855.0	6.7	2603.2	11.9
Wadi Zahr & al hayl	14	36083.0	11.1	1297.2	3.6
Wadi al Furs	12	4581.5	1.4	855.9	18.7
Wadi Sa'wan	17	9593.6	3.0	1054.9	11.0
Wadi Shahik	18	23866.0	7.4	1032.4	4.3
Wadi Hamdan	15	6349.7	2.0	788.8	12.4
Wadi al Mawrid	16	17916.0	5.5	739.0	4.1
Wadi Ghayman	19	14334.0	4.4	533.2	3.7
Wadi Hizyaz	21	8187.4	2.5	205.6	2.5
Wadi al Mulaikhy	20	6965.7	2.2	269.0	3.9
Wadi Akhwar	22	12560.0	3.9	190.8	1.5
Total		323976.8	100.0	18953.2	5.9

Table 8-3 Sana'a Basin Land use (GAF, 2007)

					Qat		Grapes		Irrigated Mixed Crops		Rainfed Corps/Nat. Vegetables		Orchard		Other Land	
	No.	Area (m^2)	Area (ha)	Area (%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
Wadi al Mashamini	1	77778536	7777.9	2.4	69.0	0.6					582.2	2.9			7125.9	2.5
Wadi al Madini	2	213300000	21330.0	6.6	350.0	3.1			1.6	0.1	1106.0	5.5			19871.8	6.9
Wadi al Ma'adi	4	111330000	11133.0	3.4	100.2	0.9			0.0	0.0	211.3	1.1			10820.6	3.8
Wadi al Kharid	3	138210000	13821.0	4.3	228.0	2.0	3.6	0.1	5.9	0.4	449.6	2.3			13133.3	4.6
Wadi A'sir	5	208750000	20875.0	6.4	593.2	5.2					186.3	0.9			20095.2	7.0
Wadi Khalaqa	6	75677104	7567.7	2.3	180.5	1.6					217.7	1.1			7169.5	2.5
Wadi Qasabah	7	64517144	6451.7	2.0	185.4	1.6			0.7	0.0	257.0	1.3			6008.6	2.1
Wadi al Huqqah	8	120270000	12027.0	3.7	965.0	8.4	84.3	1.4	126.8	8.2	820.5	4.7			10030.1	3.5
Wadi al Iqbal	13	202940000	20294.0	6.3	1384.0	12.1	32.5	0.6	58.7	3.8	1366.6	7.1	62.9	55.6	17389.1	6.1
Wadi Thumah	10	77045984	7704.6	2.4	61.8	0.5	63.7	1.1			163.2	0.8			7416.0	2.6
Wadi bani Huwat	9	327030000	32703.0	10.1	1753.0	15.3	2131.7	36.7	931.8	59.9	2713.6	18.2	9.1	8.1	25163.8	8.8
Wadi as Sirr	11	218550000	21855.0	6.7	1039.1	9.1	1559.0	26.8	5.1	0.3	437.0	2.2			18814.2	6.6
Wadi Zahr & al hayl	14	360830000	36083.0	11.1	1010.3	8.8			277.5	17.9	5412.8	28.4	9.5	8.4	29372.2	10.3
Wadi al Furs	12	45815372	4581.5	1.4	427.1	3.7	428.8	7.4			66.9	0.3			3658.8	1.3
Wadi Sa'wan	17	95936120	9593.6	3.0	415.1	3.6	630.2	10.8	0.7	0.0	171.7	0.9	8.9	7.9	8367.0	2.9
Wadi Shahik	18	238660000	23866.0	7.4	500.8	4.4	531.6	9.1			731.0	3.6			22102.7	7.7
Wadi Hamdan	15	63496708	6349.7	2.0	783.4	6.8			5.0	0.3	182.7	0.9	0.4	0.3	5378.2	1.9
Wadi al Mawrid	16	179160000	17916.0	5.5	526.5	4.6	105.0	1.8	106.9	6.9	835.1	4.7	0.7	0.6	16341.9	5.7
Wadi Ghayman	19	143340000	14334.0	4.4	288.8	2.5	243.4	4.2	1.0	0.1	846.4	4.2			12954.1	4.5
Wadi Hizyaz	21	81874360	8187.4	2.5	197.0	1.7			7.6	0.5	526.5	2.7	1.0	0.9	7454.8	2.6
Wadi al Mulaikhy	20	69657048	6965.7	2.2	227.1	2.0			21.3	1.4	730.8	3.8	20.6	18.2	5965.7	2.1

					Qat		Grapes		Irrigated Mixed Crops		Rainfed Corps/Nat. Vegetables		Orchard		Other Land	
	No.	Area (m^2)	Area (ha)	Area (%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
Wadi Akhwar	22	125600000	12560.0	3.9	186.4	1.6	0.7	0.0	3.7	0.2	483.8	2.4			11884.9	4.1

Figure 8-2 Kc values for Sana'a Basin (Adopted from GAF, 2007)

Table 8-4 Evapotranspiration (mm/day) (Vistaa Sana'a Airport, 2004, as in GAF 2007))

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
3.7	4.8	5.0	4.5	5.4	6.4	5.8	5.3	5.2	4.3	3.7	3.2

Table 8-5 Meteorological Data (Means of 1983-1990) Sana'a CAMA (source: SAWAS)

	Mean Temperature (°C)	Relative Humidity (%)	Wind Speed (m/s)
Jan	12.9	46.3	2.8
Feb	16.8	49.9	2.7
Mar	19.1	49.9	3.2
Apr	19.6	57.8	4.4
May	21.9	43.8	3.8
Jun	23.5	41.0	4.8
Jul	24.0	35.8	4.6
Aug	23.5	47.7	4.3

	Mean Temperature (^oC)	Relative Humidity (%)	Wind Speed (m/s)
Sep	21.4	39.4	3.2
Oct	18.5	38.7	2.9
Nov	15.7	39.5	2.4
Dec	13.0	39.4	2.8

1.17.3 Rainfall in Sana'a Basin

In Sana'a Basin, there are two rainy seasons separated by a distinct dry interval (May to mid-July). The annual rainfall generally varies between 150 and 250 mm, with some years having higher rainfall amounts (above 350 mm). The first rainy period starts mid-March to the beginning of April. The second rainy period starts in mid-July to the beginning of August and stops abruptly at the end of August. The months from September to February are generally dry, although occasional thunderstorms may bring some rain during these months. The average rainfall per rain day is about 16-17 mm. 13 stations are used to represent the 22 sub-basins of Sana'a Basin as shown in Table 8.6.

Table 8-6 Representative Mean Monthly Rainfalls and Stations for the 22-sub-basins

Sub-basins	W. Mashamini	W al. Madini. W al. Kharid. W. Qasbah. W. Thumah	W. Ma'adi	W. A'sir. W. Khalaqa	W. al Huqqah. W. al Iqbal	W. bani Huwat. W. al Furs. W. as Sirr	W. Shahik	W. Ghayman	W. Zahr & al Ghay	W. Hamdan.	W. al Mawrid.	W. Sa'Wan	W. al Mulaikhy. W. Hizyaz. W. Akhwar
Sub-basin No	**1**	**2, 3, 7, 10**	**4**	**5, 6**	**8, 13**	**9, 11, 12**	**18**	**19**	**14**	**15**	**16**	**17**	**20, 21, 22**
Rainfall Station	**Astan-a**	**Samnah-a**	**Maadia**	**Birbasla**	**Darwan**	**Sana'a Airport**	**Adabat**	**Darsalm Adabat**	**Mind**	**NWRA-A CAMA**	**DarsalmN WRA'A CAMA**	**Shoub**	**Wallan**
Jan	1.3	1.8	0.6	0.7	4.7	3.0	0.0	1.2	4.3	4.3	3.6	3.3	1
Feb	4.5	0.5	8	8.4	2.2	4.9	4.2	2.3	2.5	7.5	5.2	14.9	7.4
Mar	38.7	26	23.1	34.2	12.7	30.8	20.2	17.6	19.2	19.1	17.7	29.1	55
Apr	32.9	23.5	33.4	58.5	28.1	38.5	43.6	39.4	40.6	35.3	35.3	32.1	65.9
May	7.9	15.7	12.1	12.4	38.5	27.4	22.7	22.4	53	33.9	30.0	28.6	29.9
Jun	16.8	21.6	27.3	29.9	5.7	3.1	0.6	1.7	6.4	2.5	2.6	1.5	0.0
Jul	20.1	9.9	14.8	30	33.5	16.8	30.8	26.4	48.2	33.3	29.6	33.2	5.9
Aug	36.6	34.9	53.2	32.2	53.1	30.2	61.1	52.7	56.9	52.7	49.9	66.8	44.6
Sep	4.9	0.2	5	2.2	3.8	1.3	4.0	2.4	35.8	8.9	6.2	3.7	6.4

Sub-basins	W. Mashamini	W al. Madini. W al. Kharid. W. Qasbah. W. Thumah	W. Ma'adi	W. A'sir. W. Khalaqa	W. al Huqqah. W. al Iqbal	W. bani Huwat. W. al Furs. W. as Sirr	W. Shahik	W. Ghayman	W. Zahr & al Ghay	W. Hamdan.	W. al Mawrid.	W. Sa'Wan	W. al Mulaikhy. W. Hizyaz. W. Akhwar
Sub-basin No	**1**	**2, 3, 7, 10**	**4**	**5, 6**	**8, 13**	**9, 11, 12**	**18**	**19**	**14**	**15**	**16**	**17**	**20, 21, 22**
Rainfall Station	**Astan-a**	**Samnah-a**	**Maadia**	**Birbasla**	**Darwan**	**Sana'a Airport**	**Adabat**	**Darsalm Adabat**	**Mind**	**NWRA-A CAMA**	**DarsalmN WRA'A CAMA**	**Shoub**	**Wallan**
Oct	1.8	1.9	6.4	14.1	7.4	11.4	3.7	3.6	8.5	15.2	11.3	23.6	19.8
Nov	4.3	2.8	0.1	4.0	2.2	1.9	3.4	2.3	1.7	6.2	4.5	6.5	5.78
Dec	0.9	11.2	4.9	3.8	2.1	0.9	3.9	1.9	2.2	8.8	5.9	1.4	7.6
Annual	171	150	189	231	194	170	197	174	279	228	202	245	249

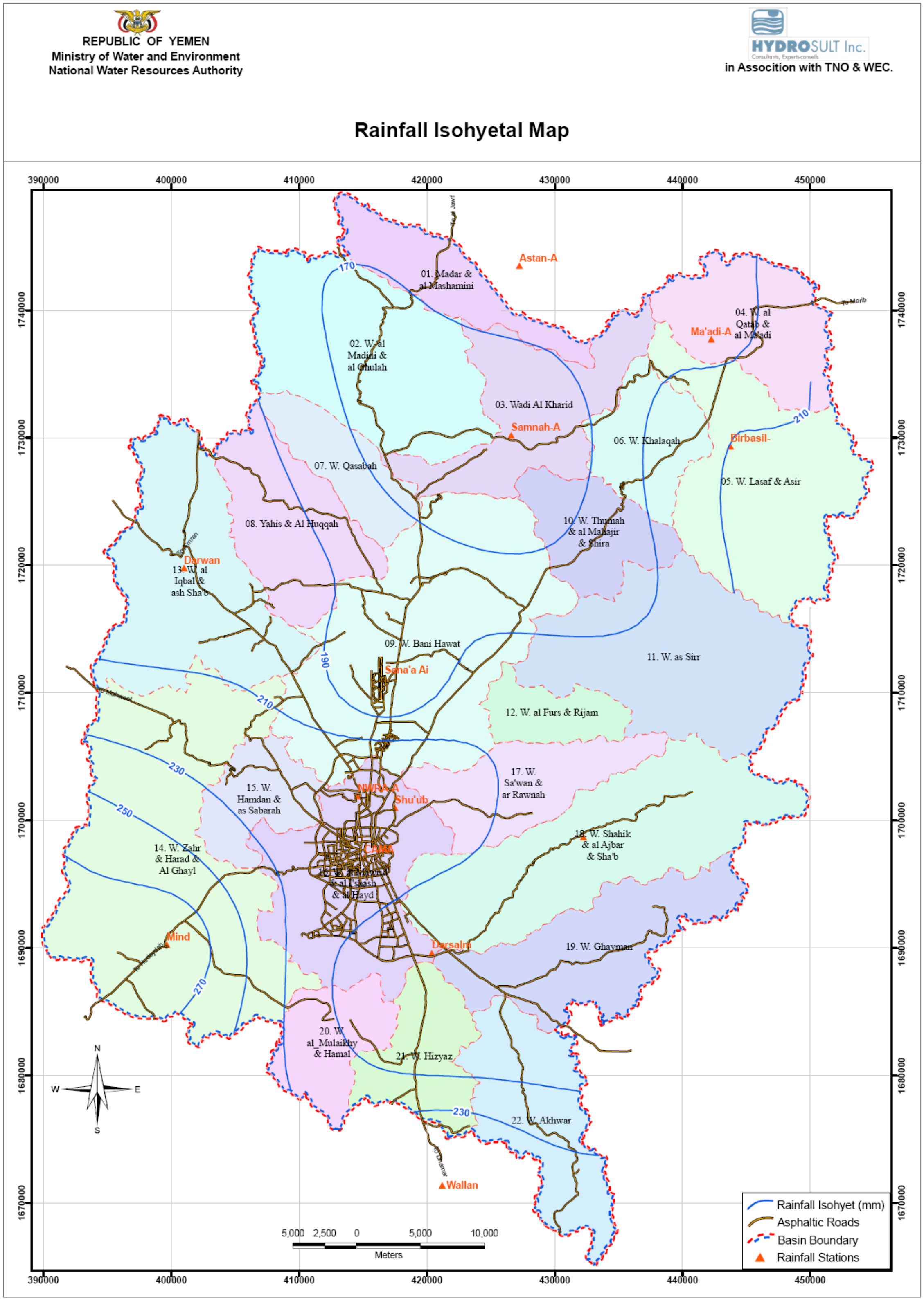


Figure 8-3 Annual Rainfall (mm) Isohyetal Map

1.18 Methodology

After compiling the necessary data, the WEAP model is used for water balance analysis of Sana'a Basin. The schematic diagram is shown in Figure 8.4.

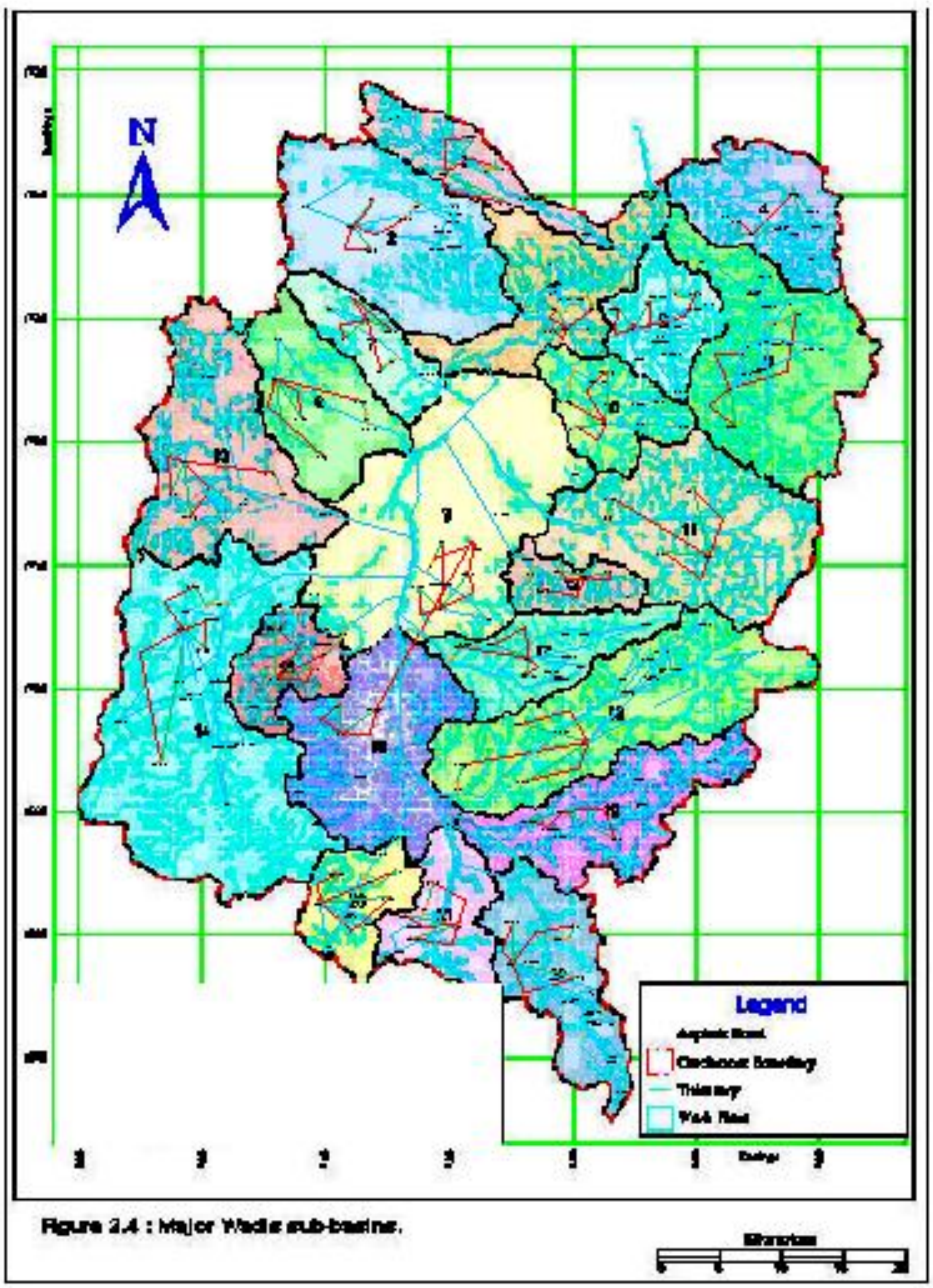


Figure 8-4 Schematic diagram of WEAP model for Sana'a Basin

WEAP supports the use of three hydrologic modeling methods: the Rainfall Runoff method FAO (Food and Agriculture Organization of the United Nations), the Water Requirement FAO approach, and the Rainfall Runoff Soil moisture method. The Rainfall Runoff Soil moisture method was chosen because it offers the most comprehensive analysis by allowing for the characterization of land use and/or soil type impacts to the hydrological processes (Sieber, 2005).

The Soil moisture method is a one-dimensional two-soil-layer algorithm for calculating evapotranspiration, surface runoff, sub-surface runoff and deep percolation for a defined land area unit. A conceptual diagram of the equations incorporated into the Soil moisture method water balance calculations are shown in Figure 8.5.

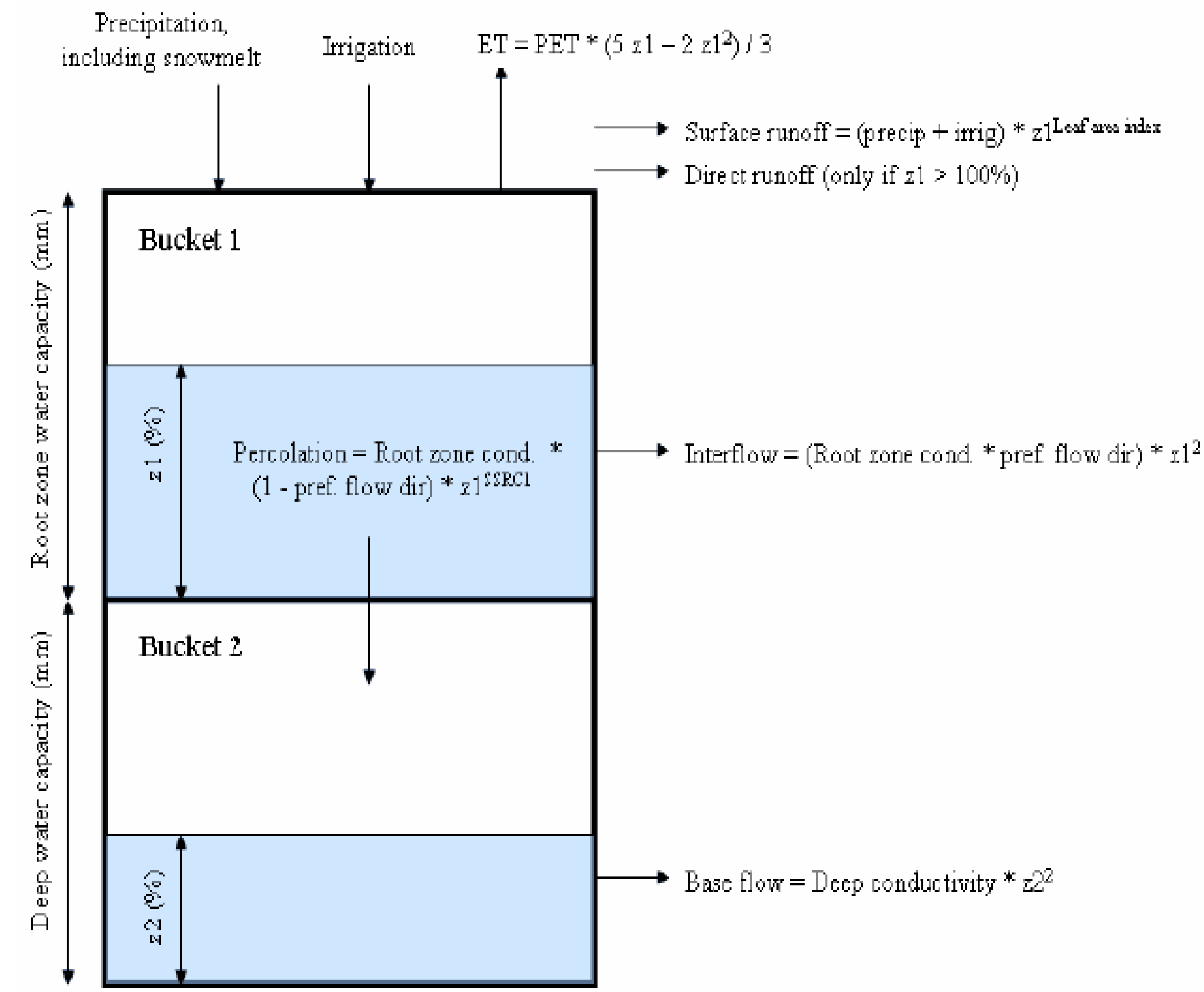


Figure 8-5 Soil moisture method Model (Source: Sieber, 2005)

Using the Soil moisture method which relatively accurately describes the hydrologic response of the basin implies that more detailed hydrologic and climatic parameters are required for the model. Consequently, the parameters and data are often difficult to define with certainty. The basic input parameters are listed in Table 8-7, along with the sensitivities identified for each parameter, which are a result of the work of Jantzen et al, (2006). WEAP imposes a model structure in terms of input parameter resolution, meaning that WEAP forces certain parameters to describe the entire catchment and others to describe smaller land unit areas such as the soil classification or land use category.

Table 8-7 Input Parameters and Sensitivity

Parameters	Unit	Resolution	Sensitivity
Land use			
Area	Sq km	Catchment	High
Deep Water Capacity	mm	Catchment	High§§
Deep Conductivity	mm/day	Catchment	Moderate
Initial Z2	No unit	Catchment	No Influence
Soil Water Capacity	mm	Soil	Moderate
Root Zone Conductivity	mm/day	Soil	Moderate***
Preferred Flow Direction	no unit	Soil	Moderate
Initial Z1	no unit	Soil	No influence
Crop Coefficient, Kc	no unit	Land use	High
Leaf Area Index	no unit	Land use	High
Climate			
Precipitation	mm	Catchment	High
Temperature	°C	Catchment	Moderate
Wind	m/s	Catchment	Low
Humidity	%	Catchment	Low

Catchment Area

A fundamental parameter of any hydrologic model is the catchment area. The catchment areas of the 22 sub-basins delineated and measured in this study was found to be well in line with the previous studies of WEC and GAF.

Deep Water Capacity

Deep Water Capacity is the effective water-holding capacity, in millimeters, of the deep soil layer or the second bucket in the Soil moisture method.

§§ In this study the sensitivity of deep water capacity was found to be low

*** The sensitivity of root zone conductivity was found to be high

Deep Conductivity

The Deep Conductivity parameter represents the conductivity rate of the second bucket, in millimeters per day. Deep Conductivity controls the transmission of base flow. WEAP applies a single value of Deep Conductivity to the entire catchment. This value is very low or zero in Sana'a Basin as base-flow in the Wadis is negligible.

Initial Z2

The "Initial Z2" parameter is the relative storage given as a percentage of the total effective storage of the Deep Water Capacity at the beginning of a simulation. WEAP, like Deep Water Capacity, forces Initial Z2 to be constant for each basin. A value of 5 percent was assigned to every sub-basin.

Soil Water (Root Zone) Capacity

Soil Water or Root Zone Capacity is the effective water-holding capacity in millimeters of the first bucket in the Soil moisture method. A value of 102 mm is applied for each sub-basin to represent average field capacity.

Root Zone Conductivity

Root Zone Conductivity or soil conductivity is the conductivity in the first bucket. Conductivity rate typically varies among soil and land use classifications. Different values are assigned depending on land use characteristics (runoff producing characteristics P1, A1, etc.) defined in earlier sections.

Preferred Flow Direction

The Preferred Flow Direction parameter is used to partition flow out of the root zone layer to the lower soil layer or groundwater. Preferred flow direction can vary by land use classification and ranges from 0 to 1. A preferred flow direction of 1 indicates 100% horizontal flow direction while 0 indicates 100% vertical flow direction. The value for Sana'a Basin tends towards zero as interflow to Wadis is minimal compared to downward percolation.

Initial Z1

The Initial Z1 parameter is the relative storage given as a percentage of the total effective storage of the Root Zone Water Capacity at the beginning of a simulation. A value of 10% is assigned for each sub-basin.

Crop Coefficient Kc

The crop coefficient parameter Kc represents the effects of vegetative evapotranspiration and soil evaporation, which vary by land class type. The parameter was created to study the required soil moisture to maximize crop biomass production. Hence, Kc is typically used to calculate the required evapotranspiration using the equation:

- (Evapotranspiration) required = Kc * (Evapotranspiration) reference,
- Kc value adopted from GAF study is used as presented in earlier sections.

Leaf Area Index

Leaf Area Index (LAI) is a parameter that varies by land use and is used to control the surface runoff response. Runoff tends to decrease with higher values of LAI. Different LAI values are used depending on the runoff producing characteristics (P1, A1, etc.) of the area.

Precipitation

Monthly Precipitation values of 13 stations in Sana'a Basin are used. The stations are described in earlier sections.

Temperature, Wind and Humidity

Temperature data are entered in degrees Celsius. Humidity is the relative humidity entered as a percentage and Wind values are entered in meters per second (Table 8-5).

Chapter 9. RESULTS BASIN MODELLING

1.19 Average Year

1.19.1 Water Supply Demand

Annual and monthly domestic and non domestic water supply demand in Sana'a Basin (M m^3); for 2010 Population forecast is shown in Table 9-1.

Table 9-1 Domestic and non domestic water supply demand in Sana'a Basin (M m^3)

Sub-basin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
11	0.07	0.06	0.07	0.06	0.07	0.06	0.07	0.07	0.06	0.07	0.06	0.07	0.77
12	0.07	0.06	0.07	0.06	0.07	0.06	0.07	0.07	0.06	0.07	0.06	0.07	0.77
13	0.22	0.20	0.22	0.21	0.22	0.21	0.22	0.22	0.21	0.22	0.21	0.22	2.54
15	0.22	0.20	0.22	0.21	0.22	0.21	0.22	0.22	0.21	0.22	0.21	0.22	2.54
16	2.49	2.25	2.49	2.41	2.49	2.41	2.49	2.49	2.41	2.49	2.41	2.49	29.32
17	0.22	0.20	0.22	0.21	0.22	0.21	0.22	0.22	0.21	0.22	0.21	0.22	2.54
19	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.85
20	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.85
21	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.74
22	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.74
7	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.72
9	1.04	0.94	1.04	1.00	1.04	1.00	1.04	1.04	1.00	1.04	1.00	1.04	12.22
All others	0.32	0.29	0.32	0.31	0.32	0.31	0.32	0.32	0.31	0.32	0.31	0.32	3.81
Sum	4.96	4.48	4.96	4.80	4.96	4.80	4.96	4.96	4.80	4.96	4.80	4.96	58.4

In Sana'a Basin, total domestic and non domestic water demand, including 20% system losses, will be 58.4 M m^3.

Using the forecast from the 2004 census, the 2010 Sana'a Basin population will be about 2.9 Million. The annual water supply demand will be 58 M m^3 for the forecasted population of about 2.9 million people.

Compared to the recharge level from direct rainfall and wadi runoff (about 54.3 M m^3/year, estimated in section 7 herein) and the available water resources, this is a very high demand.

Two sub-basins Wadi al Mawrid (16) and Bani Huwat (9) are the largest consumers. Wadi al Mawrid, where Sana'a City is located, demands about half of the total Sana'a Basin water supply. This is a challenge for water management and water right issues as people living in rural areas in other sub-basins may prefer to use the water for irrigation.

1.19.2 Irrigation water demand

The total irrigation water demand for 18953.2 ha of irrigated land in Sana'a Basin is as shown in Table 9.2.

Table 9-2 Irrigation water demand in Sana'a Basin (M m^3)

Sub-basin ID No.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
11	0.9	1.1	1.9	2.1	3.3	3.8	3.6	3.0	2.3	1.7	0.9	0.8	25.3
12	0.4	0.4	0.7	0.7	1.1	1.2	1.2	1.0	0.8	0.6	0.4	0.3	8.8
13	1.2	1.4	1.7	1.5	2.0	2.2	2.0	1.9	1.8	1.5	1.2	1.0	19.6
14	0.9	1.0	1.3	1.3	1.7	1.9	1.5	1.6	1.6	1.3	0.8	0.8	15.8
16	0.5	0.5	0.7	0.7	1.0	1.1	0.9	0.9	0.9	0.7	0.4	0.4	8.7
17	0.4	0.4	0.8	0.9	1.3	1.5	1.4	1.2	0.9	0.7	0.3	0.3	10.2
18	0.4	0.5	0.8	0.9	1.3	1.5	1.4	1.2	1.0	0.7	0.4	0.4	10.5
19	0.3	0.3	0.5	0.5	0.7	0.8	0.7	0.6	0.5	0.4	0.2	0.2	5.6
2	0.3	0.4	0.4	0.4	0.4	0.5	0.5	0.4	0.4	0.4	0.3	0.3	4.6
5	0.5	0.6	0.7	0.6	0.8	0.9	0.8	0.7	0.7	0.6	0.5	0.4	7.8
8	0.8	1.0	1.2	1.2	1.5	1.7	1.5	1.5	1.4	1.1	0.8	0.7	14.4
9	1.6	1.9	3.6	4.5	6.8	7.5	6.0	6.0	5.2	3.8	1.6	1.4	49.7
All others	2.3	2.6	3.4	3.2	4.3	4.9	4.4	4.1	3.7	3.0	2.2	1.9	40.0

Sum	10.4	12.1	17.6	18.5	26.1	29.5	25.9	24.2	21.3	16.4	10.0	9.0	221.1

The total annual irrigation water demand is 221.1 M m^3, which is equivalent to an annual demand of 11668 m^3/ha.

Wadi Bani Huwat and Wadi as Sirr are the largest consumers.

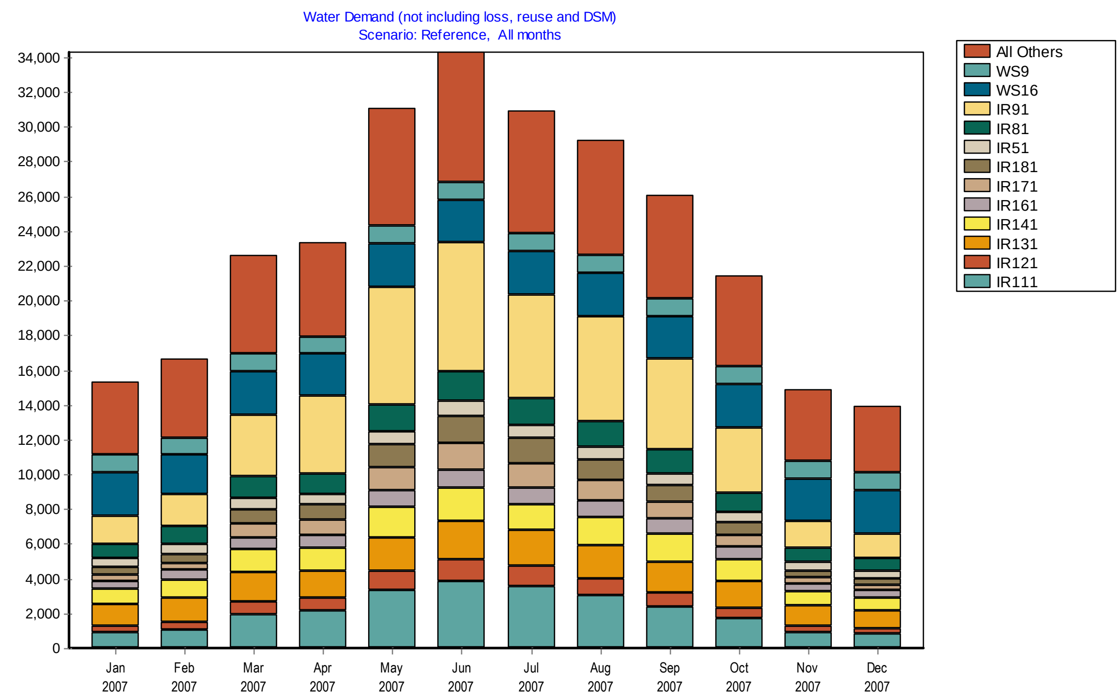


Figure 9-1 Total water demand (Water supply and irrigation) in Sana'a Basin

Table 9-3 Total water Demand (Irrigation and Water Supply) M m^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
15.3	16.6	22.6	23.3	31.1	34.3	30.9	29.2	26.1	21.4	14.8	13.9	279.5

The highest demand is in June and the lowest is in December.

1.19.3 Model Calibration

Based on the only discharge data available at the outlet of Sana'a Basin in 1995, the WEAP model for Sana'a Basin was used to attempt calibration. Table 9.4 and Figure 9.2 show the comparison of modeled result and measured data.

Table 9-4 measured (1995) and modeled outflow at the outlet of Sana'a Basin (1000 m^3)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Measured (1995)	268	194	2303	1011	643	156	187	2866	181	187	207	241	8445
Modeled	249	419	2239	2013	840	121	190	2145	79	48	68	295	8706

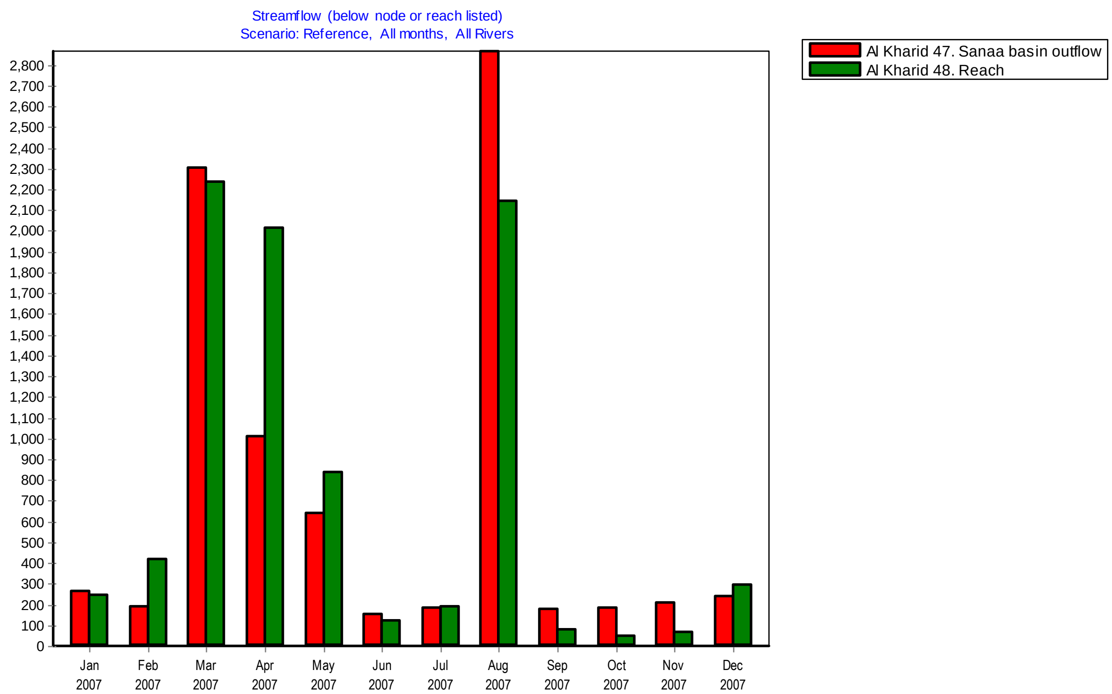


Figure 9-2 Comparison of Sana'a Basin outflow (1995 measured) and modeled at outlet of Wadi Alkharid

1.19.4 Rainfall

The mean annual rainfall estimated by arithmetic mean WEAP Model in Sana'a Basin is found to be 662.9 M m^3, as shown in Table 9.5.

Table 9-5 Mean rainfall total in Sana'a Basin (M m^3)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Rainfall	7.9	14.6	83.9	131.9	92.2	32.0	79.4	145.2	21.5	28.7	9.7	16.0	662.9

1.19.5 Catchment Runoff/Infiltration

The total average annual runoff and infiltration generated in the 22 sub-basins of Sana'a Basin is 75.4 M m^3.

Table 9-6 Average Annual Catchment Runoff/Infiltration in Sana'a Basin (M m^3)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
5.6	7.1	11.6	19.2	8.7	1.7	2.8	10.4	2.3	0.9	1.5	3.7	75.4

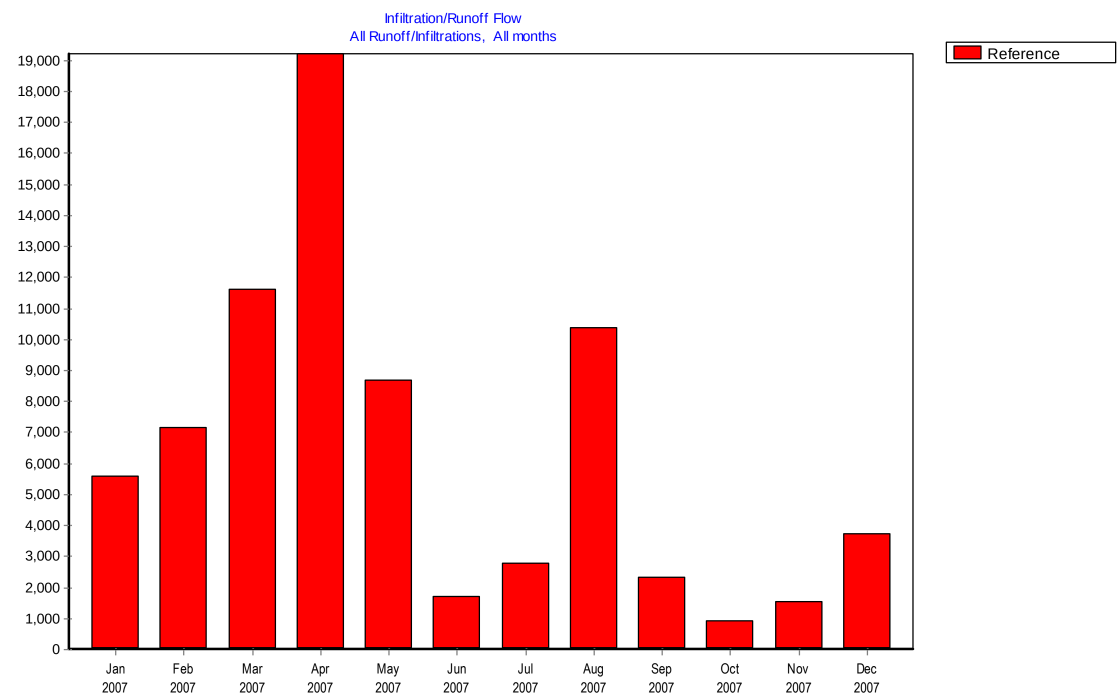


Figure 9-3 Average Annual Catchment Runoff/Infiltration in Sana'a Basin

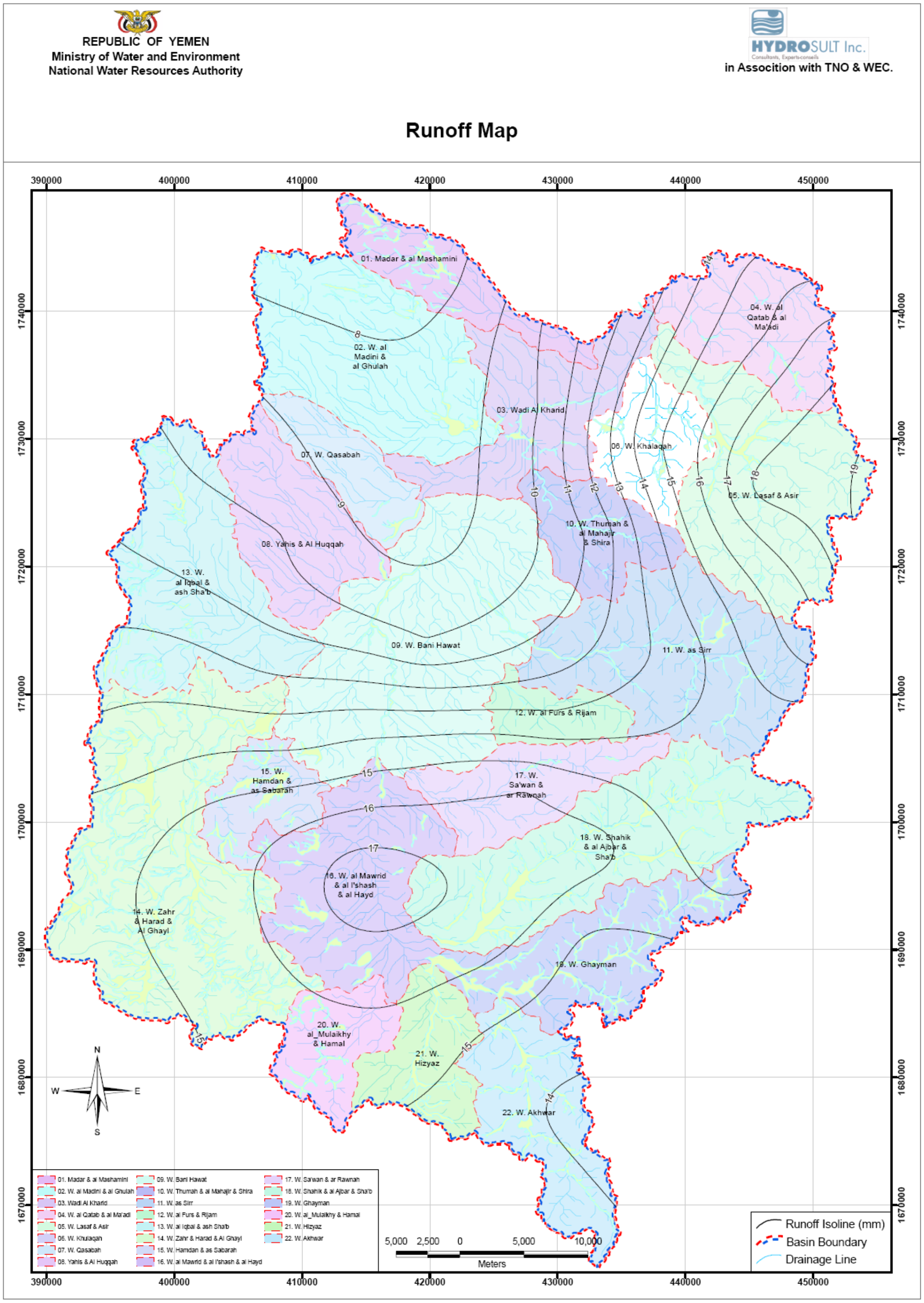


Figure 9-4 Mean Annual Runoff/Infiltration Map

1.19.6 Reservoirs

Total annual inflows to all reservoirs in Sana'a Basin are shown in Figure 9.5. The total annual reservoir inflow is about 8.8 M m^3, which is about 12% of the total runoff generated in the basin.

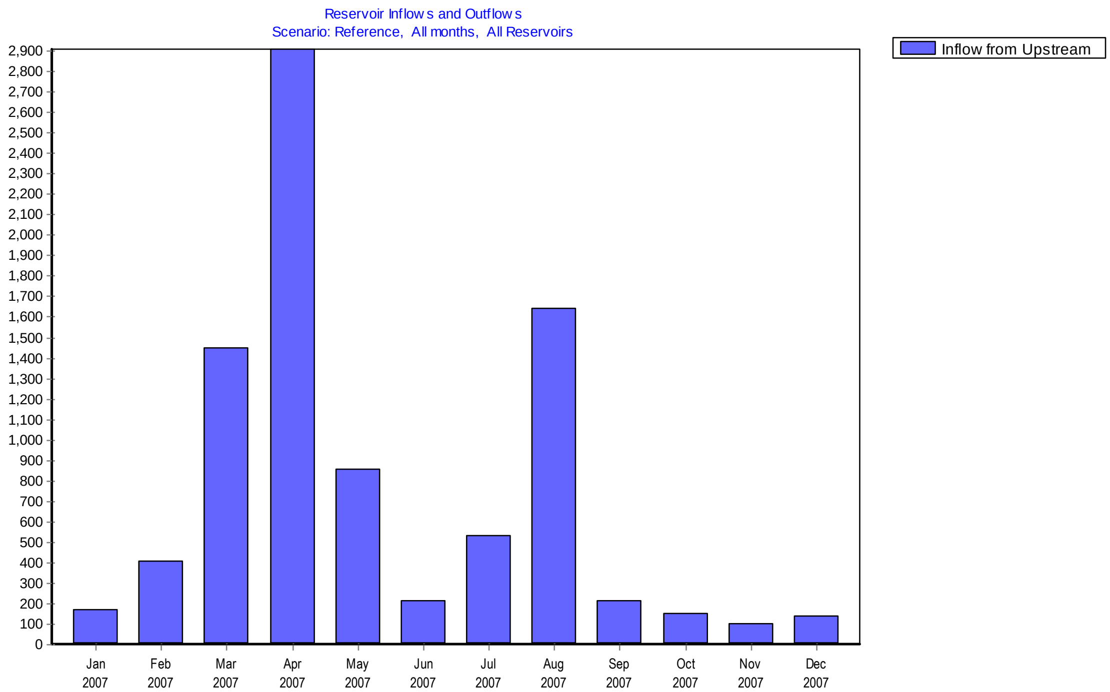


Figure 9-5 Average total annual inflows to the reservoirs in Sana'a Basin

Table 9-7 Average total annual inflows to the reservoirs in Sana'a Basin, M m^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0.17	0.41	1.45	2.91	0.85	0.21	0.53	1.64	0.21	0.15	0.10	0.14	8.8

1.19.7 Recharge

The average groundwater recharge in Sana'a Basin is shown in Table 9.8. Recharge is estimated from reservoir, catchment runoff, direct rainfall and return flow from demand sites.

Table 9-8 Average groundwater recharge (all sources) M m^3

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Reservoir	0.1	0.3	0.9	1.6	0.6	0.2	0.4	1.2	0.1	0.1	0.1	0.1	5.5
Direct rainfall	4.8	5.9	7.5	11.7	5.9	1.1	1.7	5.8	1.9	0.6	1.2	3.0	51.2

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
and Wadi Runoff													
Return flow	1.9	2.2	2.5	3.6	2.9	1.1	1.0	2.6	1.2	0.6	0.7	1.2	21.3
Total	6.8	8.3	10.9	16.9	9.3	2.4	3.0	9.6	3.2	1.3	2.0	4.3	78.1

The groundwater recharge from wadi runoff and rainfall, according to the WEAP model, is 51.2 M m^3, subtracting the direct rainfall part of 3.9 M m^3 from that previously estimated (Table 7.3); the Wadi runoff contribution is 48.3 M m^3. Therefore, the percentage of recharge from the total Wadi runoff of 66 M m^3 (Table 7.3) is 73%. The present result is in line with the WRAY 1995 estimate that 20-30% of Wadi runoff (section 7.2.4) will be lost to evapotranspiration through spate irrigation and the remainder will contribute to groundwater recharge, as basin outflow is almost negligible.

The groundwater recharge from all sources – that is, direct rainfall, wadi runoff, reservoirs and return flow from demand sites, including Sanaa's waste water treatment plant – Is about 78.1 M m^3. Most of the recharge comes from wadi runoff; recharge from direct rainfall depends on some intensive rainfalls as discussed in earlier sections.

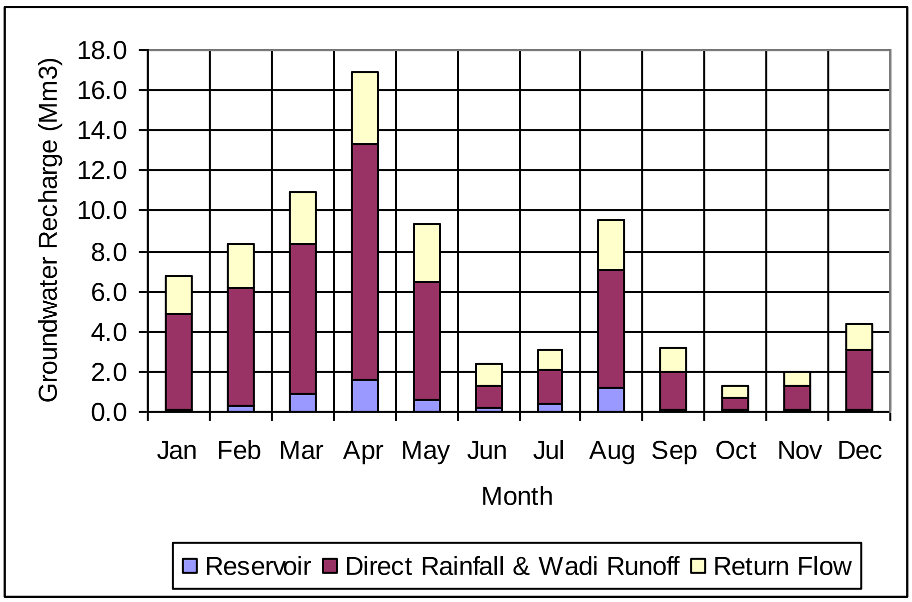


Figure 9-6 Average Groundwater Recharge in Sana'a Basin

1.19.8 Water Balance

Table 9-9 Water supply delivered from replenishable water sources, M m^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
6.8	8.4	10.0	15.0	11.8	5.2	4.3	10.1	5.5	2.5	2.6	4.6	86.8

The total annual water resources delivered from groundwater, diverted surface water (spate irrigation), and reservoirs (direct abstraction and from shallow-well recharge) is 86.8 M m^3.

Table 9-10 Unmet demand or supply delivered from non replenishable groundwater sources (mining) M m^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
8.5	8.2	12.6	8.3	19.3	29.1	26.6	19.0	20.6	18.9	12.2	9.3	192.7

This is the water delivered from deep groundwater aquifer (Mining) which cannot be replenished.

Table 9-11 Unmet demand at sub-basin level or water delivered from Groundwater (mining) M m^3

Sub-basin	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
11	0.59	0.60	1.27	1.30	2.91	3.73	3.52	2.83	2.27	1.64	0.80	0.68	22.1
12	0.30	0.34	0.55	0.54	0.99	1.23	1.16	0.96	0.79	0.59	0.34	0.30	8.1
13	0.84	0.97	1.44	1.18	1.46	2.01	1.90	1.40	1.53	1.49	1.11	0.95	16.3
14	0.20	0.15	0.49	0.00	0.00	1.11	0.93	0.29	0.41	0.87	0.68	0.53	5.7
16	2.50	2.30	2.75	2.39	3.02	3.44	3.24	2.79	3.11	3.12	2.70	2.55	33.9
17	0.25	0.12	0.37	0.53	1.13	1.49	1.39	0.87	0.77	0.62	0.21	0.16	7.9
18	0.00	0.00	0.00	0.00	0.00	0.88	1.16	0.00	0.16	0.60	0.30	0.03	3.1
19	0.02	0.01	0.11	0.00	0.00	0.69	0.62	0.06	0.30	0.36	0.21	0.12	2.5
8	0.53	0.64	1.01	0.89	1.19	1.62	1.37	1.06	1.27	1.12	0.77	0.65	12.1
9	1.67	1.71	3.35	0.77	7.07	8.73	7.14	6.44	6.27	4.88	2.34	1.92	52.3
All others	1.63	1.40	1.28	0.70	1.50	4.17	4.15	2.35	3.68	3.60	2.73	1.44	28.6
Sum	8.53	8.24	12.62	8.31	19.27	29.11	26.58	19.03	20.56	18.89	12.20	9.34	192.7

Table 9-12 Total Average Annual Sub-basin Water balance

Sub-basin	Water Balance (M m^3)
1	-0.04
2	-2.36
3	-1.51
4	0.00
5	-0.18
6	-0.77
7	-2.57
8	-13.24
9	-52.20
10	-0.52
11	-24.59
12	-9.49
13	-19.32
14	-7.46
15	-2.90
16	-34.00
17	-10.26
18	-3.64
19	-2.87
20	-2.83
21	-1.57
22	-0.40
	-192.7

Some of the sub-basins, as shown in Tables 9-11 and 9-12, require more attention as their water demand far exceeds their resources.

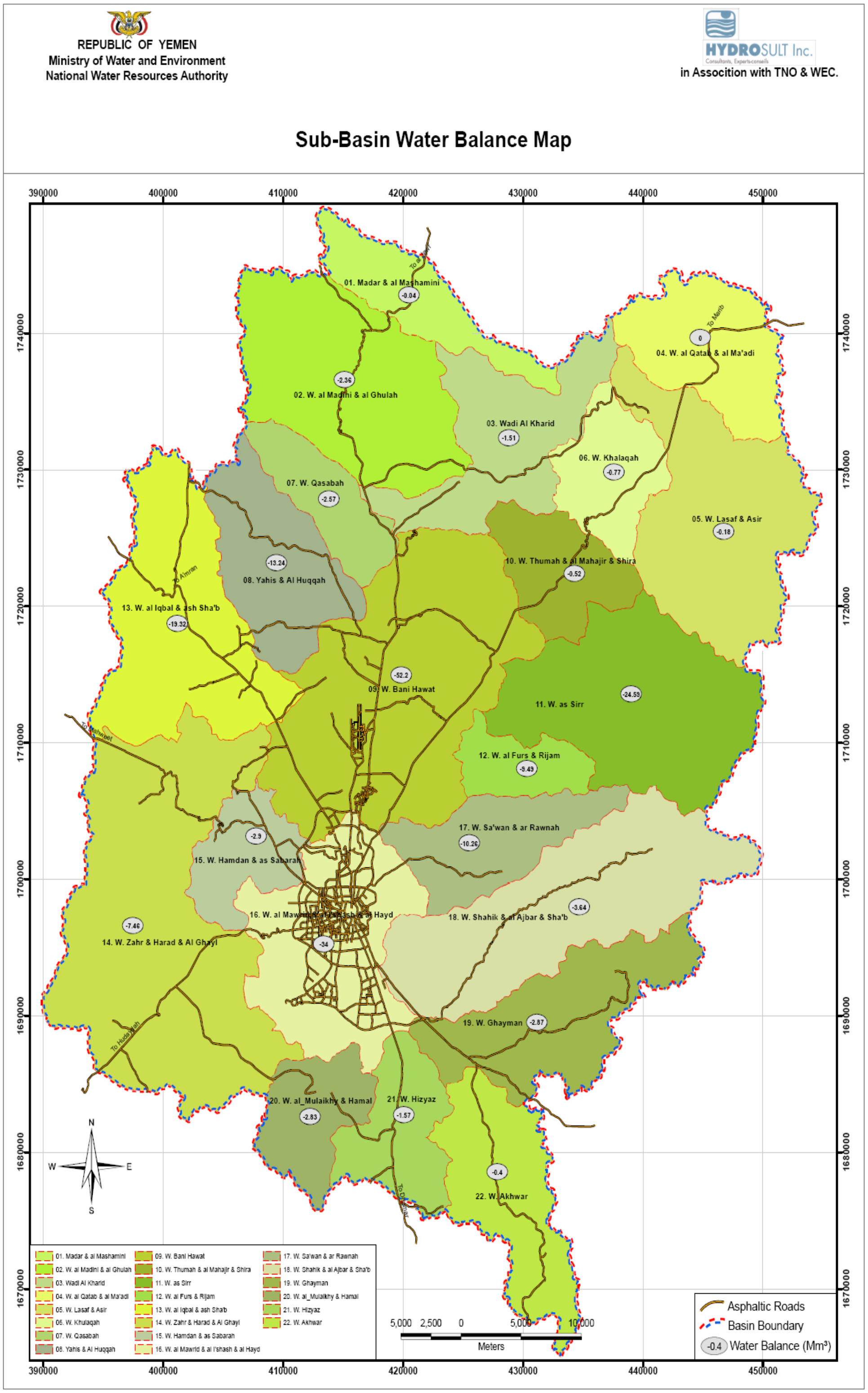


Figure 9-7 Sub-basin Water Balance Map

1.20 Year 2007

Year 2007 conditions are evaluated using the average of the four WEC stations rainfall data as representative for the basin and keeping the other parameters the same.

1.20.1 Rainfall

Table 9-13 Average Rainfall in Sana'a Basin (2007) M m^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	37.7	59.8	75.5	100.0	22.9	201.1	151.9	0	0	0	0	649

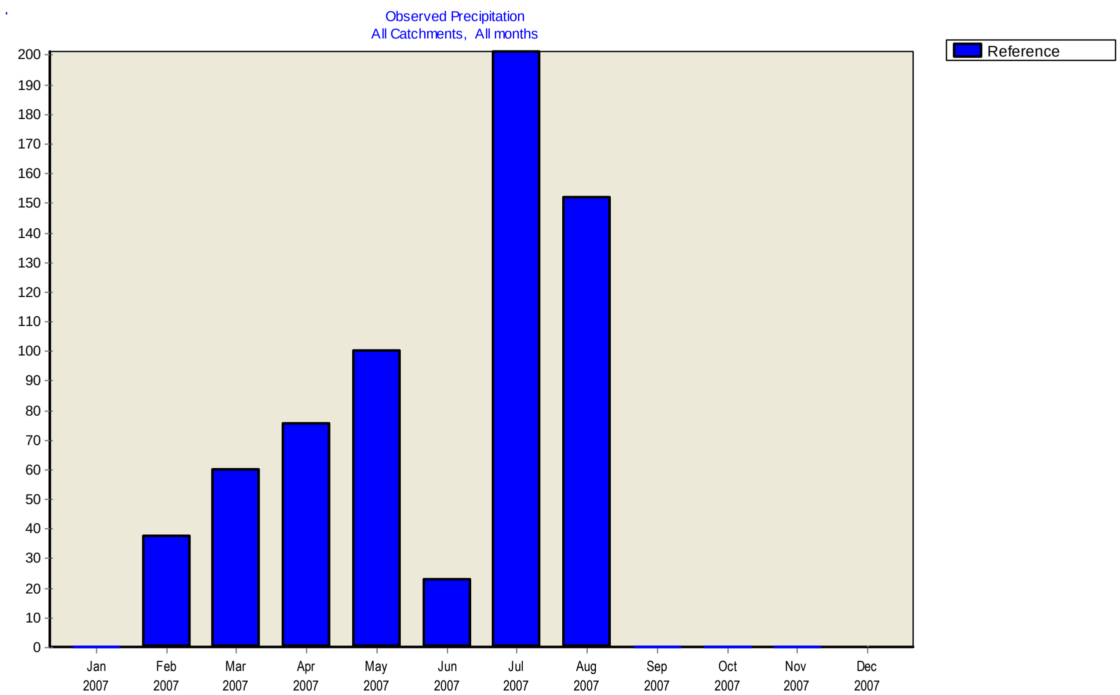


Figure 9-8 Total rainfall received in Sana'a Basin (Year 2007). M m^3

Total rainfall received in the basin in year 2007, based on WEC records, is about 649 M m^3, by comparison with the average of 663 M m^3.

1.20.2 Catchment Runoff/Infiltration

Table 9-14 Total Catchment Runoff/Infiltration Generated in Sana'a Basin (Year 2007) M m^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year

4.4	9.9	10.3	7.6	6.6	1.0	13.1	13.5	1.3	0.0	0.0	0.0	67.7

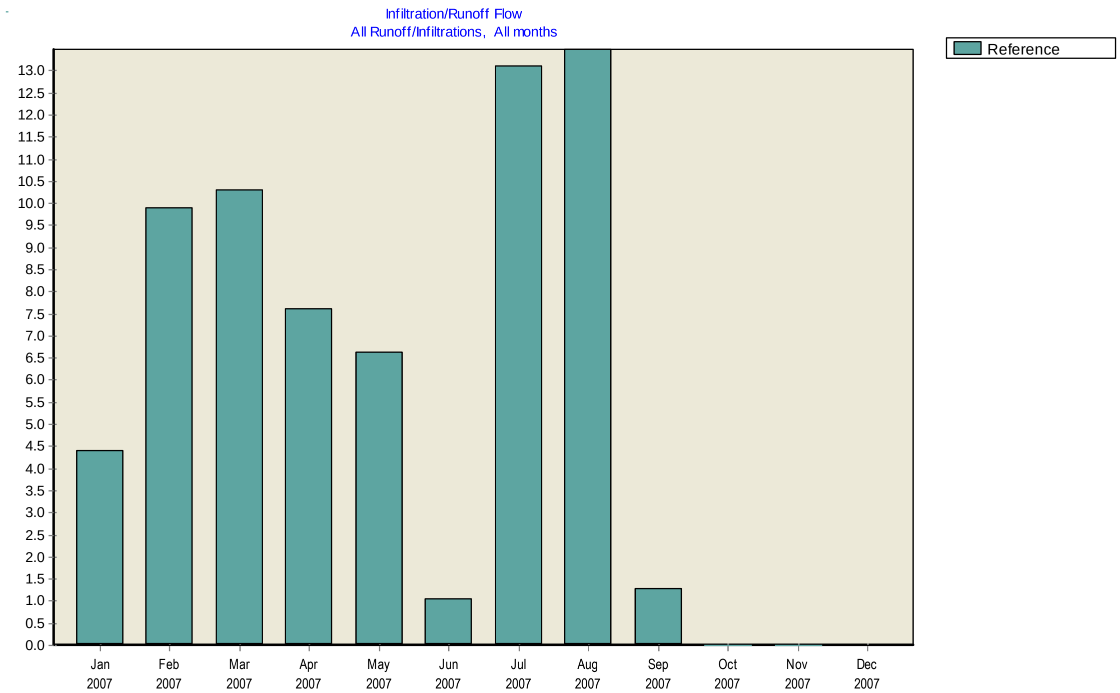


Figure 9-9 Total Catchment Runoff Generated in Sana'a Basin (Year 2007)

The total annual runoff generated using WEC station rainfall records in 2007 is about 67.7 M m^3, which is less than the average annual runoff of 75.4 M m^3.

1.20.3 Reservoir Inflow

Table 9-15 Total reservoir inflow in all dam sites in Sana'a Basin (M m^3) Year 2007

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0.1	0.6	0.8	0.7	0.8	0.1	2.0	1.7	0.0	0.0	0.0	0.0	6.8

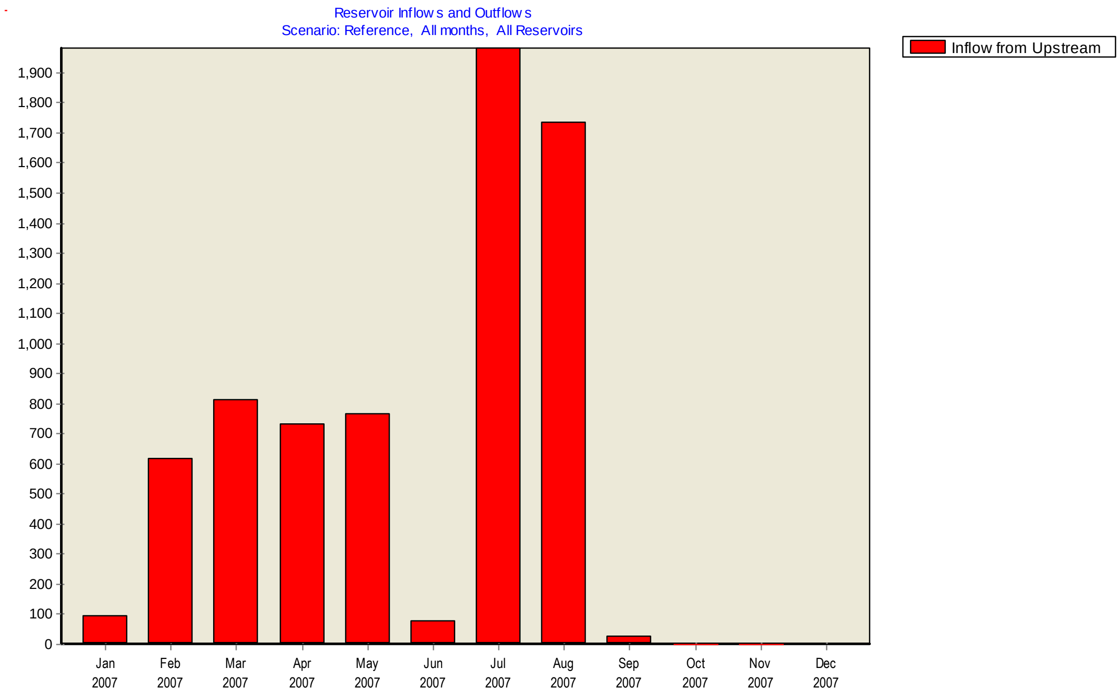


Figure 9-10 Total reservoir inflow at all dam sites in Sana'a Basin (M m^3) Year 2007

The total reservoir inflow in Sana'a Basin in Year 2007 is 6.7 M m^3, as compared to the average of 8.8 M m^3.

1.20.4 Recharge

Table 9-16 Groundwater recharge in Year 2007 (All sources). M m^3

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Reservoir	0.0	0.1	0.5	0.6	0.5	0.5	0.1	1.3	1.2	0.0	0.0	0.0	4.6
Direct rainfall and Wadi runoff	3.9	7.7	7.4	5.1	4.1	0.8	6.6	7.7	1.1	0.0	0.0	0.0	44.4
Return flow	1.5	2.3	2.6	2.4	2.2	0.8	2.7	3.0	1.0	0.1	0.1	0.1	18.7
Total	5.4	10.1	10.5	8.1	6.7	2.1	9.3	12.0	3.3	0.2	0.1	0.1	67.8

Groundwater recharges from all sources i.e. direct rainfall, wadi runoff, and reservoir and return flow from irrigation. The total amount is 67.8 M m^3, most of which will come from Wadi Runoff.

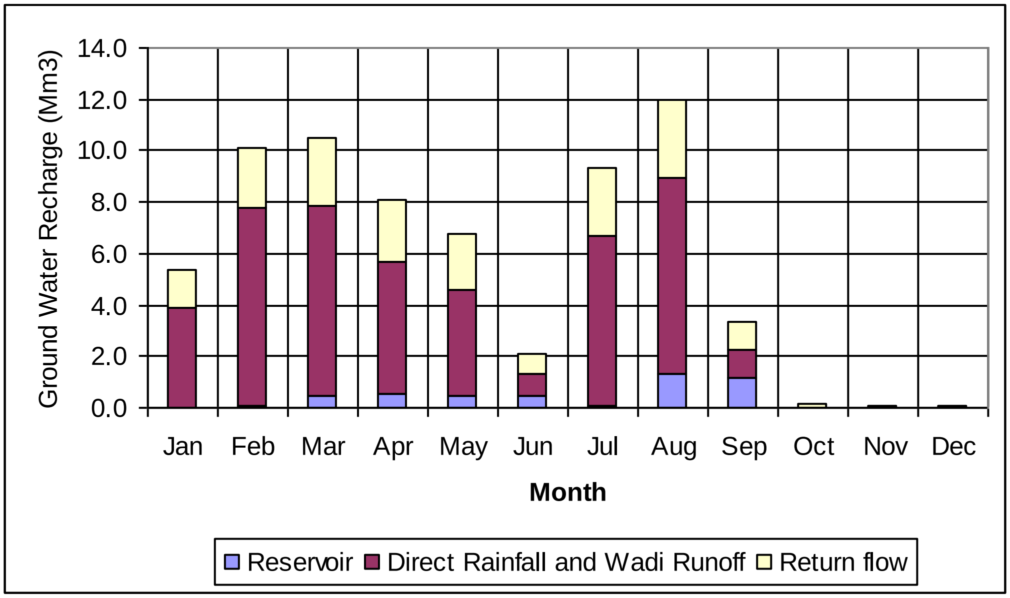


Figure 9-11 Groundwater Recharge in Sana'a Basin (Year 2007)

1.20.5 Water Balance

The total water demand in Sana'a Basin for year 2007 was 271.4 M m^3.

Table 9-17 Total water demand in 2007, M m^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
14.6	16.0	21.9	22.7	30.4	33.6	30.2	28.5	25.4	20.7	14.2	13.2	271.4

Table 9-18 Water supply delivered from replenishable water sources, M m^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
5.5	9.1	10.4	9.3	8.8	3.6	10.5	12.2	4.5	0.6	0.3	0.3	75.4

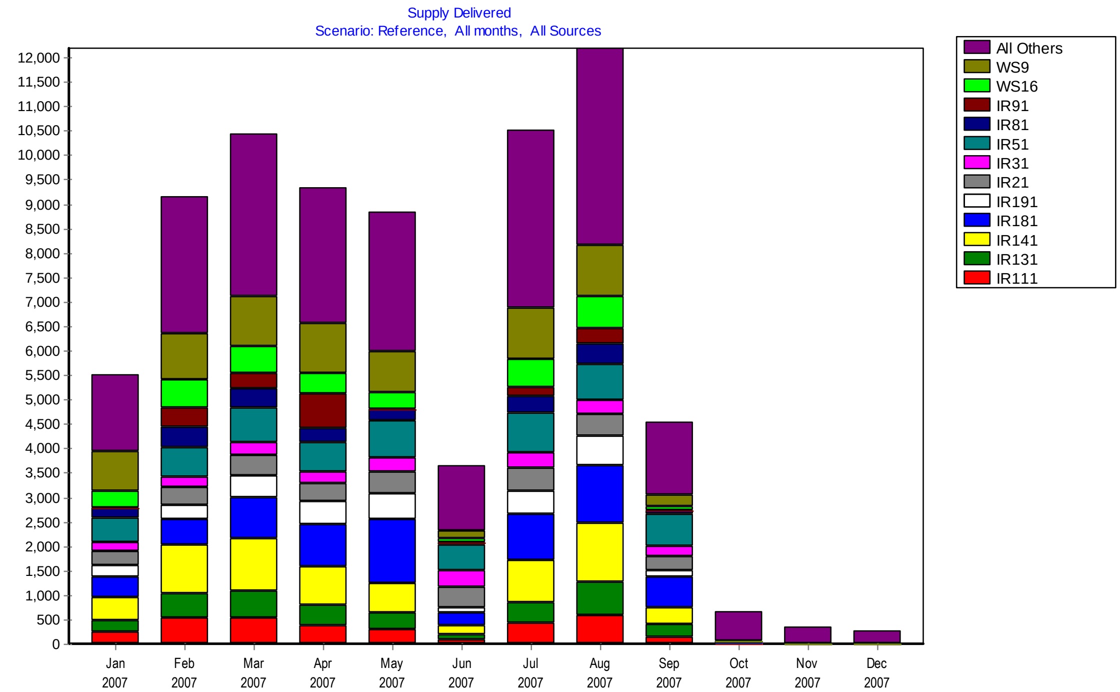


Figure 9-12 Water supply delivered to demand sites from replenishable resources. Year 2007

Water supply delivered – i.e. the total annual water resources delivered from groundwater, surface water, and reservoirs – is 75.4 M m^3, rather than 86.8 M m^3 for average rainfall condition.

1.20.6 Unmet demand

This is the unmet demand from natural recharge and surface water resources or water withdrawn from the aquifer to satisfy water supply and irrigation water demands.

Table 9-19 Year 2007 Modeled Unmet Demand or Water abstracted from Aquifer (M m^3)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
9.1	6.9	11.6	13.4	21.5	29.9	19.8	16.4	20.8	20.1	13.8	13.0	196.4

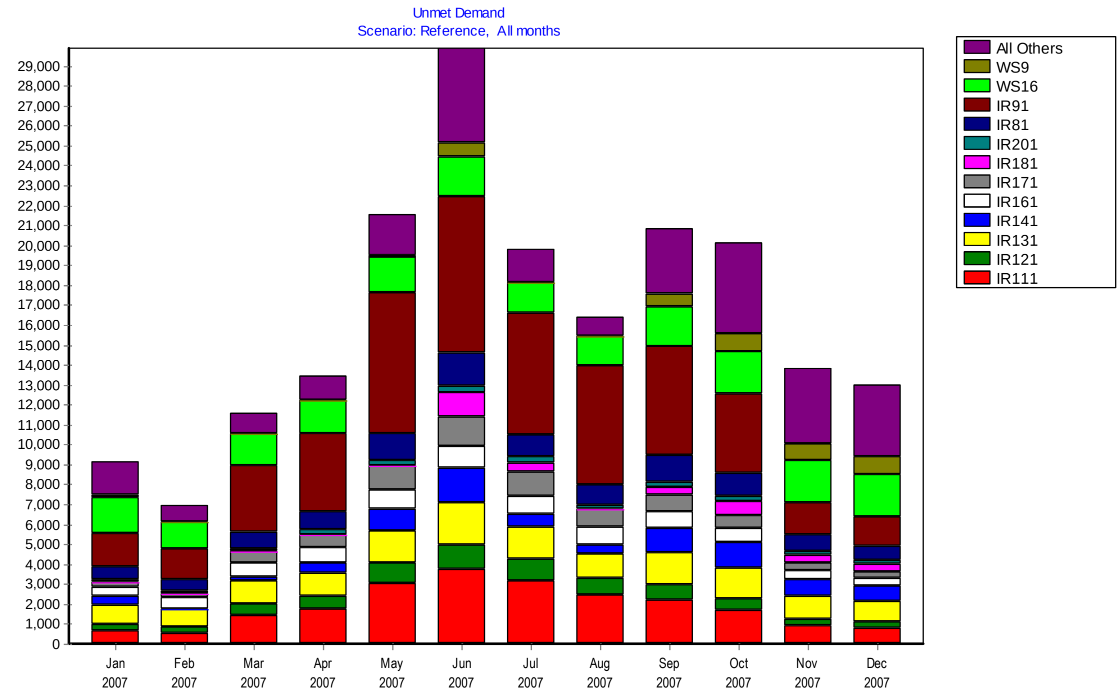


Figure 9-13 Unmet demand or water supplied from non-replenishable aquifer. Year 2007

The year 2007 water demand from the aquifer is 196.4 M m^3, which is higher than the average of 192.7 M m^3.

1.21 Year 2008

Year 2008 was much better in terms of rainfall data collection 17 stations; rainfall data including the 4 WEC stations was obtained. The summary of water balance results using the rainfall data of 2008 is as follows:

1.21.1 Rainfall

Table 9-20 Average Rainfall in Sana'a Basin (2008) M m^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0.0	0.0	0.1	3.5	167.0	18.7	52.0	39.3	4.8	118.6	4.7	0.0	408.8

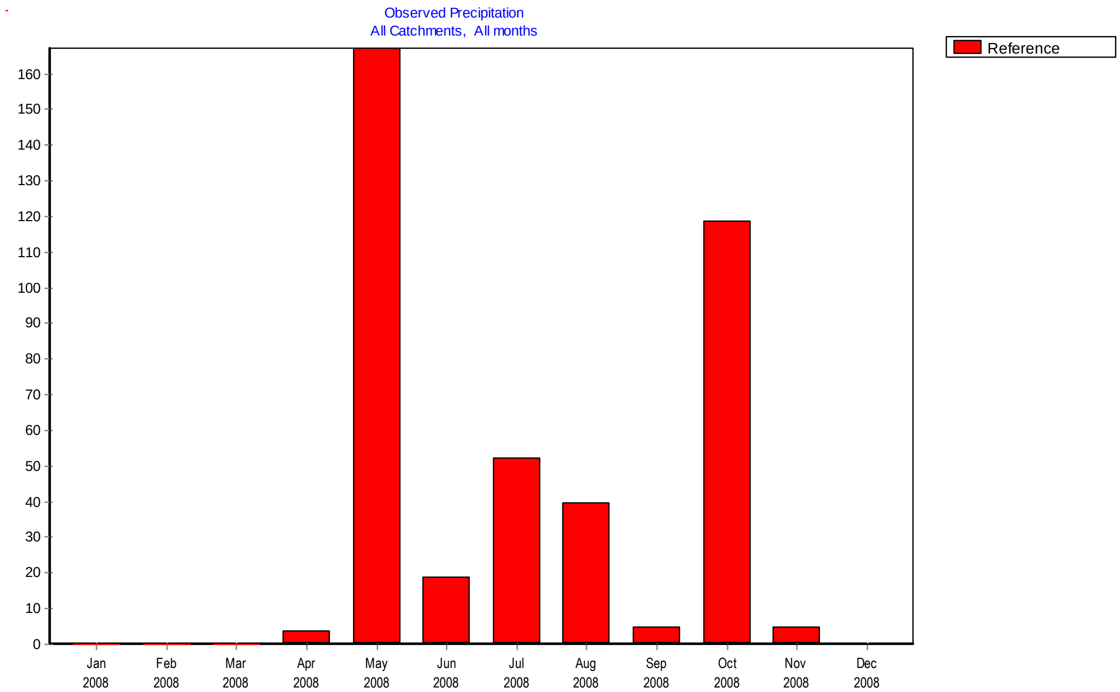


Figure 9-14 Total rainfall received in Sana'a Basin (Year 2008). M m^3

Total rainfall received in the basin in year 2008 based on 17 stations records was about 409 M m^3, compared to the average of 663 M m^3. Hence, Year 2008 was a relatively dry year compared to the average.

1.21.2 Catchment Runoff/Infiltration

Table 9-21 Total Catchment Runoff Generated in Sana'a Basin (Year 2008) M m^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
4.4	3.1	0.7	0.1	11.8	1.9	1.7	1.2	0.2	8.3	8.2	5.7	47.2

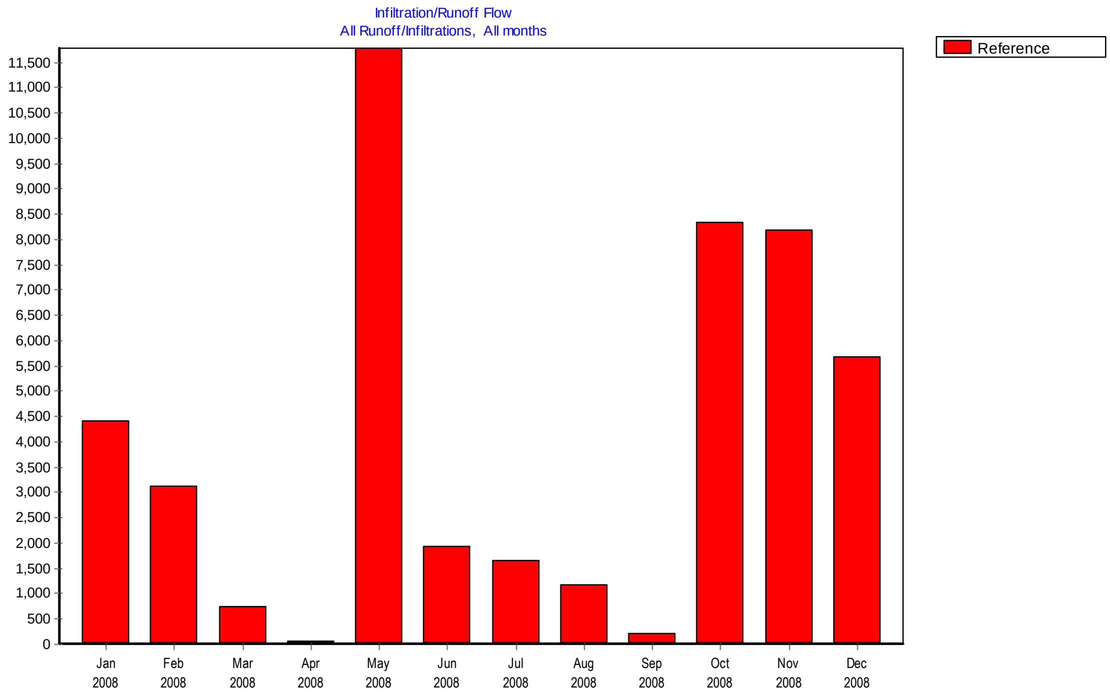


Figure 9-15 Total Catchment Runoff/Infiltration Generated in Sana'a Basin (Year 2008)

The total annual runoff in 2008, including infiltration to the GW, was about 47.2 M m^3, which is much lower than the average annual runoff of 75.4 M m^3.

1.21.3 Reservoir Inflow

Table 9-22 Total reservoir inflow in all dam sites in Sana'a Basin (M m^3) Year 2008

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0.1	0.1	0.0	0.0	1.4	0.1	0.2	0.2	0.0	0.8	0.2	0.1	3.3

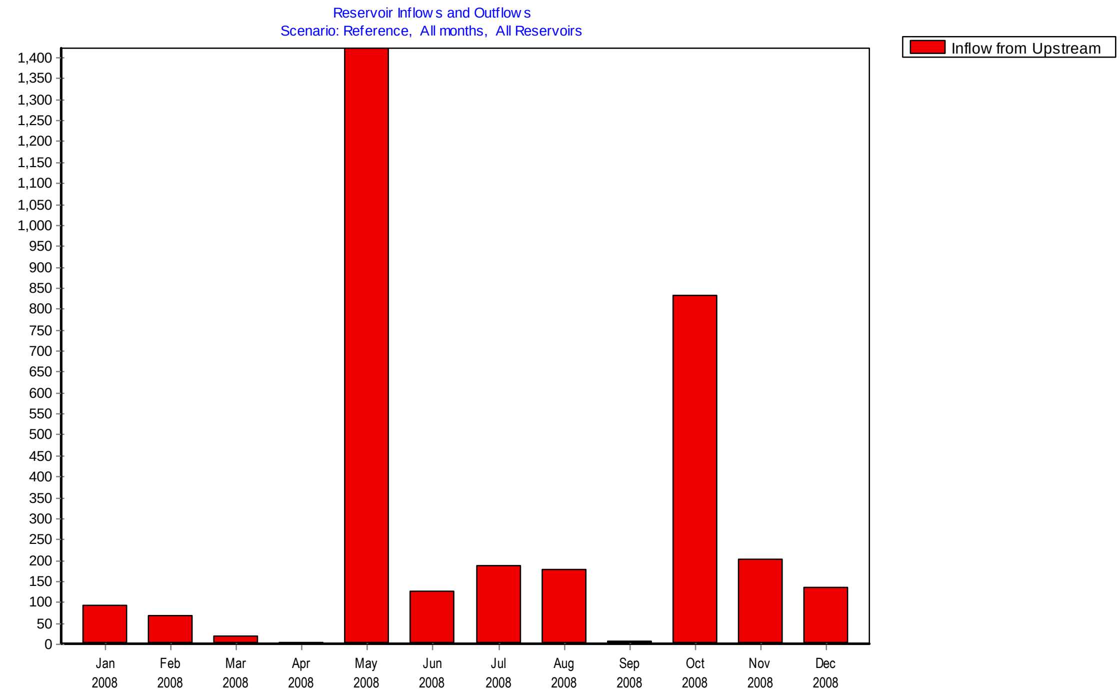


Figure 9-16 Total reservoir inflow at all dam sites in Sana'a Basin (M m^3). Year 2008

The total reservoir inflow in Sana'a Basin in Year 2008 was 3.3 M m^3, as compared to the average 8.8 M m^3.

1.21.4 Recharge

Table 9-23 Groundwater recharge in Year 2008 (All sources), M m^3

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Reservoir	3.9	2.8	0.7	0.0	6.0	1.6	1.0	0.8	0.2	4.8	7.1	5.0	33.8
Direct rainfall and Wadi runoff	0.0	0.1	0.1	0.0	0.0	0.9	0.1	0.1	0.1	0.0	0.7	0.2	2.1
Return flow	1.5	1.1	0.3	0.0	2.5	1.0	0.7	0.4	0.1	1.9	2.3	1.8	13.8
Total	5.4	4.0	1.0	0.1	8.5	3.5	1.7	1.3	0.3	6.7	10.1	7.0	49.8

The total amount of groundwater recharge from all sources – direct rainfall, wadi runoff, reservoir and return flow from irrigation – was 49.8 M m^3, most of which comes from Wadi Runoff.

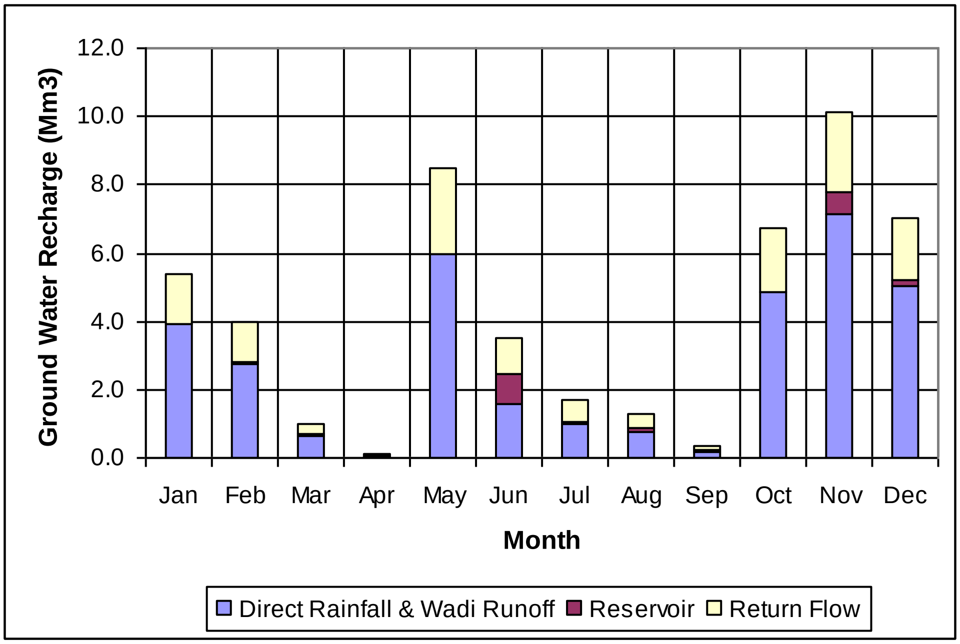


Figure 9-17 Groundwater Recharge in Sana'a Basin (Year 2008)

1.21.5 Water Balance

The total annual water demand in Sana'a Basin for the 2008 is 276.6 M m^3.

Table 9-24 Annual total water demand in year 2008, M m^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
15.1	16.4	22.4	23.1	30.8	34.0	30.7	28.9	25.8	21.2	14.6	13.7	276.6

Table 9-25 Water supply delivered from replenishable water sources. M m^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
5.5	4.2	1.2	0.1	9.2	4.2	2.1	1.5	0.4	6.9	8.7	6.6	50.5

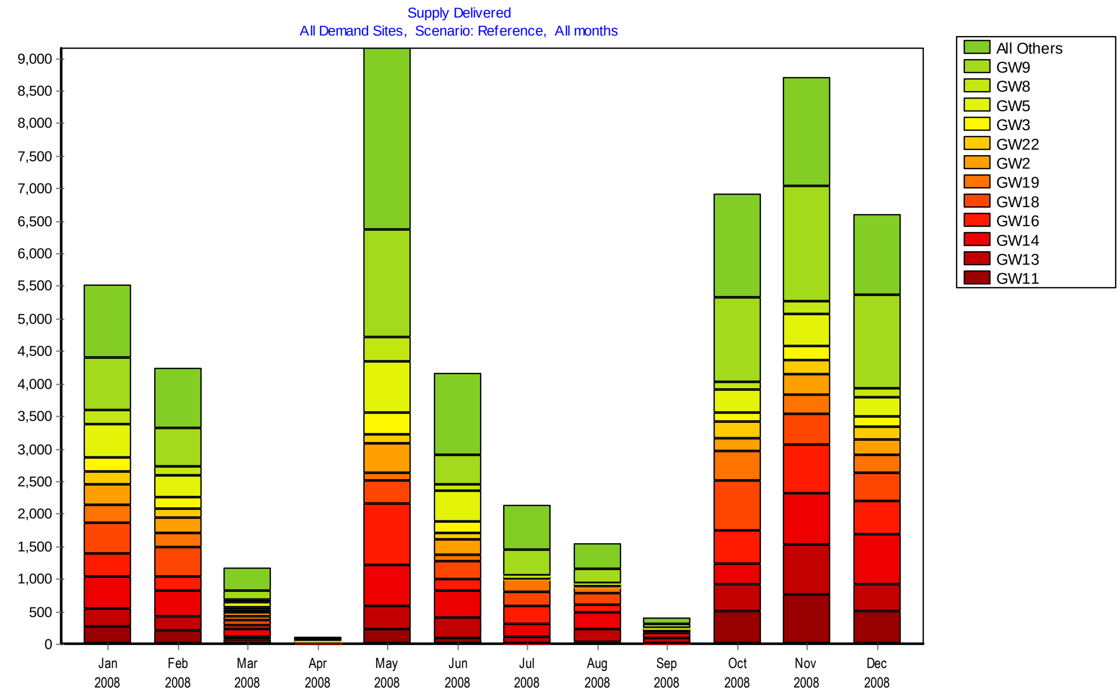


Figure 9-18 Water supply delivered to demand sites from replenishable resources. Year 2008

Water supply delivered –the total annual water resources delivered from groundwater, surface water, and reservoirs – is 50.5 M m^3, rather than 86.8 M m^3 for average rainfall condition.

1.21.6 Unmet demand

This is the unmet demand from the natural recharge and surface water resources or water withdrawn from the aquifer to satisfy water supply and irrigation water demands.

Table 9-26 Year 2008 Modeled Unmet Demand or Water abstracted from Aquifer (M m^3)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
9.6	12.2	21.2	23.0	21.7	29.9	28.5	27.4	25.4	14.3	6.0	7.1	226.3

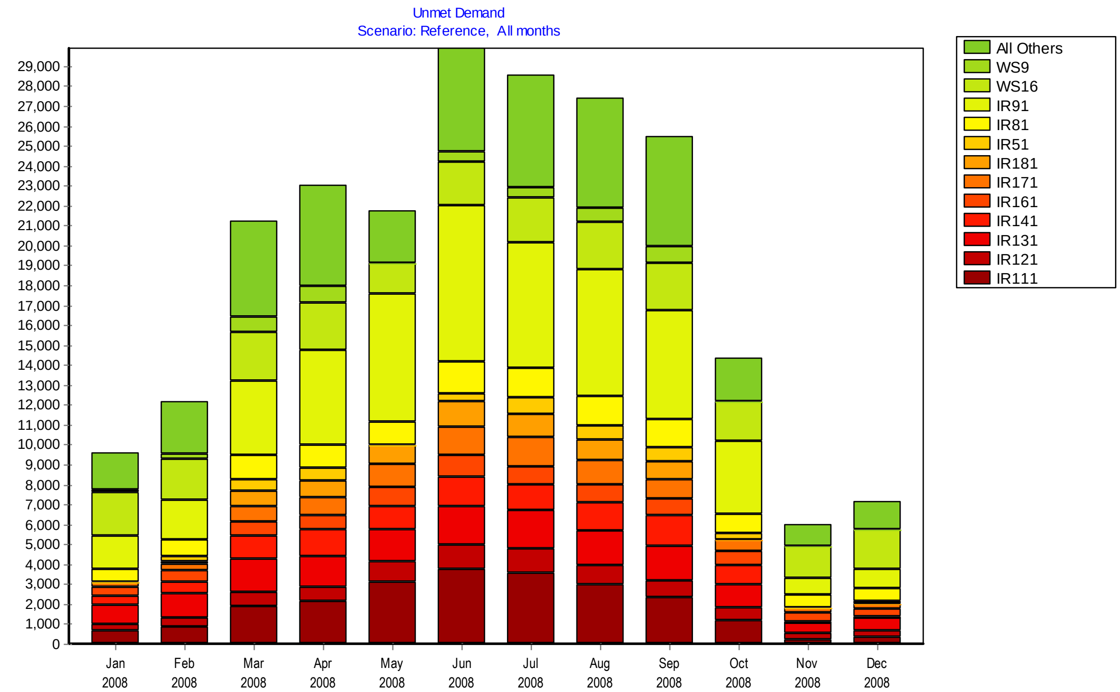


Figure 9-19 Unmet demand or water supplied from non-replenishable aquifer. Year 2008

The year 2008 water demand from the aquifer is 229 M m^3, which is higher than the average of 192.7 M m^3.

Chapter 10. CONCLUSION AND RECOMMENDATION

1.22 Conclusions

The following major tasks are performed in order to accomplish the main objectives of Activity 2, Water Balance Estimation and Sub-basin Monitoring:

- Selection of 4 experimental sub-basins and data collection and monitoring;
- Field water balance study at three farms: two modern irrigation farms (Ghadran and Al Hinami) and one traditional farm (Luluah);
- Reservoir monitoring and water balance at six reservoirs;
- Sub-basin water balance for the 22 sub-basins in Sana'a Basin;
- Overall comprehensive water balance modeling using Water Evaluation and Planning (WEAP) model;
- In addition to the data collection and monitoring under study, a lot of data, information and knowledge from previous studies such as WEC (2004), SAWAS (1996), WRAY (1995), HWC (1992), GAF (2007) are inputs to this study.
- Water balance is evaluated under average (long term), Year 2007, and Year 2008 situations.

The hydrological study has been made to estimate water balance components: (1) from three irrigation fields (Al-Hinami, Ghadran, and Luluah) through measurement of soil moisture, (2) from six reservoirs through measurements of inflow flood volume, (3) from 22 sub-basin in the Sana'a Basin using the rainfall-runoff model, (4) using comprehensive basin wide hydrological model based on the WEAP program.

Reservoir Water Balance

Reservoir water balance components for six dams (Methbel, Mekhtan, Mussaibih, Khalaqa, Arisha, and Al-Hayathem) are estimated based on measured reservoir water level using staff gauge. Stored water between flash floods are estimated from reservoir water level readings and converted to volume of flood using depth (elevation)–volume curves developed for each dam. Reservoir evaporation is estimated from GAF (2007) potential evapotranspiration data with a multiplication factor of 1.2 to account for open water evaporation rate. Estimate of leakage and direct water abstraction from reservoir are also made. The remaining terms become recharge to the aquifer due to the impoundment of water in the reservoir.

Table 10-1 Summary of the six-reservoir water balances (year 2007-2008)

Elements	Dams					
	Al- Hayathem	Arisha	Khalaqa	Methbel	Mekhtan	Mussaibih
Dam catchment area (km^2)	33.2	6.5	5.5	32.6	5.6	3.6
Reservoir area geology	Limestone	Sandstone	Sandstone (foundation cutoff wall provided)	Tertiary volcanic	Volcanic	Volcanic (foundation cutoff wall provided)
Total balance days	238	189	513	105	513	602
Annual rainfall (mm)	192	221	221	192	221	221
Total measured volume of runoff; balance period (m^3)	439380	197448	203822	9864	122210	44344
Reservoir Evaporation (m^3)	65561	4000	48712	1272	47845	19275
Release (m^3)	88373	122959	65400	1775	11863	2757
Recharge (m^3)	285447	70489	89710	6817	62502	22832
Average reservoir pool area (m^2)	52698	3925	16762	1512	15846	6547

Elements	Dams					
	Al- Hayathem	Arisha	Khalaqa	Methbel	Mekhtan	Mussaibih
Mean recharge (mm/day)	19	79	9	36	6	5

The reservoirs have different recharging rates depending on the permeability of the reservoir area. Seasonal reservoirs are more effective for recharge than those retaining water for longer period. The major conclusions from this task are:

- Before dam construction, detailed geology of the reservoir area should be examined;
- Reservoir sedimentation study should be conducted to identify the amount and type of sediment to be deposited;
- Recharge area of the reservoir and downstream effect due to dam construction should be assessed;
- Based on geology of the reservoir area, dams should be classified as recharge or direct-use type;
- Reservoir area watertightness is not required for recharge dams;
- Dams and reservoirs should be small enough to be seasonal storage for recharge dams.

Field Water Balance

The field water balance study is conducted in three farms (Ghadran, Al Hinami) located in Wadi as Sirr sub-basin using a drip irrigation system and Luluah farm using furrow irrigation in Wadi Zahr sub-basin.

From the field water balance study conducted, the computed irrigation efficiency at Luluah farm (traditional irrigation farm) is about 56%. Because Furrow irrigation is used, the water loss by deep percolation and non-beneficial evapotranspiration is significant. At the other farms (Al Hinami and Ghadran), where water is efficiently applied through implementation of modern irrigation techniques, no loss through deep percolation or non-beneficial evapotranspiration was observed from the applied irrigation water. Only if, after irrigation, heavy rain has fallen does deep percolation from the Ghadran and Al Hinami farms occur.

Rainfall-Runoff and Sub-basin water balance

Rainfall runoff modeling is determined with the SCS-CN method using different runoff classification zones for each sub-basin.

The average total annual runoff generated in the 22 sub-basins of Sana'a Basin is 66 M m^3, about 70% of which is estimated to be groundwater recharge, which is the main form of recharge in Sana'a Basin. Recharge from direct rainfall is found to be very low compared to wadi runoff. The results obtained are very comparable with the WEAP hydrological model.

Sana'a Basin Water Balance with the WEAP hydrological model

Water balances of Sana'a Basin are determined considering irrigation and water supply demands and recharge and water resource potential of the basin for average (long term), Year 2007, and Year 2008 conditions.

Water Demand

Using the forecast from the 2004 census, the 2010 Sana'a Basin population will be about 2.9 Million. The annual water supply demand will be 58 M m^3 for the forecasted population of about 2.9 million people.

The total irrigation water demand for 18,953.2 ha irrigated land in Sana'a Basin is 221.1 M m^3; this is equivalent to an annual demand of 11,668 m^3/ha.

Recharge

Average groundwater recharge in Sana'a Basin from all sources, Wadi runoff, Reservoirs, and Return flow, including west water discharge from Sana'a City is 78 M m^3. This is derived using the previous long records of rainfall in Sana'a Basin.

Table 10-2 Average groundwater recharge (all sources), M m^3

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Reservoir	0.1	0.3	0.9	1.6	0.6	0.2	0.4	1.2	0.1	0.1	0.1	0.1	5.5
Direct rainfall and Wadi Runoff	4.8	5.9	7.5	11.7	5.9	1.1	1.7	5.8	1.9	0.6	1.2	3.0	51.2
Return flow	1.9	2.2	2.5	3.6	2.9	1.1	1.0	2.6	1.2	0.6	0.7	1.2	21.3
Total	6.8	8.3	10.9	16.9	9.3	2.4	3.0	9.6	3.2	1.3	2.0	4.3	78.1

Comparison of averages from Year 2007 and Year 2008 reveals that recharge in Sana'a Basin depends on amount and intensity of rainfall, i.e. is the ability to generate runoff in the wadis. Recharge in Years 2007 and 2008 is estimated to be 67.8 and 49.8 M m^3 respectively, which is less than average.

Water Balance

The total annual current water demand (irrigation 221 M m^3 and water supply 58 M m^3) 279 M m^3. The average annual water resources replenishable from groundwater, surface water, and reservoirs is estimated at 86.8 M m^3 with monthly variation given below.

Table 10-3 Water supply delivered from replenishable water sources, M m^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
6.8	8.4	10.0	15.0	11.8	5.2	4.3	10.1	5.5	2.5	2.6	4.6	86.8

The average unmet water demand from replenishable water sources that is mined from groundwater aquifer is 192.7 M m^3.

Table 10-4 Unmet demand or supply delivered from non replenishable groundwater sources (mining), M m^3

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
8.5	8.2	12.6	8.3	19.3	29.1	26.6	19.0	20.6	18.9	12.2	9.3	192.7

The Annual summary of water balance results for average (long term) and Year 2007 and Year 2008 situations is shown in Table 10.1.

Table 10-5 Summary of Annual Water Balance in Sana'a Basin

Year	Rainfall (M m^3)	Recharge (M m^3)	Water Demand (M m^3)	Water Supply Delivered (SW&GW) (M m^3)	Water Balance (Mined from GW) (M m^3)
Year 2007	649	67.8	271.4	75.0	-196.4
Year 2008	408.8	49.8	273.5	50.5	-226.6
Long-term average (Year 2010)	662.9	78.1	279.5	86.8	-192.7

The long-term average uses the previous record of rainfall applied for the 2010 population water demand; the irrigation area is kept constant at the GAF estimate.

The recharge in Sana'a Basin is dependent on both the amount of and the intensity of rainfall events to generate runoff in the Wadis, which is the main form of recharge in the basin.

Water-saving from improved irrigation system

Irrigation is the largest water consumer: 221 M m^3 for 18953 ha (GAF 2007). With the traditional system of irrigation as determined at Luluah Farm (Chapter 5 Field Water Balance), the irrigation efficiency is about 56%, whereas, at the modern irrigation farms such as Al Hinami and Ghadran, no percolation is found. This indicates that irrigation efficiency is nearly 100% in terms of water application. Therefore, if vigorously pursued, irrigation water savings of about 40% could be achieved by modernizing the traditional farms.

Water savings from the applicationn of modern irrigation techniques is significant. If all existing traditionally irrigated areas are converted to modern farms, the total annual irrigation water demand will be reduced to 133 M m^3 from 221 M m^3. The total annual water balance of Sana'a Basin will be improved from -192.7 M m^3 to -114.2 M m^3.

Table 10-6 Comparison of average annual water balance with traditional and modern irrigation systems

Sub-basin	Water Balance (M m^3) Traditional System	Water Balance (M m^3) Modern System

Sub-basin	Water Balance (M m^3) Traditional System	Water Balance (M m^3) Modern System
1	-0.04	0.0
2	-2.36	-0.5
3	-1.51	-0.3
4	0.00	0.0
5	-0.18	-0.1
6	-0.77	-0.2
7	-2.57	-1.5
8	-13.24	-7.0
9	-52.20	-32.5
10	-0.52	0.0
11	-24.59	-13.6
12	-9.49	-5.7
13	-19.32	-10.7
14	-7.46	-0.9
15	-2.90	-2.1
16	-34.00	-30.4
17	-10.26	-5.9
18	-3.64	-0.2
19	-2.87	-0.6
20	-2.83	-1.4
21	-1.57	-0.5
22	-0.40	-0.1
	-192.7	-114.2

Although there will be a big improvement in water use efficiency with the modern irrigation system, the overall water balance of Sana’a Basin will continue to decline. Generally, the water resources of Sana'a Basin cannot sustain irrigation development from groundwater resources. The existing water demand of most of the sub-basins can be brought under control through the introduction of modern irrigation techniques; however, sub-basins 8, 9, 11, 12, 13, 16, and 17 cannot sustain their existing water demand.

1.23 Recommendations

Sana'a Basin is under a high water stress situation; presently the demand and water used by far exceed renewable water resources. The following recommendations are drawn from this study:

- Dam construction in the hilly highland areas will be effective to reduce water loss to the outlet and evaporation from the wide wadi beds of the flood plains. More dams with reservoirs are inundating sandstone/limestone geology. Their small height and capacity will be effective for recharge and direct use.
- The improved irrigation system is very effective in controlling water supply. However, irrigation has to be limited from dams and shallow aquifers. Farmer training for the management of irrigation systems is important.
- Pumping from deep aquifers should be limited to domestic and non-domestic water supply purposes.
- Import (produce) bottled water for Sana'a City outside Sana'a Basin will add value.
- Discourage Qat chewing and production or import.
- Water resource planning and delivery from Sana'a Basin should not exceed 100 M m^3.
- Hydro-meteorological data monitoring should be continued to update water resource information, especially groundwater recharge in the basin.
- Training of young engineers in hydrometeorological data collection and analysis should be given importance.

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ANNEX A RAINFALL DATA IN 2006-2007

Table-A 1 Arhab Rainfall in 2006/2007 season

Station:	ARHAB-A										
Element:	Daily Rainfall										
Year:	2006-07										
	2006						2007				
Date	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
1	0	0	0	0	0	0	0	0	0	4	0	
2	0	2		0	0	0	0	0	0	0	0	
3	0	0	0	0	0	0	0	0	0	0	0	
4	0	0	0	0	0	0	0	0	0	0	0	
5	0	0	0	0	0	0	0	0	0	2	0	
6	0	0	0	0	0	0	0	0	0	0	0	
7	0	0	0	0	0	0	0	5	0	1	0	
8	0	30	0	0	0	0	0	2	0		0	
9	0	36	0	0	0		0	0	0		0	
10	0	0	0	0	0	0	0	0	0		0	
11	0	24	0	0	0	0	0	0	0		0	
12		0	0	0	0	0	0	0	0		0	
13	0	0	0	0	0	0	0	2	0			
14	0	0	0	0	0	0	0	0	0			
15	0	0	0	0	0	0		0	0	0		
16	0	0	0	0	0	0	0	0	0	0		
17	0	28	0	0	0	0	0	0	0	0		
18	4	0	0	0	0	0	0	0	0	0		

19	0	0	0	0	0	0	0	0	0	0		
20	0	0	0	0	0	0	0	2	0	0		
21	0	8	0	0	0	0	0	0	0	0		
22	0	0	0	0	0	0	0	0	0	0		
23	0	0	0	0	0	0	0	0	0	0		
24	0	0	0	0	0	0	0	0	0	0		
25	0	0	0	0	0	0	0	0	0	0		
26	0	0	0	0	0	0	0	0	0	0		
27	0	0	0	0	0	0	0	0	0	0		
28	48	0	0	0	0	0	0	0	0	0		
29	0	0	0	0	0	0	0		1	0		
30	2	0	0	0	0	0	0		0	0		
31	2	2		0		0	0		0			
Total	56	130	0	0	0	0	0	11	1	7	0	

Table-A 2 Shahik Rainfall in 2006/2007 season

Station:	Shahik											
Element:	Daily Rainfall											
Year:	2006-07											
	2006						2007					
Date	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
1	0	0.25	0.5	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	16.25	0	0	0	0	0	0
3	0	0.5	0.75	0	0	0	0	0	0	0	0	0
4	3	0.25	0	0	0	0	0	0	0	0	0	0
5	0	0	1.75	0	0	0	0	0	0	0	0	0
6	0	0	0.5	0	0	1.5	0	1	0	0	0	0
7	0	0	0	0	2.75	7	0	0	0	5.25	0	0
8	0	5.5	0	0	0	0	0	0	0	0	0	0
9	0	4.25	0	0	0	0	0	0	0	1	0	0
10	0	1.25	0	0	0	0	0	0	0	0	0	0
11	2.5	1.75	0	0	0	0	0	0	0	0	0	0
12	1	0.25	0	0	0	0	0	13	0	0	0	0
13	9.5	0	0	0	0	0	0	0	0	0	0	0
14	0	0.5	0	0	0	0	0	0	0	7.75	0	0
15	0	1	0	0	0	0	0	0	0	11	0	0
16	0	2.25	0	0	0	0	0	0	0	0	7	0
17	0	0	0	0	0	0	0	0	0	0	0	0
18	1	0	0	0	0	0	0		0	0	0	0
19	0.25	0	0	0	0	0	0		0	0	2.25	0

20	0	0	0	0	0	0	0		0.25	0	1.5	
21	0	0	0	0	0	0	0	0	0	0	0	
22	0	0	0	0	0	0	0	0	0	0	0	
23	0	0	0	0	0	0	0	0	0	0	0	
24	0	0	0	0	0	0	0	0	0.5	0	0	
25	9.75	0	0	0	0	0	0	0	0	0	0	
26	0.5	0	0	0	0	0	0	0	0.25	0	0	
27	10.5	0	0.5	0	0	0	0	0	0	0	0	
28	35.75	0	0	0	0	0	0	0	0.25	0	22.5	
29	0	0	0	0	1.5	0	0		0.25	0	0	
30	8	9.25	0	0	0	0	0		0	0	0	
31	0	4		0		0	0		0		0	
Total	81.8	31.0	4.0	0.0	4.3	24.8	0.0	14.0	1.5	25.0	33.3	0.0

Table-A 3 Darsalm Rainfall in 2006/2007 season

Station:	Darsalm											
Element:	Daily Rainfall											
Year:	2006 - 07											
	2006						2007					
Date	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
1	0	1.75	0.5		0	0	0	0	0	0	0	0.5
2	0	0	0		0	0	0	0	0	0	0	0
3	0	1.25	0		0	0	0	0	0	0	0	0
4	0	0			0	0	0	0	0	0	0	0
5	1.75	0			0	0	0	0	0	0	0	0
6	0.5	0			0	0	0	1.5	0	0	0	0
7	0	0.25			0	0.25	0	0	0	0	0	0
8	0	33			0	0.25	0	0	0	0	0	0
9	0	10.25			0	1	0	0	0	0	0	0
10	0	15.75			0	2.25	0	0	0	0	0	0
11	1	10			0	0	0	0	0	0	0	0
12	0	1.5			0	0	0	0	0	5	0	0
13	2.5	0			0	0	0	0	0	0	0	0
14	0	23.25			0	0	0	0	0	0	0	0
15	0	1.75			0	0	0	0	0	4.75	0	0
16	0	0.75			0	0	0	0	0	6.75	42.5	0
17	0.75	0			0	0	0	0	0	0	0	0.75
18	0.5	0			0	0	0	0	0	0	3	0
19	9.25	0.25			0	0	0	0	0	0	0	0

20	0.25	1.5			0	0	0	0	0	0	0	
21	0	0.5			1	0	0		0	0	0	
22	0	0			3.75	0	0		0	0	0	
23	0	0			0	0	0		0	0	0	
24	0	0			0	0	0		0	0	0	
25	0	2			0	0	0		0	0	0	
26	0	0.25			0	0	0	0	0	0	0	
27	1.5	0			0	0	0	0	0	0	0	
28	18.5	0			0	0	0	0	0	0	0	
29	3.75	0			0	0	0		0	0	0	
30	14.5	10		0	0	0	0		0	0	18	
31	0	0.25		0		0	0		0		0	
Total	54.75	114.25	0.5	0	4.75	3.75	0	1.5	0	16.5	63.5	1.25

xxx

Table-A 4 Sunaina Rainfall in Year 2006

Station:	Sunaina											
Element:	Daily Rainfall											
Year:	2006											
Date	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1				2.25	1.5	0	0	0	0	0	0	0
2				5.5	0	0	0	0	0	0	0	2
3				8.75	0.25	28.75	0	0.75	0	0	0	0
4				0.25	0	0	0	0	0	0	0	0
5				3.25	0	0	0	0	0	0	0	0
6				0.75	0	0	0	0	0	0	0	0
7				15.25	0	0	0	1.5	0	0	0	4.5
8				0	0	0	0	13.25	0	0	0	5.5
9				0	0	0	0	2.75	0	0	0	1.75
10				0	0	0	0	7.5	0	0	0	
11				0	0	0	0	17	0	0	0	0
12				0	0	0	2	0	0	0	0	
13				0	0	0	0.25	8	0	0	0	
14				0	0	0	0.25	1.25	0	0	0	
15				0	0	0	0	2.25	0	0	0	
16				0	0	0	0	0	0	0	0	
17				0	0.25	0	0.25	0	0	0	0	
18				15.5	0	0	0.25	0	0	0	0	
19				1	0	0	0.25		0	0	0	
20				1.5	1.25	0	0	0.5	0	0	0	

21				0	0	0	0	3	0	0	0	
22				0	1.75	0	0	0	0	0	0	
23				2	4.5	0	0	0	0	0	0	
24				1.5	0.25	0	0	0	0	0	0	
25				0	1.25	0	1	0	0	0	0	
26				0	0	0	0.25	0	0	0	0	
27				0	0	0	0.25	0	0	0	0	
28				0	0	0	0.5	0	0	0	0	
29				0.25	0	0	5.5	0	0	0	0	
30				0	0	0	12	8.5	0	0	0	
31					0		11.8	0		0		
Total				57.8	11.0	28.8	34.5	66.3	0.0	0.0	0.0	13.8

Table-A 5 WEC Station 8985 Rainfall in 2007

Station:	WEC-8985											
Element:	Daily Rainfall (mm)											
Year:	2007											
Date	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	0	0.2	0	0	0	0.2	0	0.8	0	0	0	0
2	0	0	0	0	0	0.2	0	3	0	0	0	0
3	0	0	0	0	0.4	0	0	0.2	0	0	0	0
4	0	0	0	0	0	0	0	16.2	0	0	0	0
5	0	0	0	5.4	0	0	17.8	6	0	0	0	0
6	0	4.2	0	0.8	0	0	1.6	30.4	0	0	0	0
7	0	0.2	0	7	0	0	11.2	2.8	0	0	0	0
8	0	0	0	0	0	0	3.2	0	0	0	0	0
9	0	0	0	4.6	0	0	8.4	2.4	0	0	0	0
10	0	0	0	2	0.4	0	1	0	0	0	0	0
11	0	0	0	0.4	0	0	2.6	0	0	0	0	0
12	0	0	0	0.2	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0		0	0	0	0
14	0	0	0	0	0	0	0		0	0	0	0
15	0	0	0	0.4	0	0	0		0	0	0	0
16	0	0	0	0.8	18.6	0	5.8		0	0	0	0
17	0	0	0	0	0	0	3.8		0	0	0	0
18	0	0	0	5.4	0	0	0.4		0	0	0	0
19	0	0	0	0	0	0	1.2		0	0	0	0
20	0	0	0	0	0.8	0	0		0	0	0	0

21	0	0	0	0	0	0	0		0	0	0	0
22	0	0	0	0	0	0	0		0	0	0	0
23	0	0	1.4	0	0	0	0		0	0	0	0
24	0	0	0.8	0	0	0	0		0	0	0	0
25	0	0	0.8	0	0	0	0.6		0	0	0	0
26	0	0	2.4	2.4	0.2	0.8	0.6		0	0	0	0
27	0	0	0.2	0	1	0	0.6		0	0	0	0
28	0	0	6.2	0	10.4	1.4	0		0	0	0	0
29	0		0.4	0	1.4	3.2	21.4		0	0	0	0
30	0		4.6	0	2.4	0	17.4		0	0	0	0
31	0		1.4		0		0.8			0		0
Total	0	4.6	18.2	29.4	35.6	5.8	98.4	61.8	0	0	0	0

Table-A 6 WEC Station 8986 Rainfall in 2007

Station:	WEC-8986											
Element:	Daily Rainfall (mm)											
Year:	2007											
Date	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	0	0	0	0	0	0	0.2	0	0	0	0	0
2	0	0	0	0	0	0.8	1.2	0	0	0	0	0
3	0	0	0	0	0	0	0.2	2.2	0	0	0	0
4	0	0	0	0	0	0	0	14	0	0	0	0
5	0	0	0	0.2	0	0	0.2	2.6	0	0	0	0
6	0	9.4	0	0.2	0	0	1.2	8.8	0	0	0	0
7	0	0	0	3.6	0	0	5	0.2	0	0	0	0
8	0	0	0	0.2	0	0	11	0.2	0	0	0	0
9	0	0	0	1	0	0	5.6	7.2	0	0	0	0
10	0	0	0	0.4	0.2	0	18.2	0	0	0	0	0
11	0	0	0	0	0	0	14.8	0	0	0	0	0
12	0	0	0	7	0	0	0.8	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	1	0	0	0	0	4.4	0	0	0	0
15	0	0	0	3	12.2	0	0	0	0	0	0	0
16	0	0	0	3.8	27.4	0	0	11.2	0	0	0	0
17	0	0	0	0	0	0	0.2	0	0	0	0	0
18	0	0	0	2	0	0	3.4	0	0	0	0	0
19	0	0.4	0	0	0.6	0	0.8	0	0	0	0	0
20	0	0	0	0	0.4	0	0	0	0	0	0	0

21	0	0	0	0	0.2	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0.4	0	0	0	0	0	0	0	0	0
24	0	0	2.8	0	0	0	0	0	0	0	0	0
25	0	0	6	0.8	0	0	0	0	0	0	0	0
26	0	0	1.6	3	8.2	0	0.2	0	0	0	0	0
27	0	0	0.2	0	0	0.6	0	0	0	0	0	0
28	0	0	1.6	0	1.6	13.2	0	0	0	0	0	0
29	0		0.2	0	1.2	0	15	0	0	0	0	0
30	0		2.4	0	6.6	0	15	0	0	0	0	0
31	0		3.2		0		0	0		0		0
Total	0	9.8	19.4	25.2	58.6	14.6	93	50.8	0	0	0	0

Table-A 7 WEC Station 8987 Rainfall in 2007

Station:	WEC-8987											
Element:	Daily Rainfall (mm)											
Year:	2007											
Date	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	0	0	0	0	0	0.6	0	0.2	0	0	0	0
2	0	0	0	0	0	0	0	2.2	0	0	0	0
3	0	0	0	0	0	0	0	0.2	0	0	0	0
4	0	0	0	0	0	0	0	9.8	0	0	0	0
5	0	0	0	3.8	0	0	0.8	7.6	0	0	0	0
6	0	7.4	0	0.4	0	0	1.2	1.6	0	0	0	0
7	0	4.6	0	8	0	0	8.4	0.4	0	0	0	0
8	0	0.2	0	0.2	0	0	1.6	0	0	0	0	0
9	0	0	0	0.4	0	0	0	1.6	0	0	0	0
10	0	0	0	1.6	0	0	3	0	0	0	0	0
11	0	0	0	1	0	0	6.6	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0.4	0	0	0	0	0
15	0	0	0	3.6	0	0	0	0	0	0	0	0
16	0	0	0	1.4	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	1.4	0.6	0	0	0	0	0	0	0
19	0	0	0	0	1.2	0	1	0	0	0	0	0
20	0	0	0	0	0.2	0	0	0	0	0	0	0

21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	1.2	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0.4	0	0	0	0	0	0	0	0	0
26	0	0	3.6	0	0	0	0.4	0	0	0	0	0
27	0	0.2	0	0	0	0.6	0.6	0	0	0	0	0
28	0	0	5	0	4	0.8	0	0	0	0	0	0
29	0		0.2	0	0.4	0	8.6	0	0	0	0	0
30	0		0.6	0	5.2	0	1.6	0	0	0	0	0
31	0		0.2		0		0.2	0		0		0
Total	0	12.4	11.2	21.8	11.6	2	34.4	23.6	0	0	0	0

Table-A 8 WEC Station 8988 Rainfall in 2007

Station:	WEC-8988											
Element:	Daily Rainfall (mm)											
Year:	2007											
Date	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	-	-	0	0.2	0	0.4	0	0	0	0	0	0
2	-	-	0	0	0	0	0	2.2	0	0	0	0
3	-	-	0	0	0	0	0	0	0	0	0	0
4	-	-	0	0	0	0	0	8	0	0	0	0
5	-	-	0	0.6	0	0	0	9.4	0	0	0	0
6	-	-	0	0.4	0	0	0	10.4	0	0	0	0
7	-	-	0.2	4.6	0	0	0	3.2	0	0	0	0
8	-	-	0	0	0	0	0	0	0	0	0	0
9	-	-	0	4.4	0	0	0	1.2	0	0	0	0
10	-	-	0	5.6	0	4.8	0	0	0	0	0	0
11	-	0	0	0.2	0	0	0	0	0	0	0	0
12	-	1	0	0	0	0	0	0	0	0	0	0
13	-	0.4	0	0	0	0	0	0	0	0	0	0
14	-	0	0	0	0	0	0	0.6	0	0	0	0
15	-	0	0	1.6	0	0	0	0	0	0	0	0
16	-	0	0	2.8	0	0	0	7.8	0	0	0	0
17	-	2	0	0	0	0	0	1	0	0	0	0
18	-	0	0	1.6	0.2	0	0.8	0	0	0	0	0
19	-	0.2	0	0	0	0	0.2	0	0	0	0	0
20	-	0	0	1	0.8	0	0	0	0	0	0	0

21	-	0	0	0.2	0	0	1.6	0	0	0	0	0
22	-	0	0	0	0	0	0	0	0	0	0	0
23	-	0	1.2	0	0	0	0	0	0	0	0	0
24	-	0	4	0	0	0	0	0	0	0	0	0
25	-	0	2.4	0	0	0	0	0	0	0	0	0
26	-	0	2.4	0	0	0	1.2	0.4	0	0	0	0
27	-	0	0.2	0	0	0	0.6	0	0	0	0	0
28	-	0	7.6	0	10	0	0	2.6	0	0	0	0
29	-		0.2	0	0.8	0	9.4	0	0	0	0	0
30	-		0.4	0	2.8	0	2.6	0	0	0	0	0
31	-		0		0		0	0		0		0
Total		18.6	23.2	14.6	14.6	5.2	16.4	46.8	0	0	0	0

ANNEX B SCS MODEL

xxxOnly part of the rainfall will contribute directly to runoff (i.e. will be effective). The process of evaporation or percolation to groundwater will lose the rainfall remaining. In wet or less dry regions, some of these losses subsequently return to the river as baseflow. Losses are generally divided into two parts:

- Initial losses (interception by plants, filling the small depressions over the ground surface and covering the soil moisture deficit),
- Continuing loses (infiltration/percolation).

Both the initial and the continuing losses are very dependent on the soil structure, soil texture and its permeability. Land development and land use also play an important role in producing runoff, as does the slope of the land. For example, tillage or contour terracing will play a role in decreasing runoff, etc.

Taking these issues into consideration, some empirical methods have been to correlate the runoff with precipitation and soil types. The most common procedure is the SCS (US Soil Conservation Service) method. This method estimates the initial losses based on a curve number, which relies on land use, soil type, hydrologic condition and land development (if applicable, e.g. terraced). A high curve number yields low losses and hence highly effective rainfall and runoff.

The empirical method of the USA Soil Conservation method (SCS) was derived in 1972 and also known as the surface runoff curve number method. This method is widely applied in the USA and many other countries. It was developed for computing abstractions from storm rainfall. For the storm as a whole, the depth of excess precipitation (i.e. effective precipitation Pe) or direct runoff is always less than or equal to the depth of precipitation P.

The SCS method uses three variables in estimating runoff (Q). They are

- Rainfall (P),
- Antecedent moisture conditions, and
- Hydrologic soil cover complex.

There are many interrelated factors that influence infiltration volumes and rainfall excess. In general terms, these are climatic and watershed related. Infiltration, and thus rainfall excess, will vary during a storm event. One empirical description for infiltration and rainfall excess is the curve number method. At the start of precipitation, the intensity of rainfall is usually less than the rate at which water is stored. As depression storage becomes filled, and the soils vegetative cover becomes saturated, rainfall excess increases. When soil, depression area, and vegetation storage approach ultimate saturation, storage will approach a potential saturation value (S') and the infiltration rate approaches zero. Then the rainfall excess rate will equal the precipitation rate. Rainfall excess (R) and watershed storage (S) are derived from precipitation and soil type. A possible relationship over time is shown and rainfall excess (R) is expressed as:

$$\mathbf{R = P - S}$$

where

R	=	Rainfall excess
P	=	Rainfall Volume
S	=	Storage Volume on and within the soil (initial abstraction plus infiltration)

At saturation, the rate of rainfall excess is equal to the intensity of precipitation. A proportional relationship can be developed as:

$$\frac{S}{S'} = \frac{R}{P}$$

where

S	=	Storage at any time (mm)
S'	=	Storage at saturation (mm)
R	=	Rainfall excess at any time (mm)
P	=	Precipitation at any time (mm)

The infiltration as a continuous loss, initial losses and the resultant rainfall excess are tightly relevant to soil moisture content. When the soil has a moisture deficit, then some of the precipitation will be lost in order to cover this deficit before runoff begins.

The initial abstraction (Ia) is the total loss of rainfall occurring before the start of runoff (i.e. before ponding). This value covers the interception, the filling of surface depressions, filling of soil moisture deficit and sometimes, in hot climates, the evaporation may occur before runoff. In addition, each soil type might have a potential moisture retention (S'). Then the total losses (S) can be given by the summation of (Ia) and (S'):

$$S = \frac{25400}{CN} - 254$$

in millimeters and the initial abstraction Ia is usually approximated as:

Ia = 0.2 * S

For finding the suitable CNs for the dry condition (AMC class I) and for the wet condition (AMC class III), the following equations can be applied:

$$CN(I) = \frac{4.2 * CN(II)}{10 - 0.058 * CN(II)}$$

and

$$CN(III) = \frac{23 * CN(II)}{10 + 0.13 * CN(II)}$$

The formula applied by the SCS method for computing the runoff from precipitation is as follows:

$$\mathbf{Q = \frac{(P - 0.2 * S)^2}{P + 0.8 * S}}$$

where

P	is the storm rainfall sum	[mm]

S	is total loss of rainfall depending on soil type	[mm]
0.2 * S	is the initial abstraction	[mm]
Q	is the storm runoff	[mm]

ANNEX C SIX DAM WATER BALANCE CALCULATIONS

Al-Hayathem Dam Water Balance Estimate									368	m3/day					
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. Eva-poration loss between flood events (m3)	Cum. Irrigation (m3)	Cum. Recharge (m3)	Date	Stored Water Volume (M3)	Cum. Evaporation (m3)	Cum. Release (M3)	Cum. Recharge (M3)
28/05/2007		0.00	0	0		28/05/2007	0	0			09/06/2007	178623	0	0	0
09/06/2007	12.0	5.70	178623	69730	6426	09/06/2007	178623	16916	13255.9	20526	09/07/2007	127925	16916	13256	20526
24/06/2007	15.0	5.50	165070	67173	7738	24/06/2007					09/07/2007	158515	0	0	0
01/07/2007	7.0	5.30	152107	64534	3144	01/07/2007					29/07/2007	77350	7685	7364	66115
09/07/2007	8.0	4.90	127925	58961	3283	09/07/2007					29/07/2007	290554	0	0	0
15/07/2007	6.0	5.40	158515	65865	2751	15/07/2007	158515	7685	7364.38	66115	07/08/2007	272691	4494	2946	10423
29/07/2007	14.0	3.90	77350	43734	4261	29/07/2007					07/08/2007	290554	0	0	0
04/08/2007	6.0	7.10	290554	89717	3424	04/08/2007	290554	4494	2945.75	10423	17/12/2007	17714	33376	54496	18496 9
07/08/2007	3.0	6.90	272691	86021	1641	07/08/2007					17/12/2007	42108	0	0	0
12/08/2007	5.0	7.10	290554	89717	2853	12/08/2007	290554	33376	54496.4	184969	04/02/2008	28490	3089.8 0	10310. 14	3414.3 0
14/08/2007	2.0	6.75	259711	83571	1063	14/08/2007					04/02/2008	0	0	0	0
16/08/2007	2.0	6.76	260566	83727	1065	16/08/2007					Sum	439380	65561	88373	28544 7
18/08/2007	2.0	6.56	243778	80758	1027	18/08/2007									

Al-Hayathem Dam Water Balance Estimate									368	m3/day					
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. Eva-poration loss between flood events (m3)	Cum. Irrigation (m3)	Cum. Recharge (m3)	Date	Stored Water Volume (M3)	Cum. Evaporation (m3)	Cum. Release (M3)	Cum. Recharge (M3)
20/08/2007	2.0	6.58	245429	81041	1031	20/08/2007									
22/08/2007	2.0	6.38	229203	78305	996	22/08/2007									
25/08/2007	3.0	6.17	212832	75601	1442	25/08/2007									
27/08/2007	2.0	6.14	210548	75224	957	27/08/2007									
29/08/2007	2.0	6.30	222887	77260	983	29/08/2007									
03/09/2007	5.0	5.60	171772	68460	2136	03/09/2007									
10/09/2007	7.0	5.24	148332	63724	2783	10/09/2007									
17/09/2007	7.0	4.77	120560	57066	2493	17/09/2007									
24/09/2007	7.0	4.35	98394	50718	2215	24/09/2007									
01/10/2007	7.0	3.91	77788	43889	1585	01/10/2007									
22/10/2007	21.0	3.50	60937	37633	4078	22/10/2007									
29/10/2007	7.0	3.30	53523	34702	1253	29/10/2007									
05/11/2007	7.0	3.06	45312	31342	1132	05/11/2007									
12/11/2007	7.0	2.80	37248	27935	1009	12/11/2007									
19/11/2007	7.0	2.55	30297	24915	900	19/11/2007									
26/11/2007	7.0	2.35	25294	22686	819	26/11/2007									

Al-Hayathem Dam Water Balance Estimate									368	m3/day					
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. Eva-poration loss between flood events (m3)	Cum. Irrigation (m3)	Cum. Recharge (m3)	Date	Stored Water Volume (M3)	Cum. Evaporation (m3)	Cum. Release (M3)	Cum. Recharge (M3)
03/12/2007	7.0	2.15	20781	20613	537	03/12/2007									
10/12/2007	7.0	2.00	17714	19150	499	10/12/2007									
17/12/2007	7.0	2.00	17714	19150	499	17/12/2007									
07/01/2008	21.0	2.96	42108	30001	2873	07/01/2008	42108	3089.80	10310.1	3414					
14/01/2008	7.0	2.75	35795	27310	872	14/01/2008									
21/01/2008	7.0	2.48	28490	24116	770	21/01/2008									
04/02/2008	14.0	2.35	25294	22686	1448	04/02/2008									

Arisha Dam Water Balance Estimate											658	m3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation	Cum. Release (m3)	Cum. Recharge (m3)
28/05/2007		0.00	0	0		28/05/2007					09/07/2007	51573	0	0	0
9/06/2007	12.0	2.50	51573	4427	408	09/06/2007	51573	1546	40767	8199	04/08/2007	1060	1546	40767	8199
24/06/2007	15.0	1.86	27411	3244	374	24/06/2007					04/08/2007	131435	0	0	0
1/07/2007	7.0	1.68	21925	2900	141	01/07/2007					16/08/2007	111521	684	10521	8710
9/07/2007	8.0	1.54	18054	2627	146	09/07/2007					16/08/2007	127321	0	0	0
15/07/2007	6.0	1.27	11563	2089	87	15/07/2007					03/12/2007	300	1769	71671	53580
29/07/2007	14.0	0.60	1060	4000	390	29/07/2007					03/12/2007	0	0	0	0
4/08/2007	6.0	3.92	131435	6938	265	04/08/2007	131435	684	10521	8710	Sum	197448	4000	122959	70489
7/08/2007	3.0	3.83	125289	6779	129	07/08/2007									
12/08/2007	5.0	3.70	116671	6551	208	12/08/2007									
14/08/2007	2.0	3.62	111521	6411	82	14/08/2007									
16/08/2007	2.0	3.86	127321	6832	87	16/08/2007	127321	1769	71671	53580					
18/08/2007	2.0	3.69	116021	6534	83	18/08/2007									
20/08/2007	2.0	3.61	110886	6393	81	20/08/2007									
22/08/2007	2.0	3.53	105866	6253	80	22/08/2007									

25/08/2007	3.0	3.41	98555	6042	115	25/08/2007										
27/08/2007	2.0	3.34	94411	5919	75	27/08/2007										
29/08/2007	2.0	3.26	89783	5779	74	29/08/2007										
3/09/2007	5.0	3.05	78186	5409	172	03/09/2007										
10/09/2007	7.0	2.79	64928	4947	216	10/09/2007										
17/09/2007	7.0	2.50	51573	4427	193	17/09/2007										
24/09/2007	7.0	2.34	44848	4136	181	24/09/2007										
1/10/2007	7.0	1.98	31386	3471	152	01/10/2007										
22/10/2007	21.0	1.25	11134	2049	222	22/10/2007										
29/10/2007	7.0	1.00	6352	1532	55	29/10/2007										
5/11/2007	7.0	0.79	3180	1083	39	05/11/2007										
12/11/2007	7.0	0.58	3000	619	20	12/11/2007										
19/11/2007	7.0	0.40	2000	209	7	19/11/2007										
26/11/2007	7.0	0.25	1000	100	3	26/11/2007										

Khalaqa Dam Water Balance Estimate											150	m3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events (m3)	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
28/05/2007		7.56	77990	20534		28/05/2007					04/08/2007	141730	0	0	0
09/06/2007	12.0	7.45	75877	20165	1858	09/06/2007					05/05/2008	2730	30018	41250	67732
24/06/2007	15.0	7.61	79080	20723	2387	24/06/2007					05/05/2008	94902	0	0	0
01/07/2007	7.0	7.50	76783	20324	1093	01/07/2007					13/10/2008	30080	18694	24150	21978
09/07/2007	8.0	7.25	71889	19454	1195	09/07/2007									
15/07/2007	6.0	7.20	71023	19298	889	15/07/2007						203822	48712	65400	89710
29/07/2007	14.0	6.64	60771	17386	1869	29/07/2007									
04/08/2007	6.0	10.09	141730	29532	1361	04/08/2007	141730	30018	41250	67732					
07/08/2007	3.0	9.86	134894	28761	663	07/08/2007									
12/08/2007	5.0	9.65	128682	28021	1076	12/08/2007									
14/08/2007	2.0	9.53	125205	27591	424	14/08/2007									
16/08/2007	2.0	9.45	123177	27334	420	16/08/2007									
18/08/2007	2.0	9.30	118819	26769	411	18/08/2007									
20/08/2007	2.0	9.18	115774	26363	405	20/08/2007									
22/08/2007	2.0	9.05	112191	25873	397	22/08/2007									

Khalaqa Dam Water Balance Estimate											150	m3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events (m3)	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
25/08/2007	3.0	8.88	107881	25267	582	25/08/2007									
27/08/2007	2.0	8.66	102462	24477	376	27/08/2007									
29/08/2007	2.0	8.58	100589	24198	372	29/08/2007									
03/09/2007	5.0	8.32	94377	23244	893	03/09/2007									
10/09/2007	7.0	8.01	87438	22131	1190	10/09/2007									
17/09/2007	7.0	7.73	81423	21125	1136	17/09/2007									
24/09/2007	7.0	7.70	80762	21013	1130	24/09/2007									
01/10/2007	7.0	7.27	72325	19533	1050	01/10/2007									
22/10/2007	21.0	6.66	61161	17461	2816	22/10/2007									
29/10/2007	7.0	6.50	58465	16942	911	29/10/2007									
05/11/2007	7.0	6.32	55480	16358	879	05/11/2007									
12/11/2007	7.0	6.12	52382	15743	846	12/11/2007									
19/11/2007	7.0	6.01	50703	15406	828	19/11/2007									
26/11/2007	7.0	5.92	49329	15128	813	26/11/2007									
03/12/2007	7.0	5.68	45802	14406	774	03/12/2007									
10/12/2007	7.0	5.50	43246	13876	746	10/12/2007									

Khalaqa Dam Water Balance Estimate											150	m3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events (m3)	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
17/12/2007	7.0	5.45	42621	13745	739	17/12/2007									
31/12/2007	14.0	5.25	39875	13168	1416	31/12/2007									
07/01/2008	7.0	5.09	37814	12730	684	07/01/2008									
14/01/2008	7.0	5.09	37814	12730	684	14/01/2008									
21/01/2008	7.0	4.68	32799	11650	626	21/01/2008									
04/02/2008	14.0	4.25	27925	10581	1138	04/02/2008									
11/02/2008	7.0	3.95	24822	9891	532	11/02/2008									
18/02/2008	7.0	3.82	23449	9584	515	18/02/2008									
25/02/2008	7.0	3.49	20257	8864	477	25/02/2008									
03/03/2008	7.0	3.40	19460	8683	467	03/03/2008									
10/03/2008	7.0	2.95	15473	7769	418	10/03/2008									
17/03/2008	7.0	2.89	15017	7663	412	17/03/2008									
24/03/2008	7.0	2.48	11739	6897	371	24/03/2008									
31/03/2008	7.0	3.27	18308	8420	453	31/03/2008									
10/04/2008	10.0	1.77	6583	5653	434	10/04/2008									
14/04/2008	4.0	1.56	5142	5293	163	14/04/2008									

Khalaqa Dam Water Balance Estimate											150	m3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events (m3)	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
21/04/2008	7.0	1.40	4097	5026	270	21/04/2008									
24/04/2008	3.0	1.29	3365	4837	111	24/04/2008									
28/04/2008	4.0	1.25	3104	4769	147	28/04/2008									
01/05/2008	3.0	1.19	2730	4671	108	01/05/2008									
05/05/2008	4.0	8.34	94902	23326	717	05/05/2008	94902	18694	24150	21978					
07/05/2008	2.0	8.25	92815	22997	353	07/05/2008									
11/05/2008	4.0	8.03	87936	22212	682	11/05/2008									
14/05/2008	3.0	7.84	83813	21529	496	14/05/2008									
18/05/2008	4.0	7.68	80386	20948	644	18/05/2008									
21/05/2008	3.0	7.55	77880	20515	473	21/05/2008									
26/05/2008	5.0	7.34	73555	19753	759	26/05/2008									
29/05/2008	3.0	7.20	70937	19282	444	29/05/2008									
01/06/2008	3.0	7.30	72851	19627	452	01/06/2008									
05/06/2008	4.0	7.15	69992	19110	587	05/06/2008									
08/06/2008	3.0	7.04	67877	18723	431	08/06/2008									
11/06/2008	3.0	6.92	65723	18323	422	11/06/2008									

Khalaqa Dam Water Balance Estimate											150	m3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events (m3)	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
16/06/2008	5.0	6.74	62578	17731	681	16/06/2008									
21/06/2008	5.0	6.56	59534	17148	658	21/06/2008									
28/06/2008	7.0	6.31	55407	16344	879	28/06/2008									
01/07/2008	3.0	6.21	53809	16027	369	01/07/2008									
07/07/2008	6.0	6.04	51119	15490	714	07/07/2008									
13/07/2008	6.0	5.84	48113	14880	686	13/07/2008									
16/07/2008	3.0	5.82	47845	14826	342	16/07/2008									
21/07/2008	5.0	5.75	46850	14622	561	21/07/2008									
28/07/2008	7.0	5.60	44577	14153	761	28/07/2008									
04/08/2008	7.0	5.45	42621	13745	739	04/08/2008									
11/08/2008	7.0	5.40	41878	13590	731	11/08/2008									
18/08/2008	7.0	5.31	40658	13333	717	18/08/2008									
25/08/2008	7.0	5.22	39458	13079	703	25/08/2008									
01/09/2008	7.0	5.09	37814	12730	684	01/09/2008									
15/09/2008	14.0	4.87	35089	12146	1306	15/09/2008									
22/09/2008	7.0	4.76	33716	11849	637	22/09/2008									

Khalaqa Dam Water Balance Estimate											150	m3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events (m3)	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
13/10/2008	21.0	4.45	30080	11056	1783	13/10/2008									
22/10/2008	9.0	7.64	79545	20804	1438	22/10/2008									
25/10/2008	3.0	6.93	65887	18354	423	25/10/2008									
29/10/2008	4.0	7.00	67126	18584	571	29/10/2008									
12/15/2008	47.0	7.35	73732	19785	7141	15/12/2008									
1/17/2009	33.0	7.73	81423	21125	5354	17/01/2009									

Methbel Dam Water Balance Estimate											16	m3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events (m3)	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
28/05/2007		0.60	1314	1503		28/05/2007					09/06/2007	3209			
09/06/2007	12.0	1.72	3209	2803	258	09/06/2007	3209	380	575	2253	10/07/2007	0	380	575	2253
25/06/2007	16.0	0.04	975	991	122	25/06/2007					10/07/2007	4363	0	0	0
02/07/2007	7.0	0.00	0	0	0	02/07/2007					20/08/2007	0	589	805	2969
10/07/2007	8.0	2.13	4363	3371	188	10/07/2007	4363	589	805	2969	20/08/2007	2292	0	0	0
16/07/2007	6.0	1.40	2487	2394	100	16/07/2007					03/09/2007	0	303	395	1595
23/07/2007	7.0	0.79	1516	1698	83	23/07/2007									
30/07/2007	7.0	0.22	1044	1146	56	30/07/2007					Sum	9864	1272	1775	6817
05/08/2007	6.0	0.51	1234	1415	54	05/08/2007									
06/08/2007	1.0	0.60	1314	1503	10	06/08/2007									
11/08/2007	5.0	0.30	1087	1217	39	11/08/2007									
16/08/2007	5.0	0.14	1009	1076	34	16/08/2007									
18/08/2007	2.0	0.08	987	1024	13	18/08/2007									
20/08/2007	2.0	0.09	990	1033	13	20/08/2007									
25/08/2007	5.0	0.00	0	0	0	25/08/2007									

Methbel Dam Water Balance Estimate												16	m3/day		
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events (m3)	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
27/08/2007	2.0	0.00	0	0	0	27/08/2007									
29/08/2007	2.0	0.00	0	0	0	29/08/2007									
03/09/2007	5.0	0.00	0	0	0	03/09/2007									
10/09/2007	7.0	0.00	0	0	0	10/09/2007									
17/09/2007	7.0	0.00	0	0	0	17/09/2007									
24/09/2007	7.0	0.00	0	0	0	24/09/2007									
01/10/2007	7.0	0.00	0	0	0	01/10/2007									
22/10/2007	21.0	0.00	0	0	0	22/10/2007									
29/10/2007	7.0	0.00	0	0	0	29/10/2007									
05/11/2007	7.0	0.00	0	0	0	05/11/2007									
12/11/2007	7.0	0.00	0	0	0	12/11/2007									
19/11/2007	7.0	0.00	0	0	0	19/11/2007									
26/11/2007	7.0	0.00	0	0	0	26/11/2007									
03/12/2007	7.0	0.00	0	0	0	03/12/2007									
10/12/2007	7.0	0.00	0	0	0	10/12/2007									
17/12/2007	7.0	0.00	0	0	0	17/12/2007									

Methbel Dam Water Balance Estimate											16	m3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events (m3)	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
07/01/2008	21.0	0.00	0	0	0	07/01/2008									
14/01/2008	7.0	0.00	0	0	0	14/01/2008									
21/01/2008	7.0	0.00	0	0	0	21/01/2008									
04/02/2008	14.0	0.00	0	0	0	04/02/2008									
11/02/2008	7.0	0.00	0	0	0	11/02/2008									
18/02/2008	7.0	0.00	0	0	0	18/02/2008									
25/02/2008	7.0	0.00	0	0	0	25/02/2008									
03/03/2008	7.0	0.00	0	0	0	03/03/2008									
10/03/2008	7.0	0.00	0	0	0	10/03/2008									
17/03/2008	7.0	0.00	0	0	0	17/03/2008									
24/03/2008	7.0	0.00	0	0	0	24/03/2008									
31/03/2008	7.0	0.00	0	0	0	31/03/2008									
12/04/2008	12.0	0.00	0	0	0	12/04/2008									
15/04/2008	3.0	0.00	0	0	0	15/04/2008									
19/04/2008	4.0	0.00	0	0	0	19/04/2008									
22/04/2008	3.0	0.00	0	0	0	22/04/2008									

Methbel Dam Water Balance Estimate											16	m3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events (m3)	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
26/04/2008	4.0	0.00	0	0	0	26/04/2008									
29/04/2008	3.0	0.00	0	0	0	29/04/2008									
03/05/2008	4.0	0.00	0	0	0	03/05/2008									
06/05/2008	3.0	0.00	0	0	0	06/05/2008									
08/05/2008	2.0	0.00	0	0	0	08/05/2008									
12/05/2008	4.0	0.00	0	0	0	12/05/2008									
15/05/2008	3.0	0.00	0	0	0	15/05/2008									
19/05/2008	4.0	0.00	0	0	0	19/05/2008									
24/05/2008	5.0	0.00	0	0	0	24/05/2008									
27/05/2008	3.0	0.00	0	0	0	27/05/2008									
31/05/2008	4.0	0.00	0	0	0	31/05/2008									
02/06/2008	2.0	0.00	0	0	0	02/06/2008									
04/06/2008	2.0	0.00	0	0	0	04/06/2008									
07/06/2008	3.0	0.00	0	0	0	07/06/2008									
10/06/2008	3.0	0.00	0	0	0	10/06/2008									
15/06/2008	5.0	0.00	0	0	0	15/06/2008									

Methbel Dam Water Balance Estimate											16	m3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events (m3)	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
18/06/2008	3.0	0.00	0	0	0	18/06/2008									
22/06/2008	4.0	0.00	0	0	0	22/06/2008									
29/06/2008	7.0	0.00	0	0	0	29/06/2008									
08/07/2008	9.0	0.00	0	0	0	08/07/2008									
14/07/2008	6.0	0.00	0	0	0	14/07/2008									
20/07/2008	6.0	0.00	0	0	0	20/07/2008									
27/07/2008	7.0	1.30	2292	2272	111	27/07/2008	2292	303	345	658					
03/08/2008	7.0	0.85	1589	1761	78	03/08/2008									
06/08/2008	3.0	0.67	1383	1574	30	06/08/2008									
10/08/2008	4.0	0.46	1194	1366	35	10/08/2008									
13/08/2008	3.0	0.27	1070	1190	23	13/08/2008									
17/08/2008	4.0	0.08	987	1024	26	17/08/2008									
20/08/2008	3.0	0	0	0	0	20/08/2008									
24/08/2008	4.0	0	0	0	0	24/08/2008									
31/08/2008	7.0	0	0	0	0	31/08/2008									
03/09/2008	3.0	0	0	0	0	03/09/2008									

Methbel Dam Water Balance Estimate												16	m3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events (m3)	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
14/09/2008	11.0	0	0	0	0	14/09/2008									
12/10/2008	28.0	0	0	0	0	12/10/2008									
03/11/2008	22.0	0	0	0	0	03/11/2008									
05/11/2008	2.0	0	0	0	0	05/11/2008									

Mekhtan Dam Water Balance Estimate											27	m3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
28/05/2007		2.15	22982	14538		28/05/2007					16/08/2007	86848	0	0	0
09/06/2007	12.0	2.80	32925	16191	1492	09/06/2007					07/01/2008	23816	20974	4137	37921
25/06/2007	16.0	2.54	28815	15528	1908	25/06/2007					07/01/2008	37889	0	0	0
02/07/2007	7.0	2.41	26827	15198	740	02/07/2007					02/08/2008	500	19002	5507	12881
10/07/2007	8.0	4.26	59373	20066	1117	10/07/2007					02/08/2008	29125			
16/07/2007	6.0	4.04	54966	19452	812	16/07/2007					22/10/2008	7336	7869	2219	11701
23/07/2007	7.0	4.07	55691	19554	953	23/07/2007									
31/07/2007	8.0	4.59	66246	21005	1170	31/07/2007						122210	47845	11863	62502
04/08/2007	4.0	4.96	74257	22076	562	04/08/2007									
06/08/2007	2.0	5.33	82667	23177	295	06/08/2007									
12/08/2007	6.0	5.33	82667	23177	884	12/08/2007									
14/08/2007	2.0	5.26	80953	22955	292	14/08/2007									
16/08/2007	2.0	5.51	86848	23716	302	16/08/2007	86848	20974	4136	37921					
18/08/2007	2.0	5.30	81808	23066	293	18/08/2007									
20/08/2007	2.0	5.26	80953	22955	292	20/08/2007									

Mekhtan Dam Water Balance Estimate											27	m3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
22/08/2007	2.0	5.21	79762	22800	290	22/08/2007									
25/08/2007	3.0	5.20	79678	22789	435	25/08/2007									
27/08/2007	2.0	5.01	75327	22218	341	27/08/2007									
29/08/2007	2.0	5.01	75327	22218	341	29/08/2007									
03/09/2007	5.0	5.01	75327	22218	853	03/09/2007									
10/09/2007	7.0	4.85	71812	21752	1169	10/09/2007									
17/09/2007	7.0	4.65	67422	21164	1138	17/09/2007									
24/09/2007	7.0	4.49	64074	20710	1113	24/09/2007									
01/10/2007	7.0	4.33	60798	20262	1089	01/10/2007									
22/10/2007	21.0	3.75	49444	18669	3011	22/10/2007									
29/10/2007	7.0	3.63	47245	18352	987	29/10/2007									
05/11/2007	7.0	3.54	45689	18126	974	05/11/2007									
12/11/2007	7.0	3.33	41917	17570	945	12/11/2007									
19/11/2007	7.0	3.20	39661	17232	926	19/11/2007									
26/11/2007	7.0	3.11	38078	16991	913	26/11/2007									
03/12/2007	7.0	2.91	34675	16466	885	03/12/2007									

Mekhtan Dam Water Balance Estimate											27	m3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
10/12/2007	7.0	2.69	31088	15898	855	10/12/2007									
17/12/2007	7.0	2.59	29632	15662	842	17/12/2007									
07/01/2008	21.0	2.21	23816	14684	2368	07/01/2008									
07/01/2008	0.0	2.21	23816	14684	0	07/01/2008									
14/01/2008	7.0	3.10	37889	16963	912	14/01/2008	37889	19002	5506	12881					
21/01/2008	7.0	3.00	36208	16704	898	21/01/2008									
04/02/2008	14.0	2.71	31482	15961	1716	04/02/2008									
11/02/2008	7.0	2.58	29436	15630	840	11/02/2008									
18/02/2008	7.0	2.42	26978	15223	818	18/02/2008									
25/02/2008	7.0	2.28	24883	14868	799	25/02/2008									
03/03/2008	7.0	2.12	22550	14462	777	03/03/2008									
10/03/2008	7.0	2.03	21266	14234	765	10/03/2008									
17/03/2008	7.0	1.87	19035	13827	743	17/03/2008									
24/03/2008	7.0	1.72	17003	13443	723	24/03/2008									
31/03/2008	7.0	1.56	14897	13032	701	31/03/2008									
09/04/2008	9.0	1.48	13868	12825	886	09/04/2008									

Mekhtan Dam Water Balance Estimate											27	m3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
13/04/2008	4.0	1.29	11488	12329	379	13/04/2008									
16/04/2008	3.0	1.22	10634	12145	280	16/04/2008									
20/04/2008	4.0	1.12	9434	11880	365	20/04/2008									
23/04/2008	3.0	1.06	8726	11720	270	23/04/2008									
27/04/2008	4.0	0.98	7796	11505	353	27/04/2008									
30/04/2008	3.0	0.90	6881	11289	260	30/04/2008									
04/05/2008	4.0	0.84	6205	11125	342	04/05/2008									
06/05/2008	2.0	0.82	5981	11071	170	06/05/2008									
10/05/2008	4.0	0.79	5648	10988	338	10/05/2008									
13/05/2008	3.0	0.73	4987	10823	249	13/05/2008									
17/05/2008	4.0	0.64	4013	10572	325	17/05/2008									
20/05/2008	3.0	0.59	3480	10431	240	20/05/2008									
09/07/2008	50.0	0.51	2640	10205	3919	09/07/2008									
15/07/2008	6.0	0.38	1307	9830.9	453	15/07/2008									
22/07/2008	7.0	0.21	500	1500	81	22/07/2008									
29/07/2008	7.0	2.52	28507	15477	832	29/07/2008									

Mekhtan Dam Water Balance Estimate											27	m3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
02/08/2008	4.0	2.56	29125	15579	479	02/08/2008	29125	7869	2219	11701					
05/08/2008	3.0	2.41	26827	15198	350	05/08/2008									
09/08/2008	4.0	2.35	25924	15046	462	09/08/2008									
12/08/2008	3.0	2.4	26676	15172	350	12/08/2008									
16/08/2008	4.0	2.33	25625	14995	461	16/08/2008									
19/08/2008	3.0	2.28	24883	14868	343	19/08/2008									
23/08/2008	4.0	2.21	23854	14691	409	23/08/2008									
26/08/2008	3.0	2.15	22982	14538	277	26/08/2008									
30/08/2008	4.0	2.07	21834	14335	365	30/08/2008									
06/09/2008	7.0	1.95	20142	14030	625	06/09/2008									
10/09/2008	4.0	1.87	19035	13827	352	10/09/2008									
13/09/2008	3.0	1.8	18080	13648	260	13/09/2008									
20/09/2008	7.0	1.64	15942	13238	712	20/09/2008									
11/10/2008	21.0	1.18	10151	12040	1942	11/10/2008									
22/10/2008	11.0	0.94	7336	11397	963	22/10/2008									
25/10/2008	3.0	1.51	14252	12903	297	25/10/2008									

Mekhtan Dam Water Balance Estimate											27	m3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
29/10/2008	4.0	1.47	13741	12799	393	29/10/2008									
01/11/2008	3.0	2.91	34717	16473	380	01/11/2008									
08/11/2008	7.0	2.81	33086	16216	872	08/11/2008									
26/11/2008	18.0	2.5	28199	15426	2133	26/11/2008									
15/12/2008	19.0	2.13	22693	14488	2114	15/12/2008									
19/01/2009	35.0	1.51	14252	12903	3468	19/01/2009									

Mussaibih Dam Water Balance Estimate											5	m^3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events (m3)	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
28/05/2007		0.00	0	0		28/05/2007					10/07/2007	25827	0	0	0
9/06/2007	12.0	0.10	520	387	36	09/06/2007					04/08/2007	24272	1443	104	9
25/06/2007	16.0	0.10	520	387	48	25/06/2007					04/08/2007	38317	0	0	0
2/07/2007	7.0	0.10	520	387	19	02/07/2007					06/05/2008	9541	12952	1371	14454
10/07/2007	8.0	5.67	25827	10000	557	10/07/2007	25827	1442.8	103	9	06/05/2008	14532	0	0	0
16/07/2007	6.0	5.60	25141	9878	412	16/07/2007					19/01/2009	520	4880	1282	8370
23/07/2007	7.0	5.51	24272	9718	473	23/07/2007					19/01/2009	0	0	0	0
31/07/2007	8.0	5.77	26824	10174	518	31/07/2007					Sum	44344	19275	2757	22832
4/08/2007	4.0	6.81	38317	11916	303	04/08/2007	38317	12952	1370	14454					
6/08/2007	2.0	6.77	37837	11850	151	06/08/2007									
12/08/2007	6.0	6.74	37479	11800	450	12/08/2007									
14/08/2007	2.0	6.71	37123	11751	149	14/08/2007									
16/08/2007	2.0	6.66	36533	11668	148	16/08/2007									
18/08/2007	2.0	6.63	36181	11619	148	18/08/2007									
20/08/2007	2.0	6.61	35947	11586	147	20/08/2007									

Mussaibih Dam Water Balance Estimate											5	m^3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events (m3)	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
22/08/2007	2.0	6.59	35714	11553	147	22/08/2007									
25/08/2007	3.0	6.53	35021	11454	219	25/08/2007									
27/08/2007	2.0	6.49	34562	11388	145	27/08/2007									
29/08/2007	2.0	6.43	33879	11288	144	29/08/2007									
3/09/2007	5.0	6.36	33092	11172	349	03/09/2007									
10/09/2007	7.0	6.20	31327	10906	476	10/09/2007									
17/09/2007	7.0	6.06	29822	10670	466	17/09/2007									
24/09/2007	7.0	5.94	28562	10467	457	24/09/2007									
1/10/2007	7.0	5.80	27127	10226	369	01/10/2007									
22/10/2007	21.0	5.57	24850	9825	1065	22/10/2007									
29/10/2007	7.0	5.37	22952	9467	342	29/10/2007									
5/11/2007	7.0	5.29	22214	9322	298	05/11/2007									
12/11/2007	7.0	5.20	21398	9157	292	12/11/2007									
19/11/2007	7.0	5.11	20598	8991	287	19/11/2007									
26/11/2007	7.0	5.04	19987	8860	283	26/11/2007									
3/12/2007	7.0	4.95	19214	8691	226	03/12/2007									

Mussaibih Dam Water Balance Estimate											5	m^3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events (m3)	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
10/12/2007	7.0	4.90	18792	8596	224	10/12/2007									
17/12/2007	7.0	4.83	18208	8462	220	17/12/2007									
7/01/2008	21.0	4.65	16750	8113	777	07/01/2008									
14/01/2008	7.0	4.60	16356	8015	256	14/01/2008									
21/01/2008	7.0	4.54	15890	7897	252	21/01/2008									
4/02/2008	14.0	4.41	14903	7638	629	04/02/2008									
11/02/2008	7.0	4.36	14532	7537	310	11/02/2008									
18/02/2008	7.0	4.30	14093	7416	305	18/02/2008									
25/02/2008	7.0	4.24	13661	7294	300	25/02/2008									
3/03/2008	7.0	4.18	13236	7172	301	03/03/2008									
10/03/2008	7.0	4.11	12749	7028	295	10/03/2008									
17/03/2008	7.0	4.05	12339	6905	290	17/03/2008									
24/03/2008	7.0	3.98	11869	6760	284	24/03/2008									
31/03/2008	7.0	3.91	11408	6614	278	31/03/2008									
3/04/2008	3.0	3.84	10957	6467	105	03/04/2008									
13/04/2008	10.0	3.80	10703	6384	345	13/04/2008									

Mussaibih Dam Water Balance Estimate											5	m^3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events (m3)	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
16/04/2008	3.0	3.77	10515	6320	102	16/04/2008									
20/04/2008	4.0	3.72	10205	6215	134	20/04/2008									
23/04/2008	3.0	3.69	10022	6152	100	23/04/2008									
27/04/2008	4.0	3.65	9780	6067	131	27/04/2008									
30/04/2008	3.0	3.62	9600	6004	97	30/04/2008									
4/05/2008	4.0	3.61	9541	5983	155	04/05/2008									
6/05/2008	2.0	4.36	14532	7537	98	06/05/2008	14532	4880	1282	8370					
10/05/2008	4.0	4.45	15203	7718	200	10/05/2008									
13/05/2008	3.0	4.43	15053	7678	149	13/05/2008									
17/05/2008	4.0	4.40	14829	7618	197	17/05/2008									
20/05/2008	3.0	4.39	14754	7598	148	20/05/2008									
9/07/2008	50.0	3.76	10453	6299	2192	09/07/2008									
15/07/2008	6.0	3.69	10022	6152	257	15/07/2008									
22/07/2008	7.0	3.61	9541	5983	291	22/07/2008									
29/07/2008	7.0	4.05	12339	6905	336	29/07/2008									
2/08/2008	4.0	4.01	12069	6822	174	02/08/2008									

Mussaibih Dam Water Balance Estimate											5	m^3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events (m3)	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
5/08/2008	3.0	3.97	11802	6739	129	05/08/2008									
9/08/2008	4.0	3.93	11539	6656	169	09/08/2008									
12/08/2008	3.0	3.9	11343	6593	126	12/08/2008									
16/08/2008	4.0	1.23	839	1347	34	16/08/2008									
19/08/2008	3.0	0.68	376	699	13	19/08/2008									
23/08/2008	4.0	0.67	373	690	18	23/08/2008									
26/08/2008	3.0	0.65	368	673	13	26/08/2008									
30/08/2008	4.0	0.61	359	639	16	30/08/2008									
6/09/2008	7.0	0.55	352	592	26	06/09/2008									
10/09/2008	4.0	0.53	351	577	14	10/09/2008									
13/09/2008	3.0	0.50	351	556	10	13/09/2008									
20/09/2008	7.0	0.45	355	523	23	20/09/2008									
11/10/2008	21.0	0.26	415	428	46	11/10/2008									
22/10/2008	11.0	0.18	461	403	23	22/10/2008									
25/10/2008	3.0	0.18	461	403	6	25/10/2008									
29/10/2008	4.0	0.17	468	400	8	29/10/2008									

Mussaibih Dam Water Balance Estimate											5	m^3/day			
Date	No of days	Water level (m)	Volume estimated (m3)	Area (m2)	Evaporation (m3)	Date	Volume estimated (m3)	Cum. evaporation loss between flood events (m3)	Cum. irrigation (m3)	Cum. recharge (m3)	Date	Stored Water Volume (m3)	Cum. Evaporation (m3)	Cum. Release (m3)	Cum. Recharge (m3)
1/11/2008	3.0	1.18	773	1277	17	01/11/2008									
8/11/2008	7.0	1.06	633	1117	36	08/11/2008									
26/11/2008	18.0	0.09	528	386	32	26/11/2008									
15/12/2008	19.0	0.1	520	387	27	15/12/2008									
19/01/2009	35.0	0.1	520	387	50	19/01/2009									

ANNEX D SUB-BASIN WATER BALANCE CALCULATIONS

YEAR 2007 A= Hayathem Dam Site from WEC 8985 station and P1 hydrological Zone Daily Rainfall Runoff Calculation (mm)

DATE	MAR						APR						MAY						JUN						JUL					
	P	AMCt	AMCrat	CNt	S	R	P	AMCt	MCrat	CNt	S	R	P	AMCt	MCrat	CNt	S	R	P	AMCt	MCrat	CNt	S	R	P	AMCt	MCrat	CNt	S	R
1	0.0						0						0						0.2	0.4	0.09	86.2	40.7	0.0	0	0.1	0.03	85.4	43.4	0.0
2	0.0						0						0	0.0	0.0	85.0	44.8	0.0	0.2	0.2	0.05	85.6	42.7	0.0	0	0.1	0.0	85.4	43.4	0.0
3	0.0						0.0						0.4	0.0	0.0	85.0	44.8	0.0	0.0						0.0	0.0	0.0	85.1	44.4	0.0
4	0.0						0.0						0.0						0.0						0.0	0.0	0.0	85.0	44.7	0.0
5	0.0						5.4	0.0	0.00	85.0	44.7	0.0	0.0						0.0						17.8	0.0	0.0	85.0	44.8	2.1
6	0.0						0.8	1.7	0.27	88.5	33.0	0.0	0.0						0.0						1.6	5.7	0.5	91.6	23.1	0.0
7	0.0						7.0	0.8	0.16	87.1	37.7	0.0	0.0						0.0						11.2	2.3	0.3	89.2	30.7	1.1
8	0.0						0.0	2.5	0.34	89.4	30.2	0.0	0.0						0.0						3.2	4.3	0.4	90.8	25.6	0.0
9	0.0						4.6	0.8	0.16	87.0	37.8	0.0	0.0						0.0						8.4	2.4	0.3	89.3	30.5	0.4
10	0.0						2.0	1.7	0.27	88.5	33.0	0.0	0.4	0.0	0.0	85.0	44.8	0.0	0.0						1.0	3.4	0.4	90.2	27.5	0.0
11	0.0						0.4	1.2	0.21	87.7	35.5	0.0	0.0						0.0						2.6	1.4	0.2	88.1	34.3	0.0
12	0.0						0.2	0.5	0.11	86.4	39.9	0.0	0.0						0.0						0.0					
13	0.0						0.0						0.0						0.0						0.0					
14	0.0						0.0						0.0						0.0						0.0					
15	0.0						0.4	0.0	0.01	85.1	44.5	0.0	0.0						0.0						0.0					
16	0.0						0.8	0.1	0.03	85.4	43.3	0.0	18.6	0.0	0.00	85.0	44.8	2.3	0.0						5.8	0.0	0.0	85.0	44.7	0.0
17	0.0						0.0						0.0						0.0						3.8	1.9	0.3	88.7	32.4	0.0
18	0.0						5.4	0.1	0.02	85.3	43.7	0.0	0.0						0.0						0.4	1.8	0.3	88.6	32.6	0.0
19	0.0						0.0						0.0						0.0						1.2	0.7	0.1	86.9	38.4	0.0
20	0.0						0.0						0.8	0.2	0.05	85.6	42.7	0.0	0.0						0.0					
21	0.0						0.0						0.0						0.0						0.0					
22	0.0						0.0						0.0						0.0						0.0					
23	1.4	0.0	0.0	85.0	44.8	0.0	0.0						0.0						0.0						0.0					
24	0.8	0.4	0.1	86.3	40.3	0.0	0.0						0.0						0.0						0.0	0.0	0.0	85.0	44.7	0.0
25	0.8	0.4	0.1	86.2	40.8	0.0	0.0						0.0						0.0						0.6	0.0	0.0	85.0	44.8	0.0
26	2.4	0.4	0.1	86.1	40.9	0.0	2.4	0.0	0.00	85.0	44.8	0.0	0.2	0.0	0.00	85.0	44.8	0.0	0.8	0.0	0.0	85.0	44.8	0.0	0.6	0.2	0.0	85.6	42.7	0.0
27	0.2	0.9	0.2	87.2	37.2	0.0	0.0						1.0	0.1	0.02	85.2	44.1	0.0	0.0	0.3	0.1	85.8	42.1	0.0	0.6	0.3	0.1	85.8	42.1	0.0
28	6.2	0.3	0.1	86.0	41.2	0.0	0.0						10.4	0.3	0.08	86.0	41.3	0.4	1.4	0.1	0.0	85.3	43.9	0.0	0.0	0.3	0.1	85.8	41.9	0.0
29	0.4	2.1	0.3	88.9	31.6	0.0	0.0						1.4	3.4	0.40	90.2	27.6	0.0	3.2	0.5	0.1	86.4	40.1	0.0	21.4	0.1	0.0	85.3	43.8	3.5
30	4.6	0.8	0.2	87.0	37.8	0.0	0.0						2.4	1.5	0.25	88.3	33.8	0.0	0.0						17.4	6.9	0.6	92.2	21.4	5.2
31	1.4	1.7	0.3	88.5	33.0	0.0							0.0												0.8	7.7	0.6	92.6	20.3	0.0
Total	**18.2**					**0.0**	**29.4**					**0.0**	**35.6**					**2.7**	**5.8**					**0.0**	**98.4**					**12.3**

Calculations for all sub-basins and reservoirs in EXCEL Spreadsheet are given in CD

P = Daily rainfall (mm); AMC(t, rat) = Daily Antecedent moisture content; CN +Curve Number; S = Total loss (mm); R = Runoff (mm)