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Chapter 1: Introduction

1.1 Study Background and Objectives

This technical report deals with water resources, which represent the ‘natural’ boundary condition to the system being examined (i.e. the Sana’a Basin). The report describes the main components of this sub-system and presents the Consultant’s findings/recommendations related to water resources availability and use. It is prepared on the basis of (i) review of water resources documents from previous studies (reports, maps, data sheets, charts, etc.), (ii) review of other relevant documents prepared by Donors such as the World Bank (PCN, PCD, etc.), and (iii) discussions with officials and technical staff from Government institutions (NWRA, NWSA, MAI, etc.).

The aim of this report is to provide water resources and other related information required for selecting a number of zones within the Basin for pilot studies. For this purpose, a water resources assessment is undertaken by considering both the conventional and non-conventional sources of water in the Basin as well as the abstraction level distribution across the Basin and the situation of the resources at the present time.

1.2 Information Requirement

Details of the basic data/information required for water resources assessment are given in table 1.1. Important data related to the subject are summarized and tabulated in Technical Report Four (Back-Up Data). The main sources for these data are described in the next section.

Table 1.1: Details of basic water resources data/ information

Subject	***Data and Information Needed***
Climatological conditions	Rainfall Potential evaportranspiration
Surface water system	Wadi channel network Hydrological characteristic of wadi segments (perennial, seasonal, ephemeral) Wadi flow/catchment yield; water quality in main wadis
Groundwater system	Geometry and lithology of main aquifers (alluvial, volcanics, sandstones) Hydraulic properties of main aquifers Identification of main recharge and discharge zones Springs (yield and water quality)
Water-related environmental aspects	Zones prone to pollution Current and potential polluters Zones prone to flooding and flood damage Zones prone to drying up Zones of particular environmental value

1.3 Previous Studies

Over the past thirty years or so, a large number of water resources studies have been carried out in the Basin. These studies can be classified into two main categories: large-scale investigations in which attempts have been made to understand the overall situation of water resources in the Basin (*regional studies*) and more localized investigations of specific nature concerned with a particular issue or aquifer type (*local investigations*). Based on their specific objectives, the latter studies could be classified farther as *water supply type investigations* (e.g .Howard Humphreys and Sons, 1980 &1983), *research-oriented surveys* (e.g Charalamous, 1982; Jungfer, 1983), or *general review studies* (Nash, 1991; Al-Aryani et. Al, 1992). The latter two give a good review of most previous studies up to the end of the SAWAS study. Discussion of data/information relative speafically to any of these "local investigation" is given in relavant sections of the report. A brief description of the nature and main contribution of the main regional studies, which have been used as the main references for the study, is given in table 1.2.

1.4 Report Structure

Chapter two following this introductory chapter gives the geological and hydrological background of the Basin. Chapters 3 and 4 describe the conventional and non-conventional water resources comprising the Sana'a basin system, respectively. The present level of groundwater abstraction, and observed trends across the Basin, and potential areas for future expansion in pump irrigation is given in chapter 5.

Table 1.2 : Summary of the main contributions of previous regional studies

Study/ Year	***Main contribution***
SAWAS (1996)	Provides the only measured runoff data available from the Basin (Wadi Al Kharid gauging station) and new rainfall data from several stations across the Basin installed during project implementation, for the purpose of assessing surface water potential. Drilled the deepest boreholes in the Basin to assess the groundwater potential of the older sedimentary formations (Kohlana and Wajid sandstones). Carried out a well inventory which, though not covering the entire Basin, extended to the Shibam area in Wadi Surdud to evaluate groundwater availability in the region for water supply purposes. Set up a groundwater model for the Basin and carried out preliminary runs from which data gaps and limitations have been identified for future purposes. Carried out a wide hydrochemical analysis to characterize major zones within the Basin, mainly those influenced by domestic and industrial effluents from the city.
TSHWC (1991)	Prepared the first groundwater model for the Tawila sandstones for the purpose of examining the broader issues of water resources management and planning, unlike most of the preceding studies that were mainly concerned with the hydrogeological behaviour of NWSA well fields. Provided reasonable and simplified calculations for the distribution of recharge and storage across the main aquifer zones (alluvial, volcanics and sedimentary). Evaluated alternative management strategies towards an Action Plan for the Basin.
MogiPrvod-khoz (1986)	Carried out the first study covering the whole region and ,hence, delineated the main boundary of the Basin as well as a number of sub-zones (water economic units) that were recommended for water management purposes. Inventoried about 3000 water points (wells and springs) and, based on the results obtained, prepared important hydrogeological maps. Provides most of the basic information on the Basin as a whole as well as other information related to water management (agro-ecology, infrastructure, etc.).
Italconsult (1973)	Provides probably the best description of the four main aquifer systems in the Basin (Cretaceous sandstones, Tertiary basalts, Quaternary sediments, and Quaternary basalts), judging from the wide use of this information in subsequent studies. Contains useful data, particularly water levels and spring discharge rates, which constitute a good documentation of the situation of the Basin prior to any significant exploitation of the groundwater resources. Derives important hypotheses on the inflow of the groundwater resources into the Basin from neighbouring regions; namely that (1) a considerable volume of groundwater enters the north Sana'a plain, (2) there is no well-defined outlets of groundwater from this large Quaternary basin since it is apparently closed to the north by the *Jabal Assama'-Jabal A'was* limestone range, and (3) groundwater in the Cretaceous aquifer across the Sana'a plain base level is derived from deep infiltration occurring through the Tertiary volcanics surrounding the plain from the south.

Chapter 2: Geological and Hydrological Background

2.1 Geological Evolution

The Sana'a Basin has developed on a large depression within a structurally high region (Yemen Horst), which is steep-sided to the west and south but slopes gently northeastward (Figure 2.1). Exposed along the northern and southeastern boundaries of this depression are the Precambrian Basement rocks of the *Sa'dah-Hajja* and *Marib-Rada'-Al Baydah* districts, respectively (figure 2.2). Different types of tectonic movements (extension, compression, and strike-slip) have affected the region in an interactive manner.

Basement rocks are thought to have originated as a series of volcanic island arcs that were later accreted one against the other and finally sandwiched between the African and Arabian Cratons (Alsinawi and Al Aydrus, 1999, p.28). The end results were mainly NE-trending faults and the initiation of collision-related intercratonic magmatism and tectonism.

Figure 2.1 : Cross-Section showing Regional subsurface Geology (modified) from Van Der Gun and Ahmed (1995) .

Figure 2.2: Surface Regional Geology (after Itaconsult, 1973)

Uplift and peneplanation followed the final accretion/collision events and by Ordovician times the *Wajid sandstone*, a mature quartsoze fluviatile deposit, was being deposited on a gently sloping surface of eroded basement. No significant tectonic events occurred during the Paleozoic and the situation during the Triassic is not clear due to the complete absence of any sediments belonging to this age.

During the Jurassic, the *Sa'dah-Marib-Al Jawf* Basin was initiated as the entire southern Arabian sub-continent began to separate into basin-and-range provinces. The origin of this Basin is related to the disengagement of the Sub-Continent from the main block through clockwise rotation. It developed as an intercratonic rift whereby extensional faulting of the Basement resulted in the formation of a series of half-grabens trending NW-SE. These basins were filled by continental red sandstones followed by the deposition of dark-green and gray-black shales of fluviolacustrine origin (Geukens, 1966) known as the *Kohlan* Formation. The sandstones-shales of the *Wajid-Kohlan* formations constitute the oldest sedimentary rocks in the Sana'a Basin.

The Jurassic ended with a wide transgression over the entire country represented by the shallow water calcareous deposits (*Amran* Group) underlying the whole Basin but only exposed in the northern areas of *Al Kharid* (see figure 2.2 above). Throughout the Basin, the carbonates-mud deposits of this group rest generally on the *Kohlan* Formation, which becomes progressively deeper towards the south (see figure 2.1 above). This would signify that the Sana'a Basin represents one of the local depressions along which initial transgression of the Jurassic sea took place, in support of Geuken's initial conclusion that *the "Sana'a Basin area is a large syncline..., which is the site of the old Jurassic Basin*."

A period of continental environment prevailed toward the end of the Late Jurassic. A lagoonal stage occurred in the central depression of the Basin where black bituminous pyritic shale, limestone, finely bedded sandstone with fossil plants, and some lenticular gypsum in the upper have been deposited. Originally reported as the *Unnamed Formation*, this unit has been named by Al Anbaawy (1985) as *Al Gharas Evaporites* after the district area northeast of Sana'a city where extensive outcrops can be seen (see also Mosgiprovodkhoz, Volume 6). This unit is considered by Al Anbaawy to be part of the *Saba'tayn* Formation of the *Amran* Group commonly found farther east. The origin of the Evaporates has been interpreted as sedimentation in a restricted semi-isolated basin, which was cutoff from the ocean by tectonically built-up barriers (op. cit., p. 129.).

In a 100-km-long east-west transect from the Tihama to Sana'a Basin, Davison et al. (1994) found no major vertical or normal variations in the *Amran* Group suggesting that the Group records a consistent water depth during deposition of the whole sequence. They also concluded that the transect area became emergent following a relative sea level fall, leading to vadose dissolution and cementation before the deposition of the *Tawila* Group. No effect of the Mesozoic rifting responsible for the development of the *Sa'dah-Al Jawf-Marib* graben (i.e. pre-Red Sea tectonics) was observed, as the dominant structure of the Amran is mostly east-west dipping NW-SE extensional fault blocks related to the Red Sea opening (op.cit.). On the other hand, Al Anbaawy (1985, p. 137) suggests that the Amran depositional basin floor was mainly controlled by block faulting, which occurred during mid Jurassic before the deposition of the *Saba'atyn* and *Madbi* formations of this Group.

Continental sandy conglomerates of Cretaceous age (*Tawila Group*) were laid down on the merging side of the Basin that was subject to erosion (Geukens, 1966). The *Tawila Group* is exposed in two districts across the Basin (*Hamdan* and *Bani Hushaysh*) as part of the continental clastic sediments deposited from west to east down the axis of the *Al Jawf-Marib Basin* (Alsinawi and Al Aydrus, 1999, p. 51). An estimated 100 m of the *Tawila,* as well as the Tertiary rocks that normally cover and protect it, has been eroded after uplift related to the Red Sea rifting (Mitchel and Galbiati as reported in Alsinawi and Al Aydrus, 1999). In the southern volcanic part of the Basin where this protection still holds, the *Tawila* Group is found at great depths (> 700 m or so), which increases substantially towards the boundary with Dhamar Basin (see figure 2.1 above).

The volcanogenic evolution during the Tertiary is explained as a result of an upper mantle heat, with material transfer and continuous crustal attenuation which began in late Proterozoic (Precambrian) and eroded during late Tertiary (Alsinawi and Al Aydrus, 1999, p. 62). The volcanic eruptive phase began in the middle Eocene with alternation of Trap basalts and trap rhyolites. The volcanic rocks (*Yemen Volcanics*) appear to have been constructed by eruption of extensive fissure-fed basaltic flows, a number of large basaltic shield volacnoes, and ignimbrite/ash flow deposits from individual calderas (Davison et. al., 1994). The epicenter of this extensive volcanic activity appears to have been around the zone extending from the southern part of the sana'a Basin to Dhamar, as evidenced by the thickness of Tertiary volcanic rocks (figure 2.3).

Figure 2.3 : Yemen Volcanic Group Lithostratigraphy Across the Sana'a Region.(Redrawn from Davison et. at, 1994)

High mountain areas in the country correlate closely with the present outcrop of these volcanic rocks on unextended rust. This explains why the southern part of the Sana'a Basin has become surrounded with the highest chain of mountains. Sedimentary lenses are found within this volcanic pile (calcareous sandstone, mudstone, and reworked volcanic clastics), as well as abundant fossils (freshwater gastropods) and plant material. These sediments are interpreted to have been deposited in small lakes formed in depressions on a volcanic landscape (op.cit.). Major NW-SE trending faults are commonly observed on the Yemen Volcanics indicating NE-SW directed extension of the Arabian Plate. However, the NE-SW trending pre-rift type faults are also common, particularly in the southeastern areas Basin (e.g. *Wadi Ghayman* and *Wadi Shahik*) close to the Basement outcrop outside the. This would suggest reactivation of the Precambrian-initiated faults during the Tertiary time.

In addition to the *Yemen Volcanics*, discrete fields of Quaternary (Pliocene-Holocene) intraplate volcanoes occur northeast (*Marib*) and northwest (*Arhab*) of the Basin, the latter extending into the Basin where it consists of 1500 km^2, 100 to 250 m-thick basaltic plateaus peppered by many scoria cones. Alignment of these cones has commonly a north-northwest trend and the composition of the rocks indicates that they are clearly distinct from the older, more widespread flood volcanic rocks. The prevalence of NW-SE trending faults shows the continued effect of the extensional forces related to the Red Sea opening as a major control in the structural evolution of these younger rocks.

2.2 Geological Units Within the Basin

Kohlan Group (Triassic? to Middle Jurassic): It can be seen from the geological map and cross sections (figures 2.4 & 2.5) that this is the oldest sedimentary formation overlying the Basement in the major part of the Sana'a Basin although not found on surface. It consists of a green shale with sandstone and conglomeratic bands in the lower parts and sandstone and conglomerates in the upper part. Italconsult suggested that its thickness is over 300 m. Recently the SAWAS project drilled a borehole (DS1, depth: 1700 m) in the *Arhab* region (50 km north of Sana'a). Here the Sandstone below the *Amran* Group and above the Basement has a total thickness of some 40 m (the depth to the top of the Sandstone is 1200 m). The contact with the overlying *Amran* is believed to be gradational and it is not known yet if this sandstone belongs to the *Kohlan* Series or the older Wajid sandstone formation.

Amran Group (Middle to Upper Jurassic): Comprises limestones, marls and shaly limestones some 350 to 1000 m thick. The *Amran* outcrops in the north of the Basin, covering about 15% of the Basin area (figure 2.4). It occurs at variable depths beneath the Sana'a plain: at the airport the top of the

Amran is approximately 350 m deep; at *Ar Rawdah* 500 m and further south near Sana'a 900 m or more. The Amran is overlain by a sequence of lagoonal shales, marls and fine grained sandstones interbedded with lignite probably of Upper Jurassic or Lower Cretaceous age (equivalent to the "*Unnamed Formation*" of Italconsult) which outcrop in a narrow band in the north-eastern part of the Basin.

Figure 2.4: Geological map of the Basin (after SAWAS, 1996)

Figures 2.5 : Geological cross-sections. (modifid from Italconsult, 1973)

Tawilah Group (Cretaceous to Tertiary?): Comprises a series of continental cross-bedded sandstones generally medium to coarse grained with interbedded mudstones, siltstones and occasional silty-sandstones. The overlying *MedjZir* Formation is a finer grained sandstone with a higher proportion of siltstones and clays. It also contains decomposed volcanic tuffs and "soapy clay beds" associated with the start of regional volcanic activity. It has proven difficult to distinguish the *Tawilah* and *MedjZir* both in aerial photographs and drill cuttings. They are therefore mapped as one formation and referred to as the Tawilah Sandstones or "Cretaceous Sandstones". The Cretaceous Sandstones crop out over about 15% of the Basin area in the northern part of the Basin. It is thought to reach a thickness of 400 to 500 m where it has been protected from erosion by the overlying Tertiary volcanics.

Tertiary volcanics**:** Formerly called the Trap Series, these rocks outcrop over some 35% of the area of the Sana'a Basin. They form high plateaus to the south, west and east of the Sana'a plain and underlie the Quaternary deposits in the south of the Basin. The sequence is divided into two groups. The lowest group is the "Stratoid volcanics" which include the Basal Basalt (a dense homogenous basalt flow with columnar jointing), basalts, tuffs and pyroclastics interbedded with fluvio-lacustrine deposits. The upper "Chaotic volcanics" comprise mixed basalt flows and rhyolite lavas. The total thickness is variable, reaching an estimated maximum of 700 m to 900 m. Basic intrusive rocks of Tertiary age are present throughout the area in the form of volcanic plugs, dykes and sills. The alignment of the volcanic necks is oriented NNW-SSE. Dykes are well-fractured and oriented NNW-SSE and NNE-SSW.

Quaternary Volcanics*:* Volcanic activity continued into the Quaternary forming a plateau of extensive basalt cones in the north west of the Basin interlayered with tuffs and alluvial sediments. The *Quaternary Basalts* have a total thickness of about 100 m to 300 m and cover about 20 % of the area of the Basin. They overlie the *Amran* limestones, Cretaceous sandstone and Tertiary volcanics.

Quaternary Alluvial: Unconsolidated sediments (mainly alluvial) cover about 15 % of the Basin area. They are confined to wadi beds and low areas that form the Sana'a plain. Deposition appears to have been of fluvio-lacustrine nature, which led to the accumulation of clays and silts in Basins 100 m to 300 m deep. Coarse-grained colluvium and alluvium occurs in the wadi beds at the foot of hills.

Chapter 3: Water Resources Availability: Conventional Resources

3.1 Surfacewater Resources

3.1.1 Rainfall

Rainfall measurements of variable durations are available from 19 stations across the Basin and its surroundings. However, only six stations remain operational at the present as indicated in Report on Back-Up Data. Continuous measurements for the purpose of estimating annual values could only be obtained for the period 1991-1997 from five of these stations. The calculated mean values across the region range from about 400 mm/yr (As Salf station just outside the southwest corner of the Basin) to 160 mm/yr (As Samnah station in the Wadi Al Kharid area). The long-term average rainfall in the Sana'a region as a whole is 190 mm/yr (table 3.1). If however recent data (1991-1997) of only those stations occurring the Basin are considered, the mean annual increases to 220 mm. In addition, the spatial distribution of rainfall shows a gradual decrease from southwest to northeast (figure 3.1).

Table 3.1: Mean monthly and annual rainfallfor stations in Sana'a region (mm).

Serial	Station/yr	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual Total
1*	*MIND (1972-1979)*	4.31	2.54	19.20	40.61	52.97	6.40	48.24	56.89	35.77	8.54	1.66	2.23	279.37
2	*ADDAB'AT (1972-1979)*	0.00	4.93	20.23	42.71	22.69	0.60	30.83	61.11	4.67	5.20	4.00	4.53	201.50
3	*WADIZHAR (1976-1982)*	4.75	0.00	3.70	6.75	0.75	0.10	11.00	43.45	0.00	0.00	4.06	0.00	74.56
4	*DARWAN (1972-1979)*	4.11	1.06	9.54	30.97	41.23	4.43	44.23	60.37	4.31	8.43	2.46	2.46	213.60
5*	*BIRBAS'L-A (1991-1997)*	1.00	11.80	21.10	59.42	11.08	34.92	20.07	32.64	2.21	16.60	4.70	4.40	219.95
6*	*SAMNAH-A (1991-1997)*	2.80	0.80	14.60	27.00	21.00	28.80	13.90	41.90	0.30	2.40	0.10	10.70	164.30
7	*MAKARIB (1983-1985)*	1.25	0.75	15.10	16.50	29.40	0.00	1.00	13.70	0.00	0.00	0.00	13.50	91.20
8*	*MA'ADI-A (1991-1997)*	2.40	8.00	32.60	32.20	27.30	27.30	12.33	44.67	4.17	5.33	0.08	4.08	200.47
9	*MAJHIZ (1983-1985)*	2.20	3.60	9.50	60.90	57.80	2.45	3.07	23.50	0.00	0.00	0.00	3.30	166.32
10	*MAQWALAH (1983-1985)*	2.50	1.20	5.15	72.60	51.95	0.00	2.65	21.17	0.00	0.00	0.50	15.60	173.32
11*	*NWRA-A (1989-2001)*	0.60	2.40	34.70	36.07	36.07	14.63	33.57	56.41	6.21	10.42	4.25	2.23	237.54
12*	*SANA'A (1932-1999)*	4.40	3.91	26.90	48.87	26.97	7.81	45.96	61.93	6.21	4.39	5.50	4.46	247.31
13	*DUTRAT (1982-1985)*	0.65	0.00	2.85	25.10	38.05	0.00	0.60	22.47	0.00	0.00	0.00	5.00	94.72
14	*ALARAQAH (1982-1985)*	7.50	0.00	4.60	48.85	51.75	0.00	5.80	23.75	0.00	0.00	0.00	6.00	148.25
15	*ALIRRA (1986-1992)*	1.20	1.25	12.50	51.75	10.25	1.75	31.00	46.20	5.40	0.00	1.25	9.25	171.80
16	*BANI SABIR-A (1994-1995)*	0.00	36.50	0.00	4.50		0.00	11.50	20.50		0.00	0.00	0.00	73.00
17	*ALAHMAR (1984-1986)*	6.40	11.70	22.10	46.50	72.10	2.50	2.50	33.10	0.70	0.00	8.00	0.00	205.60
18	*ASR (1975-1977)*	0.00	5.33	54.70	106.67	12.33	39.30	49.77	107.67	9.40	49.07	12.80	0.87	447.90
19*	*Astan (1991-1997)*	1.90	7.10	38.58	49.17	11.67	26.25	26.92	53.17	0.58	0.17	0.00	0.92	216.42
Whole Region		***2.53***	***5.41***	***18.30***	***42.48***	***31.96***	***10.38***	***20.79***	***43.40***	***4.44***	***5.82***	***2.60***	***4.71***	***190.90***

* Inside Sana'a Basin.

Figure 3.1: Mean Annual Rainfall

3.1.2 Runoff

The Sana'a Basin, with a catchment area of about 3200 km^2 receiving about 220 mm/yr of rainfall on average, is likely to be generating a significant amount of runoff. Following heavy rains, runoff is commonly observed in different parts of the Basin, either as sheet flows in upstream areas or flash floods in the more gentle slopes around the plain, particularly upstream of the city. The evaluation of surface water potential, however, has not received enough attention in previous studies that were primarily concerned with groundwater availability (see also section 1.3 above). The available information is limited to a basin-wide estimate by Mosgiprovodkhoz (1986), limited monitoring of surface water resources in the Wadi Al Kharid (SAWAS, 1996), and a brief analysis of flood potential in the urban zone of Sana'a by Dar Al-Handasah (2000).

The TS-HWC (1992) suggest a mean runoff coefficeient (Rc) of 4 % for the Basin. This value for the Sana'a region, which lies mostly within the Central Highland Plains, appears to be reasonable considering the variations in Rc (4.3 % to 5.9 %) for the Western and Eastern slopes, respectively (see table 5.1 of Van der Gun and Ahmed, 1996, p.50). Using this value and the average rainfall of 7 years (1991-1997), the total runoff expected to be generated in the Basin is estimated at about 28.5 Mm^3/yr as shown in table 3.2.

Table 3.2: Estimated Mean Annual Runoff Calculated from Mean Rainfall Data for the Period 1991-1997.

Zone	*Rainfall (mm/yr)*	*Area (km^2)*	*Runoff (mm/yr)**	*Volume of runoff (Mm^3/yr)*
C	165	25	6.6	0.17
	190	650	7.6	4.94
B	202.5	975	8.1	7.9
A	227.5	700	9.1	6.37
	252.5	450	10.1	4.55
	277.5	275	11.1	3.05
	302.5	100	12.1	1.21
	327.5	25	13.1	0.33
	Total	3200		28.52

* Using average runoff coefficient of 4% after TS-HWC (1992)

The isohyetal map in figure 3.1 (see above) suggests that the Basin can be divided into a high runoff zone (with rainfall above the mean annual for the Basin), a moderate one, and a low runoff zone as follows:

Zone	***Area (km^2)***	***Average rainfall (mm/yr)***	***Mean annual runoff (Mm^3/yr)***
A	1550	245	15.51
B	975	202.5	7.91
C	675	189	5.1
Mean		220	28.52

With respect to runoff generating capacity (RGC) within individual wadi catchments, however, analyses of the limited Russian data (table 3.3) suggest the RGC values are significantly higher in the northeast part of the Basin as compared with other areas farther S or SW. This can perhaps be explained by the more dense surface drainage network in this area.

Table 3.3: Runoff-generating capacity of individual wadi catchments within the Sana'a Basin.

G.W. Province	***Wadi No.***	***Wadi Name (This Study)***	***Wadi Name (Russian Study)***	***Catchment Area (Russian Study) Km^2***	***Annual Runoff (Mm^3/yr)***	***Runoff Generating Capacity (Mm^3/yr/100km^2)***
North West Province	1	Madar_&_al_Mashamini				
	2	W._al_Madini_&_al_Ghulah				
	7	W._Qasabah				
	8	Yahis_&_Al_Huqqah				
	13	W._al_Iqbal_&_ash_Sha'b				
North East Province	3	Wadi_Al_Kharid	Kharid	3209	29.30	0.91
	4	W._al_Qatab_&_al_Ma'adi	Hada	167	2.19	1.31
	5	W._Lafaf_&_Asir	Sib Al Madi	110	1.46	1.33
	6	W._Khulaqah	Khulagah	72.1	0.80	1.11
	10	W._Thumah_&_al_Mahajir_&_Shira	Mahajir	80.2	0.86	1.07
East Province	11	W._as_Sirr	As Sirr	199	1.06	0.53
	12	W._al_Furs_&_Rijam	Rijam	46.2	0.13	0.28
	17	W._Sa'wan_&_ar_Rawnah	Rawnah	76.6	0.74	0.97
South East Province	18	W._Shahik_&_al_Ajbar_&_Sha'b	Asfal	205	0.95	0.46
	19	W._Ghayman	Ghayman	117	0.70	0.60
	20	W._al_Mulaikhy_&_Hamal				
	21	W._Hizyaz				
	22	W._Akhwar	Akhwar	129	0.84	0.65
South West Province	14	W._Zahr_&_Harad_&_Al_Ghayl	Zahr	322	1.48	0.46
			Zahr (South East)	45.4	0.36	0.79
	15	W._Hamdan_&_as_Sabarah	Hamdan	29.7	0.20	0.67
Central Province	9	W._Bani_Hawat				
	16	W._al_Mawrid_&_al_I'shash_&_al_Hayd				

3.2 Groundwater Resources

3.2.1 Aquifer System

Practically all the rock units contain some water at shallow environments reached by percolatin rainfall or runoff. The chances of finding groundwater at depth, however, vary significantly from one rock type to another. Hydrogeologic map and cross-sections across the Basin are given in figures 3.2 & 3.3. A brief summary of the general water-bearing characteristics of each geologic unit is given below.

3.2.1.1 Mesozoic Sedimentary Rocks

The Kohlan Sandstones are not exploited as an aquifer in the Sana'a region and its potential in terms of its distribution, possible yield, the quantity of water in storage and the quality of water is unknown. A pump test in the Sandstone borehole DS1 of SAWAS indicated a permeability and porosity comparable to the Tawilah sandstones.

The Amran Limestones are generally considered to be a poor aquifer although supplies can be obtained from zones of secondary permeability. Karst features however are poorly developed.
The depth to water is over 100 m in the plateau area in the northwest of the Basin. In the northeast in valleys leading to the Wadi al Kharid the depth to water is less than 35m and groundwater is abstracted mainly by means of dug wells. The Unnamed Formation is believed to act as an aquiclude although the regional permeability may be similar to the Amran limestones.

The Mejdzir – Tawila Cretaceous sandstone formation forms the main aquifer in the region. It has low regional permeability but locally higher permeabilities are found in weathered and fractured zones. It is heavily exploited to the northeast and northwest of Sana'a where it either outcrops or occurs beneath an unconsolidated cover of up to 50 m thickness. Depths to water in the main area of abstraction were about 30 to 40 m in the early 1970's but have declined by 2 to 4 m/yr since. In the south of the Basin, the Sandstone is confined beneath several hundreds of meters of Tertiary volcanics.

Figure 3.2 : Aquifer System in the Basin.(Modified after Mosgiprovodkhoz, 1986).

Figure 3.3:Hydrogeological Cross-Sections across the Basin.(Modified after Mosgip., 1986).

3.2.1.2 The Tertiary Volcanics

The basalt flows and stratoid sequences of the Tertiary volcanics act as aquicludes, except where fractured or where primary permeability occurs in sediments between flows. The mixed basalt and rhyolite flows at the top of the sequence are more highly fractured and contain perched aquifers which supply dug wells and feed high level springs. The upper layers of the Volcanics are highly weathered and relatively permeable where they underlie the unconsolidated Quaternary deposits in the south of the Basin. Here they are exploited together with the unconsolidated aquifer by dug and drilled wells.

3.2.1.3 The Quaternary Basalts and Sediments

The Quaternary Basalts are highly permeable due to fracturing and to the presence of clastic deposits between flows. Where the Formation is saturated it provides an unconfined aquifer. Water levels are deep ranging from 60 to 130 m depending on the elevation. Wells are generally limited to the southern edge of the outcrop where waterlevels are less than 100 m deep. In the rest of the area surface water is stored in cisterns to provide water for domestic purposes.

The unconsolidated Quaternary Alluvial deposits provide a poorly permeable aquifer which has been heavily exploited in the Sana'a Basin due to its proximity to the urban area. The aquifer is regionally unconfined but locally semi-confined. Due to the fine grained nature of the deposits in the plain, recharge is expected to be mainly indirect the most coarse grained materials along wadis and at the base of the hills.

3.2.2 Aquifer Parameters

The availability of groundwater in any particular aquifer depends primarily on its ability to *transmit* as well as *store* water. The information obtained on these two parameters (i.e. Transmissivity and Storativity or Storage Coefficient) for the aquifer systems beneath the Sana’a Basin is very limited (see SAWAS, Vol-V), considering they have been collected over a period of 32 years. Data shortage therefore consititutes a major constraint in assessing the available groundwater in the Basin, a fact that has to be kept in mind when reviewing the data presented in this section or utilizing them for planning purposes.

In the shallow environments where most aquifers are normally under unconfined conditions, transmissivity (T) is a product of an aquifer's saturated thickness (b) and hydraulic permeability (k). Having obtained T and b from drilling logs and pumping tests data, k can be estimated. Storativity(s), on the other hand, can only be determined through test-pumping provided water level measurements are obtained from both the borehole being pumped as well as at least one nearby observation well. Lack of data from observation wells has been the constraint behind the extreme paucity of storage data.

A very generalized picture of the distribution of groundwater transmissivity or, in other words, the ease with which it enters into the abstrating wells, has been given in the Russian study (Hydrogeology Report) Examining this figure in the light of the available data summarized in table3.4 and figure 3.4 shows the following:

The Amran limestone and Quaternary alluvial sediments have the lowest average transmissivity (< 30 m^2/d) in comparison with the Tertiary Volcanics (46 m^2/d) and the Tawila sandstones (280 m^2/d).

Table 3.4: Transmissivity data (mean values) as summarized from SAWAS.

	Transmissivity [m²/day]	***Saturated Thickness [m]***	***Estimated Permeability [m/day]***
Alluvium	27.9	53.9	3.5
The Tertiary Volcanics	45.8	80.5	3
The Cretaceous Sandstone	280.3	163.3	2
The Jurassic Limestone	25.6	40.3	2.2

The transmissivity of the alluvial sediments is due to mainly interaconnectivity of pore spaces (i.e. primary permeability) while flow in the other aquifers occurs through both pore spaces (primary permeability) as well as fractured and faulted zones (secondary permeability).

Secondary permeability appears to be much more signifcant in contributing to the higher T values of Tertiary volcanics and Tawila sandstones as compared with primay permeability.

The higher T values in the Tertiary Volcanics and Tawila Sandstones are resulting from increased aquifer thickness rather than true higher permeabilities.

The overall low permeabilities of the Tertiary Volcanics and Tawila Sandstones, in spite of the very high transmissivities recorded for fractured and faulted zones, suggest that the location of such zones rather than the total penetrated depth is the main controlling factor in transmissivity determination.

The extremely low permeability (0.13 m/d) of the deepest borehole with available data (Sabeen well, 850m deep) with a T value an order of magnitude lower than the average suggests that the Sandstones transmissivity in the NWSA Southern well field may be significantly lower than what has been recorded from the Western and Eastern well fields.

Although no pumping data have been yet obtained from the newly drilled boreholes in the Southern well field, the information available so far (table 3.5) indicate that the T values of these wells are likely to be very similar to that of the Sabeen well (i.e. very low) unless it so happens any one particular borehole has hit a rejuvenated fault zone related to the deep faulting system extending to the Basement.

Table 3.5 : Preliminary data available on the latest explore drilling program.

Borehole #	***Construction year***	***Total depth (mbgl)***	***Thickness of overlying sediments (m)***			***Thickness of pentrated Sandstones (m)***	***Temperature (°C)***	***Remarks***
			Alluvial	Volcanics	Total			
Sabeen (AS-1)	1992	850	160	480	640	210	38	
H8	2000	900	160	580	740	160	39	
EX-P(1)	2000	887	180	510	690	197		Not finished due to technical problems
EX-P(2)	2000	946	50	660	710	236		Not finished due to technical problems

Figure 3.4 : Comparison of transmissivity values in different aquifer systems.

3.2.3 Groundwater Recharge

3.2.3.1 Recharge Components

The ultimate source of groundwater replenishment is rainfall. However, there are a number of ways in which the process takes place, either naturally or through human interference. *Natural* processes include infiltration from rainfall (direct recharge) or percolation of runoff through barren rocks, soil and wadi beds as well as subsurface inflow between aquifer materials (indirect recharge). *Human-induced* replenishment occurs through processes such as infiltration of irrigation water, industrial water and domestic water or percolation of trapped water behind dams and other erected structures including terraces.

It is clear that most of the natural processes constitute recharge mechanisms through which certain amount of rainwater would be transferred directly (rainfall infiltration) or indirectly (percolation of runoff water) to one or more aquifers in the Basin. This replenishment ***(renewable recharge)*** constitutes the main input to the aquifers system through which the groundwater reservoir is renewed annually. On the other hand, the source of all human-induced processes as well as inter-aquifer inflow of groundwater is actually within the aquifers system itself as such processes involve recycling of subsurface water (**recycled recharge**) in the same basin including its redistribution through interaction with other basins. Therefore in making estimations of the available water resources within a large area such as the Sana'a Basin, it should be clear whether the assessment involves one or both of these two main recharge components.

3.2.3.2 Evidence of Recharge

Most previous studies have assumed that recharge takes place and therefore went ahead to either estimate it or adopt a published value. The results reported so far indicate the bulk of inflow into the aquifer system is occurring in the Tawila (see next section). Yet the isotopes data collected from this aquifer (Jungfer 1984, NWRA 2001) suggest that this aquifer contains mostly palaeowater since it receives either very little recharge or none at all. As an initial step for resolving this issue, one has to look for any evidence for the occurrence of recharge. Several have been found:

a. The very first groundwater study in the Basin has shown a water level rise in the Quaternary alluvium, Tertiary volcanics, and the Cretaceous (Tawila) sandstones. It ranged from 0.42-1.13 m (South of the city) and 0.13-0.55 m (north of the city) for the period between 1965 and 1972 (Italconsult, 1973, figures 29 and 30). This rise was occurring when the central part of the plain has already become subject to a considerable overdraft as mentioned earlier, i.e. replenishment has been masked by overexploitation in this part.

b. Between 1980 and 1990, a considerable volume of water level data became available, including monthly values and hydrographs for NWSA observation wells. Laes and Bamatraf (1991) reviewed these data for the purpose of detecting water table fluctuations and estimating annual groundwater level declines. Unfortunately, not enough attention was paid to seasonal changes, which normally serve as the first signs of rainfall percolation as a recharge component to the aquifer system. Reanalyzing these data shows clear evidence of 'water mound' following rainy seasons, which eventually disappears as the additional volume of water spreads across the aquifers.
c. The NWSA monitoring program has been discontinued after completion of the SAWAS project, but NWRA has just started a new program. The limited data that have become available so far also show evidence of recharge (see below).
d. Participants in stakeholders meetings arranged during this study have reported on a number of cases where water table has risen significantly due to the construction of small dams in Bani Hushaysh (Mukhtan), Bani Bahloul (Al Lujama), and Sanhan (Hajrat al Dhabayina). Site visits to some of these dams and discussions with locals have confirmed the occurrence of induced recharge in existing wells nearby.

3.2.3.3 Delineation of Recharge – Discharge Zones

Groundwater ***discharge*** can occur naturally at topographically low areas (local or ultimate base level) or via pumping wells. Hence two types of zones may be identified: *natural discharge* zones and *abstraction* zones. Evidence for the occurrence of natural groundwater discharge may or may not appear on the ground, particularly where the shallow environment conditions are favorable for subsurface discharge. Discharge through well abstraction, however, is easily detectable. ***Recharge*** zones are more difficult to detect without proper monitoring. However, it is understood that factors such as rock permeability, altitude and other topographic features, etc. play a major role in controlling the occurrence of subsurface flow into the groundwater system. The criteria applied and the steps followed in identifying these different zones are summarized in table 3.6 below.

Table 3.6: Summary of steps for identifying discharge / recharge zones

Aim	***Criteria used***	***Steps followed***
Identification of base levels and etection of actual natural discharge	Topography, altitude, surface features and drainage systems.	1. Studying the topography sheets (1:50000) and the hydrogeologicl map of WEC-ITC to identify the major physiographic features in relation to the main hydrologic units and hydrogeological zones in the Basin.
		2. Field visits through which it became evident that discharge normally occurs in two points: subsurface into the thick alluvium just south of the limestone plateau (marked M in figure 3.5) and at the surface as outflows from the Wadi Al Kharid system across the limestone (marked K in figure 3.5A).
Delineation of major abstraction zones (areas of human-induced discharge) from irrigation return flow and wastewater	All available data / information relevant	3. Plotting rainfall, evapotranspiration and moisture variation (moistening coefficient isolines) on a separate map (figure 3.5.B). 4. Plotting all 1994 pumping wells from the SAWAS study on a map showing surface exposure of different water-bearing rocks in the Basin (figure 3.5C) as well as any topogphic features that may appear to have some control on the spatial distribution of the wells. 5. Using qat as a main indicator of expansion in irrigation during the period 1994-2000 and, hence, delineating the irrigated areas covered by this crop as identified in the remote sensing study. 6. Plotting the irrigated areas of qat on a topographic map with contour lines to delineate major zones where this crop is currently cultivated as well as likely to expand to in future (figure 3.5D). 7. Delineating the urban zones presently affected or likely to be affected in the future, by wastewater disposal directly or indirectly (figure 3.6A and B).
Delineation of potential natural recharge zones	Primary and secondary permeability of exposed rocks	8. Categorizing of the geologicl units into 3 main groups of different permeability potentials (high, moderate, and low) using the hydrogeological condition map of Mosgiprovodkhoz to identify potential areas of primary permeability. 9. Delineation of the most promising zones by superimposing the fracture system from the hydrogeological map (WEC-ITC, 2001) on the zones delineated through the previous point (figure 3.7A
	Topography and altitude	10. See figure 3.5 A above
	Potential amount of water available for replenishment through natural processes.	11. Using the most recent data available for establishing spatial distribution of rainfall (see section 3.1 above) 12. Calculating the volume of potential runoff and its variation across the Basin (see section3.1 also.
	Moistening and evapotranspiration conditions	13. Examining the interaction between the moistening and evapotranspiration conditions, as depicted in figure 2.2 (Main Report) of the Russian study, to identify the zones where most suitable conditions for rainfed prevail (see figure 3.5D above).
	Overall potential for natural (renewable) recharge occurrence.	14. Superimposing the information obtained through steps 11 to 13 to divide the most promising zones on the basis of their overall potential for recharge (both direct and indirect)- figure 3.7B.

3.2.3.4 Estimation of Recharge

3.2.3.4.1 Previous Studies

Renewable Recharge

Estimates of groundwater recharge have been based on throughput flow and/or infiltration from rainfall, either directly or indirectly. Few actual estimates have been made over the past thirty years or so, which are frequently reproduced in subsequent studies. Often, not enough attention is paid to the background and the source of the figures compiled from other studies such that some confusion may arise. This is perhaps best illustrated by the most recent compilation of data (DAR AL-HANDASAH, 2000) reproduced in table3.7 below.

Table 3.7: Summary of reported recharge in Sana'a Basin (as compiled by DAR AL-HANDASAH, 2000).

Consultant	***Year***	***Recharge Rate, M^3/yr***	***Estimated Recharge Area*, km²***
Italconsult	1973	59	3930 to 6550
Howard Humpheries	1977	45	3000 to 5000
Howard Humpheries	1983	28	1870 to 3111
Charalambous	1982	24	1670 to 2780
USSR	1985	63	4200 to 7000
SAWAS	1990	35	2333 to3889
Alderwish	1995	32	2133 to 3555
Average		41	2733 to 4556

* Assuming a recharge coefficient of 3 to 5 percent and mean annual rainfall of 300 mm.

The data as presented in this table are confusing. Some of the values given in the table are for renewable recharge while others are for total usable groundwater assuming that a substantial volume of this resource enters the Basin from the sandstone outcrops outside its boundary. Similarly, some of the estimates have been reported by original authors for the entire Basin while other values are relevant to specific zones within the Basin only. Taking the average of all reported figures without knowing how they were obtained or what they actually represent could certainly lead to the wrong conclusions.

Figure 3.5A: Main Physiographic Features Showing Main Discharge Zones.

Figure 3.5B: Moisture, Evapotranspiration and Rainfall Distribution.

Figure 3.5C: Major Abstraction Areas in 1994 Based on SAWAS Well Inventory.

Figure 3.5D: Main Abstraction Areas in 2000 Depicted from Qat Irrigation Areas.

Figure 3.6A: Existing and Additional Sanitation Services for the City of Sana'a. (Source: Dar Al-Handasah, 2000)

Figure 3.6B: Sewerage System Construction Phasing. (Source: Dar Al-Handasah, 2000)

Figure 3.7A: Typical Hydrogeological Conditions as Interpreted in terms of Primary and Secondary (fracture) Permeability of Water-bearing Rocks.

Figure 3.7B: Potintial Zone of Direct and Indirect Recharge shown also are the Main Subsurface Discharge Zone (M) and Surface Outflow (K).

A close analysis of the presented data shows that they belong to two main categories: those obtained from NWSA wellfield data and studies (the first four) and those based on more diversified observations (the last three). The following points are relevant to the earlier estimations:

- ***Italconsult*** has actually reported two different values in the final report: one for recharge within the limited area investigated by the consultant (25 Mm^3/yr on page 30) and another for the inflow to the Basin most of which has been assumed to occur as subsurface flow extending to outside the defined boundary of the catchement (67 Mm^3/yr., p. 136). Out of this total inflow, 59 Mm^3/yr has been estimated to occur in the sandstone aquifer (26 Mm^3/yr in the Western wellfield and 33 Mm^3/yr in the Eastern), with the remaining 8 Mm^3/yr in the alluvium and volcanics or flowing in springs. The value reproduced in the table above is therefore what has been estimated by Italconsult as exploitable groundwater in the sandstones due to total inflow (and not recharge alone). Hence if the recharge value reported by Italconsult is plugged into the table instead, the values given for estimated recharge area would change to 1667 to 2778 km^2, which are much closer to the actual area on which Italconsult has used in its calculation (2400 km^2).

- ***Howard Humphreys & Sons (1977)*** re-examined the work of Italconsult using the same approach (throughput technique) and estimated that the exploitable resources were significantly less (31.85 Mm^3/yr).

- ***Charalambus (1982)*** questioned the hypothesis that recharge occurs by deep percolation through the volcanics and commented that the use of 'throughput technique' was probably inappropriate. Instead he suggested that a recharge of about 25 Mm^3/yr takes place mainly through the outcrop areas or where alluvial cover is thin. This is exactly the same value obtained for recharge by Italconsult, considering that they have assumed only half of the area under study was only contributing.

- ***Howard Humphreys & Sons (1983)*** has also rejected the notion of deep percolation and consented with Charalambus that recharge only occurs in wadis where the sandstone is exposed or under thin cover. They suggested that replenishment is far less than previously estimated and gave a figure of 25 Mm^3/yr (800 l/s) for the northeastern sandstone outcrop.

Perhaps the main conclusion to be drown from these early studies is what has been stated by Howard Humphreys & Sons (1983) that '*reliable estimates will only be possible when the extent of the sand-*

stone groundwater catchment is known and the age of groundwater under the volcanic cover has been determined'.

With respect to the first part of this conclusion, the Russian study (Mosgiprovodkhoz (1986) and subsequent investigations have contributed some new information and the lateral extent of the sandstone is now fairly well identified. Its thickness however is still not very well known, particularly in the southern areas where the base of the aquifer is still not reached (see below). Regarding the age of the water, isotopical data indicate that the Tawila sandstone has received little or no recharge (see above). These two facts would suggest that we are still far from being able to determine an accurate figure for the Basin recharge. Nevertheless, an account of the more recent estimates shown in Dar Al-Handasah's table is given below:

- ***Mosgiprovodkhoz (1986)*** actually assigned a value of 55.87 Mm^3/yr to recharge across the entire Basin (51.73 direct infiltration and 4.14 lateral inflow), which was mistakenly reported by following investigators as 63 Mm^3/yr. This happened due to the fact that Dubay et. al. (1984), who were the first to adopt this value, have obtained this figure from the initial results of the Russian study before its finalization.
- The ***SAWAS*** estimation was obtained early on during phase 2 of the study. It was based on a calculation of inflow in the southern part of the Basin which, 'if applicable to the whole Basin' would give a figure of 35 Mm^3/yr. It is obvious that SAWAS team itself had some doubt about this approach. Later on (SAWAS Tech. Report, # 5, 1996) they go back to the old figure of Italconsult (25 Mm^3/yr for 2400 km2) and simply extrapolate it to the entire area (3200 km^2) to come up with a value of 32 Mm^3/yr for the entire Basin, an approach that is still questionable.
- The most extensive analysis of the Basin recharge has been undertaken by ***Alderwish (1995)***. Both renewable and recycled recharge has been included in this analysis but a basic assumption made is that percolation through wadi beds is the most important mechanism of groundwater recharge. The combined results from a groundwater model and a simple method of channel water balance were used to develop a regression model which relates the wadi flow to recharge in two wadi areas : *Dahr* and *Sirr*.. The regression equation was then applied to other wadis across the Basin for assimulating total recharge components for 20 years (1974-1993). The mean values for this period were as follows:

Wadi recharge:	38.5 Mm^3/yr
Irrigation recharge:	18.6 Mm^3/yr
Urban recharge:	8.8 Mm^3/yr
Total recharge:	65.9 Mm^3/yr

- The annual values obtained shows significant variation in total recharge (from 142.7 to 20.5 Mm^3/yr) attributed mainly to very erratic wadi recharge. The variation of this recharge component (from 2.8 Mm^3/yr to 129 Mm^3/yr) seems rather unreasonable. In our opinion, this is due mainly to over-estimation of upland runoff, using the regression equation, which is then translated directly to wadi recharge. The upland runoff (i.e. not including runoff at wadi outlets) calculated by this method ranged from 3.2 Mm^3/yr to 291.8 Mm^3/yr giving an average of 74 Mm^3/yr, which is more than twice the value estimated for the total runoff in the Basin in this study.
- A recharge estimated value that is often quoted (42 $Mm^3/year$) but not included in the above table reproduced by Dar Al-Handash is that of the ***High Water Council*** (TS-HWC (1992). This value has been derived using an empirical approach, based on either a percentage of rainfall (3-5%) or runoff (75%) for areas where mean annual rainfall is above or below 250 mm, respectively.

3.2.3.4.2 This Study

While indirect recharge is a more important mechanism for groundwater replenishment in arid and semiarid regions, quantitative assessment of this recharge component is very difficult. This is mainly due to the large number of factors involved (flow duration, runoff volume, wetted area, hydraulic gradient, soil properties, moisture content, aquifer type and depth, and vegetation cover) and the limited information available on such parameters. In the case of the Sana'a Basin, there is hardly any information on most of these factors. It is therefore not surprising that the estimation obtained so far fails to give any confidence on the amount of recharge occurring throughout the Basin, within reasonable limits of accuracy.

With such limitations, the approach taken in this volume is to carry out both qualitative and semi-quantitative assessment based on a review of available information relevant to each recharge component quantitative assessment based on water based on water balance calculations given in the following volume. The aim is to:

- Delineate potential areas through which recharge is likely to be taking place
- Identify most promising zones, then
- Evaluate the potential recharge in each zone in terms of the maximum and minimum amount of natural as well as human-induced replenishment.

Basic assumptions made were as follows:

- *Renewable recharge (direct):* Average annual rainfall is calculated as decribed above. An infiltration rate of 3 to 5 % is assumed. These two values are applied in calculating minimum and maximum direct recharge from precipitation, respectively.
- *Renewable recharge (indirect):* Spatial distribution of potential runoff is determined as given in section 3.1.2. For the proportion of wadi flow percolating into the groundwater system, a wide range of estimations has been suggested as shown in table 3.8. Based on the data displayed in this table and considering that major wadi channels in the Sana'a Basin are significantly narrower than in the Tihama, the following two values have been adopted:
  - 40 % recharge from flow in main wadi channels
  - 20 % recharge from runoff in other upland areas.

Table 3.8: Summary of data on wadi recharge assessment in some major hydrological basins/wadis in Yemen

% of recharge from runoff	Wadi / Basin	Assessment method	Reference	Remarks
75	Sana'a	Estimation	TS-HWC, vol IX	Based on data eview
60	Sana'a	Regression / extrapolation	Alderwish	Limited data from 2 wadis only (Dahr and Assir)
57	Tihama	Estimation	TS-HWC, vol X	Based on previous assessment by DHV (1988) from long-term rainfall-runoff measurements in major Tihama wadis
20	Tihama	Estimation	TS-HWC, vol X	Same as above but for foothill runoff only
65	Surdud	Simulation modeling	TS-HWC, vol X	Based on one-year (1984) data taken from Van der Gun (1986)

Based on the above data as well as the information given in table 3.6 and figures 3.5 – 3.7, the following generations can be made.

- *Renewable recharge (groundwater inflow):* According to Italcconsult, lateral inflow of groundwater from the sandstone outcrops outside the Basin constituted about 34 Mm^3/yr in 1973 (59-25 Mm^3/yr). Assuming the substantial increase in abstraction over the past 30 years, a reduction of at least 50 % in the inflow is likely to have occurred. Hence and until more data become available, an inflow of 17 Mm^3/yr is considered reasonable.
- *Recycled recharge (urban zone):* City effluents (domestic + industrial) as well as raw sewage contribute to this recharge component. Estimating of the total volume of water consumed and the basis on which discharge from this sector have been calculated are given in chapter 4.
- *Recycled recharge (rural zone):* Recharge in the rural areas is assumed to occur across the entire Basin wherever groundwater irrigation is practised, with an extremely heavy concentration

in the central plain areas between the 2100-2400 m contour lines. Irrigation return data used in previous studies (as a % of groundwater abstracted) are summarized below:

	SAWAS (1996)	***Alderwish (1995)***	***TS-HWC, Vol.X***
Method of assessment	Assumption	Water balance calculation based on limited field experiments (3 sites)	Simulation based on a one-year data
% irrigation return (average)	25	34	36
% irrigation return (specific crops)			
Qat		30	
Grapes		23	
Apples		51	

Considering that *Qat* is the predominant cash crop at the present and assuming that a gradual decrease in irrigation return is likely to be occurring with increasing use of modern irrigation techniques, a value of 25 % is adopted in this study.

3.2.4 Groundwater Storage

Replenishment of the groundwater system from rain events results in the accumulation of fresh water resources in the upper layers of the aquifer system. In addition, subsurface inflow of groundwater from areas outside the catchment boundary may occur, depending on the location of the groundwater basin divides with respect to this boundary. These resources, together, constitute the total volume of water that could be withdrawn from the system (i.e. commandable) as long as the as the natural setting and the prevailing hydrological/hydrogeological conditions remain unchanged. Moreover, accessibility to the commendable water in storage may not be possible under the current economic conditions or technological know-how. What could be obtained under such conditions (i.e.usable storage) may be significantly less than the commendable, depending on the overall situation. This would be ideally the case prior to any groundwater exploitation in the region, inside the Basin or outside within the limits the aquifer system extend to.

Over the past thirty year or so, groundwater abstraction in the Basin has severely disturbed its natural system and at extremely rapid rate since the early 80s. Surrounding regions such as the Amran valley and Dhamar plain have also been subject to serious overexploitation. Adverse effect related to this uncontrolled heavy abstraction has manifested itself most commonly in the form of a widely spreading water level declines across the Basin. Other secondary effects that may eventually become a limiting factor in groundwater use in certain areas include a general increase in the salinity level as well as the appearance of groundwater with a calcium chloride composition that is considered to be unusual (Al-Mooji, 2000).

These observations constitute an undisputed evidence for the dynamic nature of water availability in the Basin. The complexity of the system should also be appreciated because of the various processes (both natural and human-induced), which contribute to maintaining balance in the system through addition or withdrawal from the renewable resources. For example, while overexploitation would certainly contribute to exhausting the usable storage, it may at the same time induce subsurface inflow from outside the Basin. By the same token, recharge inputs from irrigated and domestic areas would rise over the years as the amount of groundwater applied to these areas increases.

Obviously any estimates of the available groundwater resources in a large basin such as the Sana'a require a *continuous* record of geological, climatological, hydrological, etc. data from a *dense*, *representative* monitoring network across the basin. Nevertheless, and until such a network is established, estimates can be made to the best of the information availability. Interpretation of any obtained results, however, should be treated with extreme care bearing in mind that, at best, they may serve as indicators about a system whose dynamics are far from being understood completely.

3.2.4.1 Previous Estimates

Two different approaches have been taken to estimate the renewable water resources in the Basin: calculation of the total annual inflow and assessment of the usable storage. Italconsult (1973) Mosgiprovodkhoz (1986) have applied the first method while the second one was used by TSHWC (1992)

Italconsult (1973)

Conducting the first groundwater investigation in the Basin, the Consultant had no information to enable them estimate inflow by the usual water balance method. On the basis of the limited information obtained during their study duration, they determined the steady groundwater flows in the various aquifers and the perennial average spring flow occurring at the time, then applied a simplified Darcy equation to calculate the volume of groundwater flow. The total groundwater inflow to the Basin has been estimated at 67 Mm^3/year for a study area of 1128 km^2 covering essentially the south-central part of the Basin surrounding the city from east, west and south.. Important findings from this preliminary estimate are outlined below:

- The prepared flow net and flow channels analyzed for making the estimate was prepared from data collected from the Wadi Dahr Cretaceous sandstones and the Quaternary aquifer along the Jabal Nahdayn gorge only.
- The resulting volume of groundwater flowing through this sandstone region (26 Mm^3/year) was considerable such that the abstraction of the present throughput should not greatly affect the hydrodynamic conditions prevailing in the upstream areas (i.e. the Hamdan-Dahr plateau zones).
- For the other sandstone region of Wadi As Sirr, where hydraulic conductivity was available for only borehole, groundwater transmissivity has been assumed to be comparable to Wadi Dahr. The high figure obtained for groundwater flow (33) appeared reasonable considering the significantly wider spatial extent of the outcrops in this region.
- Very little groundwater flow was estimated within the Quaternary alluvial sediments (2 Mm^3/year). The continuous drop in the water level of this aquifer already occurring around the city, as explained above, was considered a good evidence for the paucity of water resources in this aquifer.
- Although the presence of groundwater in the various volcanics (i.e. both Quaternary and Tertiary) has been confirmed, it was not possible to quantify the flow within these water-bearing rocks, because of lack of data on their hydrodynamic state and their hydraulic coefficients. However, the Consultant felt groundwater in these rocks should not amount to very much and, hence, assigned a tentative figure of 3 Mm^3/year as the annual flow volume.

The main conclusion from this study was that *the Basin must stretch much farther south than the limits of the surface drainage catchment*. This conclusion was based on the fact the estimated inflow, when compared with the catchment area, would translate to a recharge of 18% of the average annual rainfall. This was considered excessively high and unreasonable as the overall infiltration coefficient deduced by the Consultant was between 3 and 5% of the rainfall, which was estimated at about 330 mm/year. Furthermore, the Consultant hypothesized that *the groundwater resource in the Tawila sandstones across the plain areas is derived from very deep infiltration that occurs through the trap volcanics in the southern part of the Yemen Highlands*. According to them, the Sana'a Basin constitutes one of the main base-levels of the Yemen Highlands affecting the bedrock aquifers

Mosgiprovodkhoz (1986)

A general statement has to be made about this study before getting into details related to this section. It is apparent that this Consultant has spent a great deal of effort, particularly as they were the first to cover the entire the Basin. A huge amount of data and basic information has become available through the study. Unfortunately, this information has not been presented very well. Moreover, all reports prepared by the Consultant are extremely difficult to read because of poor English.

Like the previous consultant, Mosgiprovodkhoz also considered the Tawila sandstones as the major source of groundwater in the Basin. The Quaternary basalts in southern Arhab were considered second in importance while groundwater confined to the rest of the Quaternary volcanic areas, the Tertiary volcanics, and the Amran Jurassic limestone has been considered of no interest from the water supply point of view. No mention was made on the relative importance of the Quaternary alluvial deposits although clearly included in the Consultant's calculations in table 5.7, pp. 153-162 (Volume 2, part 1: Report). Several observations can be made about this Consultant's approach and main findings:

- The Consultant estimated what they referred to as *predicted usable groundwater resources (PUGR)*, which supposedly comprises both renewable and non-renewable resources (i.e. total storage), by applying hydrodynamic analytical methods.
- Estimation was made only for the upper aquifereous layers (with the exception of Sana'a plain), as conditioned by the large of these deposits (over 300 m), relatively low capacity, and by the fact that the upper aquifer is fed primarily by rainfall infiltration.
- Evaluation of the PUGR was made for existing abstraction areas as well as potential sites for additional groundwater supplies, namely fault zones, wadi beds, and sites adjacent to slopes with highly permeable rocks.
- Natural groundwater resources in these areas are considered to form through infiltrating rainwater, lateral inflow, and vertical leakage through aquifers.
- On the basis of 'hydrographic features of the IInd order', the Basin was divided into two main zones: Zone A (Sana'a Basin) with 11 sub-zones and Zone B (Wadi Kharid) with 5 subzones. Zone A will refer to as Sana'a Plain from this point onwards so as not to confuse it with the main Basin.
- Depending on the topographic relief and structure in each subzone (plateau, slopes, wadi bottoms, and fault area) 66 regions were identified within the Basin.
- The total PUGR in the entire Basin were estimated at about 80.9 Mm^3/year, of which 16 Mm^3/year is in the Kharid zone and 64.9 in the Sana'a Plain zone. Within the latter, 15.1 Mm^3/year has been considered usable within the city well fields existing at the time (Western and Eastern).

TSHWC (1992)

In this study, the concept of renewable and nonrenewable (storage) resources has been applied in estimating the available groundwater resources in the Basin. The basic theme for the study is that *the high profitability of cash crops like qat and grapes has been the major reason behind the tremendous growth of irrigated area which, in turn, is causing water level declines*. The rationale used for the approach was as following:

- The current water use rely heavily on abstraction from the storage, which is difficult to quantify due to limitations in the available hydraulic parameters, particularly specific yield and water levels, and aquifer geometry.
- Since much of the storage occurs at considerable depth, exploitation of these resources for irrigation purposes will be limited to cash crops, especially qat and grapes; abstracting water for low-value staple food crops (such as cereals) will be limited within about 150 meters below ground level (mbgl) as it becomes uneconomical
- The storage depth is less of a constraint for municipal supplies (provided the quality is suitable) and, hence, the deeper aquifer (i.e. the sandstones) could be exploited for this purpose without competition from irrigation.
- For technical reasons, pumping becomes difficult at depths beyond 250 mbgl, hence this level mark has been chosen as the maximum depth to which the groundwater storage can at present be commanded for either high value crops or municipal water use.
- The volume commanded for water supply (i.e. commendable storage) is taken as 50 % of aquifer storage within a pumping lift of 250 meters and non-urban commanded supply (essentially agriculture) is taken as 50% of the storage within a pumping lift of 150 meters.
- Only 50 % of the commendable storage will become available as *usable storage* due to technicalities in abstraction.

3.2.4.2 This Study

Usable Storage

For the same reasons given above, the TSHWC method described above have been adopted. However, our calculation was carried out for the different sub-basins identified in this study. The basic variable applied in this approach (static water level below ground surface) has also been updated (table 3.9) through the following steps:

a. Outcrop areas across the six groundwater provinces as well as subsurface lithological sequence of the aquifer materials were determined by using the relevant maps and hydrogeologic cross-sections.
b. The 1984 water level information for each aquifer type and sub-basin across the entire Basin were summarized from the Russian study.
c. The average annual water level decline, as determined from the socio-economic survey of this study, was applied to estimate the 2001 water levels in each region.
d. Water levels during 1999 were obtained from the NWRA well inventory suevey, which covered four zones (Sana'a area, Sanhan, Bani Al Harith, and Hamdan.
e. 1991 water level data were summarized from the SAWAS study for the central and southern areas of the Basin (8 wadi zones plus the city).

Table 3.9: Estimation of the current water table position in thehydrogeological provinces.

Groundwater Province	***1984 water levels****	***Ave. drop in 2001***	***Estimated 2001 water levels***
Central (B. Bareth-Al Aman)	60 (122)	1.75	90
Eastern(B. Hushaysh)	106.2 (187)	3.0	157
Southwestern (Hamdan-B. Matar)	66.3 (46)	0.8	80
Southeastern (Snhan-B. Bahloul)	52.6 (51)	2.3	92
Northwestern (Arhab)	67.6 (37)	4.5	144
Northeastern (Nihm)	36.5 (21)	0.4	43

* Between brackets is the number of wells from which the average has been calculated.

The current position of the water table has been estimated from steps b,c, and d. The SAWAS data, however, was used to verify the values assumed by the TSHWC, which presumably were for 1991. It can be seen that the water levels applied by the TSHWC into their calculations were over-estimated by between about 15% (for boreholes) and over 100% (for dug wells). As such, values reported for storage by the TSHWC should be taken as very conservative estimates when compared with results obtained in the present study. The spatial distribution and subsurface lithology (table 3.10) were determined from the geological cross-sections and hydrogeological maps presented in previous chapters. The results obtained for usable storage are shown in table 3.11. Previous results by HWC (1992) are given in table 3.12 for comparison purposes.

Table 3.10: Aquifer systems and their distribution across the hydrogeological provinces.

Parameter		***Central***	***Southwestern***	***Eastern***	***Southeastern***	***Northwestern***	***Northeastern***	***Entire Basin***
Total area (km2)		502	428.4	360.3	656.4	677.8	611.8	3236.7
Approximate aquifer spatial distribution	Q_a/K_{sst}	260						
	$Q_v/T_v/K_{sst}$		90					
	Q_v/J_{lst}	14				517.8		
	T_v/K_{sst}	75	283.4	135.3	603.7		40	
	$Q_a/T_v/K_{sst}$	65	20	25	52.7			
	K_{sst}/J_{lst}	80	35	200		40	292.8	
	J_{lst}	8				120	279	
	Total	502	428.4	360.3	656.4	677.8	611.8	

Table 3.11: Usable storage in the hydrogeological provinces.(see index below table 3.12)

Hydrologic Unit	***Province***	***Aquifer***	***Area (km2)***	***SWL (mbgl)***	***Sy (%)***	***ΔB1***	***CS1 (Mm^3)***	***ΔB2***	***CS2 (Mm^3)***	***US (Mm^3)***
Musyrka	Central Plain	Alluvium and sandstones (Q_a/K_{sst})	260	90	3	60	468	160	1248	624
		Volcanics and limestone (Q_v/J_{lst})	14		1		8.4		22.4	11.2
		Volcanics and sandstones (T_v/K_{sst})	75		3		135		360	180
		Alluvium, volcanincs and sandstones ($Q_a/T_v/K_{sst}$)	65		3		117		312	156
		Sandstones and limestones (K_{sst}/J_{lst})	80		1		48		128	64
		Limestone (J_{lst})	8		1		4.8		12.8	6.4
		Total	502				781.2		2083.2	1041.6
	South-Western	Volcanics and sandstones ($Q_v/T_v/K_{sst}$)	90	80	3	70	189	170	459	229.5
		Volcanics and sandstones (T_v/K_{sst})	283.4		3		595.1		1445.3	722.7
		Alluvium, volcanincs and sandstones ($Q_a/T_v/K_{sst}$)	20		3		42		102	51
		Sandstones and limestones (K_{sst}/J_{lst})	35		2		49		119	59.5
		Total	428.4				875.1		2125.3	1062.7
	Eastern	Volcanics and sandstones (T_v/K_{sst})	135.3	157	3	-	-	93	٣٧٧,٥	188.7
		Alluvium, volcanincs and sandstones ($Q_a/T_v/K_{sst}$)	25		3	-	-		69.8	34.9
		Sandstones and limestones (K_{sst}/J_{lst})	200		2	-	-		372	186
			360.3			-	-		819.٣	409.٦
	South-eastern	Volcanics and sandstones (T_v/K_{sst})	603.7	92	2	58	700.3	158	1907.7	953.8
		Alluvium, volcanincs and sandstones ($Q_a/T_v/K_{sst}$)	52.7		3		91.7		249.8	124.9
			656.4				792		2157.5	1078.7
Wadi Al Kharid	North-western	Volcanics and limestone (Q_v/J_{lst})	517.8	144	1	6	31	106	548.9	274.5
		Sandstones and limestones (K_{sst}/J_{lst})	40		2		4.8		84.8	42.4
		Limestone (J_{lst})	120		1		7.2		127.2	63.6
			677.8				43		760.9	380.5
	North-eastern	Volcanics and sandstones (T_v/K_{sst})	40	43	1	107	42.8	207	82.8	41.4
		Sandstones and limestones (K_{sst}/J_{lst})	292.8		3		939.9		1818.3	909
		Limestone (J_{lst})	279		1		298.5		577.5	288.8
			611.8				1281.2		2478.6	1239.2

Table 3.12: Estimates of Commandable and Usable Storage (Mm^3) – TSHWC, 1992

Zones	Area Km^2	SWL mbgl	Sy %	ΔB1 m	CS1 Mm^3	ΔB2 m	CS2 Mm^3	US Mm^3
1. Uplands (Zones A,B,D,E,F)								
Area NE and NW of wellfields:								
Quaternary Volcanics (QV / AL)	325	-	-	-	-	-	-	-
Amran Series (AL)	330	100	1	50	165	150	495	248
Tawilah Sandstone (TS)	590	100	3	50	885	50	885	443
Quaternary Volcanics (QV / TS)	170	-	-	-	-	-	-	-
Quaternary alluvium (Qa / AL)	20		-	-	-	-	-	-
Uplands SE and SW of Sana'a								
Tertiary Volcanics (TV)	1070	100	1	50	535	150	1605	802
2. North plain (Zone C – north)								
Quaternary alluvium (Qa / TS)	260	100	3	50	390	150	1170	585
Tawilah Sandstone (TS)	150	150	3		-	100	450	225
Urban area (Zone C – central)								
Quaternary alluvium (Qa / TV)*	130	50	10	-	-	50	650	650
			1	-	-	150	195	97
Deep Tawilah Sandstone (TS)	130	150	0	-	-	100	1	1
3. South plain (Zone C - - south								
Quaternary alluvium (Qa / TV)	170	50	1	100	170	200	340	170
Deep Tawilah Sandstone (TS)	170	200	0	-	-	50	1	1
Totals	3213				2230		6046	3221

Notes:

SWL = Rest water level in mbgl.

Sy = Specific yield.

ΔB1 = Aquifer thickness above depth of 150 m (low value crops).

CS1 = Commandable storage for low value crops.

ΔB1 = Aquifer thickness above depth of 250 m (urban and high value crops).

CS2 = Commendable storage for urban supplies and high value crops.

US = Total usable storage (50% of commandable storage).

* = The quaternary alluvium (Qa/Tv) has been divided into upper and lower reaches. The usable storage Us for the upper and lower reaches is assumed to be 100% and 50% of CSm, respectively.

Chapter 4: Water Resources Availability: Domestic Wastewater Reuse

4.1 Introduction

The urban population in the city of Sana'a has grown by an order of magnitude in the past 25 years from 135 000 in 1975 to the present estimate of 1 323 536 (see Main Report). The prevailing conditions in the region has resulted in an incredibly high growth rte of 7.54 % in the urban population at the present (CSO, 1999). At this rate, the population could multiply 6-fold over the next 25 years to reach about 9 million by 2025. However, it is more expected that the growth rate will drop in the years to come such that by 2020 the urban population may reach around 4 million. As such, there is still a good chance that the Sana'a area will become one of the major urban zones in the southwetsern Asia region.

In consequence , a tremendous increase in water consumption throughout this urban centre can be expected. This increase will be caused not only by population growth but also by greater per capita consumption as the society continues to adopt modern lifestyles. Moreover, an urban centre of this scale is expected to become so complex that it induces a significant growth of various industries in the urban area as well as a vast expansion of agricultural development within the Basin. This would, in turn, aggravate the existig water-related, particularly between the city and the neighbouring areas that constitute potential zones for further urbanization on the one hand and, on the other, for increased water abstraction in industrial-agricultural expansion.

Up till now, the development of infrastructure srvices in the water supply and sanitation sector could not keep pace with urbanization and population growth. The sewerage networks became deficient in meeting adequate sanitary conditions as a result of which significant portions of the city suffered from sewerage flooding. As the city occurs in a major runoff zone (Wadi As Sailah), the draonage system across the urban zone facilitates mixing of the sewage with natural recharge water feeding the groundwater system. It is estimated that at present about 21.5 % of the urban population represnting only 9.5 % of the total currently inhabited area, are connected to the municipal sewerage system (Dar Al-Handasah, 2000). The remaining 78.5 % still depend on cesspits for direct sewage disposal. On-site disposal of domestic sewage is therefore an important source of groundwater recharge. Moreover, the existing sewerage networks were discharging into oxidation ponds until commissioning of the new wastewater treatment plant near the airport few months ago. Effluent of these ponds (now from the new plant), as well as bypassed raw sewage, flow along Wadi As Sailah where it is mainly used for irrigation (mostly fodder cereal crops)

The limited water use in the past influenced both domestic wastewater quantities and disposal methods. While dry disposal of excreta was widely practiced, limited gray water[1] was usually directed to local gardens for irrigation. As water use increased, water-based disposal methods became a widespread practice leading to greater reliance on on-site cesspits. In the early 1980s, a sewerage system was constructed in Sana'a to cover the old part of the city in addition to areas along the collection mains to a temporary treatment plant consisting of a series of oxidation ponds. Since construction, the sewerage system has been expanding (mainly through more connections and not physical expansion), which resulted in overloading conditions of the oxidation ponds and an increasing percentage of bypassed flows of raw sewage. Collected wastewater from Sana'a was measured in 1994 and 1997 by Al-Hamdi (2000) to average 10,200 and 14,200 m^3/d, respectively. Based on the calculated domestic water consumption as estimated by this researcher, the coverage of the sewerage system and the on-site disposal of domestic wastewater in Sana'a in 1995 were estimated as follows:

a. Sewerage system

Total domestic water consumption:	50,700-53,500 m^3/d
Assume 90% wastewater disposal[2]:	45,600-48,200 m^3/d
Collected wastewater:	10,200 m^3/d (3.7 Mm^3/a)
Coverage of sewerage system:	20% of population

b. On-site disposal

Thus, coverage of on-site disposal:	80%
Raw sewage to cesspits:	35,400-38,000 m^3/d (13-14 Mm^3/a)

4.2 Wastewater Reuse as a Resource

Wastewater becomes a valuable resource when it can be renovated efficiently and economically to a suitably high quality, and where there is a market developing for such water. Arar (1991) lists the following specific reasons for the growing interest in wastewater reuse in developing countries:

1. High population growth, leading to greater quantities of wastewater.
2. Increasing environmental concerns reflected by stricter pollution control measures leading to higher quantities of wastewater to be treated at great expense.
3. Growing water scarcity in many arid and semi-arid regions of the world (increased demand and, hence, willingness to pay).

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[1] Wastewater from kitchen activities in addition to that from washing, bathing and laundry.

[2] 10% of water use is assumed to be lost through consumption, evaporation, spillage, etc.

4. The nutrient value of wastewater adds attraction for agricultural use.
5. Depending on the degree of treatment, reclaimed wastewater is a reliably available resource that may be fit for irrigation, industrial, and municipal uses.

If not properly reused, wastewater should be considered an economic and financial liability since it deteriorates the environment by lowering the economic utility of high-value water resources, and as it requires expensive treatment for those resources to be restored to a quality suitable for further use. On the other hand, when wastewater is collected, treated and reused, in many cases it becomes an economic asset since it allows to replace and hence release higher quality fresh water for higher value uses.

This section consists of two parts. The first part gives an overview of the types of wastewater use, incentives for adopting reuse, and various considerations related to it. The second part analyzes the reuse possibilities in Sana'a.

4.3 Criteria and Types of Wastewater Reuse

Treated wastewater is used in the three main water using sectors: agriculture, municipal and industry. Five general characteristics of wastewater influence decisions concerning reuse:

- Quantity of available wastewater: This is influenced by population, the per capita water consumption, and the sewerage coverage.
- Quality of wastewater: Effluent quality depends greatly on the tap water composition from which the wastewater derives, the type of wastes carried, and the type and degree of treatment.
- Availability and costs of alternative water sources: The easily accessible and cheaper water resources will be developed first, leaving the more expensive alternatives of, for example, import or desalination to the last. The cost of reuse alternatives typically falls between the two extremes.
- Availability of funds: This depends to a large extent upon governmental policies toward infrastructure subsidies and the degree of local cost recovery.
- Public attitude towards wastewater reuse.

Wastewater reuse for agriculture : Wastewater reuse for agricultural irrigation is an old and relatively widespread practice not only in the water short regions, but also in water rich countries. In these cases, the economic rationale is based on avoiding the cost of the deterioration of the rivers that would otherwise be polluted.

Advantages of raw/treated wastewater reuse for irrigation can be summarized as follows:

- An increase in agricultural production, as in many cases, acreage under rain-fed farming is converted to wastewater irrigation.
- Utilization of the nutrient content of wastewater, which results in a reduction of fertilizer application; the economic value of the nutrients in the reused wastewater has been estimated to range 3-5 US¢/m3 (Shuval et al., 1986).

Wastewater reuse for municipal uses: Wastewater reuse for municipal purposes can be divided into two main categories: potable and non-potable uses. Potable reuse of wastewater is further divided into direct and indirect uses. Direct reuse implies that wastewater is treated to a level acceptable for human consumption. Reclaimed wastewater for direct potable use usually goes through two separate conventional and advanced treatment processes. Indirect potable reuse of wastewater is more common and in fact often unwittingly applied through the disposal of previously treated wastewater into surface or groundwater, which is used downstream or down gradient as source for potable water supply.

Non-potable reuse of reclaimed wastewater is one strategy that holds possibly more promise, since it (1) tends to require less expensive treatment, (2) is associated with lower health risks, (3) faces minimal public rejection, and (4) still fully supports resource conservation. Non-potable municipal reuse of reclaimed water can be divided into two general categories, namely outdoor uses and indoor uses. Outdoor uses include the irrigation of landscape, greenbelts, golf courses, public parks, sport fields, etc., in addition to fire-fighting, while indoor uses include toilet flushing, train washing, etc.

Wastewater reuse for industrial and environmental uses: The availability of well treated wastewater at comparatively low cost, and the scarcity of water resources in general or of the good-quality water, are strong incentives for innovative reclamation projects. The use of treated wastewater to reduce, halt, or even reverse saline water intrusion in coastal aquifers is an example of environmental protection. A 32 US$ million reclamation project in Salalah, Oman, consisting of partial wastewater collection, an advanced wastewater treatment plant, and a groundwater recharge system, is expected to produce 20,000 m3 of daily effluent. It was concluded that the project will decrease pollution disposal to the environment, reduce the current seawater intrusion, and will avoid the need for development of costly water supply options like desalination (Walsh, 1996).

Treatment technology selection: The treatment to be adopted for reclamation depends mainly on the wastewater composition, the standards to be met and the particular intended purpose of the effluent.

Complexity of technology varies widely between the simple, low cost oxidation ponds to the expensive reverse osmosis (Figure 4.1). Many developing countries apply raw sewage reuse, mostly in agriculture. This comparatively widespread practice is completely demand-driven and commonly benefits poorer farmers. In these cases the financial incentives for the farmers outweigh both the prohibitive governmental regulations and the presumed traditional or social bias against wastewater reuse.

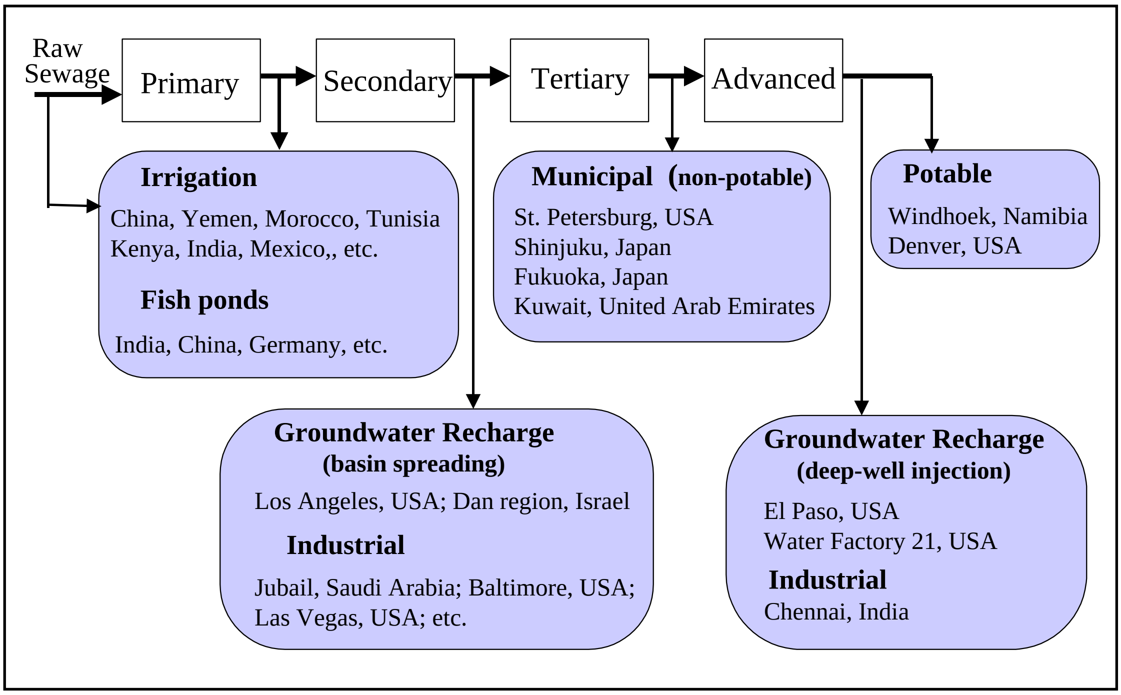

Figure 4.1: Schematic presentation of reuse options and treatment technologies, with examples ("advanced treatment" covers tertiary and in some cases includes reverse osmosis)- Source: Al-Hamdi, 2000.

Socio-cultural perception: Public opinion and acceptance of wastewater reclamation are considered critical factors in wastewater reclamation projects. The view of Islamic tradition towards water seems to be of a ritual[3] nature, while the concerns with health aspects are left to be resolved through the growing human knowledge. In Islam, water has been characterized into three main categories, namely tahur, taher, and mutanajjs. Tahur is fit for ritual uses and considered the cleanest of the three. Although not fit for ritual purposes, taher is considered to be clean enough to be used for mundane uses such as cooking, washing, bathing, etc. The third category, mutanajjs, is considered unclean and not fit for use due to contamination that has changed one or more of its properties (color, taste or odor). Nevertheless, both taher and mutanajjs water can be converted into tahur water if adequate dilution with tahur water takes place, as the resulting water has the general properties of the tahur water.

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[3] Mainly water use for ablution.

Removal of impurities through treatment can also convert taher and mutanajjs water into tahur. A body of Muslim scholars, the Organization of the Eminent Scholars of Saudi Arabia, has approved the reuse of wastewater after adequate treatment for all purposes including ritual uses (Wilkinson, 1978; Farooq and Ansari, 1983). The increasingly positive attitude of Islam towards wastewater reuse may be viewed as an encouraging factor for public acceptance.

Economic and financial considerations: Costs limit the investment in reuse technology in areas where fresh water resources are readily available and thus cheap. As water resources become scarcer, especially in the urban areas of arid and semi-arid zones where the alternative of water import from other regions is associated with expensive conveyance infrastructure and rising competition and conflicts, wastewater reclamation becomes a cost-effective alternative. Similarly, stringent effluent quality standards also promote wastewater reuse as they raise the discharge costs and narrow the cost differential between treatment for discharge, and reuse.

Municipal wastewater reuse projects often are high in capital cost, since besides the expensive sewerage system and treatment facilities, storage and a conveyance and distribution network need to be included.

Since most wastewater reuse projects are directed towards the agricultural sector, sustainability of those projects should take into account the ability and willingness of farmers to contribute to the costs of treatment and distribution. Experience in Peru indicates that local farmers may be willing to compensate for some O&M tasks associated with treatment, storage, and the delivery system through in-kind contributions (Bartone and Arlosoroff, 1987). Nevertheless, it seems that contributions by farmers to recover part of the costs of reclamation projects may only be successful if farmers accept the principle of cost recovery and if other water resources are scarce and expensive.

4.4 Incentives for Wastewater Reuse

Incentives for wastewater reuse vary according to a complex set of national and local circumstances.

Economic Incentives: Economic incentives may be divided into macro and micro-level incentives. Macro-level incentives are those realized from the conservation of water resources or environmental quality by alleviating or delaying the need to develop expensive water supply augmentation projects or by reducing environmental pollution, thus minimizing any future restoration costs. Micro-level incentives are those that trigger individuals to directly prefer, although sometimes at a risk, using renovated or raw wastewater (e.g. the direct, unregulated use of raw sewage for irrigation north of the city.

Financial Incentives: Even though wastewater collection and treatment are considered services for which beneficiaries are to be charged, in many cases, especially in the developing countries, full cost recovery is usually not realized. Nevertheless, in areas facing serious water scarcity, benefits from reuse may justify the additional treatment and distribution costs. Moreover, in other areas with strict effluent quality standards and restrictive discharge criteria, reuse becomes also financially feasible. Governmental policy can thus contribute to the financial feasibility of reuse projects. It may thus be concluded that many developing countries, with limited economic capacity to invest in expensive treatment facilities and with a low cost recovery potential, will find it increasingly difficult to justify reuse projects unless direct financial gains can be made.

Social incentives: With concerns growing over environmental protection and pollution control, the public approval of wastewater reclamation projects is generally rising. However, socio-cultural factors, e.g., perception of the health related risks to bodily contact, and the educational and awareness levels of the public, strongly influence the extent and success of wastewater reuse projects. Some of these perceptions and habits may have been codified in religious and traditional teachings.

Technical incentives: Treatment technology is no longer considered the limiting factor in wastewater reuse projects. Nevertheless, appropriate technology selection to suit the local conditions increases the sustainability and financial feasibility of reuse projects. In the developing countries, with limited financial capacity and abundant unskilled labor, low-technology solutions are usually preferred, which commonly means less mechanization, lower degree of automation and maximum involvement of the local community in the different phases of project implementation (planning, construction, operation and maintenance) (Veenstra et al., 1997).

4.5 Quantitative Aspects of Wastewater Reuse Options in Sana'a

In general, assessing wastewater quantities takes place through direct measurements of influent to treatment plants. In case of partial coverage of the sewerage system, knowledge of the water use can result in adequate estimation of wastewater quantities. In the Sana'a case, not only is the exact coverage of the sewerage system unknown (no regular measurements), the per capita water consumption is estimated to vary widely between those connected to the public water supply and those supplied by private vendors. Thus, using the available population and public water supply production data, generated wastewater quantities in the city can only be estimated (see chapter 3 for assumptions and calculations used to estimate wastewater disposal to on-site cesspits).

Historical data of wastewater flow of the sewerage system were collected from various reports. In order to obtain updated flow records, direct measurement of the water level above the inlet weir of the oxidation ponds were conducted in the period of 4-24 March 1997 by means of a 5 bar Tirtaharapan Absolute Pressure Logger.

In order to measure the total wastewater flow, arrangements were taken to block the bypass outlet so as to force the entire flow to pass the weir and thus enter the collection sump of the pond system. The logger was set to record water level readings with a frequency of once every five minutes. Even though the measurement period (20 days) does not indicate any seasonal variation, it took place during the spring, and hence could represent the annual average of the higher flows during the summer, as a result of the higher domestic water consumption, and lower flows during the winter.

4.5.1 Wastewater quantities

The total inflow to the ponds has been measured at several occasions. NWSA records indicate an average inflow of around 5,000 m^3/d in 1988. The continuous increase in house connections, both legal and illegal, has increased the flow considerably. With about 13,000 house connections, Suleiman (1990) estimated the influent to the ponds in 1990 to be 8,300 m^3/d, covering 17% of the city's population. Ludwig (1991) reported an estimate of 8,000 m^3/d of collected raw wastewater from Sana'a. In 1992, the total wastewater flow was measured to range between 8,000-8500 m^3/d (Veenstra et. al, 1995). The High Water Council (HWC, 1992) indicated that the total wastewater flow to the ponds was 8,000 m^3/d in 1990 and projected an increase to 13,200 and 26,400 m^3/d by the year 1995 and 2025, respectively. The total flow was measured for a period of 10 days in March 1994 to average 10,197 m^3/d, with an average daily peak factor of 1.86 (Howard Humphreys, 1995).

4.5.2 Groundwater recharge

Eighty percent of the city's population discharges around 13-14 Mm^3/a of raw sewage through cesspits to the underground (chapter 3). This discharge contaminates groundwater, thus leading to possible health problems from the drinking of contaminated groundwater and from direct exposure to overflowing wastewater. Although some quality improvement (reduction of suspended solids, BOD and pathogens) is expected from the passage of the leachate through the soil, and from dilution with groundwater, nitrogen and bacteriological contamination have been detected in local shallow as well as deep wells (chapter 3; Wiesenekker, 1996; Al-Hamdi, 1997). Nevertheless, given the water scarcity in the area, this discharge has augmented considerable amounts of recharge water, representing 25-60% of the total average annual natural recharge to the regional aquifer (Figure 7.8).

In the household, groundwater, whether supplied from the public distribution network or from private vendors, is mostly used for non-potable purposes; most drinking water is obtained from bottled mineral water or containers sold by private filtration stations. The continuous growth of the city and the financial constraints to expand the sewerage system, suggest that the use of cesspits will continue to expand for the foreseeable future. It is, therefore, advisable to re-evaluate, and regulate, direct discharge of untreated wastewater to the underground in order to maximize groundwater recharge, while at the same time minimizing the environmental and health effects. The mandatory use of on-site pretreatment units, such as septic tanks, prior to final discharge to cesspits could enhance the quality of percolating wastewater through a reduction in suspended solids and BOD, and may, on the long run, prove attractive for consumers (lower rate of clogging, and thus shallower cheaper pits).

4.5.3 Direct irrigation of fodder and cereal crops

As of 1997, a total of 14,200 m^3/d or 5.2 Mm^3/a of raw sewage is collected from the city to the oxidation ponds at Al-Rowdda, north of Sana'a. Part of the collected flow (in the order of 40–50%) is treated, while the rest is bypassed to the ponds' discharging point in a natural channel along the Bani-Howat wadi (Figure A2.1, Appendix 2). During the winter months (non-irrigation season) the water reaches a natural evaporation/infiltration pond near the village of Bait Daghaish, about 23 km north of Sana'a. During the summer, the flow is fully utilized by the farmers downstream of the ponds. Wastewater irrigation is mainly taking place within the wadi, along a strip of approximately 80 meters wide and 13 km long to form a total cultivated area of around 100 hectares. This area would not be used to cultivate fodder and cereal crops if wastewater were not available, but most probably it would be converted to dry farming (cereals) or groundwater irrigation (cash crops). The wastewater irrigation is dominated by the cultivation of sorghum, wheat, and alfalfa, in addition to some onions, tomatoes and potatoes. Naturally growing grass along the wadi is mainly used for animal grazing. Farmers obtain wastewater either from gravity diversion of the main channel to the fields or through pumping, using small portable suction pumps, from small retention ponds that facilitate pumping and at the same time yield stable settled sludge that is then used as fertilizer or soil conditioner. Basin irrigation is the main irrigation method; nevertheless, some furrow irrigation was observed. No protective measures[4] seem to have been taken by farmers during wastewater irrigation; nearly all agriculture related activities are performed manually in similar ways irrespective of the origin of the irrigation water.

With the exception of some vegetable plots, cash crops, particularly qat and grapes, are seldom irrigated with wastewater. Farmers consistently reported that wastewater irrigation of qat and grapes is mostly negative. Unspecified yield reductions and a change in the taste of grapes were suspected by farmers to be the result of wastewater irrigation. Among farmers, wastewater is thought to “burn” qat trees, as a change in leaf color and yield has been experienced in the past.

Direct wastewater disposal is prohibited by Law[5] unless the discharging agency (in this case, NWSA) takes the necessary measures to remedy all adverse effects associated with such discharge. Article 30 of the Environmental Protection Law establishes regulatory standards for the collection, treatment, discharge and reuse of wastewater. These standards combine the three major guidelines of WHO, FAO, and USEPA for wastewater reuse (Ayers and Westcot, 1985; Mara and Cairncross, 1989; Pescod, 1992). The WHO guidelines were adapted to minimize the direct health hazards of wastewater irrigation. The FAO guidelines deal mainly with the chemical quality requirements for irrigation water and the USEPA recommendation limit trace elements in irrigation water.

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[4] Any measure to avoid contact with wastewater such as wearing boots or gloves.

[5] Environmental Protection Law (Law No. 26, 1995).

4.6 Discussion of Options for Wastewater Reuse in Sana'a

Identification of alternatives and criteria

Given the wastewater quantity and quality expected from the new treatment plant in Sana'a, six alternative reuse options can be identified for evaluation. These alternative *scenarios* are: (1) direct irrigation of fodder and cereal crops, (2) direct irrigation of existing groundwater irrigated cash crops fields, (3) groundwater recharge and recovery for irrigation of existing groundwater irrigated cash crop fields, (4) groundwater recharge and recovery for potable use, (5) municipal irrigation of public areas and green belts, and (6) non-potable domestic use. For simplicity these options will be referred to as scenarios (1) through (6) in the following sections. These alternatives are evaluated against five main *criteria* or *objectives*, i.e. (1) minimal health hazards, (2) minimal costs, (3) maximal public acceptance, (4) minimal environmental impact, and (5) maximal water resources conservation. These objectives are refered to as criteria (1) through (5). The identified scenarios are evaluated and accordingly scaled and valued against the five criteria factors (sections 9.2-9.6), and the outcome is summarized in Table 7.10. The valuation is based on a scale of 4 points, from –3 to 0, corresponding to increasing attainment of the objective.

Health hazards

The health effects associated with the presence of organic and inorganic chemicals in wastewater are excluded from this analysis due to the limited knowledge of their short and long-term health implications and the confined scope of this research. The analysis here is limited to the direct hazards from pathogenic organisms (helminths, bacteria and viruses). A scale of 0 to -3 is used, where 0 indicates no risk, while -1, -2 and -3 indicate low, moderate and high risk, respectively. For scenario 1, a low risk score -1 reflects the limited contact of wastewater to farmers and the disinfected nature of the effluent. Scenario 2, carries the additional potential risk to consumers, thus increasing the risk score to -2. For scenario 3, the associated health risk is almost nil due to the additional natural purification and dilution that takes place in the underground layers, which justifies a risk score of 0. If the recharged wastewater is to be recovered for potable use (scenario 4), then two factors influence the associated health risks, namely, the extra treatment prior to recharge, and the additional treatment prior to consumption. Nevertheless, given the origin of the recharged water, a low risk score of -1 is used in this analysis. For scenario 5, the main health risks will depend mainly on the reliability of the disinfiction process and the effectiveness of the management and regulation. Although it is quite difficult to assess the health risks associated with this alternative, especially given the inadequate local institutional environment, an overall low/moderate -1/-2 risk score is used. The health risk associated with scenario 6 depends on the extra treatment needed to upgrade the effluent to acceptable quality. The high contact level to which consumers are exposed, which includes washing, bathing, cooking, etc., justifies the use of a moderate risk score of -2.

Costs

Although for the purpose of comparison here the cost of sewage collection and treatment are excluded, the costs for the additional treatment, conveyance, injection, recovery and storage are to be included. A cost score of 0 to -3 is used to analyze each of the alternative options for additional costs, where 0 indicates no added costs, and -1, -2 and -3 reflect low, moderate and high additional costs, respectively. For scenario 1, no additional costs are considered since treated wastewater would flow through the wadi to be used by farmers along the natural effluent channel, and thus a score of 0 is used. For scenario 2, a cost score of -2 is used, which reflects the need for conveyance structures to transport treated wastewater to groundwater-irrigated cash crop areas, in addition to costs for inter-seasonal storage. For scenario 3, a cost score of -2 reflects the need for injection and recovery wells, in addition to conveyance structure to transport the recovered water to existing groundwater-irrigated cash crop areas. A maximum cost score of -3 is used for scenario 4, which reflects the need for extra treatment prior to recharge and delivery in addition to injection and recovery wells. In order to reuse the treated wastewater for scenario 5, a distribution system and storage facility are needed, reflected in a cost score of -2. For scenario 6, a dual distribution may be needed in addition to extra treatment and storage facilities, thus justifying the use of the maximum cost score of -3.

Public acceptance

In order to evaluate the reuse options with respect to public acceptance, the degree of bodily contact either to the farmer (occupational risk) or end-user is taken as a key variable, assuming that acceptance is inversely proportional to the perceived degree of bodily contact. A scale of 0 to -3 is used to quantify public acceptance, where a score of 0 indicates no contact and thus maximum acceptance, while -3 indicates maximum contact (drinking) and hence maximum rejection. Scenario 1 suggests a low level of bodily contact (limited to farmers) and since most cultivated crops are not intended for human consumption, an acceptance score of 0 is used. On the other hand, a score of -2 for scenario 2 is justified by the high likelihood that consumer preference would lower the value of effluent-irrigated cash crops, especially since freshwater-irrigated cash crops are widely available. Consumers may not object to cash crops irrigated with groundwater, originally recharged with treated effluent (scenario 3), and, thus, this alternative comes with a score of 0. On the other hand, even though extra treatment prior to both recharge and consumption may be necessary, public rejection is expected to be high if the recovered groundwater (scenario 4) is used for potable use. A maximum score of -3 is used in this case. Scenario 5 is associated with a limited degree of bodily contact, especially if precautions[6] are taken, thus reducing the score to a low -1. Higher degree of bodily contact associated with wastewater reuse for scenario 6 suggests the use of the higher score of -2.

4.6.1 Scenario evaluation and selection

During the previous analysis, cross-valuation between those variables was not taken into account. In other words, the conservation score of -3, which indicates a lack of contribution towards water resources conservation, is not necessarily equal in weight to the -3 factor for public acceptance. Even though it is beyond the scope of this work, partial cross-valuation of the five variables is attempted below.

The first four criteria are directly related to the quality of the wastewater, while only the last criterion is related to its quantity. Because of the overriding importance of the water scarcity, this criterion should be attributed more weight by multiplying all conservation factors by a common correction factor. This correction factor can be approximated through the ratio between the cost to develop a sustainable new water resource, which in Sana'a's case is import of desalinized seawater, and the cost to upgrade wastewater to high quality through advanced treatment. It is reported that desalination and delivery of desalinized seawater to Sana'a from the coastal area would cost around 7.5 US$/m^3, while secondary plus advanced wastewater treatment7 costs are in the order of 2-2.5 US$/m^3 (Asano, 1985; Kruseman, 1997). The ratio of the two costs, 3, is used to correct the factor values (Table 4.1).

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6 Could include: awareness programs, warning signs, low pressure irrigation techniques, and nighttime irrigation scheduling.

7 Including reverse osmosis.

Table 4.1 Multi-criteria analysis of wastewater reuse scenarios in Sana'a.

Criterion Scenario	(1)	(2)	(3)	(4)[a]	(5)[b]	Arithmetic sum[b]
(1)	-1	0	0	-1	-2 (-6)	-4 (-8)
(2)[c]	-2	-2	-2	-1	0 (0)	-7 (-7)
(3)[c]	0	-2	0	-3	0 (0)	-5 (-5)
(4)	-1	-3	-3	-1	0 (0)	-8 (-8)
(5)	-1/-2	-2	-1	-1	-2 (-6)	-7/-8 (-11/-12)
(6)	-2	-3	-2	0	0 (0)	-7 (-7)
	0 = No risk -3= Max. risk	0=No extra cost -3=Max. cost	0=Max. acceptance -3=Min. acceptance	0=No threat -3=Max. threat	0=Max. contribution -3=No contribution	

a Reflects mainly groundwater contamination.

b Values between brackets have been multiplied by a correction factor of 3.

c Using wastewater to replace groundwater.

Table 4.1 identifies two distinctive categories of feasible reuse alternatives: those with a summation of less than –5, and those with a summation of greater than or equal to -5. The two scenarios 1 and 3 have the highest overall score and are the most appealing. On the other hand, scenarios 5 and 4 have the lowest potential. Even though wastewater reuse for fodder and cereal crops appeared earlier to be an obvious option, it shifts to the less-appealing category after corrected for water scarcity. Although this alternative brings an extra income for some local farmers, it does not contribute towards the conservation of water resources. It is clear from Table 4.1 that the only truly attractive alternative for wastewater reuse in Sana'a is groundwater recharge and recovery for irrigation of existing groundwater-irrigated cash crop fields.

4.7 Conclusions and Recommendations

Due to a low per capita water consumption in the Sana'a city, the wastewater production quantity is small (7-9%) when compared to over all water demand in the basin area.

As of 1997, the collected portion of wastewater totals around 5.2 Mm^3/a, which represent about 20-25% of the total wastewater production within Sana'a. This portion is currently being utilized by farmers, mostly to irrigate fodder and cereal crops along the effluent channel.

At present, 75-80% of the total raw sewage from the city is discharged to the underground via cess-pits, thus artificially recharging the underground aquifers, but also causing unchecked local ground-water contamination. This contamination has lead a large portion of the population to rely on private unregulated small filtration stations for drinking water.

Even though direct irrigation of fodder and cereal crops is considered financially beneficial to a small number of farmers, it has not reduced any pressure on the local groundwater resources.

At present, the quality of the wastewater makes it unsuitable for agricultural reuse, which is mainly attributed to the unsatisfactory treatment in the overloaded oxidation ponds and high percentage of bypassed flow.

With the new treatment plant (under construction), there will be greater capacity to withstand future expansion of the sewerage system and produce adequate quality effluent for further reuse.

Given the local circumstances in the Sana'a basin, evaluation of six reuse alternatives shows that groundwater recharge and recovery for cash crops irrigation is likely the most appropriate alternative.

Chapter 5: Groundwater Consumption

5.1 Introduction

The widespread terraced fields and rain harvesting structures (in upland plains and hill slopes) and wadi training and diversion structures (in spate areas) stand as evidence of the high efficiency acquired by the local inhabitants in the Basin over generations in utilizing the limited surface water available in the Basin. In terms of water resources management, therefore, very little can be done regarding surface water, mainly in relation to maintenance and rehabilitation works. Most activities towards sustainability, however, are expected to be related to the groundwater resources. Such activities are to be targeted towards augmenting the supply (supply management) as well as regulating abstraction and increasing water-use efficiency (demand management).

The aim of this chapter is to give an overview of the current groundwater abstraction in the Basin, the relative consumption in the three main sectors (agricultural, domestic, and industrial), and the possible future trends over the planning period.

5.2 Demand in Agriculture

5.2.1 Background

Several studies have attempted to estimate the amount of groundwater consumed in irrigation. These estimates were based either on well inventory data alone (SAWAS, 1996) or crop water demands determined from agronomic investigations (TS-HWC, 1992) or both (Italconsult, 1973). Moreover, irrigation water requirements were obtained through a variety of methods, including specific modeling programs such as the FAO “CROPWAT” (TS-HWC, 1992) and specialized remote sensing-satellite imagery techniques (WEC-ITC, 2001).

Review of the available data indicates inconsistencies in some of the main data used (e.g. irrigated areas) or assumptions made (e.g. crop water requirements and irrigation efficiencies) as a result of which it is difficult to correlate data. To overcome this, our aim in this study is to: (i) establish criteria for irrigation water requirement calculation, and (ii) apply such criteria to assess the present situation and making future extrapolations.

5.2.2 Irrigation Water Requirement (IWR)

Two main parameters are required for estimating IWR: irrigation efficiency (IE) and water demand (WD) by the different crops cultivated. Based on a review of IE estimations from different regions across the country, the High Water Council (TS-HWC, Vol. V) recommends the following figures for obtaining a reasonable range of IWR values in any region:

35 %: low efficiency
55 %: medium efficiency
75 %: high efficiency.

The rationale behind using such a range rather than a single value is to allow inter-regional as well s intra-regional comparisons. This is particularly relevant to a region such as the Sana'a Basin where both high efficiency (e.g. in terraced slopes) and low efficiency (e.g. in central plain areas) can be expected.

For WD calculations, it is essential to obtain reasonable estimates of the crop evapotransiration (ET_c) and the irrigated areas (IA) of the different crops cultivated through groundwater application. The irrigated crops currently grown across the Basin have been classified through remote-sensing / satellite images (WEC-ITC, 2001) into: qat, grapes, fruit trees, and mixed cereals & others. The last crop will be excluded from the present calculations assuming that groundwater use is practically limited to qat and grapes, cash crop that are expected to expand farther in the future. This may be an over-simplification at the present that may be justified as follows:

- Cereals are predominantly grown in highland plains (upland plateau areas) and lowlands (Wadi Al Kharid region) that essentially constitute rainfed-spate-baseflow mixed irrigation zones.
- Field observations show increasing expansion of qat, often inter grown with grapes, at the expense of fruit trees extraction as a result of which many areas have been (and still are) converted to groundwater irrigation.
- Recent flooding of the urban market with more fruit at lower prices, due mainly to inadequate marketing and storage facilities, suggest that an increasing number of farmers may be motivated towards growing more qat at the expense of fruit trees.

5.2.3 Groundwater Consumption in the Sector

With regards to estimating groundwater consumption in irrigation, the IWR per hectare for qat and grapes, calculated on the basis of data presented by the HWC, are given below:

IWR (*10^3 m^3/ha)	***Low efficiency***	***Medium efficiency***	***High efficiency***	***Average****
Qat	20.5	14.2	7.9	14.2
Grapes	27.5	19.1	10.6	19.1

Notice that the average IWR m^3/ha values correspond to those at medium efficiency and are higher than the values used by the HWC (see Vol. IX, table 2.1, p. 8) and corresponds to that at medium efficiency (55 %).

Applying the above data to the irrigated areas, as determined recently by WEC-ITC (2001), gives the total water demand values shown in table 5.1.

Table 5.1A: Irrigation Water Demand (Mm3) for the year 2000

	Low efficiency		Medium efficiency		High efficiency	
	Qat	Grapes	Qat	Grapes	Qat	Grapes
IWR (*10^3 m^3/ha)	20.5	27.5	14.2	19.1	7.9	10.6
Total area (*10^{3}ha)	11.1	8.1	11.1	8.1	11.1	8.1
Total demand (Mm^3)	227.1	225.1	157.3	155.8	87.5	86.5

To judge which of the above scenarios is more representative of the actual field situation, real data are needed. Data available on field groundwater application are summarized below:

	Alerdwish (1995)		Al-Hamdi (2000)		This study	
	Qat	Grapes	Qat	Grapes	Qat	Grapes
Aver. water application						
(m/yr)	-	-	1.25	0.80	0.80	0.80
(*10^{3}m^3-ha)	8	7	12.5-15	8-9.5	-	-

Al-Hamdi explained the higher water application in qat at the time of the survey (1996-1998) as an over-irrigation that reflected farmers' 'priority', who apparently did not want to take any risk with the harvest from this crop. The above data would therefore indicate that the IWR for both qat and grapes are most likely around 8,000 m^3/ha. This would suggest a total irrigation water demand of about 154 Mm^3/yr for the year 2000, which implies that irrigation practice is likely to be close to high efficiency conditions (75 %). This, in turn, means the total groundwater abstracted for irrigation during this year is around 205 Mm^3. This value is almost identical to the figures projected by the HWC for this year (207 Mm^3).

Table 5.2: Expansion in Qat / Grapes cultivation between 1984 and 2000 (Sources Mosgiprovodkhoz, 1986; TS-HWC, 1992; Al-Derwish, 1995; and Al-Hamdi, 2000)

	1984	1990	1993	1996	2000
Qat (ha)	1195	6657	7993	5500-8000	11080
Grapes (ha)	697	3944	4753	5400-7900	8156
Total (ha)	1892	10601	12746	10900-15900 (aver.=13400)	19236
IWR- Mm^3 (@8000 m^3/ha)	15.1	84.8	102.0	107.2	154.0
Water use- Mm^3 (@75 % efficiency)	20.1	113.0	136.0	143.0	205.0

Expansion in qat/grapes cultivation across the Basin over the last few years is shown in table 5.2 extrapolating from the data in this table gives the projected values shown below:

Year	***Water Use*** ***(Mm^3)***
2005	240
2010	283
2015	327
2020	394
2025	465

5.3 Groundwater Use for Domestic Supply

In the absence of actual statistics, a reasonable estimation of consumption in domestic use can be achieved with the availability of two pieces of information: population census and average per capital consumption in both urban and rural areas. Official records on population census are available from the Central Statistics Office for the years 1975, 1986, and 1994. Per capita consumption, on the other hand, is normally left to consultants' judgment since there are no published official figures. The most recent assessment on groundwater use for domestic water supplies (SAWAS, 1996; Al-Hamdi, 2000; and Dar Al-Handasah, 2000) are all based on the 1994 census but use different figures for growth rate and per capita consumption.

All three studies concentrated on demand in the urban area. Both SAWAS and Dar Al-Handasah predict that the official growth rate of 1994 (6.1%) will decline in the future (at least till the year 2025) while Al-Hamdi expects a possible increase after sometime. He also assumes a slight drop in per capita use of public supply (from current 75-78 for 1995 to 70 l/d) while use of private supplies remains the same (40 l/d). On the other hand, SAWAS assumes prevailance of an estimated average of 50 l/d (range: 26-70 l/d) up to 2025. Three scenarios given in these two studies are compared in table 5.4

Table 5.4: Different Scenarios for population increase in greater Sana'a urban area as predicted by SAWAS (1996) and Al-Hamdi (2000).

	Limited grow rate		***Moderate grow rate***		***High grow rate***	
	Population ($*10^3$)	***Growth rate***	***Population ($*10^3$)***	***Growth rate***	***Population ($*10^3$)***	***Growth rate***
1995						
SAWAS	1,007,000	5.7 %	1,008,000	5.8 %	1,010,000	6.0 %
Al-Hamdi	972,011	8.83 %				
2000						
SAWAS	1,270,000	4.2	1,303,000	5.0 %	1,336,000	5.6 %
2010						
SAWAS	1,701,000	2.7 %	1,965,000	4.0 %	2,233,000	5.2 %
AL-Hamdi	1,676,300	3.7 %	2,020,700	5.0 %	3.540,500	9.0 %
2025						
SAWAS	2,343,000	2.0 %	3,387,000	3.6 %	4,671,000	5.0%
AL-Hamdi	2,890,900	3.7 %	4,200,900	5.0 %	12,896,300	9.0 %

The results displayed in this table show significant variation, which reflect the large differences in the adopted/assumed values of population growth rate and per capita consumption.

In the light of these officially published growth rate data, the SAWAS / Al-Hamdi estimation can be assumed to represent lower and upper boundaries for the expected situations in the urban region. Comparison of population growth in both the urban and rural areas was presented by Dar Al-Handasah as shown in table 5.5A.

Table 5.5A.: Urban and Rural Population in Sana'a Basin as predicted by Dar Al-Handasah (2000) - Millions.

Year	***Urban***	***Rural***	***Total***
2000	1.30	0.74	2.04
2005	1.64	0.81	2.45
2010	2.00	0.89	2.89
2015	2.39	0.99	3.38
2020	2.82	1.08	3.90

1. Growth rate:

    Urban: 5.6 % in Base year (1997) assumed to decline to 3.3 % in 2020.

    Rural: 2 % based on previous studies estimates (not specified).

2. Population in census year (1994): Urban = 954,448; Rural = 657,100.

The Consultant gives demand forecasts for the urban zone that, at the present, occupies about 110 km^2 compared with 77.4 km^2 and 94.5 km^2 in 1990 and 1995, respectively. This rapid and vast expansion into the surrounding rural areas signifies that groundwater abstraction within the current administrative boundaries of '*Amanat Al-Asimah'* (national capital) is for both domestic and non-domestic purposes including institutions use, commercial, industrial and public gardens/urban irrigation. The forecasts shown in table 5.5B represent the situation where the course of events develop with hardly any intervention (Option I-Do Minimum). The Consultant also describes two other options in which the total supply requirement is expected to double or almost triple with the provision of adequate sanitary services.

It appears that Dar Al-Handasah has not paid attention to the fact that not all rural populations of the Governorate live within the Basin. By assuming a rural population of 657,100, their projections for this sector are significantly over-estimated. In the present study, the proportions of the population in the 9 major districts encompassed by the Basin are estimated on the basis of information obtained from the 1994 census suppled by Dr. A. Aziz Thabet of the WB, with thankes).

Table 5.5B: Extrapolation of water demand for domestion use by Dar Al-Handasah, 2000

	Unit	1997	2000	2005	2010	2015	2020
Population Total: of which	No.	1123942	1306688	1640091	2005034	2398657	2821433
Existing system		832717	885204	1100690	1368633	1701802	2116075
		292225	421484	539401	636401	696855	705358
Domestic							
	(l/c/d)	46	35	35	35	35	35
Non Domestic							
	(%of Total)	30%	30%	30%	30%	30%	30%
Total Domestic Consumption							
	m^3	1875	16.69	20.95	25.61	30.64	36.04
Total Non Domestic Consumption							
	m^3	8.03	7.15	8.98	10.98	13.13	15.45
Total Consumption							
	m^3	26.78	23.85	29.93	36.59	43.78	51.49
Total Supply Requirement including physical losses @ 20% of production							
Option 1	(MCM)	33.48	29.81	37.41	45.74	54.72	64.36

Selection of growth rates and per capita consumption were based on two major considerations:

1. It is likely that the recently observed high growth rate in the urban zone is being gradually offset by a corresponding rise in the population of surrounding rural areas. Among the main factors contributing to this would be the expanding facilities in the city outskirts induced by the growing complexity of roads network and heavy traffics, increasing number of city dwellers, etc. due to Government centralization as well as innovation of job opportunities.

2. With the current expansion, the neighboring rural areas are gradually shifting to ‘more-water – demanding’ domestic life styles which, in turn, would necessitate higher per capita consumption.

Based on these hypotheses and taking into consideration the growth and per capita consumption rates as described above, the new calculations are performed for three different ‘water demand’ zones: urban water demand zone (UW), rural water demand (RW), and urban-rural (mixed) water demand (URW) zone. (See Main Report for location). Adopted growth and per-capita water demand rates assumed for each zone are given below:

	UW	URW	RW
Growth rate (%)	5.6	3.0-3.5	2.0
Consumption/head (l/d)	70	35	21
Per-capita consumption (m^3/yr)	25.55	12.78	7.67

The results obtained (table 5.7B) appear to be very reasonable judging the consumption for the base year (24.4 urban Mm^3) when compared with the value of 26.2 Mm^3 for consumption in the following year (1995) as estimated by SAWAS.

Table 5.6: Projection of the population in Sana'a basin (by district) based on 1994 Census.

	Urban	**Urban - Rural**			**Rural**						**Total**
District	**Sana'a**	**Bany Al Hareth**	**Bany Hushaish**	**Sanhan**	**Hamdan**	**Bany Matar**	**Bany Bahlowl**	**Arhab**	**Khawlan**	**Nehm**	
Percent	**5.6 %**	**3.5 %**	**3.0 %**	**3.5 %**	**2.0 %**	**2.0 %**	**2.0 %**	**2.0 %**	**2.0 %**	**2.0 %**	
1994	954,448	49,179	54,375	46,518	47,415	34,370	14,481	27,061	14,704	8,397	1,250,948
1995	1,007,897	50,900	56,006	48,146	48,363	35,057	14,771	27,603	14,998	8,565	1,312,306
1996	1,064,339	52,682	57,686	49,831	49,330	35,759	15,066	28,155	15,298	8,736	1,376,882
1997	1,123,942	54,526	59,417	51,575	50,317	36,474	15,367	28,718	15,604	8,911	1,444,851
1998	1,186,883	56,434	61,200	53,380	51,323	37,203	15,675	29,292	15,916	9,089	1,516,395
1999	1,253,349	58,409	63,036	55,249	52,349	37,947	15,988	29,878	16,234	9,271	1,591,710
2000	1,323,536	60,454	64,927	57,182	53,396	38,706	16,308	30,476	16,559	9,456	1,671,000
2001	1,397,654	62,569	66,874	59,184	54,464	39,480	16,634	31,085	16,890	9,646	1,754,481
2002	1,475,923	64,759	68,881	61,255	55,554	40,270	16,967	31,707	17,228	9,838	1,842,382
2003	1,558,574	67,026	70,947	63,399	56,665	41,075	17,306	32,341	17,572	10,035	1,934,941
2004	1,645,855	69,372	73,075	65,618	57,798	41,897	17,652	32,988	17,924	10,236	2,032,415
2005	1,738,022	71,800	75,268	67,915	58,954	42,735	18,005	33,648	18,282	10,441	2,135,069
2006	1,835,352	74,313	77,526	70,292	60,133	43,590	18,365	34,320	18,648	10,649	2,243,188
2007	1,938,131	76,914	79,852	72,752	61,336	44,461	18,733	35,007	19,021	10,862	2,357,069
2008	2,046,667	79,606	82,247	75,298	62,562	45,351	19,107	35,707	19,401	11,080	2,477,026
2009	2,161,280	82,392	84,714	77,934	63,814	46,258	19,490	36,421	19,789	11,301	2,603,393
2010	2,282,312	85,276	87,256	80,662	65,090	47,183	19,879	37,150	20,185	11,527	2,736,519
2011	2,410,121	88,260	89,874	83,485	66,392	48,126	20,277	37,893	20,589	11,758	2,876,774
2012	2,545,088	91,349	92,570	86,407	67,720	49,089	20,682	38,650	21,001	11,993	3,024,549
2013	2,687,613	94,547	95,347	89,431	69,074	50,071	21,096	39,423	21,421	12,233	3,180,255
2014	2,838,119	97,856	98,207	92,561	70,455	51,072	21,518	40,212	21,849	12,478	3,344,327
2015	2,997,054	101,281	101,154	95,801	71,865	52,094	21,948	41,016	22,286	12,727	3,517,225
2016	3,164,889	104,826	104,188	99,154	73,302	53,135	22,387	41,836	22,732	12,982	3,699,431
2017	3,342,123	108,495	107,314	102,624	74,768	54,198	22,835	42,673	23,186	13,241	3,891,457
2018	3,529,282	112,292	110,533	106,216	76,263	55,282	23,292	43,527	23,650	13,506	4,093,842
2019	3,726,921	116,222	113,849	109,933	77,789	56,388	23,758	44,397	24,123	13,776	4,307,156
2020	3,935,629	120,290	117,265	113,781	79,344	57,515	24,233	45,285	24,606	14,052	4,531,999
2021	4,156,024	124,500	120,783	117,763	80,931	58,666	24,717	46,191	25,098	14,333	4,769,006
2022	4,388,762	128,857	124,406	121,885	82,550	59,839	25,212	47,115	25,600	14,619	5,018,844
2023	4,634,532	133,367	128,138	126,151	84,201	61,036	25,716	48,057	26,112	14,912	5,282,222
2024	4,894,066	138,035	131,982	130,566	85,885	62,257	26,230	49,018	26,634	15,210	5,559,884
2025	5,168,134	142,867	135,942	135,136	87,603	63,502	26,755	49,998	27,167	15,514	5,852,617

** Growth rate of only 3.0% since this district has more mountaneous areas compared with Sanahan and Bani Al-Harith.*

Table 5.7A: Projection of the population in Sana'a basin (by water-use zone and district), based on 1994 Census.

Zone	**Urban**	**Urban - Rural**			**Rural**						**Total**
District	**Sana'a**	**Bany Al Hareth**	***Bany Hushaish**	**Sanhan**	**Hamdan**	**Bany Matar**	**Bany Bahlowl**	**Arhab**	**Khawlan**	**Nehm**	
Percent	**5.6 %**	**3.5 %**	**3.0 %**	**3.5 %**	**2.0 %**	**2.0 %**	**2.0 %**	**2.0 %**	**2.0 %**	**2.0 %**	
1994	954448	49179	54375	46518	47415	34370	14481	27061	14704	8397	1,250,948
2000	1,323,536	60,454	64,927	57,182	53,396	38,706	16,308	30,476	16,559	9,456	1,671,001
2005	1,738,022	71,800	75,268	67,915	58,954	42,735	18,005	33,648	18,282	10,441	2,135,070
2010	2,282,312	85,276	87,256	80,662	65,090	47,183	19,879	37,150	20,185	11,527	2,736,519
2015	2,997,054	101,281	101,154	95,801	71,865	52,094	21,948	41,016	22,286	12,727	3,517,225
2020	3,935,629	120,290	117,265	113,781	79,344	57,515	24,233	45,285	24,606	14,052	4,532,000
2025	5,168,134	142,867	137,265	135,136	87,603	63,502	26,755	49,998	27,167	15,514	5,853,940

** Growth rate of only 3.0% since this district has more mountaneous areas compared with Sanahan and Bani Al-Harith.*

Table 5.7B: projection of water consumption (Mm^3/year) by water-use zone.

Year	**Urban**		**Urban-Rural**		**Rural**		**Total Consumption (Mm^3/yr)**
	Population	**Consumption (Mm^3/yr)**	**Population**	**Consumption (Mm^3/yr)**	**Population**	**Consumption (Mm^3/yr)**	
1994	954,448	24.4	150,072	1.9	146,428	1.1	27.4
2000	1,323,536	33.8	182,563	2.3	164,901	1.3	37.4
2005	1,738,022	44.4	214,982	2.7	182,065	1.4	48.6
2010	2,282,312	58.3	253,193	3.2	201,014	1.5	63.1
2015	2,997,054	76.6	298,235	3.8	221,936	1.7	82.1
2020	3,935,629	100.6	351,336	4.5	245,035	1.9	106.9
2025	5,168,134	132.0	415,268	5.3	270,538	2.1	139.4

5.4 Groundwater Demand for Industry

5.4.1 Previous Studies

Considering the heavy investment by both the Government and private in industrial development within the national capital and around it, this urban center constitutes a growing and important water consuming sector. To estimate industrial water demand, information about the structure and composition of industrial outputs and average water requirement per unit of output is needed. Both SAWAS and Dar Al-Handasah have estimated abstraction by industry without any attepts to obtain such information. The High Water Council used the industrial survey of 1986 to project the gross value product (GVP) of various industrial outputs in relation to the gross domestic product (GDP). Correspondingly, the average water requirement parameter was redefined from per unit of physical output to per unit of GVP (TS-HWC, Vol. IX).

5.4.2 This Study.

5.4.2.1 Introduction:

The economic activities in the study area of Sana'a basin are mainly agricultural and industrial activities which need a huge amount of water if compared to the amount needed for domestic uses. In the industrial sector, water is used either as production input (e.g. mixing agent, solvent or preservation agent) or it is used in the industrial processes (boiling, cleaning, cooling and heating). The required amount of water varies according to type of industry, the type of process and the nature of outputs produced. Many methods are available for estimating industrial water requirements. This study used the 'gross water requirements method', which is most suited given the limitations of available data.

The gross water requirement method was used for estimating the industrial water requirements for the Sana'a basin area, where the dominant industries are manufacturing and quarrying and mining. This method is discussed below.

5.4.2.2 Methodology

5.4.2.2.1 Gross water Requirement Method

The gross water requirement method depend on identifying (a) the physical outputs of the different industrial products, and (b) the average water requirement per unit of physical output in varies industrial sub sectors. The water requirements for each sub sector were estimated by using the following equation:

$$WR_r = \sum_{z=1}^{n} (WR_{rz} * PO_{rz}) \qquad (1)$$

Where WR_r is the water requirement for the sub sector (r=1,2,3...),WR_{rz} is the water requirement per unit of z^th product (z/= 1,2...n) in the r^th sub-sector, and Po_{rz} is the physical output of z^th product in the r^th sub sector.

The physical output data of various products in each industrial sub sector were taken from
The physical output survey of 1995 for Sana'a Basin. The water requirements of physical outputs were taken from the technical secretariat of the high water council report volume (V), 1992.

5.4.2.3 Results and Discussion

5.4.2.3.1 Base year water requirement estimates

Base year water requirement for each industrial sub-sector in Sana'a basin estimated directly by using equation (1). This was made possible by availability of data on physical outputs of Sana'a basin industries.

The water requirements obtained for the chemical sub-sector especially medicines and plastic products were high because it were computed according to the 1988 old prices which consider amount of 2 million liter of water is needed to produce physical outputs of value of 1 million Yemeni Rials. This result is a very high estimate of water requirements for the sub sector.

To correct the errors occurred due to the chemical products, their water requirements was taken from the High Water Council Report volume (V) for the year of 1988 for the whole Yemen and then Sana'a basin share of water requirements was computed for year(1988). In order to find Sana'a basin water requirement for the year 1995, the historical growth rates was applied . The results obtained after correction was 3.29 Mm^3 (Table 5.8).

Table 5.8: Sana'a basin industrial sub sector water requirement (1995)

No.	***Industry Type***	***Water requirement (Mm^3)***
1	Mining and Quarrying	0.001568
2	Food, Beverage and Tobacco	0.726285
3	Textile	0.627428
4	Wood products	0.015721
5	Leather	0.001512
6	Paper and Printing Metallic	0.383225
7	Metallic	0.016572
8	Non metallic	0.061172
9	Chemical industries	1.455305
	Total	3.288

5.4.2.3.2 Future projection of industrial water demands

In order to project industrial water requirements over the planning horizon(1995-2025), information is needed on future time paths of industrial production for each industry type. Because predictions regarding industrial outputs are difficult to make, especially at the level of disaggregation considered, an alternative approach involving the use of 'gross value of production (GVP)' was adopted. The details are presented below.

The first step in this aproach was to convert water requirements per unit of z^th^ physical output for sub-sector r (WR_{rz}) to average water requirements per unit of GVP in that sub-sector(AWR_r). This was done by using the following equation:

$$AWR_r = \{\sum_{z=1}^{n} (WR_{rz} * PO_{rz})\} / \sum_{z=1}^{n} GVP_{rz} \qquad (2)$$

where GVP_{rz} is the gross value of production of output z in sub-sector r.

In the next step, the water requirements for the r^th^ sub-sector for a future year were obtained by multiplying the sub-sectors' projected GVP by AWR_r. The GVP projections were obtained on the basis of 1995 data on gross value of industrial production by sub-sectors taken from the Sana'a basin industrial Survey for 1995. Growth rates for manufacturing, and mining sub-sector were used to project GVP of industries in the respective sub-sectors.

The future water requirement estimated by using two scenarios:

a. Historical Growth Rate (HGR) which assuming that rates observed during (1990-1995) would continue in the future. These growth rates were 2.83% and 9.8% for manufacturing, and mining and quarrying sub sectors, respectively.
b. Planned (Target) Growth Rates (PGR) which assume that growth rates from the first five-year plan (1996-2000)

would continue into the future.

The target (planned)growth rates for manufacturing sub sector is 8% and 0.55%for mining and quarrying sub sector. The Gross Value Product (GVP) of manufacturing & quarrying and mining sub sector were projected under historical growth rates (HGR) and planned growth rates (PGR) scenario during the period 1995-2025.

The water requirement corresponding to the projected gross value are shown in table 5.9. The results indicated that water requirement were high under the planned growth rates scenario and low under the historical growth rates scenario.

Under planned growth rates PGR scenario , water requirement for manufacturing & quarrying and mining sub sector are estimated to increase from 3.29Mm^3 in the base year (1995) to 33.07Mm^3 in the year 2025 . Over the same period ,water requirements would increase to 7.62Mm^3 under the historical growth rates HGR scenario table 5.9.

Table 5.9:- Projected Water Requirement under the HGR &PGR Scenarios For Sana'a Basin

Year	***HGR***			***PGR***		
	Manufactoring (Mm³)	***Mining And Quarrying (Mm³)***	***Total (Mm³)***	***Manufactoring (Mm³)***	***Mining And Quarrying (Mm³)***	***Total (Mm³)***
1995	3.286	0.00157	3.29	3.286	0.00157	3.29
2000	3.7785	0.0025	3.78	4.829	0.00161	4.83
2005	4.344	0.00399	4.35	7.0955	0.00166	7.10
2010	4.9949	0.00637	5.00	10.4257	0.0017	10.43
2015	5.7428	0.01	5.75	15.3188	0.00175	15.32
2020	6.6027	0.01622	6.62	22.508	0.0018	22.51
2025	7.59	0.0259	7.62	33.072	0.00185	33.07

The water requirement differences between across these scenarios widens with time. (figure 5.1). For example , the water requirement under the HGR scenario in 2010 are about 48% of the W.R. estimated for PGR scenario; this percentage is decreases to 23% in the year 2025. These difference mainly stem from the cumulative effect of the growth rate assumptions used to make future projection regarding the expansion of the sub sector.

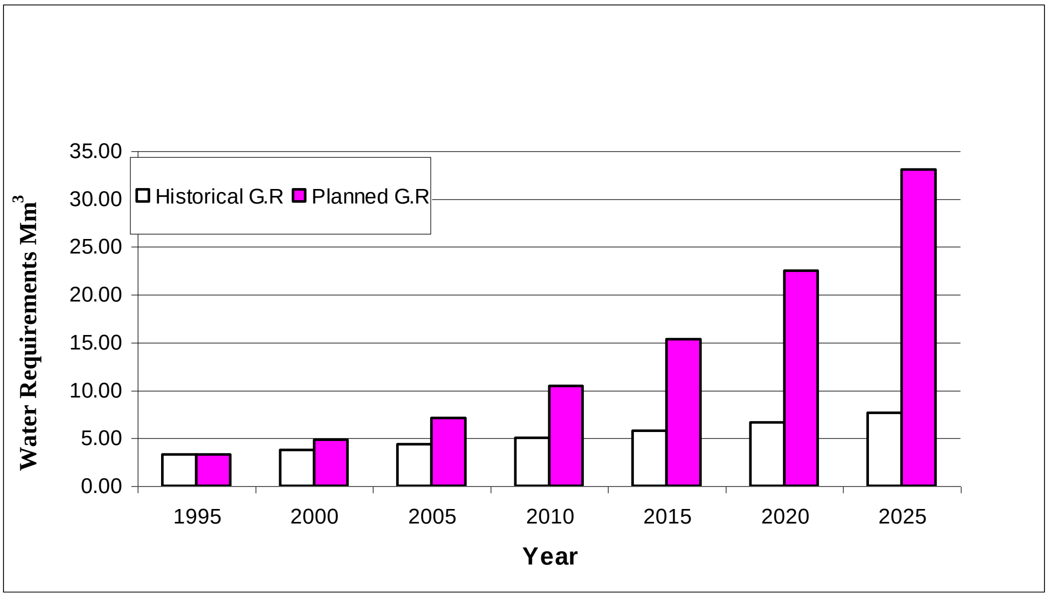

Figure 5.1 : Projected Water Requirements for Manufactoring and Minning& Quarrying sub sectors (Sana'a Basin)

Clearly, the water requirement consistent with planned growth rates can not be met from currently available water resources in the area. In fact it may be difficult to sustain the historical growth rates of the industrial sector without effective water management and conservation measures. The tremendous different between industrial water demand according to HGR (historical growth rate) and PGR (S-year plan growth rate) raises some concern. Until official figures confirming whether or not the plan has been realized, it is suggested to adopt average values of the estimations shown in the tables 5.9. Hence, the projected values adopted will be as follows:

Year	Demand (Mm^3)
2000	4.3
2005	5.2
2010	7.7
2015	10.5
2020	14.5
2025	20.0