Sana'a University
Water and Environment Center (WEC)

Sana'a Basin Well Inventory Project

The Sana’a basin Study

Volume I: Main Report

Final Report

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Summary and Conclusions

- The Sana'a Basin extends over a total area of about 3250 km2. It covers twelve districts of the Sana'a Governorate. Nine of these districts lies totally or mostly within the Basin (the National Capital, Bani al Harith, Sanhan (including Bani Bahloul), Khawlan, Bani Hushaish, Nihm, Arhb, and Bani Matar) while the remaining three (Raydah, Iyal Suraih, and Kharif) only touch on the Basin from its northwestern border.
- Based on the information available on the geology, the aquifer system and the surface water drainage pattern, the Basin has been divided into tow main hydrological units and six groundwater zones comprising 22 major wadi sub-basins:

Hydrolgical Unit	Groundwater Zone
Musayreka	1. Eastern (Bani Hushaish) 2. Southern (Sanhan) 3. Southwestern (Hamdan and Bani Matar) 4. Central (Bani al Harith and National Capital)
Wadi al Kharid	1. Northeastern (Nihm and western part of Arhab) 2. Northwestern (Arhab and northern part of Hamdan)

- In total, 13425 water points were recorded across the Basin during this well inventory program: 5321 boreholes, 7589 dug wells, 346 dug/bore, 146 springs, and 24 dams/pools (surface water bodies). Out of these, 4048 water points were not operational, being either temporarily in use or used intermittently when needed, abandoned, or dry.
- The highest of wells were found in Wadi As Sirr (sub-basin 11, Bani Hushaish) and Wadi Bani Huwait (sub-basin 9, Bani al Harith). A total of 2288 and 2256 were recorded in these tow sub-basins, respectively, which means that about 40% of the total number of wells occur in these wadi areas.
- Extremely high well concentration is observed in these two areas (i.e Bani al Harith and Bani Hushaish). Up to 97 wells pre square kilometer were registered in Wadi Sa'awan, signifying a tremendous risk of well interference and well inefficiency not only in this wadi but also in surrounding sub-basins as well which also have a high concentration of wells per km^2.
- Sub-basin 9 also has the highest number of dry (493 wells) and abandoned wells (313 wells) suggesting that the Bani al Harith area is being subjected to a serious groundwater depletion.
- Recent drilling activities is mostly concentrated in sub-basins 9 and 11. Since 1995, 432 and 374 boreholes have been drilled in these two sub-basins, respectively, indicating that there is a strong drive to abstract deep groundwater in Bani Hushaish and Ban al Harith.

- Groundwater is abstracted from four main aquifers across the Basin: alluvium (mostly in the Central zone), volcanics (most dominant in the Southern and South western zones, sandstones (currently exploited in the Bani Hushaish, Hamdan, and Nihm areas but also found throughout most of the Musayreka hydrologicl unit in significantly deeper horizons), and liemstones (in the Wadi al Kharid hydrological unit, i.e the Northwestern and Northeasterngroundwater zones).
- Recorded depths of wells (in meters below ground level)range as follows:
  - Dug wells: 2 to 90 mbgl
  - Dug/bore: 27 to 400 mbgl
  - Borehole: 13 to 1699 mbgl

  Two facts explain the wide range of borehole depths: (1) the existence of very shallow of drilled in the volcanic terrains, particularly in the southern groundwater zone (Sanhan/Bani Bahloul) where hand digging is difficult and at the same time there is a risk of loosing water in wells to much deeper fractured zones upon deepening, and (2) the existence of deep exploratory boreholes ushc as two SAWAS wells drilled to over 1500 meters.
- The average well yield ranges from 6 l/s (boreholes) to 3 l/s (dug and dug/bore), and 0.062l/s (springs). However, springs of significantly high yield exist such as one spring in Nihm with 9.26 l/s and another in Sanhan with 6.25 l/s. Close to 50% of the operating wells / springs (1293 water points) were found to be discharging at a low yield of less than 4 l/s, 23% (669 water points) had a discharge rate of 4-6 l/s, and the remaining 32% (940 water points) were pumping at a rate exceeding 6l/s.
- The quality of water is generally good as the majority of all wells have electrical conductivity of less than 2000 μS/cm. A noticeable exception is north of the Sana'a city (Bani al Harith area) affected by pollution or the Arhab-Nihm areas where the salinity is higher because of natural leaching of the carbonate rocks.
- Almost 26% of the wells, mainly dug, have temperatures of less than 20 ^{o}C while 69% have temperatures ranging between 20-30 ^{o}C. Only 257 wells (about 3%) recorded temperatures more than 30 ^{o}C. Temperatures of up to 55 ^{o}C have been recorded in the northeastern areas of sub-basin 9, and a total of 14 deep boreholes have temperatures in excess of 40 ^{o}C.
- Approximately 60 % of total measured wells have pH of less than 8 with about 54% being in the range of 7 to 8, the normal pH range for groundwater in general. The remaining 40 % has pH in excess of 8. pH of up to 12.6 close to anomalous pH of 2.5 have been found in the volcanic terrain
- Water use patterns were determined for 9001 water points. 87% of them (7848 water points) were being used for irrigation, while only 10% (912 water points) were reported for municipal use (drinking + domestic). Due to accessibility problems, the total number of wells used for industry could not be assessed.

- The total number for which information on irrigated areas could be collected is 7779, of which 3407 (44%) are boreholes, 4093 (53%) dug wells, 213 (3%) dug/bore, and the remaining 66 (<1%) springs and 16 dam/pool water. Irrigated areas per individual well vary between 0.001 and 46 hectares with an average irrigated of about 3.25 hectares per well
- The general trend obtained for groundwater flow from both dug wells and boreholes is very similar. Groundwater flows from the Eastern, Southern, and Western high plateau zones towards the Central zone and eventually northwards towards *Wadi al Kharid* where it is known to be discharged naturally through the *Al Kharid* springs.
- Total abstraction is estimated at about 260 million m^3 from the different aquifers as shown below

Aquifer Type	Abstraction in million m^3
Alluvium	13.79
Volcanic	88.66
Sandstone	118.42
Limestone	17.66
Unknown	15.92
Total	258.95

Recommendations

- Two different approaches should be taken for managing the available water resources in the Basin. Surface water use should be enhanced in the northern part of the Basin(Wadi al Kharid hydrological unit) to make use of both surface and sub-surface water flowing out of the Basin. A demand management approach is needed for the remaining major part (Musayreka hydrological unit).
- Groundwater protection zones should be delineated on the basis of the well concentration and total abstraction observed in the sub-basins. The Bani al Harith and Bani Hushaish areas (Centrral and Easter groundwater zones) need immediate attention.
- Regular monitoring of both dug wells and boreholes abstracting from the various aquifer types is urgently needed. The current monitoring program of NWRA is to be evaluated and expanded on the basis of the hydrological network suggested previously by WEC 2002 and the new findings of this study.
- Much more information is needed on the aquifer geometry and the hydraulic parameters of the aquifer systems (transmissivity and storage coefficient). This should be a main objective for the field investigations that are expected to follow this study (i.e. geological, hydrogeological,geophysical, and hydrochemical investigations as defined in part III of this study).

- Groundwater recharge studies with a focus on the Central and Eastern groundwater zones are needed. Such studies should be based on the fact that the abstraction is much more during the dry (winter) period than during the wet (spring and summer) period as well as make use of the existing dams and pool water available during this latter period.
- Extensive and consolidated research on water use efficiency, particularly groundwater, is urgently needed to answer the many questions related to speculations on current water use. At the same time, a basin-wide campaign should be initiated for implementing modern irrigation techniques and demonstration farms set up to convince local farmers on the water saving efficiency of such methods.
- Regular updating of well inventory data is needed once every two years in the heavy abstraction zones and once every four years in the remaining zones. Care is to be taken to carry out such field activities during the wet season to get as much as possible of water level measurements.

Introduction

This study has been carried out by the Water and Environment Centre for the National Water Resources Authority (NWRA) in conjunction with the Sana'a Water Supply and Sanitation Project (SWSSP) of the Ministry of Electricity and Water (MEW). The study involves 2 major components:

- A basin-wide water point inventory
- A literature survey/review and preparation of Terms of References for future field investigations (geological, geophysical, hydrogeological, and hydrochemical) to be carried out in the Basin.

The Terms of Reference (TOR) for the activities carried out in the present study within the scope of the above study components are shown in Appendix A. In accordance with this TOR, the main findings of the study were presented in a draft report submitted to NWRA in April 2003. The NWRA responded with some comments in late June 2003 (Appendix B). The present output is the final report of the study which incorporates the NWRA comments as well as gives a more in-depth analysis of the main findings. It consists of two volumes:

Volume One (Main Report): presents all the main findings, conclusions, and recommendations related to the study as a whole. This first volume consists of three main parts:

- Part I: Principal characteristics of the Sana'a Basin as interpreted on the basis of the review of previous studies and field observations during the present study.
- Part II: Main findings of the well inventory survey in the Basin
- Part III: Terms of Reference for Phase II Studies that are likely to be implemented in the near future..

Volume Two (Annexes): gives details of all data obtained through the well inventory program. It consists of two Annexes:

Annex I is a summary of the main results obtained for the six groundwater zones occurring in the Basin: *The Northwestern Zone, the Northeastern Zone, the Eastern Zones, the Southern Zone, the Southwestern Zone, and the Central Zone.* This Annex gives tables and graphs (histograms) for the following data for each of the sub-basins (a total of 22 sub-basins) constituting the six groundwater zones:

- Total Number of water points
- Total number of wells that were actually abstracting water during the well inventory program (i.e. operational wells)
- Total abstraction in each sub-basin of the six groundwater zones (in Mm^3)
- Total irrigated area in each sub-basin (in hectares)

It includes a summary of the main data collected from the field for each of sub-basin in each groundwater zone. Annex II displays all data (i.e. master data file).

Part I: Principal Characteristics of the Sana'a Basin

Chapter 1: General Background

1.1 The Sana'a Basin Water Resources Management (SBWRM) Project

The Sana'a Basin is experiencing a serious depletion of groundwater resources with an associated alarming degradation in water quality. The situation is further complicated by the absence of an integrated water resources management plan for the basin including lack of data, a regulatory framework to manage the groundwater extractions and inefficient irrigation practices. To address some of the existing water problem issues, the Government and the World Bank have agreed to prepare a three-phase program over a period of 15 years. The objectives of the proposed Sana'a Basin Water Resources Management (SBWRM) Program are:

a) to increase both quantity and the usable life of the groundwater resources available for domestic and industrial use in the Basin, and so postpone the date at which the new supplies have to be brought in from outside the Basin; and

b) *to simultaneously increase the efficiency of agriculture water use so as to allow time for a gradual shift to a less water-based rural economy in the Basin*.

The SBWRM Program will be implemented through an Adaptable Program Credit (APC) financed by IDA. This would allow IDA and the Government of Yemen to agree on a long-term (15 years) program to be implemented in three consecutive phases. Each phase would be built in the experience and progress of the preceding one and starting only after certain milestones have been met. A number of studies have been identified as necessary to the preparation of a Sana'a Basin Water Management Project. These studies are designed to fill the gap in the information and knowledge required to develop a project targeted at the real water issues in the basin

In the first phase (five years), technological solutions and institutional arrangements will be tested on a pilot basis in three representative sub-basins for later incorporation into a full-scale basin-wide program to be implemented during the subsequent two phases. The objectives of this phase are:

a) to test and develop demand and supply management methods for large-scale implementation throughout the Basin during the subsequent phases of the program;

b) to establish the regulatory, legal and institutional framework needed for more sustainable water resources management in the Basin; and

c) *to carry out the preparation of the Phase II project of the Program*.

This phase, which will be implemented in three sub-basins, is expected to focus on enhancing supply management through groundwater recharge structural means (particularly small retention dams and underground recharge) as well as on improving demand management through the betterment of irrigation efficiency. In parallel with demand and supply management, the project will also assist in setting up water monitoring system and addressing the social and institutional issues. The project will take place within the context of the strategic water resources management plan for the basin currently being developed by NWRA with assistance from UNDP.

1.2 Study Area

The Sana'a Basin is located in the western highlands of Yemen opposite the Red Sea and the Gulf of Aden (figure 1.1). It is mostly an intermontane plain surrounded by highlands from the west, south and east. On a regional scale, the Basin extends across the central part of the Sana'a Governorate (figure 1.2) and covers about 24% (3250 km^2) of its total area (13,550km^2). It includes parts or all of twelve administrative districts occurring within the Sana'a Governorate. Practically all of the local populations of three of these districts (*Kharif, Raydah,* and *'Iyal Surayh*) live outside the Basin. Therefore these districts have been excluded from all further discussions. Rural districts examined within the context of this study are *Bani Hushaysh, Bani Al Harith, Khawlan, Bani Matar, Arhab, Hamdan, Nihm, Sanhan-Bani Bahlul,* and *Al Amana*, or the Sana'a urban area (figure 1.3).

There is a significant variation in altitude both east-west and north-south. The highest point in the Basin is in the southwest end (*Jabal An Nabi Shu'ayb*) and has an elevation of almost 3700 m.a.s.l. The lowest (about 1900 m.a.s.l.) is in the northern extremity where the *Wadi Al Kharid* exits the Basin towards the main basin by the same name. The predominant climate is arid although semi-arid conditions prevail in localized areas, particularly along the western highlands.

Slight differences have been found in the catchment boundary of the Basin, as defined in different studies. Up till now, however, the total area (3209 km^2) given by Mosgiprovodkhoz (1986) has been referred to frequently in subsequent studies until the ITC-WEC (20001) gave a figure of 3158 km^2 based on satellite images. By matching the boundary adopted in both studies and comparing them with the 1:50 000 topographic sheets, the present study came up with a total area of about 3250 km^2.

Figure 1.1: General location of the study area.

Figure 1.2: Regional setting of the Sana'a Basin.

Figure 1.3: Main district zones within the Basin.

1.3 Geological Units

1.3.1 Stratigraphic Sequence

The stratigraphic sequence of Sana'a basin ranges from Precambrian to Recent with some missing periods as shown in the geological column (figure 1.4a). The Phanerozoic rocks of the Sana'a basin mainly consist of sedimentary and volcanic rocks. The subsurface data reveal the occurrence of the Precambrian rocks such as observed in the *Arhab* and *Al-Hitarish* wells which represent the deepest wells drilled in Sana'a basin (see SAWAS, 1996).

The oldest sedimentary rocks (the Kohlan Group) consist mainly of clastics with grain sizes ranging from coarse to medium and consisting of sandstones, (the lower part) interbeded with shale and siltstones, which contain plants remains. This group is exposed in the *Jabal Salab* in *Nihm* area and recorded in the Sana'a Basin from subsurface data such as in *Arhab* and *Hatarish* wells. It has maximum thickness about 45-50 m thick (SAWAS, 1996). The age is wide ranging from lower to middle Jurassic (Bydoun, 1982, Diggens, et al 1988).

The Jurassic rocks, which are represented by Amran Group, are exposed in the northern part of the Basin such as in the *Thoma* and *Nagil Bin Ghailan* areas. They consist mainly of limestone, gypsum with intercalated shales in some interval horizons such as in *Wadi Al-Ahjur* formation. In all the other part of the Sana'a basin, *the Amran* group is recorded from subsurface only and at different depths. It has a thickness ranging from 320 m in the northern part Basin and decreasing southward to about 100 m near the boundary of the Basin. This southward decrease of the group probably signifies approaching the edge of the Basin. The age of this group is determined by Geukens (1966) and Al-Anbaawy (1985) as middle to upper Jurassic.

The Tawilah group is exposed in large area around Sana'a city especially in the northwestern part as in *Wadi Dhahr* and in the northern part such as in *Al-Hatarish* area and underneath the alluvium deposits in most of the Basin (see figure 1.4b). The age ranges from late Cretaceous to Eocene. The total thickness reaches more than 400 m as in *Al-Gharas* area. A thinning of the group to around 150 m westward may point to the source area in that direction. It consists mainly of medium to coarse grain, trough cross-bedded sandstones. The sandstones are generally mature quartz arenites. Conglomerates of well-rounded quartz and quartzite clastics are common. This group has been divided in Sana'a basin into two mappable units, the *Gharas* formation for the lower par and the *Medjzir* formation for the upper part.

The Tertiary volcanics (formerly known as the Yemen Volcanics) consist of alternating lava, flows of basalt, andesites or trachytic porphyries. These Tertiary volcanic rocks form today the Yemen Plateau, which reach more than 3660 m above sea level. They are Oligo-Miocene in age and the thickness is in excess of 2000 m in some places. The main body of these volcanic rocks consists of basalt, silicic-ignimbrites and tuffs. Rhyolites ignimbrite units tend to be more common in the upper part of the stratified sections.

The Quaternary volcanic rocks are dominated by alkali basalt. They occur widely around the Sana'a area and more common to the northern part. Their age has been determined at about 5 million years. Two types of eruptions can be recognized within these Quaternary volcanics. The first eruption involves the cinder cones, which are found in the northern part of the Basin and further to the north of it. The second is the lava sheet rocks that occur along the Sana'a-Amran road.

The Quaternary sedimentary deposits are mainly alluvial materials and conglomerates, which reach in thickness more than 30 m in middle of the Basin such as in the Sana'a University compass.

1.3.2 Water Bearing Characteristics

The Amran Limestone is 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 100m 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 Limestone.

The Cretaceous Sandstone 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.

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.

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 water levels 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 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, into coarse-grained material along wadis and at the base of the hills.

With respect to hydraulic parameters, table 1.1 shows that 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 1.1: Transmissivity data (mean values) as summarized from SAWAS.

	Transmissivity [m^2/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 higher T values in the Tertiary Volcanics and Tawila Sandstones can be seen to be 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.

Figure 1.4a: Geological column of the stratigraphy units inside the Basin and its vicinity (……..)

Figure 1.4b: Geological units outcropping inside the Basin and its vicinity (after SAWAS, 1996).

Chapter 2. Natural Boundaries of the Basin

2.1 Regional Boundaries

The Sana'a Basin is located in the northwestern part of Yemen, within the so-called Yemen Highlands that form a distinct landform region in this part of the country (figure 2.1) with its high peaks, deep canyons, steep slopes and highland plains or peneplains. It extends across the Highland Plain zones, which separates the Western and Eastern Slopes of the Highlands. The ***Western and Eastern Slopes*** are characterized by highly irregular and dissected topography, particularly in their upper regions with steep slopes. Elevations (m.a.s.l) range from a few hundred in the foothills to about 3300 (*Jabal Kanin*) to 3500 (*Jabal Asham*) and 3700 (*Jabal An Nabi Shu'ayb*) in the mountains surrounding the city from the south to south-east and southwest. These mountains enjoy moderate to rather high rainfall of up to ~ 400 mm/yr. However, the Western Slopes receive almost twice as much precipitation as the Eastern Slopes (figure 2.2), being favorably oriented in relation to the movement of moist air masses.

The Highland Plains constitute elevated plateau areas enclosed by the Western and Eastern Slopes. Physical conditions (mainly because of cool, temporate climate) are favorable for sustaining a relatively large population. Several conditions have contributed to the formation of these plains, mainly:

- Tectonic movements extending from the Mesozoic to the Quaternary have been accompanied by strong subsidence, which affected the faulted domes along the Yemen Mountain Massif and formed major depression zones such as *Sana'a, Ma'bar,* and *Dhamar.*
- Subsidence movements in the *Wadi Al Jawf* faulted region and neighboring areas to the west have accelerated erosional processes due to surface water flow that also contributed to the formation of the depression zones.
- The strong continental effect and dryness caused by the surrounding mountains has resulted in a high degree of physical disintegration and increased the role of wind as an erosion factor whereas the vegetation cover has decreased.

Variations occur within the Basin that can be attributed to the effect of the significant different physiographic features of the regional zones described above. Such variations can be observed from east to west as well as north south. The catchment characteristics of the Basin, in terms of altitudes, raining events, wadi system, surface drainage pattern, …etc., essentially reflect these variations.

Figure 2.1: Main physiographic features within the Basin (see attached legend) .

Legend for figure 2.1:

Mountains

Sr No	Name	Altitude (m.a.sl.)	East	North	Sr No	Name	Altitude (m.a.sl.)	East	North
1	Jabal an Nabi Shu'ayb	3666	390269	1689588	23	al Majawiha	2931	454380	1728275
2	Jabal Ayban	3187	405867	1691237	24	Jabal al Manaarah	2948	453254	1729827
3	Jabal Kanin	3244	432570	1665495	25	Jabal Rahqah	3120	401311	1682805
4	Jabal al Lawz	2344	444532	1699771	26	Jabal al Jaedib	2980	400597	1689039
5	Jabal Asham	3440	449523	1700506	27	Jabal al Jaedib	2829	400456	1690455
6	Jabal al Madhhar	3200	445902	1705432	28	Jabal ar Rayyani al Qayl	2858	396464	1716463
7	Jabal Kil	3240	446416	1706460	29	Jabal Zin (Qudam)	3000	397758	1724591
8	Jabal Sara'	3177	449217	1717276	30	Jabal Dhufar	3020	407792	1742509
9	Jabal Sara'	3000	448528	1715683	31	Kawlat al hadheerah	2978	406147	1743091
10	Jabal al Gharboub	2880	408417	1684207	32	Jabal Durb	2880	406334	1734412
11	Jabal Zufar	3004	411778	1686812	33	Jabal Mahdad	2880	434673	1670582
13	Jabal Qirwan	2880	430143	1692537	34	Jabal al Hijrah	2780	433963	1673620
14	Jabal Nuqum	2889	419351	1697219	35	Kawlat ar Rajwah	2800	412968	1745509
15	Jabal ar Rayd	2904	431690	1702389	36	Qatwaan	2740	412969	1748921
16	Qarn al Harr	2920	441796	1705504	37	Jabal Dhabab	2824	435488	1717717
17	Qarn al Harr	2880	438705	1705851	38	Jabal Ayyub	2740	435335	1720280
18	Jabal as Sadr	2840	444262	1693382	39	Bani Risam	2780	440585	1720744
20	Jabal ash Shutfah	2880	433912	1695193	40	Jabal al Jamimah	2840	431642	1706355
21	Najd al Martah	2900	453484	1723932	41	Kawlat al Munaqqab	2740	394948	1711148
22	Najd al Martah	2792	451312	1722988	42	Jabal as Sama	2280	424235	1725594

Peneplains (Qaa's)

Sr No	Name	Altitude (m.a.sl.)	East	North	Sr No	Name	Altitude (m.a.sl.)	East	North
1	Qa' Sahman	2700	397951	1688550	11	Qa' Jidr	2100	412369	1709121
2	Qa' Dayaan	2600	412765	1678724	12	Qa' al Qaryah	2200	406878	1708959
3	Qa' al Haql	2700	409846	1682018	13	Qa' Ma'dat	2700	408952	1687233
4	Qa' an Nahem	2600	406478	1686137	14	Qa' al qula,d	2700	398710	1692214
5	Qa' al Mulayki	2600	404073	1683655	15	Qa' al Mafjur	2500	401872	1694849
6	Qa' al A'rawed	2400	416041	1679728	16	Qa' Malih	2600	395964	1704242
7	Qa' al Qaydhi	2400	418064	1678810	17	Qa' Raqqah	2300	402968	1713677
8	Qa' Artil	2300	415684	1684864	18	Qa al Ma'azib	2800	392207	1693753
9	Qa' al Qubbatayn	2600	430262	1670225	19	Qa' al Munaqqab	2600	393788	1711263
10	Qa' al Adhrah	2100	411825	1712674					

Legend for figure 2.1

Figure 2.2: Mean annual rainfall across the Basin (mm).

2.2 Hydro (geo) logical Boundaries

The study area as a whole constitutes a catchment zone for the *Wadi Al Kharid*. This wadi flows northwards for about 70 km before turning east where it joins *Wadi Madhab* to form the *Al Jawf* surface water system disappearing into the desert area of *Ramlat as Saba'atayn* (see Van der Gun and Ahmed, 1995, figure 5.1, p.41). It is a semi-closed basin surrounded by mountains from all directions except at the outflow zone of *Al Kharid* along the northern boundary.

The general drainage pattern in the Sana'a Basin is ephemeral centripetal (Davison et. al. 1994). Significant local differences, however, are observed within. Such differences are mainly due to the complexity of the geological history of the Basin and its location across three different physiographic regions with variable climatic conditions, as explained above. On the basis of these differences, the basin will be divided into separate hydrological units which, in turn, will be divided into several groundwater zones, depending on the effective groundwater source or sources that commonly serve the local populations. Within each groundwater zone, major wadi catchment zones will be delineated. These are expected to serve as water management zones either individually or through combined zones if necessary.

2.2.1 Hydrological Units

Hydrologically, the Sana'a Basin can be divided into two an upper (northern) unit and a lower (southern) one. These units will be referred to as the *Wadi Al Kharid Hydrological Unit* and the *Musyareka Hydrological Unit*, respectively (figure 2.3).

Figure 2.3: Hydrological units and groundwater zones within the Basin.

The ***Wadi Al Kharid Hydrological Unit*** lies along the western limb of the regional NW-SE graben system of *Al Jawf-Marib-Shabwa,* where thick deposits of the Amran Group have been deposited (Davison et. al, 1994; Van der Gun and Ahmed, 1995, fig. 2.2, p.4; and Al Anbaawy, 1985, fig. 23, p.114). The main features of this region are therefore controlled by the strong aridity prevailing across the region as well as the physical / chemical properties of the carbonate rocks and their local structural features.

The general pattern of the surface drainage is along the numerous faults and fracture system, which develop on the exposed limestone formations. However, significant local differences are caused by the presence of uplifted Basement and the Amran down-faulted trough along the eastern and western boundaries of the Basin, respectively.

The ***Musayreka Hydrologic Unit*** is on the northeastern edge of the high ground where large flood volcanic provinces developed due to the piling up of thick volcanic flows coupled with enhanced heat flow Davison et. al, 1994). It covers a total area of approximately 70% of the Basin, spreading across the southern volcanic provinces and the central alluvium plain surrounded by some sandstone outcrops. The watershed areas of this catchment are characterized by a significant contrast in the geological outcrops and climatic conditions which result in important variations in surface characteristics (landform features, soil properties, vegetation cover, rock permeability, etc.), hence the development of local differences in the drainage system. This part of the Basin constitutes essentially a hydrologically closed system with an ephemeral centripetal drainage pattern. Runoff water descending along a fairly well developed wadi drainage system of dendritic to trellis pattern (mainly from the southern and eastern watershed zones), sinks into the lowland areas extending from the city of Sana'a to *Jabal Aş Şama'*. Practically no surface water flows pass this east-west mountain which forms a pronounced structure across the plain, except perhaps unusually wet conditions where extremely heavy flooding may result in some flow pass the west end of this structure.

2.2.2 Groundwater Zones

The occurrence of various aquifer systems throughout the Basin signifies differences in groundwater use across the region. Most likely, some of these aquifers extend outside the Basin surface boundaries, particularly the regional ones such as the *Tawila* sandstones. In theory, groundwater zones within the Basin cannot be delineated without adequate knowledge of the subsurface configuration of the aquifers. From the practical point, however, it is important to know which aquifer or aquifers are serving most of the population in any one region. Using this 'common water use' criterion, we can identify six groundwater zones (figure 2.3): two in the *Al Kharid* Hydrological Unit (Northwestern and Northeastern) and four in the *Musayreka* Hydrological Unit (Eastern, Southeastern, Southwestern, and Central).

2.2.3 Water Management Zones

Within each groundwater zones, there are a number of major wadi catchment zones, or sub-basins. On the basis of surface water drainage systems and topography, a total of 22 sub-basins have been identified (figure 2.4). While the local populations in these zones share the groundwater resources in an aquifer system that may extend beyond their wadi boundary, the use of the surface water flowing in the wadi is fully under control. Such use, in turn, affects the amount of recharge percolating into the shared groundwater resources. Abstraction within the wadi areas for agriculture and other purposes would also be reflected in the groundwater conditions in the groundwater zones as whole.

Such activities, therefore, should be harmonized for the purpose of managing all available water resources within any particular groundwater zone on an integrated basis. Hence, management of water resources within the Basin should be implemented at the level of the major wadi catchment sub-basins. For practical purposes, however, a combination of the sub-basins or selected areas within them are likely to be more appropriate to manage water resources in a region the size of the Sana'a Basin. Any zone selected as described herein is to be referred as a *water management zone*.

Figure 2.4: Major wadis sub-basins

Chapter 3: Integrated Water Resources Management

3.1 Groundwater abstraction and water use trends in the pervious studies

The abstraction began to exceed recharge during the mid-1980$_S$, and by the 1990 the groundwater storage was reported to be depleting at a rate of over 100 Mm^3/Year. The total abstraction was estimated to be about 180 Mm^3 in 1990 (TS-HWC). Several studies have attempted to estimate the total abstraction in the basin by adopting the relative groundwater consumption in three main sectors (agricultural, municipal, and industrial).

a) Municipal water use:

Many previous studies tried to estimate the total abstraction and demand in this sector, and in the absence of actual statistics, a reasonable estimation of domestic consumption can be achieved with the availability of two pieces of information: population census and average per capita consumption in both urban and rural areas, but those studies concentrated on demand in the urban area.

The most recent assessment of 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 depends on the growth rate, and per capita consumptions. (Al Hamdi, 2000) 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 assume prevalence of an estimated average of (50 l/d) up to 2025. Table 5.11 shows the comparing between the previous studies on domestic water use.

Table 5.11: Municipal water use between 1984 and 2000 (Mm^3/Year)

	1990	1995	2000	2005
WEC,ITC, 2001	-	27.4 (1994)	37.4	48.6
Dar Al-Handash, 2000	-	33.5 (1997)	29.8	37.4
TS, HWC, 1992	13.1	19.4	27.8	38.6

b) Agricultural water use:

Some previous studies estimates are based either on only well inventory (SAWAS, 1996) or crop water demands determined from agronomic investigations (TS-HWC,1992) or both (Italconsult, 1973). The TS-HWC,1992 estimated the total irrigation water abstraction to be of 151 Mm^3 in the year 1990, and increasing to 207 Mm^3 in the year 2000 and future to 244 Mm^3 in the year 2005. While the (WEC, ITC, 2001) estimated the total groundwater abstracted for irrigation during year 2000 about 205 M m^3 increasing to 240 Mm^3 in the year 2005. Table 5.12 gives the historical development of the groundwater use in agricultural between 1984 and 2000.

Table 5.12: Irrigation water use between 1984 and 2000 (Mm^3/year)

	1984	1990	1993	2000	2005
WEC,ITC, 2001	20	113	136	205	240
TS, HWC, 1992	-	120	133	207	244

c) Industrial water use:

The economic activities in the Sana'a Basin are mainly agricultural and industrial activities which need huge amount of water if compared to the amount needed for the domestic use. In the industrial sector, water is used either as production input (e.g. mixing agent, solvent or preservation agent) or it's used in the industrial processes (boiling, cleaning, cooling, and heating).
Considering the heavy investment by both, government and private industrial development within the national capital and around it, this urban center constitutes a growing and important water consumption sector. Several studies predicted and estimated the water use and demand in this sector, Table 5.13 presents the differences between some of this estimate.

Table 5.13: Industrial water use in some pervious studies (Mm^3)

	1995	2000	2005
WEC,ITC, 2001	3.2	4.3	5.2
TS, HWC, 1992	3.1	4.2	5.6

3.2 Overview of Water Resources Management Issues

The prevailing water resources problems are essentially resulting from the increasing supply-demand imbalance due to the rapid expansion of the city. Further expansion is expected to aggravate the problems both directly (increasing demand in domestic water supply for the urban population) and indirectly (creating local markets for consuming more water in the agricultural and industrial sectors). The extent of such problems would to a large extent be determined by the interaction of the city with its neighbouring rural areas, which results in the development of three different water –use as described in chapter 3 above. It is therefore convenient to assess the situation and describe the issues on the basis of these zones.

Table 3.1 indicates that while drinking water shortage, the most widely publicized problem, is limited to the urban zone (i.e. Greater Sana'a city), groundwater-mining-related issues are more widespread across the entire Basin. These are the more sensitive and rapidly spreading problems that are likely to prove most challenging for attaining sustainability, if at all.

Table 3.1: Matrix of Problems of Critical Issues Related to Groundwater Mining and Water Supply Shortage.

Water -Use Zone	***Main Problem***	***Critical Issue***	***Evidence***	***Source***
Urban	Water supply and sanitation facilities shortage	Level and quality of service provision.	Proportion of population now in the future with no, or inadequate; provision of safe water; sanitation and wastewater disposal facilities; consumption per head; reliability of supplied …etc.	Shortage of investment funds; rapid growth of urban settlements; poor maintenance; inefficient services; lack of fairness in allocations; inadequate sewerage and drainage system.
Basin-wide (Urban, Urban – rural, and Rural Zones)	Groundwater mining	Supply-demand imbalance.	By sector and/or region; future trend.	Growth in population; upgraded standard of living (i.e. increasing per capita demand); over-use of groundwater; inefficient service
		Rapid depletion of major regional aquifers	Drying-up of spring and dug wells; lowering of water levels in boreholes; reduction of perennial flow in major Wadis; drop in well yield	Growth in population; expansion of a subsidized agricultural sector; introduction of modern drilling technology and pumps
		Deterioration of groundwater quality (*mainly in Bani Al-Harith district*)	Increased salinity in wells; soil salinization; incidences of water related diseases.	Upconing of saline water; poor irrigation practice; inadequate drainage systems; growth of polluting industries.
		Inefficient use	Performance measures such as system efficiency, agronomic norms, and economic value of water.	Absence of incentives to conserve water; poor system maintenance; low public awareness of water situation; limited access to imported technology.
		Growing conflicts among users	Co-existence of surpluses and deficits among regions/sectors; growing shortages in particular uses; competition for limited supplies.	Growing imbalance of water supply and demand; weak institutional arrangement; absence of water legislations; failures and/or absence of planning and forecasting.
		Costs of future abstraction	Growing environmental stress; development of water markets and transfers; rising cost of marginal water supplies. Unit costs of projected drilling; pimp installation; fuel consumption compared to current and past level.	Exhaustion of easy options in the face of growing demands; absence of demand management.
Rural Zone		Inadequate water quality.	Incidences of water related diseases; change in taste; odor	Shortage of funds for construction of adequate water supply schemes; lack of proper maintenance, shortage of sources for good quality water.

3.3 Information Requirements for Integrated Water Resources Management

3.3.1 Nature of IWRM Information

The complexity of water- related issues in the Sana'a Basin is a direct result of its size in terms of physical area and human population, its limited water resources, and the absence of proper institutional arrangements. The information displayed in table 3.1 above suggests that integrated water resources management (IWRM) in such a complex system as the Sana'a Basin involves a wide variety of information. Such information can be divided into three categories:

- Information on the supply side, or water resources information.
- Information on the demand side, i.e. socio-economic information.
- Information relevant to the facilities/arrangements through which interaction between supply and demand can proceed, i.e. water-related infrastructure.

Details of the *water resources information* required, how to collect it and suggested formats for analyzing presenting the information are shown in table 3.2 (A, B, and C). Collection of this information has been initiated almost thirty years ago through a number of studies or projects implemented for specific purposes as explained above. Most of these studies were related to the development of NWSA well fields hence the information collected are mainly limited to certain zones around the city where the well fields were to be constructed. The data collection process normally stopped shortly after project termination for reasons described above. Moreover, most of the data cannot be found or accessed as no suitable database arrangements were made.

At the present, limited information is being collection by either NWRA or NWSA as indicated in the table. Preparation for the collection of more information is also underway as shown. However it is not clear what arrangements have been made, if any, to ensure data collection continuity as well as analysis and storage of the information for future purposes.

The *socio-economic information* is perhaps more difficult to collect for three main reasons:

- It is still difficult for many decision makers to comprehend the importance of acquiring such information, as they may perceive it as unnecessary, too subjective, and/or irrelevant to the planning and management process.
- The nature of this information requires a multi-disciplinary team with diverse backgrounds that normally cannot be found within any one organization of the local water sector.
- There are very little well-trained local staff in such institutions, including NWRA and NWSA, who can carry out the field investigations required for collecting information that reflect reasona-

bly well on the water consumption issues.

Because of these limitations very little useful information has been collected with regards to water consumption in the Basin. Whatever collected has been obtained through senior local and/or international short-term consultants hired normally by Donors, directly or indirectly, for specific assignments not including any training. As such concerned authorities such as NWRA or NWSA still remain unable to take such a responsibility.

In the context of the present study, the term infrastructure is taken in the broad sense of incorporating any facility or arrangement made to enhance water management.. As such it includes not only water-related technical infrastructures but also water legislation and environmental protection measures. While the previous two categories can be classified as either supply (mainly technical) or demand (mainly agro-socio-economies), this category of information involves both. Hence the local staff dealing with this information is expected to have a combination of technical and non-technical (social sciences) background. Preferably such staff should also be senior people with management perception and leadership capabilities.

All three main institutions in the water sector (MAI, NWRA and NWSA) have been active in collecting parts of this information, as deemed necessary or perceived relevant to their specific needs. As such the available information is fragmented and not necessarily utilized for common goals related to water resources management.

3.3.2 Information gaps and how to fill them.

Review and analysis of the available information indicate a significant gap in the information required for the management of water resources in the basin toward sustainability. Figure 3.2 suggests that the nature of this gap varies from almost total absence of data (e.g. wadi discharge) to data discontinuity (e.g. water level) or inadequacy (e.g. aquifer parameters).

Essential data and basic information to be collected for filling the existing gaps and the proposed institutional arrangement for their acquisition are shown in tables 3.2 A, B and C. These tables also show the actions that need to be taken as well as the organizations responsible or normally involved in such activities. Immediate actions for filling some these gaps are given in table 3.3. Implementations of these actions can be within the short-term program as described in section 3.3 below.

Table 3.2A: Information to be collected on the supply side

Issue	***Data/information needed***	***Activities/required actions***	***Status / agency code***	***Suggested format***
Natural surface water systems	(a.) wadi channel network (b.) hydrological characteristic of wadi segments (perennial, seasonal, ephemeral) (c.) wadi flow/catchment yield (d.) water quality in main wadis	• field survey combined with prior map/photo/satellite image analysis • operation of stream gauging stations • collecting existing data	**4**	• hydrological map (1:100,000) • time series of flow and EC
Natural groundwater systems	(e.) Geometry and lithology of main aquifers: alluvial, volcanics, sandstones (f.) hydraulic properties of main aquifers (g.) identification of main recharge and discharge zones (h.) springs (yield and water quality)	• geological field survey • geophysical surveys • exploratory drilling • aquifer testing program • well inventory • groundwater monitoring (water levels and water quality) • chemical analysis	2 2 3 3 2 1 4	• aquifer map (1:100,000 or better) • piezometric/water level maps • groundwater quality maps • time series of groundwater level and groundwater quality
Climatological conditions	(i.) rainfall (j.) potential evaportranspiration	• installation/operation of a rainfall stations • installation/ operation of meteo-stations • analyzing existing meteorological and rainfall data	1 1 4	• time series of rainfall • isohyetal maps • time series of various meteorological variables • mean monthly Penman ET values for different zones

1: Activities currently undertaken by NWRA on regular basis more or less.

2: Near-future NWRA activities under preparation.

3: Activities currently undertaken by NWSA (Sana'a office) on the basis of needs and funds availability.

4. Activities carried out irregularly , usually on project-basis.

Table 3.2B: Information to be collected on the demand side

Issue	***Data/information needed***	***Status / agency code***	***Activities / required actions***	***Suggested format***
Agriculture and water use	(a.) areal distribution and number of ha of rain-fed, spate-irrigated, baseflow/spring irrigated and groundwater irrigated zones (b.) cropping patterns and cropping calendars in each of these zones (c.) crop yields in each of the zones (d.) irrigation methods used (e.) irrigation efficiencies (f.) soil types (g.) agricultural inputs and methods	• agricultural field survey • inquiries at relevant institutions • study of reports, maps, recent photos, satellite images, etc.	4	• tables
Industry and water use	(h.) location, size and type of main water using industries (i.) waste water production, quality, treatment and disposal	• field survey • inquiries at relevant institutions • review of reports	4	• location map • tables indicating pollution loads for each site (quality and quantity)
Population and domestic water use	(j.) population numbers and density (k.) population growth numbers (historic data and prognoses for the future) (l.) per capita use of water (m.) numbers of people served by NWSA and GAREWS	• review of statistics • inquiries at relevant institutions • review of reports	4	• tables
Socio-economic factors	(n.) general economic setting and trends (o.) sources of income, income distribution (p.) employment opportunities outside agriculture (q.) production cost of water (r.) land ownership/tenure (s.) break-down of production cost for main crops (t.) crop prices (u.) conflicts on water and conflict resolution (v.) perceived problems related to water (w.) attitude towards change	• review of reports and statistics • socio-economic field survey	4	• report (s) • tables

Table 3.2C: Information to be collected on infrastructure

Issue	***Data/information needed***	***Status / agency code***	***Activities / required actions***	***Suggested format***
Water-related technical infrastructure	(a.) dams (b.) wells (c.) irrigation schemes (d.) water supply schemes (e.) sewerage systems (f.) flood control systems	• area-wide well inventory • inquiries at relevant offices (MAI,NWRA, NWSA, etc) • reviewing reports	4 4 4	• detailed location map • systematic tables with relevant details (lay-out, size, production, water quality, beneficiaries, etc.)
Water-related environ-mental aspects	(g.) zones prone to pollution (h.) current and potential polluters (i.) zones prone to flooding and flood damage (j.) zones prone to drying up (k.) zones of particular environmental value	• field surveys • inquiries at relevant institutions • review of reports	4 4 4	• map (s)
Legal, political and institutional aspects	(l.) existing water rights and related legal framework related to water (m.) local leadership and organization (n.) outline of public administration (o.) institutes/organizations related to water (p.) regional and national government policies on economy, agriculture, en-vironment and water	• review of relevant laws, docu-ments and reports on water rights • inquiries at relevant institutions • field interviews	4 4 4	• report (s) • tables and charts

Table 3.3: Information gaps.

Information Group	***Missing Information***
Supply	• Spatial distribution of rainfall and other meteorological data. • Reliable and continuous data on surface water runoff. • Data on chemical composition of rain and surface water. • Spatial variation of aquifer thickness and lithology. • Degree and nature of the hydraulic continuity between aquifereous formations. • Variation in lithology and thickness of the sandstones. • Hydraulic significance of clay and paleosol layers found in between volcanic deposits or intercalated with sedimentary formations, particularly the Tawila sandstones. • The significance of these layers also with respect to the chemical evolution of groundwaters. • Degree and nature of the hydraulic continuity between the Tawila sandstones and the overlying volcanic and/or alluvial layers. • Reliability of the pumping test data and analysis in the aquifer systems, particularly the volcanics. • Accuracy of hydrogeological parameters. • Continuation of water-level measurement in wells and of ground-control (location and altitude of well) • Lack of a recent well and spring inventory, of a monitoring program and of isotopic analysis. • Characteristics of the groundwater divide, especially in the south, southwest, and northeast. • Reliable recharge estimates. • Reliable figures and time series data on abstractions/discharge rates. • Lateral and vertical flow between permeable and semi-permeable units of the aquifer system. • Reliable estimates of storativity in different aquifer units. • Spatial distribution (as well as possible origin) of salinity.
Demand	• Total area of irrigated land and related water abstractions. • Reliable figures and time series data on abstractions/discharge rates.
Infrastructure	• Reliable topographical maps, aerial photographs and satellite imagery. • Location and characterization of potential pollution source (pesticides used by farmers, hydrocarbons around the oil well field and plants) and their impact on water quality. • Reliable chemical and bacteriological analysis.

3.4 Water Resources Management Program (2003 to 2015)

Examination of table 3.1 shows that the nature of the identified issues ranges from strictly technical matters that should be handled by one or more Government organizations to more complex problems, which require collaborative efforts. Any remedial action to be introduced should be specified as technical, physical, policy, or institutional. The recommended measures, specific arrangements required, and the time zones within which the measures are to be introduced are summarized in 3.4 (A and B). Table 3.4A describes short-term actions that are recommended to be taken within the first three years of the project. This phase concentrates essentially on initiating a number of activities most of which will continue during the remaining period of the project. It is the more difficult phase because it involves a wide variety of policy actions that require strong and effective institutional arrangements. The success of the project would practically depend on how well this phase is handled. This phase has therefore to be monitored very closely and y necessary changes have to be made all along through the program.

Table 3.4A: Short –Term program (year1 to year 3) for water resources measures required

(P = Policy; I = Institutional; T = Technical; Ph = Physical)

Serial number	*Action Details*	*Code*
1	Increase city water supply (NWSA)	P
2	Stop groundwater contamination (NWSA)	P
3	Establish an adequate hydrological monitoring network (NWRA)	T
4	Initiate a basin wide public awareness program (NWRA+MAI)	I
5	Formulate and initial the application of national water low, regulation steps, and institutional arrangements in the basin (NWRA + MAI + EPC + MPO + Donors).	P
6	Initiate field investigations (Hydrogeology, Geo-technical, Geophysics …etc) in the selected sub basin (NWRA + NWSA + MAI)	T
7	Initiate applied research (WEC in conjunction with NWRA + NWSA + MAI + EPC)	T
8	Carry out a basin-wide Socio-economic –agriculture. Water use –cropping pattern survey (MAI + NWRA)	T
9	Carry out a basin-wide awareness program (NWRA + MAI)	I
10	Initiate capacity building (NWRA + MAI + EPC + NWSA).	I
11	Initiate dialogue between the main stakeholders for policy formulation (NWRA).	I
12	Formulate and promote specific water resources strategies and management plans for the Basin through seminars, formal and informal meetings, brochures, media, etc. (NWRA)	P
13	Establish an accessible, public–oriented data-base and water information center (NWRA + WEC + Others)	Ph
14	Formulate a Water Resources Action Plan (NWRA)	P

Table 3.4B: Long –term program for year 4 to year 12.

Serial number	*Action Details*	*Code*
1	Consolidate the awareness program.	I
2	Make proper arrangement for securing a firm but socially acceptable and government –backed enforcement of the water law and supporting legislations, possibly including the establishment of a “water cost”.	I
3	Continue field investigations and expand to other areas such that the entire basin is covered by the end of this phase.	T
4	Consolidate research activities and WEC-Sector link.	I-T
5	Continue capacity building	I
6	Consolidate stakeholders’ cooperation for policy implementation and water low enforcement.	I
7	Activate water information center programs.	I-T

Part II: Well Inventory Survey in the Basin

Introduction

This part gives the main findings from the well inventory field survey, in which information from about 13425 water points across the 22 sub-basins of the Sana'a Basin have been recorded. It consists of 2 chapters:

- Chapter 4: Field activities and data acquisition.
- Chapter 5: Results

Chapter 4: Field Activities and Data Acquisition

4.1 Previous Well inventory Studies

Although a number of initiatives have been taken to count the number of wells in the Sana'a Basin, none of the previous well inventory programmes covered the entire Basin.

Well inventory surveys carried out in the Basin since the first groundwater investigation in the Basin are shown in table 4.1 below.

Table 4.1: Previous well inventory surveys in the Sana'a Basin

Study / Year	Scope of inventory	Approx. no. of wells
Italconsult (1973)	Central plain areas around the city of Sana'a. (1200 km^2)	173
Dubai (1984)	Presumably all basin (estimate only)	3000
Mosgiprovodkhoz (1986)	Presumably all Basin)	4000
SAWAS (1996)	Central plain and foothill areas around the city of Sana'a	4500
NWRA (1999)	Southern parts of the central plain only and foothill areas around the city of Sana'a	1027

4.2 General Objectives for the Well Inventory Program

This well inventory program is expected to contribute to the overall understanding of the situation of water resources in the Sana'a Basin through:

- Updating the available data and information on the Basin in general.
- Updating information about location of wells and springs, together with the quantity and quality of water available from these springs.
- Improving our understanding on the available water resources in the basin in terms of both quantity and quality.
- Assessing spatial variation in groundwater use for irrigation.
- Developing an efficient methodology for regularly updating well inventory that can be followed up by NWRA in future.

To achieve the above objectives, a complete inventory of all water points throughout the Basin (wells, springs, and surface water pools) has been carried out. The main findings across the Basin are given in chapter five below. More detailed information related to specific sub-basins within the Basin are given separately in Volume II.

4.3 Metodology

4.3.1 Collection of Field Data

A wide range of field data have been collected as can be seen from the sample of field questionnaire given in Appendix B. The information obtained for each water point include the following 16 main parameters:

1. Water point identification
2. Zone number
3. Site name
4. District
5. Well type
6. Well status
7. Well location coordinates (in UTM)
8. Static water level (measured or estimated)
9. Well yield (measured)
10. Water use classification
11. Irrigated area (in hectares)
12. Water quality indicators (EC)
13. temperature
14. pH
15. Lithology (Aquifer type)
16. Total abstraction (m^3)

4.3.2 Presentation of the Results

The results obtained were calculated on the basis of the Basin as a whole as well for each of the 22 sub-basin within the Basin. The sub-basin results are presented in Volume II of the report while this volume presents the basin-wide statistical analysis of the main results. These statistical data are given in terms of tables which display the average results of the main parameters as well as maps. Two types of maps have been prepared:

- **Single water-ponit** maps in both A3 and A0 sizes in which the location of the different types of water points, the total depth of wells, and their average yields are shown, and
- **Well aggregate** maps (km^2 maps) in which the results of each group of wells occuring within one square kilomete are given in A3 size.

4.3.3 Calculation of Abstraction

Groundwater abstraction rates depend on the yield of each well and its pumping duration. This duration varies significantly from the rainy season (normally between March and August) to the dry season which starts in late summer-early autumn and continues throughout the winter until about end February. Taking this into consideration, the period of well operations are divided in a dry season and a wet season. Using the field survey data, the duration of pumping hours in each season were calculated as follows:

- dry season during which wells work longer hours equivalent to an average of 246 days or 35 weeks. This was calculated by taking the dry period as 8 months based on the meteorological data and the response of the farmers to the questionnaire.
- wet season whereby abstraction is reduced significantly to an average of 120 days or 17 weeks. This was also based on meteorological data and the response of the farmers.

Three other parameters were also taken into consideration:

- Aquifer type (alluvium, volcanic, sandstone, limestone),
- Well type (dug, dug/bore, boreholes),
- Water use (drinking, domestic, tankers, industry, animal).

Using the analytical tool *Statistical Packages for Social Sciences*, or SPSS, annual abstraction was estimated through the following steps:

Step 1: Selection of the type of aquifer (alluvium, volcanic, sandstone, limestone). Then for each aquifer type:

Step 2: Selection of the type of well abstracting water (dug, dug/bore, or borehole).

Step 3: For each well type, the use of water was determined (irrigation, domestic , tankers, industry, animal).

Step 4: Determination of the average well/spring yield in liters per second.

Step 5: Calculation of the total duration of abstraction for each well by multiplying the daily pumping hours by the number of working days per week by 35 weeks (for the dry season) or 17 weeks (for the wet season).

The total number of abstracting wells was then categorized into several groups, based on the information obtained from steps 1 to 5, and the total annual abstraction in the Basin calculated by the summation of the results obtained from the different well types.

4.4 Well Inventory Study Team

One of the main purposes of this program is capacity building of local engineers/technicians in the Water Sector, particularly the NWRA staff members who are expected to carry out future well inventories and similar activities throughout major basins such as the Sana'a. The study team for this program has therefore been selected with care such that it represents a homogeneous technical team yet representing main Sector players (NWRA, the GDI of the Ministry of Agriculture and Irrigation, and the WEC) who can work in harmony without unnecessary disruptions to the program that may arise due to personal or other conflicts of interests.

The well inventory field team consisted of a number of work groups that were directly responsible for collecting field data/information. Six to seven teams (2 to 3 persons each) have been engaged in this activity. These teams were shuffled several times as deemed necessary by field situations and requirements. In the end, six teams became permanent for carrying out the survey in different sub-basins as shown in table 4.2. In each team, one person took measurements (*Observer*) while the other had to fill out the forms (*Recorder*) acting also as a team supervisor. Also, two senior persons were selected as *Coordinators* to form a liaison between the relevant teams and the overall *Team Leader* of the Program as indicated in the table. Specific tasks for each team member can be seen in table 4.3.

Table 4.2: Names and divisions of Well Inventory field teams.

Team Number	*Observer*	*Recorder/Team Leader*	*Coordinators*	*Study Team-Leader*
Team A	Ayoub Al-Mohab	Abdul-Mughni Al-Ja'fari`	Dr. Abdulla Noa'man	Dr. Yusuf Al-Mooji
Team B	A.Aziz Ar-Rabou'i	Ali Atrous		
Team C	Ali Al-Ghail	Abdul-Lateef Hussein		
Team D	Jalal Al-Suraimi	Saleh Al-Dhabi	Dr. Taha Al-Tahiri	
Team E	Ali Shami	Omer Faqeer		
Team F	Abdul-Wahed M. Saeed	Ali Al Kouri		
Team U	Abdul-Baqi Al-Mansoub	Hani Al-Aswadi		

Table 4.3: Day-to day activities of the WIP work teams.

Group member	***Office tasks***	***Field tasks***
Coordina-tors	• Prepare daily work plans and targets. • Prepare and distribute work materials (maps, proformas, equipments…etc.). • Delegate specific responsibilities as required by work nature and progress. • Review field sheets and data record and supervise afternoon data revision and completion. • Keeping tract of attendance and performance of team members. And supervising data inputting. • Keeping direct contact with study Team Leader and Administration to ensure work progress and efficient performance. • Assist supervisor in executing daily field excursions. • Daily consultation with supervisor on work progress.	• Guidance and general supervision of work teams. • On-site checking of data quality thru selection of some sites on an-ad-hoc basis. • Regular checking of field equipments to make sure they are in good working conditions. • General field investigations and maps checking. • Direct supervision of work team performance. • Function as recorders with the responsibilities given below.
Observers	• Cleaning, checking, and calibrating all equipment used every afternoon. • Reporting any equipment malfunctioning to the • Follow-up of purchasing and replacement of spare parts, batteries, etc. • Assist field partners (recorders) in checking and reviewing recorded information, and preparing back-up copies of all sheets/maps.	• Take all measurements requires at well sites. • Proper handling of equipment during and after measurements. • Assisting other colleagues whenever required.
Recorders / Supervisors	• Preparing field sheets (photocopying, recording serial numbers, etc.) • Preparing maps and other field material required for recording data (pencils, markers, etc.). • Together with the supervisor, reviewing recorded data and preparing them in the proper format for computer inputting • Preparing and keeping a clean copy of all filled-in/updated sheets, maps, etc. (back-up copies) to be kept always in order.	• Recording all measured data carefully while paying attention to how measurements are taken by fellow observer. • Recording any other information observed person-ally at site. • Keeping all field sheets, maps, etc. clean and make

		sure recorded information remains always eligible.

Chapter 5: Results of Well Inventory

5.1 Data analysis and presentation

According to the Terms of Reference, analysis of data is to be performed such that the final form in which results are presented is compatible with existing formats adopted by NWRA for previous inventories in Taiz and Hadhramawt. For this purpose, all raw field data have been entered into the computer using the Data Base program adopted by NWRA. Using this program, the data were tabulated, cleaned, linked, etc. They were then converted to EXCEL files for graphic preparation and so on.

In accordance with the TOR, the following main maps are produced:

- Updated piezometric map of scale 1: 100,00 approximately
- Groundwater quality map of scale 1: 100,00 approximately
- Groundwater abstraction map of scale 1: 100,00 approximately

In addition, graphs, maps and figures showing in particular statistics and trends of relevant groundwater parameters are given. Brief descriptions of the results displayed in these figures, maps, etc are given in sections 5.3 to 5.6 below.

5.2 Digital Photographs

Various digital photographs have been taken for each site from which the best ones showing well numbers and other identification features for future references have been kept. All digital photos were included with the final draft report in a CD.

5.3 Number and Spatial Distribution of Water Points

5.3.1 Number and Status of Water Points

This is the first well inventory covering the whole Sana'a Basin since the SAWAS study which covered essentially the southern and central parts of the Basin. A total of 13425 water points were inventoried, distributed throughout the Basin. Five types of water points were identified: three types of wells (dug, dug/bore and boreholes), springs and dam/pool, which refer to surface water bodies in dams or depression areas. The status of these water points during the well inventory varied from operational to dry as indicated in Table 5.1, which presents the distribution of the water points and their current status.

Table 5.1: Types and status of water points

Water point Type	Total	Operational	Intermittent	Temporarily not in use	Abandoned	Dry
Dug well	7589	4026	656	355	1130	1422
Dug/Bore	346	215	2	15	82	32
Borehole	5321	3536	8	399	1217	161
Spring	145	144				1
Dam/Pool	24	16	2	3		3
Total	13425	7937	668	772	2429	1619

As can be seen from this table, almost 70% of the total water points were reported as operational, while the remaining 30% are used when needed, abandoned, or dry.

5.3.2 Location & Distribution

The location is provided by means of GPS 12 Units, with receiver 12 parallel channels. The locations are taken by measuring the coordinates UTM-N and UTM-E for each water point. Although well elevation readings are identified by the GPS, their variability is far less than the expected variation of the groundwater level within the whole basin. For more accuracy, therefore, the water point's elevation is taken from the topographic maps. Figures 5.1 to 5.4 show the distribution of all water points and their status, in relation to the 22 sub-basins within the Sana'a Basin.

5.4 Well Construction / Design

5.4.1 Year of construction

Not only that the previous studies did not cover the whole Basin but these studies did not distinguish between the different types of wells existing across the Basin. An exception is the last inventory by the Dutch (SAWAS 1996), which only differentiated between two types of wells (shallow and deep) although it appears that the SAWAS study reported only on deep wells mostly as they were interested primarily in the sandstones aquifer..

Data collected from13107 wells during the current well inventory survey (table 5.2) show that 9207 wells (or 70% of the total wells) were dug or drilled before the year 1990, 9% between 1990-1995, and 21% after 1995. Since the SAWAS field survey was undertaken around 1990, it means that the total number of wells reported by SAWAS during 1995 (4500 wells) essentially represented 50% of the actual total number of wells existing at that time. This seems reasonable since the SAWAS only covered the central and south western parts of the Basin. Moreover the current findings also mean that practically 30% of the wells in the Sana'a Basin have been constructed after the well inventory undertaken during the SAWAS study

Figure 5.1a: Well types.

Figure 5.1b: Total number of wells per square Kilometer.

Figure 5.2a: Operating wells.

Figure 5.2b: Intermittent wells.

Figure 5.3a: Abandoned wells.

Figure 5.3b: Dry Wells.

Figure 5.4: Springs and dams.

Table 5.2: Number of wells grouped according to pre and after the SAWAS study carried out during 1990-1995

Well Type	***Number of wells constructed***			***Total***
	Pre 1990	***1990-1995***	***after 1995***	
Dug well	5494	475	1601	7570
Dug/Bore	310	8	28	346
Borehole	3403	698	1090	5191
Total	9207	1181	2719	13107

5.4.2 Well depth

The depth of dug wells are generally less than 50 meters below ground level (mbgl) as shown in figure 5.5a. Many of these wells are dug to only few centimeters below the water level such that there is very little water in the well. The majority of the boreholes (91%) are drilled to total depths ranging between 100-400 meter (figure 5.5b). Only 4% of the boreholes are deeper than 400 meters. Most of these deeper boreholes belong to the Local Water Supply and Sanitation Authority. The maximum depth penetrated so far is 1700 m in zone 16 (Sana'a City), by one of the National Water and Sanitation Authority (NWSA) exploratory wells. Table 5.3 summarizes the depths of different well types shown in figures 5.5a and 5.5b.

Table 5.3: Well depth in meters below ground level.

Well Type	***Total depth of well (mbgl)***					***Total***
	< 50	***50 -100***	***100 – 200***	***200 – 400***	***> 400***	
Dug well (no.)	7281	258	0	0	0	7539
Dug/Bore (no.)	25	123	173	25	0	346
Borehole (no)	25	203	1757	2990	215	5190
Total number	7331	584	1930	3015	215	13075

5.4.3 Well Diameters

In general, the diameter of dug wells and dug/bore ranges between 0.5 and 8.2 meters, with most wells falling within the range of 1.5-2.5 m diameter. Usually the wells are lined with stones or concrete in areas of thick alluvium. The diameter of boreholes ranges between 8 and 12 inches (0.2-0.3 m). About 3960 boreholes use casing material. and the wells stainless steel casing is steel with diameter ranges between 6 and 18 inches (0.27 – 0.45 m) as shown in Table 5.4.

Figure 5.5.a: Total depth of dug wells.

Figure 5.5.b: Total depth of boreholes.

Table 5.4: Well casing and diameters in inches

Casing Material	Casing diameter in inches								Total
	6	8	10	12	14	16	17	18	
Steel	12	1292	1316	1220	53	45	17	4	3959

5.4.4 Water Lifting Methods

Out of 8808 wells abstracting water from wells, 8490 wells (or 96%) are reported to be lifting water by mechanical means as shown in table 5.5. Seventeen (17) different types of pumps are installed, most common of which is Caprari. As for engines, there are 19 different types of engines and the most common is Yanmar.

Table 5.5: Water lifting means

Water lifting device	Number of wells
Motor Pump	7563
Submersible Pump	659
House Pump	308
Bucket	318
Total	8808

5.4.5 Pump Setting

Data on pump setting in the various types of wells abstracting water from the main aquifer types are summarized in table 5.6. Mean values for the dug wells are in the range of 21 to 33 mbgl increasing to between 59-102 and 132-171 for the dug/bore an boreholes, respectively. However, it can be seen that some boreholes are drawing water from depths exceeding 400 mbgl in all aquifers except the alluvial.

Table 5.6: Pump setting in meters below ground level

Well type	***Aquifer type***				
	Alluvial	Volcanics	Sandstones	Limestones	Unknown
	Dug				
Minimum	3	3	2.4	6	4
Mean	33	21	30	26	25
Maximum	75	87	76	81	54
	Dug/Bore				
Minimum	27	15	26	21	28
Mean	97	89	102	86	59
Maximum	162	183	189	180	90
	Borehole				
Minimum	42	25	38	42	48
Mean	132	170	171	185	165
Maximum	183	450	576	420	360

5.5 Hydrogeological Parameters

5.5.1 Aquifer Type (Llithology)

There are four main aquifer types in the Sana'a Basin (figre 5.6a).: alluvium, which represent 20% of the total number of wells, volcanics with 42% of the wells, sandstones representing about 26% of the wells, and limestones with 8% of the wells. It is not known which one of these four aquifers represents the remaining 4% of the wells.

With respect to the type of wells in each aquifer, a significant variation has been observed. For dug wells, 46% of them are in the volcanics, 31% in the alluvium, 12% in the sandstones, and 7% in the limestones. For boreholes, 47% of them are in the Sandstones, 37% in the volcanics, 9% in the limestones, 4% in the sandstones, and only 3% in the alluvium. Thus almost half the dug wells are in volcanics while half the drilled ones are in sandstones as indicated in Table 5.7.

Figure 5.6a: Well yields in litres/second.

Table 5.7: Number of wells in each aquifer type

Well Type	Aquifer type								Total
	A	V	S	L	U	C	G	Sh	
Dug well	2389	3510	920	574	189	1	3	3	7589
Dug/Bore	50	126	100	65	5	0	0	0	346
Borehole	175	1951	2480	451	263	0	0	0	5320
Total	2614	5587	3500	1090	457	1	3	3	13255

A: alluvium; V: volcanics; S: sandstones; L: limestones; U: unknown; C: crystalline; G: gypsum; Sh: shale

5.5.2 Well/Spring Yield

Logistic problems, related mainly to the fact that the inventory extended to the wet season when many wells were not operational and owners were either not at site or would not operate the engines, have made it difficult to take water level measurements on all wells visited. Out of 8577 water points identified as operational, the yield of only 2902 could be measured (Table 5.8). Close to 50% of the operating wells / springs (1293 water points) were found to be discharging at a low yield of less than 4 l/s, 23% (669 water points) had a discharge rate of 4-6 l/s, and the remaining 32% (940 water points) were pumping at a rate exceeding 6l/s. Table 5.8 presents the actual yield for each well. The majority of the water points with higher yields are boreholes which practically spread across the entire Basin except the eastern highland (plateau) areas (figure 5.6b). The heavy concentration of these high-discharge boreholes in the central-western areas (sub-basins 8 and 13) is noteworthy and may signify a high productivity of the relatively young (Quaternary) volcanics covering these areas.

Table 5.8: Categorization of water points according to yield in l/s

Well Type	Yield in liters per second			Total
	< 4	4-6	>6	
Borehole	730	537	871	2138
Dug well	463	113	52	628
Dug/Bore	69	19	15	103
Spring	31		2	33
Total	1293	669	940	2902

The average yield for the different types of water points is calculated as 6 l/s for the borehole, 3 l/s for both the dug and the dug/bore, and only 0.62 l/s for the springs. NWSA water supply wells reported to yield more than 15 l/s.

Figure 5.6b: Aquifer types supplying existing wells.

5.5.3 Depth to groundwater

Of the total number of wells recorded, 11637 had water in them when visited. Approximately 60% of the water levels (6997 wells) were measured by using electrical tapes or at least estimated, using field observations as well as information supplied by owners on number of pipes, etc. Depth to water level was measured in 83% of the total number of dug wells. In all of them, the water level did not exceed 50 mbgl (figure 5.7a). 62% of the water level measurements in boreholes ranged between 100-400 mbgl (figure 5.7b). Table 5.9 summarizes the depth to water in the different types of wells.

Table 5.9: Depth to groundwater in meters below ground level

Well Type	***Depth to water in meters below ground level***				***Total***
	< 50	**50 -100**	**100 - 150**	**150 - 200**	
Dug well	5051	90	0	0	5141
Dug/Bore	97	36	11	1	145
Borehole	161	483	899	156	1699
Total	5321	609	910	157	6997

Figure 5.7a: Average water levels in meter below ground level (dug wells)

Figure 5.7b: Average water levels in meter below ground level (boreholes)

5.5.4 Groundwater Flow (Potentiometric surface)

In order to draw a piezometric or a water table map representing the potentiometric surface for groundwater flow, detailed *and* accurate information on the abstracting wells is needed. This is usually obtained through exploratory maps in which the exact depth from which water is being abstracted, exact topographic elevation of the well, etc. can be obtained. Obviously for an inventory of over 13000 wells most which are private wells with no well lithology, design, etc., it is impossible to obtain such a map with accuracy level required. This is why an international regional project like the SAWAS Project could not prepare such a map. Instead, they took the Italconsult data of 1973 on the basis of which they drew up a map for the National Capital surroundings only.

With such limitations, however, there is another way of determining the general flow direction of ground-water. This is done by taking the groundwater elevations (in meters above sea level), averaging them for every group of wells within one square kilometer, and drawing a well elevation map per km^2. The general trend obtained from both dug wells (figure 5.8a) and boreholes (figure 5.8b) is very similar. Groundwater flows from the Eastern, Southern, and Western high plateau zones towards the Central zone and eventually northwards towards *Wadi al Kharid* where it is known to be discharged naturally through the *Al Kharid* springs. This is in agreement with the general conclusions in the SAWAS study that:

> *"the general trend of groundwater flow is to the north. In the mountainous areas, the direction of low is east (on the western slopes) and west (on the eastern slopes).* In the Basin itself, groundwater flows north." (SAWAS, Main report, 1996, p.75).

Figure 5.8a: Potentiometric surface (water level elevation above sea level per square kilometer) - dug wells.

Figure 5.8b: Potentiometric surface (water level elevation above sea level per square kilometer) – boreholes .

5.5.4 Electrical conductivity

Electrical conductivity (EC) was measured at 7772 water points (figures 5.9 a and b). Close to 6000 water points (77%) have less than 1000 µS/cm, 18 % range between 1000-2000 µS/cm, and only 15% are reported to have EC in excess of 2000 µS/cm (Table 5.10). It is observed, however, that the higher salinities are mainly recorded in dug wells. Of the more saline wells (see figure 5.9a), 127 are in zone 9 (*Wadi Bani Huwat*), 88 wells in zone 10 (*Wadi Thumah*), and 75 wells in zone 5 (*Wadi A'sir*).

Table 5.10: Electrical conductivity in µS/cm

Well Type	***< 1000***	***1000-2000***	***> 2000***	***Total***
Dug well	3210	1093	386	4689
Dug/Bore	150	43	12	205
Borehole	2489	236	19	2744
Springs	120	11	3	134
Total	5969	1383	420	7772

Figure 5.9a: Electrical conductivity distribution per square kilometer (Dug wells)

Figure 5.9b: Electrical conductivity distribution per square kilometer (Borehole)

5.5.5 Temperature

In general, the temperature of groundwater increases with depth because of the hydrothermal gradient in the area, which, in turn, is influenced by the volcanic activity among other tectonic factors. It is therefore expected that the deeper the well the higher its water temperature, especially if it lies within the vicinity of areas subjected to recent volcanic activity or along fault zones. On the other hand, it is obvious that shallow dug wells are affected by the penetration of sun rays that raise the water temperature, particularly in those wells that are uncovered and have very little water in them. A clear trend for groundwater temperature may not, therefore, be very obvious but the general effect of these two main factors may be detected.

Table 5.11 shows that almost 26% of the wells, mainly dug, have temperatures of less than 20 ^{o}C while 69% have temperatures ranging between 20-30 ^{o}C. Only 257 wells (about 3%) recorded temperatures more than 30 ^{o}C. Although a good number of these wells are in *Bani al Harith* (sub-basin 9), such wells with higher temperatures are practically found across the Basin (figure 5.10b) indicating most likely the significance of geothermal effect throughout the whole area. Temperatures of up to 55 ^{o}C have been recorded in the northeastern areas of sub-basin 9, where high tectonic activity has resulted in a very complex geological structure as signified by the uplifting of deeper geological formations and/or their re-orientation along fault zones (e.g *Jabal as Sama'*). 14 deep boreholes with water levels of 200 mbgl, most of them in this area, have temperatures in excess of 40 ^{o}C.

Table 5.11: Temperature of water

Well Type	**< 20**	**20-30**	**> 30**	**Total**
Dug well	1968	2669	12	4649
Dug/Bore	28	170	4	202
Borehole	28	2381	240	2647
Springs	67	63	1	131
Total	2089	5283	257	7629

Figure 5.10a: Temperature distribution per square kilometer (Dug wells)

Figure 5.10b: Temperature distribution per square kilometer (Borehole)

5.5.6 pH

Approximately 60 % of total measured wells have pH of less than 8 with about 54% being in the range of 7 to 8, the normal pH range for groundwater in general. The remaining 40 % has pH in excess of 8 (Table 5.12). It is interesting to see also that there is no significant difference between the pH of water in the different types of water points. This may signify that the water abstracted from most wells is mixed groundwater rather than coming from a single aquifer layer, considering that the majority of wells are production wells in which owners try to maximize the yield rather select a particular aquifer zone. It is also important to see from figure 5.11 that the pH in volcanic terrains is generally higher than in other areas.

Table 5.12: pH of water in the various types of well points

Well Type	**< 7**	**7-8**	**>8**	**Total**
Dug well	180	2510	1798	4488
Dug/Bore	7	96	93	196
Borehole	229	1403	1048	2680
Springs	4	59	65	128
Total	425	4068	3004	7492

Figure 5.11a: pH distribution per square kilometer (Dug wells)

Figure 5.11b: pH distribution per square kilometer (Borehole)

5.6 Groundwater abstraction

5.6.1 Duration of Abstraction

Unlike NWSA boreholes, which work 24 hours a day, the private wells owned by locals only operate part of the day. In general, the average daily working hours during the dry season were found to be 10, 3, and 8 hours for boreholes, dug wells, and dug/bore, respectively. For the wet season, the average daily working hours were 8, 4, and 6 for boreholes, dug wells, and dug/bore, respectively. Also, some wells work only one day a week while others pump water 7 days a week (NWSA wells). Table 5.13 (a and b) shows categorization of wells according to daily working hours and weekly working days during each season.

Table 5.13a: Categorization of wells according to their daily working hours

Hours/day	***Number of wells***	
	Dry season	Wet season
0-5 hours	3673	3544
5-10 hours	1823	3517
10-15 hours	1748	318
15-20 hours	220	85
20-24 hours	26	26
Total	7490	7490

Table 5.13b: Categorization of wells according to their weekly working days

Days/week	***Number of wells***	
	Dry season	Wet season
0-2 days	1652	1490
2-4 days	991	2018
4-6 days	2364	2650
7days	2483	1332
Total	7490	7490

On a seasonal basis, the total working hours per borehole during dry season varies between 35 (for those that work only I hour/day and 1 day/week for 35 weeks) to 5880 hours (for NWSA wells that work 24/day and 7 days/week for 35 weeks), with an average 2250 hours. For dug wells, the range is from 35 to 3920 hours, with an average 573 hours. For dug/bore, it varies between 35 to 4410 hours, with an average of 1847 hours.

During the wet season, however, the total number of working hours for boreholes vary between 17 (for. those that work only I hour/day and 1 day/week for 17 weeks) and 2856 hours (for NWSA wells that work 24/day and 7 days/week for 17 weeks), with an average of 630 hours. For dug wells, the range is between 17 and 1666 hours, with an average 360 hours, and for dug/bore between 17 and 1904 hours, with an average 507 hours.

Based on the sum of working hours in both dry and wet seasons (Table 14), the annual pumping hours for the different types of wells abstracting groundwater from the Basin are as follows:

Borehole: 2905 hours.
Dug well : 934 hours.
Dug/bore : 2377 hours.

Table 5.14: Annual pumping hours of wells

Well Type	Pumping hours		
	Dry season	Wet season	Total
Borehole	2250	630	2905
Dug	573	360	933
Dug/Bore	1847	507	2354

5.6.3 Aquifer Yield

By relating the well/spring discharges measured to the geological formation from which groundwater is being abstracted, it was possible to obtain information on the productivity of the different types of aquifer. The result is displayed in table 5.15 from which it can be seen that it agrees very well with the well discharges. For example, the average yield in alluvium (3 l/s) is exactly the same as what has been obtained for dug wells, which are primarily in this aquifer type. Similarly, the average yield of the sandstones (5.7 l/s) agrees well with that for boreholes .

Table 5.15: Aquifer yield as estimated on the basis of well types pumping from each aquifer (l/s)

	Aquifer type				
Estimated yield (l/s)	Alluvial	Volcanic	Sandstone	Limestone	Unknown
	3.3	5.0	5.7	3.9	4.5

5.7 Abstraction and Use

5.7.1 Well Concentration

One of the important features of Sana'a Basin discovered during this study is the heavy concentration of wells per square kilometers as well as the significant variation in the well concentration from zone to zone. It was striking to find out that to 92 wells / km^2 were observed in some of the areas in *Bani Hushaysh*, which is generally characterized by a significantly higher number of wells /km^2 as shown in figure 5.12. In general, there is much less concentration of wells in the northwestern and southwestern plateau areas as indicated in this map.

5.7.2 Water Use Patterns

Water use patterns were determined for 9001 water points (Table 5.16). 87% of them (7848 water points) were being used for irrigation, while only 10% (912 water points) were reported for municipal use (drinking + domestic). Many of the wells used for industry could not be visited due to difficulties in accessibility. These wells are either at industrial zones or military camps that were impossible to enter. Only 15 industrial wells were inventoried and were not included in the calculations shown in table 5.16 since this number does not represent the real number of industrial wells in the Basin. In this table, the "other" column refers to wells for special uses such as for mosques (9 wells), poultry farm (I well), hospital (1 well) , Hammam (1 well) , or for aquifer recharge (1 well). Out of the supply wells shown in Table 5.16`, 63 boreholes belong to NWSA.

Table 5.16: Water use patterns for the different types of water points

Well Type	***Water Use***							***Total***
	Irrigation	Supply	Domestic	Tankers	Industry	Animal	Other	
Borehole	3419	168	162	85	14	3	8	3859
Dug well	4156	9	503	11	1	56	10	4746
Dug/Bore	206	5	15	2	0	2	1	231
Spring	51	1	49	0	0	43	0	144
Dam/Pool	16	0	0	0	0	3	2	21
Total	7848	183	729	98	15	107	21	9001

5.7.3 Irrigated Areas

Since the Basin's water resources are mainly used for irrigation, it is important to know how much water is being abstracted for this purpose (see Volume II) as well as how much land is being irrigated with the water. The total number for which information on irrigated areas could be collected is 7779 as shown in table 5.17, of which 3407 (44%) are boreholes, 4093 (53%) dug wells, 213 (3%) dug/bore, and the remaining 66 (<1%) springs and 16 dam/pool water.

Irrigated areas per individual well vary between 0.001 and 46 hectares with an average irrigated of about 3.25 hectares per well. The smaller plots are mainly irrigated by dug wells while most of the larger plots between 20 and 50 hectares are irrigated by boreholes.

Table 5. 17: Size of irrigated areas for each water point type (in hectares)

Well Type	Irrigated area in hectares				Total
	0-5	5-10	10-20	20-50	
Borehole	1909	893	550	55	3407
Dug well	4045	34	13	1	4093
Dug/Bore	158	34	20	1	213
Spring	53	3	1		57
Dam/Pool	5	1		3	9
Total	6170	965	584	60	7779

5.7.4 Total Abstraction

As indicated before, the total abstraction in the Basin, on the basis of sub-basins, is given in Volume II. By relating the abstraction to local geology, it is possible to estimate how much water is being abstracted from each aquifer type. The result is shown in Table 5.18 which gives a summary of annual groundwater abstraction for different uses, based on the number of wells, type, pumping hours, aquifer, and use. However, it is emphasized that these results should be used as gross estimations only since the water pumped from the majority of wells in the Basin is mixed water that may not represent a particular aquifer type.

Table 5.18: Annual groundwater abstraction in Sana'a Basin (Mm^3/year)

Aquifer Type	Sector use in million cubic meter			Total
	Irrigation	Municipal	Industry	
Alluvium	10.83	2.96	4.50*	13.79
Volcanic	76.86	11.80		88.66
Sandstone	108.44	9.98		118.42
Limestone	16.43	1.23		17.66
Unknown	5.49	10.43		15.92
Total	218.05	36.40		258.95

* Adopted from WEC-ITC, 2001 since no better estimation could be obtained in the current study.

Figure 5.12a: Number of abstracting wells per square kilometer.

Figure 5.12b: Total Annual Groundwater Abstraction (m^3)per Square Kilometer (see figure 5.12a for number of wells).

Appendix A: TOR for the study

Introduction

These Terms of Reference (TOR) are prepared as part of a number of studies which are expected to contribute to a better understanding of the Basin's characteristics. They come within the context of the Basin-wide inventory survey through which all the basic information are collected, as described above, for future reference. The TOR concerns the following studies, which are expected to be implemented shortly after this study: *Geological investigation/Geophysical investigation (chapter 6) and Hydrogeological/ Hydrogeochemical investigations (chapter 7).*

Chapter 6: Geological and Geophysical Investigations

6.1 Geological Survey

6.1.1 Background

The evolution of the Sana'a Basin has occurred through a diversity of geologic events as summarized in table 6.1. Two major factors have contributed to the complexity of the surface as well as the sub-surface geology across the Basin: the effect of the two young rift systems bounding the region from the south (*Gulf of Aden Rift*) and west (*Red Sea Rift*) and their superimposition on the much older regional *Najd* fault system. This has resulted in the accumulation of old (Paleozoic to Mesozoic) sedimentary formations on the crystalline Basement with significant differences in the nature and total thickness of the younger rocks overlying the sedimentary sequence in the northern and southern areas. As a result of this, the Basin behaves essentially like two different groundwater provinces: a northern one incorporating essentially the *Arhab* and *Nihm* regions and a southern one comprising the remaining seven regions (*Bani Hushaysh, Bani Al Harith, Khawlan, Bani Matar, Hamdan, Sanhan-Bani Bahlul,* and *Al Amana*. The important geological features of these two parts of the Basin, with respect to their control on groundwater flow and chemical evolution is still not very well known.

6.1.2 Objectives:

- To identify the geological outcrops exposed across the entire Basin.
- To determine the surficial features of all geological units, including stratigraphic sequence, structure, geochemical nature, geomorphological properties, and any other useful information.
- To determine the variation in lithology and thickness of all outcropping geological units, with a special attention given to the sandstones and any other units interlayering within this formation.
- To describe the structural evolution of the Basin as a whole and indicate the correlations between the different geologic units.
- To calculate the true thickness from the apparent thickness of different stratigraphic units.

6.1.3 Scope:

- Review existing technical reports relevant to the subject, particularly those at NWRA (National Water Resources Authority), SWSSP (Sana'a Water Supply and Sanitation Project), WEC (water and

Environment Centre at Sana'a University), and GMRSA (the Geological and Mineral Resources Survey Authority).

- Consult with technical personnel / specialists at GMRSA and GED (Geology and Environment Department at Sana'a University) to identify/locate special reports based on concentrated scientific research such as post-graduate university dissertations and Consultants' investigations related to specific issues.
- Review and provide adequate interpretations of available aerial photos, satellite images of different scales.
- Carry out laboratory testing on rock samples and crushed sediments.
- Carry out extensive field investigations covering the entire Basin with special attention to the Hamdan-Bani Hushaysh-Nihm areas where the sandstones stratigraphy is complicated by intensive tectonics.
- Study the information displayed in table 5.1 for the purpose of verifying the geological events responsible for he structural evolution of the Basin.
- Prepare a comprehensive report on the main findings.

6.1.4 Deliverables:

- Detailed description of geological units occurring within the Basin.
- Evidence and location of major faults and other groundwater flow controlling structures.
- Comprehensive description of the structural/geological evolution of the Basin.
- Spatial variation in the lithology of the main geological formations with special emphasis on the presence of lake or any other clayey sediments that bear on the chemical composition of groundwater.

6.1.5 Output Format

- A basin-wide surface geological map of 1:100 000 scale.
- A basin-wide geological structure map of 1:100 000 scale.
- Localized maps of the sandstone areas with scales ranging from 1:5000 to 1:20 000 as deemed necessary.
- Interpreted boreholes of selected deep wells representing the different aquifer systems so as to show the strategraphic sequence and spatial variation in lithology.
- A report describing the results of the investigation.

Table 6.1: Summary of the geological evolution events in the Sana'a Basin

Age	***Tectonic events***
Quaternary	Late volcanic activity occurred where a lot of dykes and plugs of different trends (the dominant trend N-S, NW-SE and E-W) intruded all the stratigraphic sequence from Precambrian to the Tertiary rocks. Along N-S fractures the present area of the Sana'a city, the rocks is eroded away forming the intermountain plain of Sana'a basin. The post tectonic movement occurred during the Quaternary time. This movement accompanied with volcanic activity intruded the old rocks, and this stage of volcanic activity has very distinction morphology where it characterize by its distribution as scatter cones, cinders, dykes and plugs and sometimes spread as lava flow in the low land.
Tertiary	The Sana'a basin stratigraphic sequence was intruded by Yemen volcanic rocks covering all the old sedimentary rocks. In the final stage of volcanic eruption, the Sana'a basin was subjected to compressional stage where the Sana'a anticline is formed with fold axis of N-S trend. This axis dies out in the north with steep plunge in the south. Another stage of extensional faulting has resulted in the shaping of present area which was contemporaneous with the opening of Gulf of Aden and Red Sea. These are extensional faults such as the Hadda, As Sirr and wadi Quthi faults, which are all striking E-W.
Cretaceous	Sana'a basin was subjected to uplifting and received a lot of clastic rocks of Tawilah group. In late Cretaceous both Amran and Tawilah groups were affected by E-W tectonic movement resulted in the formation of extensional faults such as Wadi Dhahr and Al-Sabeen faults.
Jurassic	Sana'a basin was subjected to subsidence forming deep depression of NW-SE trend and Amran group was deposited giving rise to a thickness of more than 1600 m such as in Arhab and Al-Hitaresh wells.
Ordovician	The initial main trend of Sana'a basin is formed and the continental elastic sediments (Kohlan Formation) were deposited.
Cambrian	Old tectonic of two trends (N-S & NW directions), which were probably reactivated from Hijaz and Najd Progenieses.

6.2 Geophysical Survey:

6.2.1 Background:

Surface and borehole geophysical methods are valuable tools for hydrogeological mapping. They provide information on rocks and fluid properties both in vertical and lateral extent. A number of studies employing vertical electrical soundings (VES) techniques have been carried out in the Sana'a Basin including Italconsult, 1973; Sha'aban, 1982; Van Kuijk, 1991; Al-Gabery, 1991; and Mosgiprovodkhoz,1986 who undertook the only survey at a regional scale. While this study however was essentially limited VES, the original data from the survey has never been made available for any further interpretation. The only electro-magnetic (EM) data (Exxon, 1987) have been made available to the SAWAS study in which it was stated that these data need further re-interpretation. The Japanese study (JICA, 1992) carried out a more comprehensive study including VES, EM and seismic reflection (SR) survey. This study however was limited to the southern part of the Basin covering essentially the *Sanha*n district and the southern areas of the city. As such, comprehensive basin-wide investigations employing the various geophysical methods applicable to groundwater exploration has not been carried out to date.

6.2.2 Objectives:

- To determine the spatial distribution of the different geological units occurring within the Basin as well as around it periphery, both in the horizontal and vertical directions.
- To obtain reliable geophysical cross sections for areas where the Tawila sandstones are cropping out or buried in relatively superficial zones.
- To assess the thickness, continuity and possible displacement of the main geological formation in order to delineate the geometry of main aquifer systems.
- To assess distribution pattern of fresh, brackish and saline water in the subsurface.

6.2.3 Scope:

- Review previous geophysical studies, particularly reports of exploration companies (for oil as well as other natural resources) available with the various organizations within the Ministry of Oil and Mineral Resources (MOMR).
- Based on the geological conditions and the accessibility of the sites, select the appropriate geophysical technique for obtaining information as specified under deliverables.

- Undertake geophysical data acquisition in a number of pilot areas within the Musyareka hydrological unit such that all the groundwater zones occurring in this main part of the Basin are represented, especially and including a selected number of short-distance measurements at the locations where the presence of a contaminant plume or saline waters is inferred from the 2002 well inventory survey or any other previous study.
- Select a number of wells across the Basin (both N-S and E-W) from the newly obtained well inventory data and carry out geophysical logging to validate the results of surface geophysics.
- Submit a comprehensive report on the main findings.

6.2.4 Deliverables:

- Detailed features of the main geological units across the Basin including thickness and spatial variation in lithology.
- Detailed description of all thin layers of fine-grained sediments, especially clayey layers that may be intercalated within the main sedimentary or volcanic deposits, which may of significance with respect to the groundwater flow or its chemical evolution.
- Position and possible trends of major faults or other regional structures that may control groundwater evolution, including salt layers and related tectonic features.
- Location and spatial distribution of zones that are likely to contain brackish and/or saline groundwaters.

6.2.5 Output Format:

- A number of geophysical cross sections (at least five oriented such that the Basin ***and*** its periphery is well covered) depicting the lithology and structure, as well as a profile perpendicular to these sections.
- Maps of 1:100 000 scale showing the vertical and lateral extent of brackish and saline groundwaters, as interpreted from geophysics in correlation with actual well log data.
- Interpreted borehole logs for selected wells and recommended sites for a near-future exploratory program required for giving a complete picture of the Basin.
- A report describing the results of the investigation.

Chapter 7: Hydrogeological and Hydrogeochemical Investigations

7.1 Hydrogeological Survey:

7.1.1 Background

The water resources problems prevailing in the Basin are essentially resulting from the increasing supply-demand imbalance due to rapid expansion of the city. While the current policies emphasize heavily on demand management, augmentation of the supply can always ease the pressure on the aquifer system, especially the heavily exploited Tawila sandstones. This necessitates a good understanding of the aquifer system. Of particular importance are the spatial distribution of the different aquifereous units, their dynamics (for example, the inter-connectivity of the various layers), and their hydraulic properties such as transmissivity (T) and storativity (S). None of these parameters are well understood despite the fact that groundwater investigations in the Sana'a Basin started more than 30 years ago. One of the main reasons for this is that the Basin has never been investigated in a comprehensive manner as most studies were primarily focused on how to obtain more drinking water from the sandstones for the city. Moreover, such studies were often carried out in a hurry after the water problem reaches critical levels, i.e. no proper planning and no time allowed for scientifically based results that normally require relatively long time.

7.1.2 Objectives:

- To examine and assess the aquifer systems' dynamics.
- To obtain reliable hydrogeological maps.
- To collect additional physical information on the aquifer units, particularly in relation to their lateral and vertical extents, their interconnectivity, and their lithology at both macro and micro levels.
- To assess the hydraulic properties of the different aquifers.

7.1.3 Scope:

- Critically review all previous information (maps, cross sections, water level data, etc) related to the hydrogeological properties of the geological units occurring within the Basin and its periphery, including the recent well inventory survey.
- Obtain all geological maps and material required for work from different government organizations and scientific institutions.
- Prepare hydrogeological maps of 1:100 00 scale or larger (as may be necessary in some cases especially the sandstone areas around NWSA well fields), including a potentiometric map based on the most recent data available.

- Determine clearly the areal extent of the sandstone aquifer outside the Basin and the hydrogeological conditions in these periphery zones (i.e. where and how groundwater is likely to be lost to other regions beyond the catchment main boundary).
- Carry out proper pump tests on a number of wells, selected on the basis of the results from the well inventory and in close consultation with *both* NWRA and SWSSP, to determine T and S such that a good understanding of the aquifer parameters across the Basin can be achieved.

7.1.4 Deliverables:

- Set of maps showing the spatial distribution of the aquifer units, groundwater flow structures such as major faults, the water table(s), flow directions.
- Set of hydrogeological cross sections across the Basin from various directions including at least N-S and E-W.
- A structural map showing the position, trends, and nature of major faults (i.e. closed or open; groundwater flow direction up or down, etc.).
- Tabulated information of all hydrogeological data available to date.
- Raw data and analytical results of pump tests.

7.1.5 Output Format:

- Maps of scale 1: 100 000 and larger.
- Cross-sections with reasonable scales indicating both horizontal distance and vertical exaggerations.
- Interpreted boreholes for selected wells.
- Report describing results and main findings.

7.2 Hydrogeochemical Survey:

7.2.1 Background

The chemical composition of groundwater can pose serious limitations on the utilization of any particular aquifer system. Evaluation of groundwater quality is therefore an essential component of the overall assessment of water resources for the purpose of sustainable development. As far back as 1973, the Italconsult study has shown that while the EC of groundwater in the Basin was acceptable for different purposes (generally below 1000 $\mu S/cm^2$), relatively high salinities were observed in a number of wells north of the city towards *Ar Rawdha*. By 1995 when the SAWAS study was undertaken, these pockets (ponds) of saline waters have caused a plume of contaminated groundwater due to a significant rise in water table. Such an increase in salinity has been accompanied with an abnormal shift in groundwater composition towards Ca-Cl_2 facies, which is peculiar for shallow groundwater systems evolving under normal conditions. Elsewhere the groundwater composition varied from $CaHCO_3$ (in the limestone and other sedimentary areas) to $NaHCO_3$ (in the volcanic terrain) though usually of a mixed nature and lower salinity levels.

7.2.2 Objectives:

Generally speaking, the following three main activities can significantly contribute to a better understanding of the chemical evolution of groundwaters across the Basin:

1. Identification of the chemical processes that occur along flow lines.
2. Determination of the reactivity of sediments comprising the different aquifers in an attempt to assess water-rock interaction.
3. Introducing water quality monitoring on a regular basis as an integral part of IWRM, particularly with respect to groundwater pollution in the main recharge zones.

Specific objectives to be pursued can be as follows:

- To characterize the different groundwater occurring in the Basin on the basis of their chemical composition.
- To assess the origin of each groundwater type through the application of environmental isotope techniques as part of an integrated geochemical approach.
- To delineate the spatial distribution of brackish and saline waters.
- To assess the nature and extent of pollution, both within the urban center (Sana'a city proper) and its peripheral zones subjected to irrigation practice.
- To contribute to the understanding of the recharge mechanis.

7.2.3 Scope:

- Study and critically all hydrogeochemical data available.
- Examine the results of the recent well inventory survey and propose a water sampling program to be implemented regularly.
- Identify all chemical, isotopic, and biological parameters to be analyzed and propose a time schedule for the routine analysis of such water quality indicators, both in the field and in the laboratory.
- Prepare guidelines for all field activities and laboratory procedures required.
- Initiate and actively supervise the collection and analysis of water samples according to a well-defined program that includes training of local staff.

- Carry out geochemical modeling exercises to identify major hydrochemical processes and assess water-rock interaction.

7.2.4 Deliverables

- Hydrochemical data files compatible with the NWRA database information system
- Spatial distribution of different hydrochemical zones.
- Typical groundwater composition expected in each geological terrain (e.g. the volcanic region in the south) and tthe shallow groundwater system as a whole (as opposed to the deeper hydrothermal?system).
- Identification of the source(s) of brackish and saline groundwaters.
- Identification of pollution sources as well as potential zones vulnerable to such pollution risks.

7.2.5 Output Format:

- Hydrochemical maps of scale 1: 100 000 and larger.
- Map of scale 1: 100 000 showing pollution sources, pathways, and vulnerable zones.
- Cross-sections with reasonable scales indicating both horizontal distance and vertical exaggerations.
- Computer files with analytical data (chemical, biological, and isotopic) as well as other support information such as location, geological formation, sampling depth, etc.
- Report describing results and main findings.

Appendix B: NWRA Comments on the Draft Final Report