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Chapter 2. THE PREPARATORY ACTIVITIES

The preparatory activities were aimed at reviewing and analyzing previous scientific data and information generated through the large number of projects implemented in the Sana'a Basin, in an effort to assess the level of these studies and the coverage and depth and to ultimately outline the gaps in data and information in the hydrogeology of the basin.

The studies and reports reviewed cover a period of over thirty years starting with the Italconsult study of 1973 up to the most recent of 2005.

The activities included under this section were defined by the Inception Report as:

- Sub-activities that can be categorized as follows: Inventory and review of existing reports, maps and supplementary data and information,
- Processing and inter-preparation of all data and information reviewed, and
- Identification of main information gaps.

I OUTPUTS OF INVENTORY AND REVIEW OF PREVIOUSLY EXISTING REPORTS, MAPS AND SUPPLEMENTARY DATA

A thorough inventory and review of relevant reports, publications and maps was carried out in the first stage of this study. The important sources from which the previous data were collected are:

- Water and Environment Centre (WEC) Library,
- The Central Library of Sana'a University,
- Faculty of Science Library,
- Food and Agricultural Organization (FAO) Library,
- National Water Resources Authority (NWRA) Library,
- National Water and Sanitation Authority (NWSA) Data Bank,
- Petroleum Exploration and Production Authority (PEPA) Data Bank,
- Geological Survey and Mineral Resources Board (GSMRB) Library,
- Local Corporation of Water and Sanitation of Sana'a (LCWSS) Data Bank,
- Ministry of Agricultural and Irrigation (MAI) Documentation Centre, and
- Personal libraries of officials, university staff, researchers, etc.

Hard and Soft copies of the previous studies representing several project reports, Ph.D and M.Sc Theses, scientific papers, thematic maps (Topographic, Geologic & Hydrogeological Maps) and sub-surface geological, hydrogeological and geophysical cross-sections

Historically, water supplies in Sana'a Basin were obtained by tapping both shallow dug wells and springs. The construction of boreholes and the introduction of powerful pumps began in the 1960s and increased rapidly from the mid-1970s onwards. To that effect, a large quantity of hydrogeological data and information was made available by these boreholes.

The review of literature (the recent well inventory carried out by the Water and Environment Centre, WEC, 2001) indicated that the total number of water points in the Sana'a Basin is 13,426, of which 5321 are bore holes, 7589 dug wells, 346 dug/bore, 146 springs and 24 dams/pools (surface water). At present, the rate of water level drop in Sana'a Basin ranges between 5-6 m/yr. Recent reports of the World Bank indicated that, in Sana'a Basin, the withdrawals of groundwater exceed renewable resources by 400% (Yemen Times, 2000). The annual abstracted groundwater is estimated at 260 MCM (WEC, 2002). The Annual recharge was estimated at 52 MCM (Al-Derwish, 1995). The agricultural sector uses about 80% of the abstracted groundwater, whereas domestic use is only about 20%.

A thorough review of previously collected data was carried out. A brief summary of the inventory outputs is given below.

1.1 Data related to the delineation of aquifers

Aquifer delineation and distribution in the Sana'a Basin is illustrated in a number of publications and maps. The following sections describe this aspect.

1.1.1 Previous geological maps and studies

The important stage in the geological study of the Sana'a Basin was marked by the publication of the Yemen Arab Republic (YAR) geological map scaled 1:500,000. This map was published in the United State of America (USA) in 1978 and was based on satellite imagery data. The stratigraphic division of the sedimentary and igneous rocks in this map is based upon the scheme offered by Geukens for the Arabian Peninsula. The geological structures and tectonics of the area were further detailed in 1983 by the Federal Institute for Geosciences and Natural Resources in its geological map scaled 1:250,000 (Al-Subbary, 1995).

Three geological maps were reviewed and studied in the course of the preparatory activity. These maps are:

1.1.1.1 Geological map of Sana'a, sheet 15 G, 1:250,000

The Natural Resources Project. Ministry of Oil and Mineral Resources, Oil and Mineral Cooperation, Mineral Exploration Board; Republic of Yemen, by Robertson Group (1990-1991)

1.1.1.2 Geological map 1:100,000 by Jungfer (1987)

1.1.1.3 Geological map of the Yemen Arab Republic, sheet Sana'a, 1:250,000

Ministry of Oil and Mineral Resources, Sana'a, Republic of Yemen/Federal Institute of Geoscience and Natural Resources Hanover, 1991, Federal Republic of Germany . By W. Kruck and U. Schäfer

The geological maps cited differ in their information content and thematic focus. From each of the maps, specific information was derived. The Robertson Group map puts emphasis on the lithology and was created mainly on the basis of satellite imagery with very limited field work.

The Jungfer map is the only one of the three maps that refers to the initial subdivision of Italconsult (1973) and was prepared in a larger scale of 1:100,000. The BGR Map pronounces more the stratigraphy and was also based on satellite imagery with limited field observations (GAF Report, 2007).

In addition to the above cited maps, the geological maps prepared by Italconsult, 1973, Mosgiprovodkhoz (Russian) 1986, SAWAS, 1996 and WEC, 2001, were reviewed and studied. The recent geological map prepared by GAF, 2005 was used in the preparation of the new geological map of Sana'a Basin prepared by Hydrouslt, 2007 for the purpose of this project.

The stratigraphic sequence of Sana'a Basin ranges from Precambrian to recent, with some periods of hiatus. The Phanerozoic rocks of the Sana'a Basin consist mainly of sedimentary and volcanic rocks. Subsurface data reveal the presence of the Precambrian rocks as recorded in Arhab and Al-Hatarish wells (DS1 in Arhab and DS2 in Al Hatarish areas), which represent the deepest wells drilled in Sana'a Basin (Kruseman and Vasal, 1996).

The different lithostratigraphic units in the Sana'a Basin in an ascending time line are the Kohlan sandstone formation of Triassic – Jurassic age, the Amran Group of Jurassic age, the Tawilah Group of the Cretaceous age, the Tertiary Volcanics Group of the Tertiary age, the Quaternary Volcanics of the

Quaternary age, and the Alluvial deposits of the Quaternary age. The surface distribution and outcrops of these lithostratigraphic units are shown in the geological map (Figure 1) (GAF, 2005). For more details, please refer to Technical Note 1.

1.1.1.4 Lateral and vertical facies changes of the Cretaceous Tawilah Group:

Al-Subbary (1995) carried out detailed sedimentological studies at several outcrops of Tawilah Sandstone in western Yemen. During that study, both lateral and vertical facies changes of Tawilah Sandstone were examined at several localities in the Sana'a Basin in order to determine the depositional environment during sedimentation. Data for the sedimentological analysis were collected from Area I (Figure 2.1), which includes eleven sections (only five of them located within Sana'a Basin). Of the eleven sections located along traverse I, only four are located within Sana'a Basin. These sections are:

1. Jabal Iram,
2. Jabal Marmar,
3. Jabal Thuma,
4. Jabal Kura'a, and
5. Ghulat Asim.

Extensive study of the sections measured has enabled the recognition of facies and facies associations of the Tawilah Group. These are summarized below:

The sedimentary sequences of the Tawilah Group can be subdivided into those deposited in either a continental or a marine environment. The facies associations classified below are used to produce a detailed picture of these two types of environment.

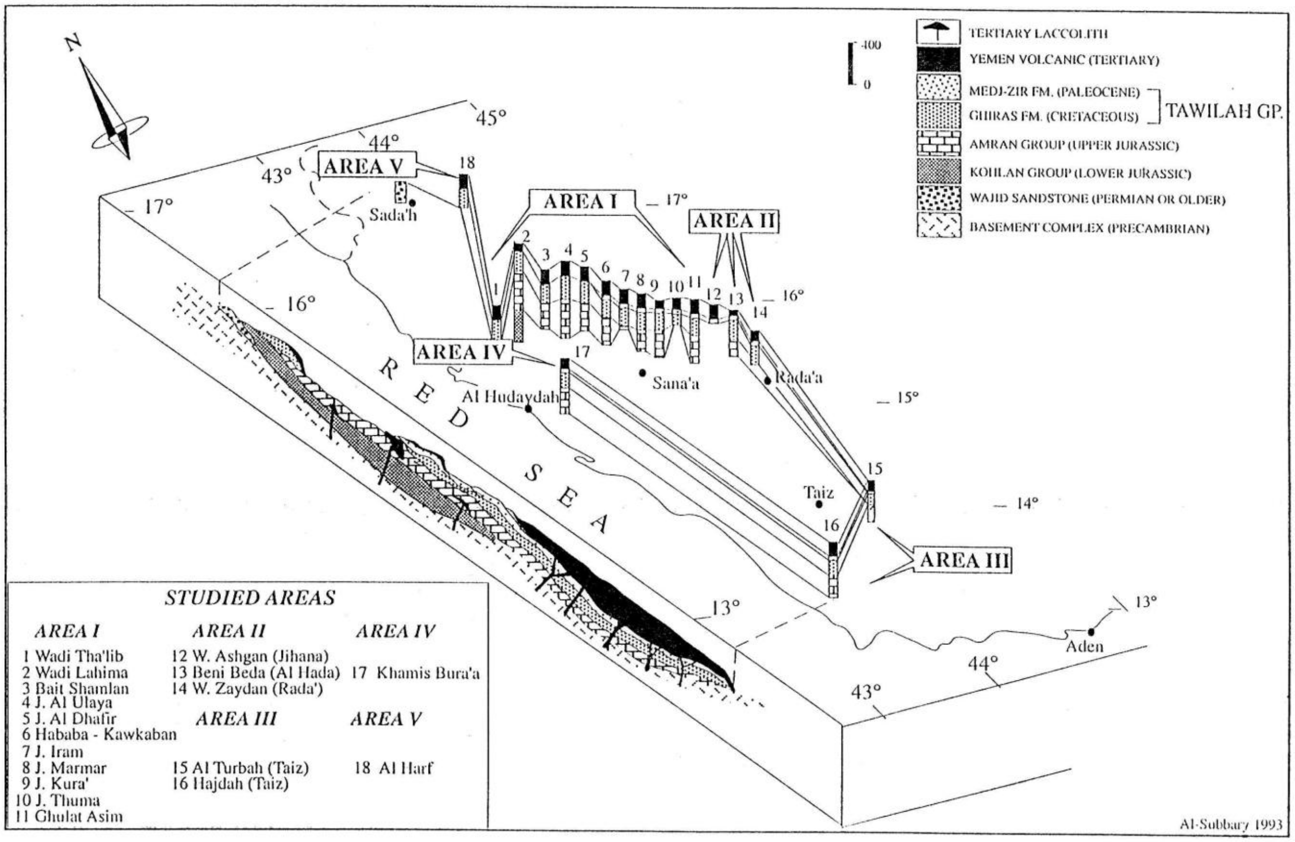

Figure 2-1 Block diagram showing the distribution of Tawilah Group, study sections and a schematic of north-south sections along the Red Sea coast (After Geukens, 1966 and Al-Subbary, 1995)

Detailed sedimentological outcrop description has allowed the recognition of twelve principal facies, grouped into four sedimentary facies associations. These facies are characterized by their lithology, bed thickness, and primary and secondary sedimentary structures. Each facies is characterized by a particular association of rock types and sedimentary structures and the analysis of these sedimentary facies has produced the following four broad facies associations:

A. The **Fluvial Basal Facies Association (FBA)** comprises a thin (1-5 m) basal conglomerate, locally brecciated, with very thin beds of laminated, slightly rippled fine sandstones / siltstone units at the top of this unit.

B. The **Fluvial Sandy Facies Association (FFA)** comprises very thick sandstone dominated sequences (100-300 m) interbedded with conglomerates and a few mudstones.

C. **Shallow Marine Fine Facies Association (MFA)** comprises a thickness of less than 10 m dominated by fine sandstone with intercalated mudstones and claystones, and finally,

D. The **Lacustrine Facies Association (LFA)** which comprises thinner units, < 50 m thick, dominated by ferruginous mudstone with intercalated fine sandstones, claystones, cherts and very thin layers of limestone.

These facies associations show abrupt alterations which allow about 16 depositional cycles to be defined within the Tawilah Group. The facies designations used here follow the code scheme of Miall (1977, 1978).

1.1.1.4.1 Fluvial Basal Facies Association (FBA)

The lower facies, 1-5 m thick, is the most variable, both in terms of lithology and sedimentology. It was deposited conformably above the late Jurassic- early Cretaceous limestone rocks of the Amran Group at Iram, Marmar, Thuma and Ghulat Asim sections. This Facies association comprises three Facies:

a. Facies 1 Basal Conglomeratic Facies (Cm),

b. Facies 2 Breccia – Conglomeratic Facies (G ms),

c. Facies 3 Transitional Sandstone Facies (Sr).

1.1.1.4.2 Fluvial Facies Association (FFA)

This facies association occurs commonly in the lower part of the Ghiras Formation where it consists of about 30 m of inter-bedded conglomeratic sandstone and subordinate medium to fine-grained sandstone arranged in up to five or more fining-upward sequences. Each sequence comprises a lower erosion surface overlaid by trough to lenticular sandstone units from 0.5 to 3.0 m thick, passing vertically into very fine sandstone. This facies association comprises four facies which frequently pass transitionally into one another.

a. Facies 4 Trough cross- bedded sandstone (St),

b. Facies 5 Planar-tabular cross-bedded sandstone (Spt),

c. Facies 6 Conglomeratic Channel Fill

d. Facies Gt.

1.1.1.4.3 Shallow Marine Facies Association (MFA)

This facies association occurs in the upper part of the Tawilah Group which is the Medj- zir Formation (about 100 m thick), and consists of sequences of sandstone inter-bedded with mudstone and siltstone. The best-developed example of this facies association occurs in the studied exposure of Beni Hushaish-Nihm districts and in particular at the Jabal Marmar section. This facies association comprises four facies which frequently pass transitionally into one another:

a. Facies 7 Very fine sandstones siltstone and mudstones (Fsc),

b. Facies 8 Giant Cross-Bedded sandstones (Sg),

c. Palaeosol-Dominated Facies. Palaeosol-dominated facies comprises a thickness of ≤ 60 m of fine sandstones dominated by iron concretions and palaeosols. The designation of palaeosols-dominated facies is important for recognizing regions or stratigraphic intervals characterized by relatively long-term low sedimentation rates. This facies has been identified from the upper part of the Tawilah Group and is recognized in all the studied sections and conformably overlies the shallow marine facies association and underlies the Lahima Member (lacustrine facies),

d. Facies 9 Concretionary iron-rich Sandstone Facies (Sfe).

1.1.1.4.4 Lacustrine Facies Association (LFA)

These deposits are recognized in the upper part of the Medj-zir Formation. The unit is described for the first time and assigned to the Lahima Member.

Analysis of outcrops and measured sections in the sequence of these rocks, based on vertical grain-size variation, nature of fossil content and rock association can be grouped into three sedimentary facies within the Lahima Member; these facies are:

a. Facies 10 the fluvial- lacustrine sandstones facies (Scf),

b. Facies 11 the lacustrine mudstones facies (Lms),

c. Facies 12 the carbonaceous micrites facies (Cm).

These facies were briefly described in Table 2.1.

Table 2-1 Facies and sedimentary structures of the Tawilah Group in the studied area of western Yemen

Facies No.	Facies Association	Facies Code	Lithofacies	Sedimentary Structures	Interpretation	Stratigraphic Occurrence
12		^{C}m	Carbonaceous mud	Organic rich laminated and flaser-bedding	Lake floor deposits	Lalilima Member only
11	LFA	^{L}ms	Mud, silt	Laminated to massive	Lake deposits	Lahima Member only
10		Sef	Very fine sand, silt and mud	Ripple cross-lamination, very few tabutar cross-bedded, with freshwater mollnses and gastropods	Flivio-laeustrine deposits	Lahima Member only
9		Sef	Weathered ferruginous sand with soils	Massive with some pedogenic features	Soil weathering products	Kura' Member only
8	MFA	Sef	Sand, medium to coarse-grained	Very large seale-planar cross-bedded	Tidal current deposit	Zijan Member only
7		Fse	Very fine sands, silt and mud	Fanminated to massive with a horizon of marine fauna	Starllow marine deposits	Zijan Member only
6		^{G}t	Gravels, stratified	Trough cross-bedded	Channel-fill deposits	Shibam and kawkaban Member
5	FFA	Spt	Sand, medium to very coarse, pebbly in places	Solitary sets of planar-tabuiar cross-bedded	Channel bars, in braided rivers	All Ghiras Formation
4		^{S}t	Sand, medium to very coarse, pebbly in places	Trough cross-bedded (fossil wood in places)	Channel fills in braided rivers and point bars	All Ghiras Formation
3		^{S}r	Very fine-grained sands	Ripple marks and laminations	Nearshore, ware reworked deposits	Thuta Member only
2	FBA	^{G}ms	Massive matrix supported gravel	————————	Debris flow deposits	Thuta Member only
1		^{G}m	Massive crudely bedded gravel	Inebriation	Braided stream deposits, (Lags)	Thuta Member only

1.1.1.5 Geological Structural Setting

The Sana'a Basin has not been studied structurally in detail and there are only limited studies derived from seismic and drilling information. The basin is located close to very active and more complicated structural trends where oceanic floor spreading is currently going on (in the Red Sea to the west, the Gulf of Aden to the south, two other active boundaries such as the Zagrous thrust to the east and in the north the Dead Sea strike slip fault). These boundaries represent the major tectonic trends and the most important structural elements, which have controlled the formation of any reactivation structures. The structural trends which controlled the formation of the Sana'a Basin are inherited from the proterozioc trends which were rejuvenated during the early Jurassic time where a deep depression was formed by NW-SE trend. The Sana'a Basin is subjected to different tectonic trends of compressional and extensional regimes. The extensional regime is the most dominant structures in the area and has obscured all the old structures.

1.1.1.5.1 Surface Structures

The main structural elements of Sana'a area are shown in the structural map of the Sana'a Basin, (Al-Sanabany, 2000). The dominant faults are of at least three trends with directions of N-S, NE-SW and NW-SE. Three main structural groups are recognized, namely:

- **north-west fault group:** which includes NW and NNW faults running almost parallel to the Red Sea and sometimes oblique to the Red Sea trend.
- **north-east fault group:** which includes NE and ENE faults which possibly follow the trend of the Gulf of Aden and
- **east-west fault group:** The majority of the wadis in the Sana'a Basin are faulted valleys such as Wadi Dhahr and Wadi As-Sir in Hamdan and Bani Hushaish districts respectively. The trends of these faults were recorded by many authors (Abou-Khadrah, et al, 1983; El-Anbaawy, 1985, Al-Subbary, et al 2000 and Al-Kotbah 2002).

A few kilometers west of Sana'a City, drilling of some wells showed a thickness of hundreds of meters of basalt where sandstone was expected at shallow depth. This indicated the presence of a fault in the area, which was confirmed by satellite images of Sana'a Basin in the year 2000 that showed a major fault in north-South direction along the Sana'a Basin west of Sana'a City (Naaman, 2004).

1.1.1.5.2 Subsurface structures:

The subsurface structures were detected from different subsurface data derived from Italconsult (1973), Exxon, (1987) and SAWAS, (1994). The deepest well in Sana'a Basin is DS1 (Arhab well) in the northern part of the basin with a depth of 1699 m. Other deep wells are in Al-Asbahi area whereby the borehole depth reached 1000 m and Al-Sabeen well of 850 m depth in the south of Sana'a Basin. The correlation of these well logs shows that the Sana'a Basin is subjected to several faults of both north and south down throw. These faults have resulted in the formation of half grabens such as the area between the Arhab and Al-Hitarish wells (DS1 and DS2). Along the Sana'a plain towards the south, a large number of wells were drilled through the alluvial and Tawilah Sandstone rocks lying at shallow depth. In Al-Sabeen area, on the other hand, abrupt change in the top level of Tawilah Sandstone subsided to a depth of 650 m beneath the volcanic rocks indicating an important fault in the Al-Sabeen area (Al-Kotbah, 2002). More details on the surface and subsurface structures of Sana'a Basin are given in Technical Note 1.

A comprehensive summary of the structural evolution (Tectonic Events) of Sana'a Basin is given in Table 2.2.

Table 2-2 Summary of the Evolution of 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 the entire stratigraphic sequence from Precambrian to Tertiary rocks. Along N-S fractures in the present area of Sana'a City, the rocks have eroded away forming the intermountain plain of Sana'a Basin. The post tectonic movement occurred during the Quaternary time. This movement, accompanied by volcanic activity, intruded the old rocks, and this stage of volcanic activity has very distinctive morphology characterized 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 a fold axis of N-S trend. This axis dies out in the north with a steep plunge in the south. Then another stage of extensional faulting resulted in the shaping of the present area, which was contemporaneous with the opening of the Gulf of Aden and Red Sea. These extensional faults, such as the Hadda, Assier and Wadi Quthi faults all strike E-W.
Cretaceous	Sana'a Basin was subjected to uplifting and received a lot of clastic rocks of Tawilah group. In the late Cretaceous period, both Amran and Tawilah groups were affected by E-W tectonic movement resulting in the formation of extensional faults such as the Wadi Dhar and Al-Sabeen faults.
Jurassic	Sana'a Basin was subjected to subsidence, forming a 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 probably reactivated from Hijaz and Najid Progenieses.

1.1.2 Geological Cross-Sections

A detailed review has been carried out for several previous subsurface hydrogeological cross-sections in Technical Note 1. The most important cross-sections are briefly described below:

1.1.2.1 Italconsult Geological Cross-Section (1973)

Three sub-surface hydrogeological cross-sections of N-S, NE-SW, and NW-SE directions were constructed by Italconsult, (1973) on the basis of lithological data of deep wells. These cross-sections are described below:

1.1.2.2 Cross-Section (WSW - ENE)

This cross-section was constructed based on lithological data of wells SE-3, ST-6 and SE-6. It is ENE-WSW in direction. It shows the vertical stratigraphic sequence of the geological units from the

Jurassic Amran limestone at the base of the section to the Quaternary deposits at the top. It also shows that the maximum thickness of alluvial lies in the Al-Rawdah area.

1.1.2.3 Cross-Sections (N - S)

This cross-section was based on lithological data of the German well, as well as nos. SE-1, SE-4 and ST-3. It is N-S in direction. It shows the vertical stratigraphic sequence of the geological units from the Triassic-Jurassic Kohlan sandstone at the base of the section followed by Jurassic Amran limestone and Cretaceous Sandstone of Tawilah group, Tertiary Volcanic and Quaternary Alluvial deposits at its top. The lithological units dip towards the south. the Alluvium Aquifer reaches its maximum thickness in the northern part of the Al-Rawdah area (Figure 2.2).

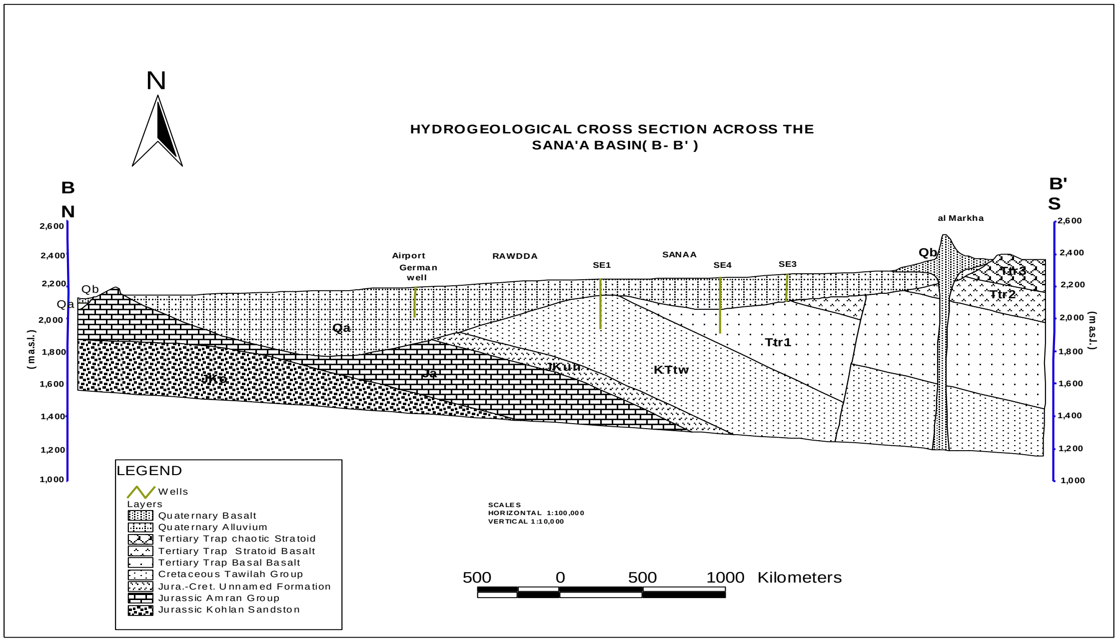

Figure 2-2 Geological cross-section B-B' across the Sana'a Basin (after Italconsult, 1973)

1.1.2.4 Cross-Section (NNW-SSE)

This cross-section was constructed based on lithological data of wells nos. SE-8, SE-7, ST-6, ST-5 and SE-1). It is NNW-SSE in direction starting at the limit of the Sana'a Basin and ending at Jabal Nuqum Mountain (Figure 2.3). It shows the vertical stratigraphical sequence of the geological units from the Triassic-Jurassic Kohlan sandstone at the base of the section, followed by Jurassic Amran limestone, Cretaceous Sandstone of Tawilah group, tertiary volcanic and Quaternary Alluvial deposits at the top. The NNW part of the section is characterized by volcanic activity, represented by volcanic dykes and flows. The Tawilah Sandstone group pinched out NNW in the Al-Ma'mar area. The Alluvium Aquifer reaches its maximum thickness in the Sha'ub area towards the SSE direction.

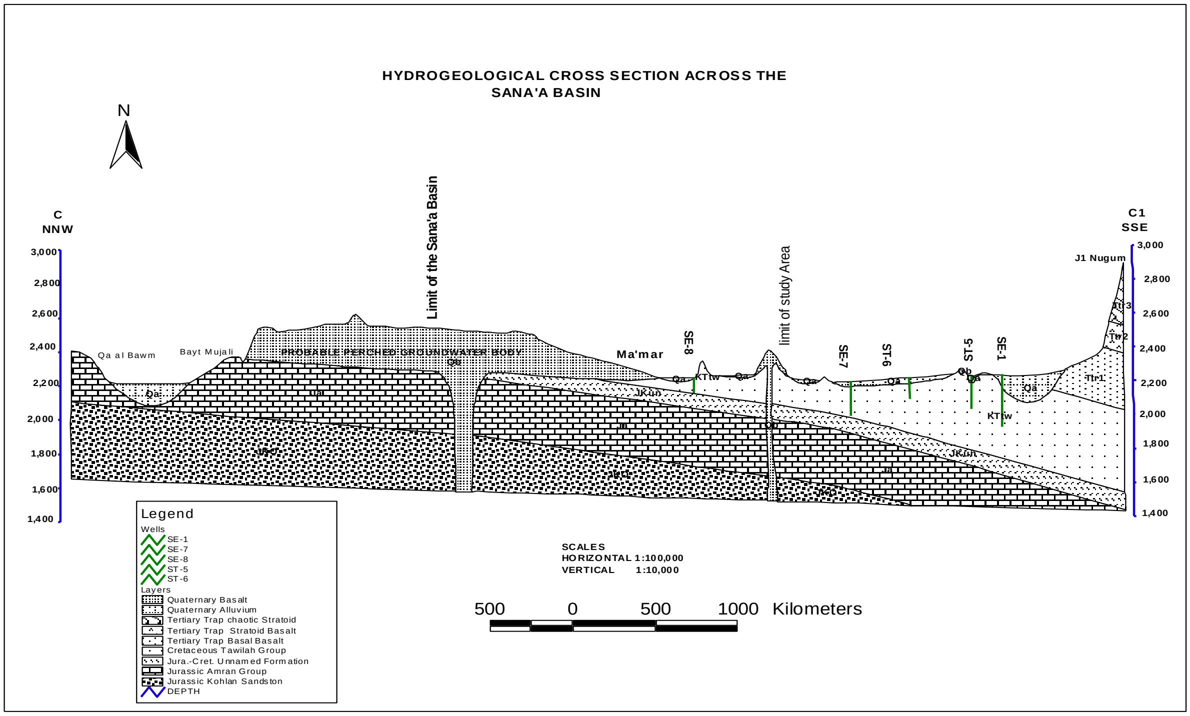

Figure 2-3 Geological Cross-Section C-C' across the Sana'a Basin (after Italconsult, 1973)

1.1.2.5 (II) Mosgiprovodkhoz (Russian) Regional Geological Cross-Sections (1986) (Figure 2.4)

These cross-sections were constructed to provide a regional picture concerning the subsurface geological conditions of the basin. They also provide information about the lateral distribution and thickness of the different lithostratigraohic units. They were modified by WEC, 2001 and can be briefly described as below:

1.1.2.5.1 Cross-Section A-B (N-S)

It extends from the north to south of the Sana'a Basin. The lithological description of wells SE4 1P, 5P, P19, 4P 10P was used to construct this section. It is clear from Figure 2.4, that:

- Litholostratigraphic units dip towards the south;
- Jurassic Amran limestone is exposed in the northern part of the basin;
- Cretaceous Tawilah sandstone has been eroded in the northern part;
- Volcanic rocks are exposed in the southern part of the basin;
- Quaternary Alluvial is mainly exposed in the central part of the basin.

1.1.2.5.2 Cross-Section C-D (E-W)

It extends from west to east along the northern part of Sana'a Basin. The lithological description of well 10P has been used to construct this section. It is clear from Figure 2.4 that:

- Jurassic Amran limestone is exposed in the central part of the cross-section;
- Cretaceous Tawilah sandstone has been detected in the eastern part;

- Volcanic rocks are exposed in the eastern and western parts of the basin.

1.1.2.5.3 Cross-Section E-F (E-W)

It extends from west to east along the southern part of Sana'a Basin. The lithological description of wells 3P and 5P was used to construct this section. It is clear from Figure 2.4, that:

- Jurassic Amran limestone and Cretaceous Tawilah sandstone are detected in the subsurface covered by volcanic and alluvial sediments;
- Volcanic rocks are exposed at the surface covering an extensive area;
- Quaternary Alluvial sediment is mainly present in the central part of the cross-section.

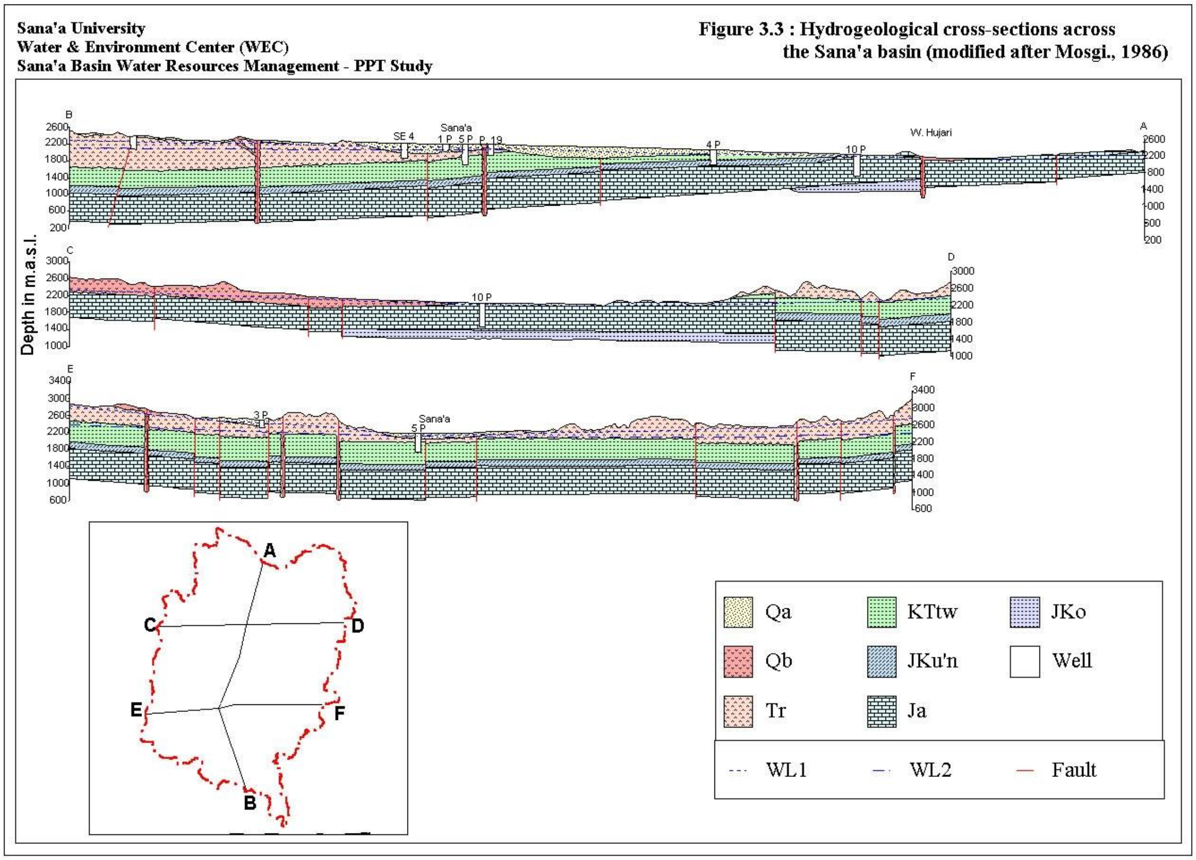

Figure 2-4 Geological Cross-Sections (A-B, C-D, E-F' across the Sana'a Basin (Modified after Mosgiprovodkhoz, 1986)

1.1.2.6 WEC's Regional Geological Cross-Sections (2001)

These geological cross-sections show regional subsurface geology beyond the boundaries of Sana'a Basin. They extend from the Tihama coastal area (Red Sea Coast) on the west to Ramlat Al-Sabateen on the east and from Sa'dah governorate on the north-east to Aden governorate on the south-west (Figure 4). These cross-sections provide information about lateral and vertical extents of the different lithostratigraphic units and can be briefly described as below:

1.1.2.6.1 Cross-Section A –A' (E-W)

It is a regional cross-section modified by WEC, 2001 after Van der Jun et al, 1995. It extends from Tihama coastal plain in the west to the plateau in the east (Figure 2.5). It provides a regional picture about the distribution of the different lithostratigraphic units.

1.1.2.6.2 Cross-Section B-B' (NW-SE)

This cross-section was modified by WEC, 2001 after Van der Jun et al, 1995 (Figure 2.5). It extends from Sa'dah in the north to the Aden governorates in the south. It gives a regional view of the distribution of the different lithostratigraphic units.

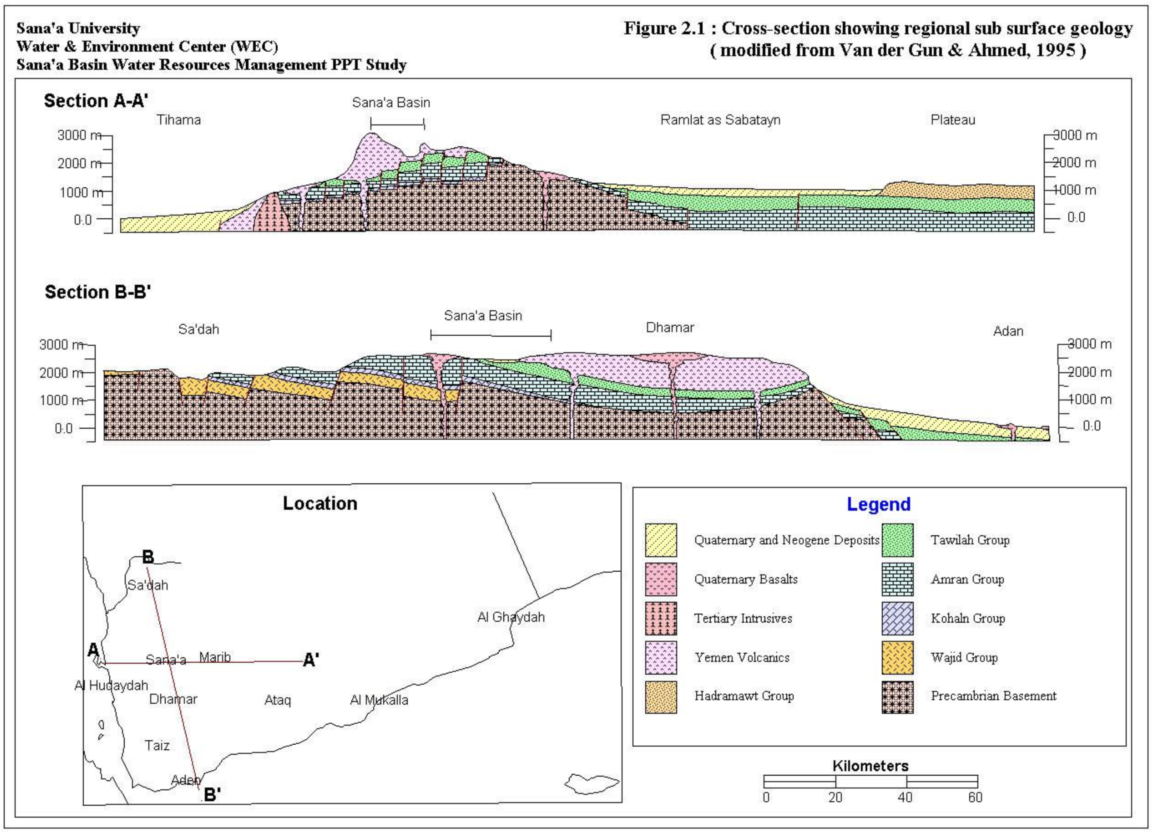

Figure 2-5 Geological Cross-Sections across the Sana'a Basin showing regional subsurface geology (modified from Van der Gun & Ahmed, 1995)

1.1.2.7 Foster, et al, 2003 Hydrogeological Cross-Sections

In a recent study carried out by Foster S.S.D., 2003, for the purpose of appraising the groundwater balance and the scope of management in Sana'a Basin, two N-S and E-W hydrogeological cross-sections were produced (Figure 2.6). A brief summary of these cross-sections is given below:

1.1.2.7.1 Cross-Section A-A' (N-S)

This cross-section extends from north to south passing through Sana'a City (Figure 2.6). It is clear that the Alluvium Aquifer has attained its maximum thickness in the area north of Sana'a City i.e. at the airport. The Tawilah Sandstone has been almost eroded in the same area where the Alluvium Aquifer reached its maximum thickness to the north of Sana'a City. Towards the south of the city, the Tawilah

Aquifer has been subjected to faulting and covered by a considerable thickness of tertiary volcanic rocks and the Tawilah Sandstone is dipping towards the south.

1.1.2.7.2 Cross-Section B-B' (W-E)

This cross-section extends from west to east, passing through Sana'a airport (Figure 2.6). It is clear that parts of the Tawilah and Alluvium Aquifers are outcropping in the Sana'a plain. The Tertiary Volcanic rocks are present towards both east and west of the cross-section. The Alluvium Aquifer has reached it maximum thickness in the area north of Sana'a City, i.e. at the airport, and the Tawilah Aquifer shows approximately uniform thickness.

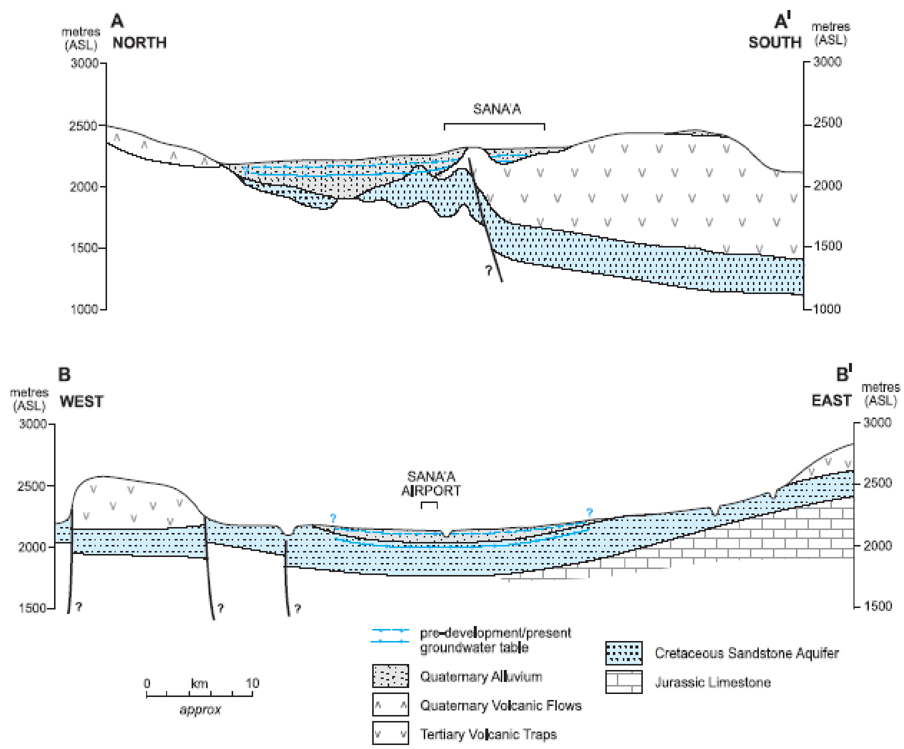

Figure 2-6 Hydrogeological cross-sections of the Sana'a Basin illustrating the occurrence of the Cretaceous Sandstone and Quaternary Alluvium Aquifers (After Foster et al, 2003)

1.1.3 Previous geophysical data (Seismic, Resistivity and Electromagnetic)

Several geophysical studies were carried out in the Sana'a plain. The most important geophysical studies are those conducted by Italconsult, 1973, Shaaban, 1980-1982, Mosgiprovodkhoz, 1986, SAWAS (Van kuijk 1990 & 1991), Exxon, 1986, Al-Gabery 1991, JICA, 1992 and Lamis, 2000. The review of these studies indicates that:

- The original reports of most of these geophysical data are not available and are scattered in several locations.
- The surveys covered only limited and small areas of Sana'a Basin, therefore a comprehensive picture of the subsurface geological and structural conditions of the groundwater aquifers is lacking.

- The geophysical studies were carried out in scattered sub-basins, therefore a complete delineation of the groundwater aquifer cannot be realized.
- Each geophysical survey was conducted for a specific purpose.
- A correlation between the results of the previous geophysical surveys was impossible.
- Most of the raw geophysical field data are not available in order to effect re-interpretation.

It has been concluded that the Sana'a Basin is a structurally complex area. The nature of the subsurface structures is not clear and the correlation between the results from previous geophysical studies was impossible. It therefore requires a detailed geophysical study.

A brief description of the previously collected geophysical studies is given below:

1.1.3.1 Italconsult (1973)

Italconsult carried out 228 Vertical Electrical Soundings (VES) in the Sana'a plain. The results obtained from the interpretations of these VES curves were represented in the form of a resistivity map and seven geo-electrical cross-sections. Three geological cross-sections were constructed based on electrical resistivity and well log data. These sections illustrate the lithological sequence, composed of Quaternary Alluvial, Quaternary basalt, Tertiary Volcanic, Tawilah group (sandstone, siltstone and clay beds), and Amran limestone group. They recommended that it would have been useful to investigate in detail the entire Sana'a plain and not just the southern half of it. (For more detail, please refer to Technical Note 1).

1.1.3.2 Shaaban (1980 & 1982)

Shaaban's geophysical work was based on 68 VES which were conducted by Italconsult (1973) and his own observations in the Sana'a Basin. He made reinterpretations and reconsiderations of VES data and correlated the results with the geological and hydrological data available in order to shed more light on the groundwater potential of the water-bearing horizons in Sana'a Basin. The corresponding resistivity values assigned for the different lithostratigraphic units are presented in Table 2.3.

Table 2-3 Lithostratigraphic units with corresponding resistivity range values

Sr. No.	Litostratigraphic Unit	Resistivity Value (Ohm-m)
1	Quaternary basalts	200-2000
2	Tuffs of Yemen volcanic	30-50
3	Dry, sandy alluvial	50-250
4	Moist, clayey alluvial	5-15
5	Sandstone	50-120
6	Marls and shale	3-15
7	Limestone	30-80

1.1.3.3 Mosgiprovodkhoz (1986)

In this study, 428 Vertical Electrical Soundings (VES) were carried out with depth of investigations varying between 10 and 500 m. Results obtained from the interpretation of these VES curves were represented in the form of geological cross-sections based on electrical resistivity values which were deduced from Italconsult (1973) and well log data. Unfortunately, Vol-2 Part III and Vol.6, which contain catalogues & graphic material, could not be found.

1.1.3.4 Exxon (1987)

Seismic reflection study for oil exploration was conducted along Sa'ada-Thamar and Al-Hodeidah-Sirawah areas passing through Sana'a Basin. Some of these seismic sections were conducted in Sana'a Basin. The data were processed and then represented as seismic cross-sections. These sections were interpreted by Exxon in terms of subsurface geologic structure and stratigraphic features (SAWAS, Technical Report No. 6, 1991). These sections were used in the course of this study in order to delineate the lower boundary of Tawilah Sandstone or top of Amran limestone. For more information, please refer to the Technical Note 1.

1.1.3.5 Van Kuijk (1990 & 1991)

In 1990, 32 VES were effected in the southern part of Sana'a Basin. The survey was carried out by SAWAS-2 Project. The total spread length of the VESs was between 2000 and 2600 m. The main objectives of this study were to determine the depth of the Tawilah Sandstone Aquifer and to locate suitable drilling sites for two exploration wells. The results of this study were presented in the form ofan iso-apparent resistivity map for AB = 2000 m (AB/2 = 1000 m) and geo-electrical cross-section. This cross-section could not indicate the presence of Tawilah Sandstone group under the Yemen volcanic, because of the great thickness of both Alluvial and Tertiary Volcanic units (probably > 350 m) and the relatively small contrast in resistivity between the Tawilah Sandstone and the overlying lithostratigraphic units.

In addition, 38 VES were carried out East of Shibam. The main objectives of this survey were to determine the thickness and aerial distribution of the Tawilah Sandstone Aquifer, and to locate suitable drilling sites for two exploration wells. The results of this survey were presented in the form of an iso-apparent resistivity map (AB = 2000 m). This survey could not indicate the interface between Tawilah Sandstone Aquifer and the underlying Amran limestone group due to overlapping between the resistivity values of the two aquifers. Furthermore, in most parts of the area surveyed, this interface is expected to be at greater depth (> 400 m).

1.1.3.6 Al-Gabery (1991)

Al Gabery conducted geophysical surveys in the Shibam-Kawkaban area northwest of Sana'a Basin. These surveys included Very Low Frequency Electromagnetic (VLF), geo-electrical resistivity (VES) and seismic refraction surveys aimed at determining the subsurface sedimentary succession and its structural control. He used 38 measuring points of VLF Electromagnetic, 14 VES and 3 seismic refraction profiles. Integration of the three geophysical methods above and drilling was done to identify the hydrogeological conditions that are controlling the ground water systems in that particular area.

1.1.3.7 JICA (1992)

Under the Jica project, the following geophysical surveys were carried out:

- **Electromagnetic Survey:** Eight measuring lines were conducted to investigate the shallow subsurface structures and the geological conditions in the flat valley plain of south Sana'a. The results of this survey indicate the presence of subsurface structures such as fracture zones.

- **Electrical Surveys:** 14 Vertical Electrical Soundings (VES) were conducted in the southern area of Sana'a by SAWAS project in (1989). The Tawilah Sandstone Aquifer present under Yemen volcanic at a depth of several hundred meters could not be detected in this study
- **Seismic Reflection Survey:** The purpose of this seismic reflection survey is to obtain the subsurface geological structures at a depth of 700 to 1200 m, where the Tawilah Sandstone is expected to be present. Five seismic lines A, B, C, D and E were planned. A brief summary of this survey is given in table 2.4.

Table 2-4 A summary of seismic reflection survey (JICA, 1992)

Line No.	Length (km)	Purpose of the investigation
A	14	To clarify the subsurface conditions in the southernmost area along the highway. The area is expected to have perched aquifers in Alluvial and Yemen volcanic units, and confined aquifer of Tawilah Sandstone. A syncline structure is probably inferred near the line.
B	10	To clarify the subsurface conditions along the tarmac road between Sana'a and Jihanah town. A fault was inferred running EW in direction and at a right angle to the line.
C	4.5	To clarify the subsurface conditions in the central area. The line is set along the drain in the direction of the valley.
D	4.5	To clarify the subsurface conditions in the vicinity of the northernmost area. A fault was inferred running parallel to the wadi course.
E	7	To clarify the subsurface geological condition in the northeast area of study area. A fault was inferred running parallel to the wadi course.

1.1.3.8 SAWAS (1993)

The geophysical survey carried out by SAWAS, (1993) provides details of the subsurface structures in Sana'a south, along with a predicted elevation of the top of Tawilah Sandstone Aquifer. In this study, it has been confirmed that Al-Sabeen faults with down throw in the Hizyz area form a large full graben. This graben is very valuable for looking at groundwater (SAWAS, TR No.10, 1993,). In the northern part, another full graben is interpreted from subsurface data.

1.1.3.9 Lamis (2000)

In this study, re-interpretation of aeromagnetic data was done to deduce the subsurface structures for Sana'a Basin and the thickness of rock units above the basement rocks. The study showed that the average thickness of these units south of Sana'a Basin was between 2500 and 3500 m. In addition, the study deduced subsurface structures.

1.1.4 Well log data (Supplementary Data and Information)

Intensive efforts were made to obtain the maximum possible information through the collection and review of reports, including well log data from several international and local firms and sources. Well log data were collected from Italconsult, 1973, Dar Al-Handasah (1980), Howard Humphry (1981-82), NWSA (1984-01), Mosgiprovodkhoz, 1986, SAWAS, 1990-95, and local drilling companies, etc. Table 2.5

presents the names of the drilling companies and number of drilled boreholes that have technical drilling reports in Sana'a Basin. The data obtained were sorted, tabulated and then used to draw professional subsurface cross-sections. This data was used, along with the data collected from NWRA data bank (WEC, 2001), to construct the GIS thickness and structural contour maps for the upper and lower boundaries of the different aquifers in Sana'a Basin.

Table 2-5 Drilling companies and number of drilled boreholes that have technical drilling reports

Company	No. of wells drilled
Italconsult (1973)	16
Dar Al-Handasah (1980)	07
Howard Humphery (1981-82)	32
NWSA (1984-2001)	27
Mosgiprovodkhoz (1986)	14
SAWAS, 1990-1995	02
Other local companies	38
Total	136

1.1.4.1 Review of lithological data of NWRA data bank / WEC,2001

Additional data on well lithological description were obtained from the NWRA data bank. These data were collected by the WEC team through structured interviews arranged with well owners during the well inventory survey conducted in 2001. Table 2.6 gives the total number of these wells and number of wells in each sub-basin.

The above-mentioned data were sorted, tabulated and then used to draw professional GIS structural contour maps for the upper and lower boundaries of the different aquifers in Sana'a Basin.

Table 2-6 Number of Wells that have lithological description in each sub-basin (WEC, 2001)

Sr. No.	Sub-Basin	No. of wells
1	Wadi Al-Mashamini	27
2	Wadi Al-Madini	77
3	Wadi Al-Kharid	159
4	Wadi Al-Ma'adi	325
5	Wadi A'Sir	616
6	Wadi Khulaqah	137
7	Wadi Qasabah	78
8	Wadi Al-Huqqah	303
9	Wadi Bani Huwat	2250
10	Wadi Thumah	403

Sr. No.	Sub-Basin	No. of wells
11	Wadi as Sirr	2286
12	Wadi Al-Furs	502
13	Wadi Al-Iqbal	356
14	Wadi Zahr and Al-Ghayl	723
15	Wadi Hamdan	175
16	Wadi al-Mawrid	829
17	Wadi Sawan	1087
18	Wadi Shahik	1639
19	Wadi Ghayman	618
20	Wadi Al-Mulaiky	261
21	Wadi Hizyaz	273
22	Wadi AKhwar	270
Total Number of Wells		13394

1.2 Aquifer Geometry

The geology and geometry of rocks and sediments control the behavior of ground water. The aquifer geometry is mainly concerned with delineation and definition of aquifer units, their lateral extent (spatial distribution of the aquifer rock units), sub-surface geological cross-sections and structural controls on the regional groundwater flow (faults, low permeability units and rock boundaries). Aquifer geometry is also concerned with the aquifer depth from the ground surface, aquifer thickness, position of lower and upper boundaries of the aquifer with respect to the mean sea level. The following sections describe the geometry of the main aquifers in the Sana'a Basin as defined by the previous projects and investigations.

1.2.1 The Quaternary Alluvium Aquifer geometry

Aerial extent:

Based on the study conducted by WEC, (2001), the unconsolidated deposits of the Quaternary Aquifer cover about 15% of the Sana'a Basin area (i.e. about 480 km^2). The lateral extent of the Alluvium Aquifer is known from the geological map (SAWAS, 1996). It is mainly present in the center of the area and is confined to wadi beds and low areas that form the Sana'a plain.

Thickness:

The alluvial thickness map prepared by Foppen, 1996 shows that the aquifer consists of three or four depositional basins. The deepest basin is situated north of the city and reaches depths of more than 300 m. South of Sana'a, the depth is about 100 m (Foppen, 1996).

1.2.2 Quaternary and Tertiary Volcanic Aquifer Geometry

Aerial extent and thickness:

The lateral extent of the Tertiary Volcanics is well known from the geological map (SAWAS, 1996). It outcrops over about 35% of the area of the Sana'a Basin (Foppen, 1996). The base, however, is only known at the northern edge of the outcrops, in the vicinity of Sana'a City where boreholes are fully penetrating the volcanics (Foppen, 1996). The thickness of the aquifer increases rapidly southwards to about 600 m in the southern part of Sana'a town. Towards the south, the thickness is not known. Geophysical surveys have not been successful in determining the base due to the poor contrast in resistivity between the un-weathered basalts and the Cretaceous Tawilah Sandstone (SAWAS, 1991).

1.2.3 Cretaceous Tawilah Sandstone Aquifer geometry

Aerial extent:

The Cretaceous Tawilah sandstone outcrops cover about 15% (i.e. about 480 km^2) of the basin, spreading over a large area around Sana'a City, especially the north-western part, in Wadi Dhahr and in the northern part of the basin, such as the Al-Hatarish area and underneath the alluvial deposits in most of the Sana'a Basin. It is also exposed at Bani Hushaish and Nihm areas towards the eastern and north-eastern parts of the Sana'a Basin respectively. It is thought to reach a thickness of 400 to 500 m where it has been protected from erosion by the overlying Tertiary Volcanics (Naaman, 2004).

Thickness:

The top of the Cretaceous Tawilah Aquifer is present at a shallow depth northeast and northwest of Sana'a town, as detected from boreholes drilled for public water supply. The northern boundary with the Amran Limestone has been inferred from limited boreholes and geophysical data. Where it is overlain by Tertiary Volcanics, the top of the sandstone is known only from two wells. The emergency drilling program of 1987/1988 has provided information on the base of the sandstone in the western well-field. In addition, well DS-1 at Al-Hataresh and Al-Sabeen well provided valuable information about the thickness of the Tawilah Aquifer. The depth to the "Unnamed Formation" increases from 210 at the northern end of the well-field to over 400 m. It has been found that the thickness of this aquifer is in the order of 300 to 400 m where it has been protected from erosion and less in the outcrop areas (Naaman, 2004).

1.3 Boundaries of the Groundwater Flow System

1.3.1 Impermeable lower boundary

The Jurassic unnamed and Amran lithostratigraphic units are assumed to be impermeable, since the data show that both units have very low water production. This means that there is no flow across the boundary of the Cretaceous Sandstone and the unnamed rock units (Foppen, 1996).

1.3.2 Western Boundary

The western boundary of Sana'a Basin is represented partially by the escarpments southwest of Shibam, where elevations drop from over 2600 m.a.s.l east of Shibam to around 2100 m.a.s.l southwest of Shibam. This area is part of the catchment of Wadi Surdud (Foppen, 1996).

Along the eastern and northern slopes of Wadi Al-Ahjar, a great number of springs exist. They are found at a distinctive topographical level of 2300-2500 m.a.s.l, which corresponds with the lowest part of Tawilah Sandstone or the Amran limestone upper boundary. The yield of these springs is limited: 0.3-10 l/s and comes from the western, northern and eastern slopes of Wadi Al-Ahjar. In term of modeling, this can serve as an indication of the outflow across the western boundary of the model. From Shibam further north, the area becomes Amran Limestone (Foppen, 1996). From the escarpment further south, the area becomes Tertiary Volcanics. No significant springs or discharge zones are present towards the south. It is not known whether the Cretaceous Sandstone is present below the Tertiary Volcanics (Foppen, 1996).

1.3.3 Southern Boundary

There is no particular information about the southern boundary of the area. It is not known whether Cretaceous Sandstone is present or at what depth. Also, it is not known if and how groundwater flows in this part of the Cretaceous Sandstone. With regard to aquifer geometry for modeling two cases can be assumed:

- The Sandstone is present and forms a broad syncline towards Taiz where it outcrops at the surface.
- Just north of the Sabaeen well the sandstone is faulted and there is a possibility that the sandstone blocks north and south of the fault line are not connected. South of the fault line, the sandstone is present and forms a broad syncline towards Taiz.

In both cases, it is clear that the presence of physical boundaries of the sandstone (faults, complete erosion of sandstone) south of Sana’a is completely unknown (Foppen, 1996).

1.3.4 Eastern Boundary

It has been reported by Foppen, 1996 that the groundwater flow seems to be directed towards the east with groundwater levels from 2500 m.a.s.l in the west to 2000 m.a.s.l in the east. Going from the Yemen volcanics to the east, first the Cretaceous Sandstone outcrops and then the Jurassic Amran Limestone. If the Amran limestone group was assumed to be impermeable, then all groundwater would be collected in the Tawilah and flow either north, south or even west (Foppen, 1996).

1.3.5 Northern Boundary

Since groundwater in the basin flows from south to north and since Jabal As Sama close to Sana’a Basin to the north, it is very clear that groundwater must leave the area through the Amran limestone. Eventually, part of the groundwater will be discharged into Wadi Al-Kharid springs (Foppen, 1996).

1.4 Data Related to Capacity of Aquifers

Previous literature related to the capacity of aquifers has been collected. These data can be subdivided into four types i.e. pumping test, well inventory, recharge and discharge data.

1.4.1 Pumping test data and Hydraulic Parameters of the Aquifer Systems

Pumping test data were collected from several sources i.e. Italconsult (1973), Dar Al-Handasah (1980), Howard Humphry (1981-82), NWSA (1984-2001), Mosgiprovodkhoz (1986), SAWAS Project (1990-95), local drilling companies, etc. A very generalized picture of the distribution of aquifer transmissivity or, in other words, the ease with which it enters into the abstracting wells, has been given in the Selkhozpromexport study, 1986 (The Hydrogeological Report). As reported by SAWAS, 1996, the hydraulic parameters of the different aquifer systems can be summarized in Table 2.7.

Table 2-7 Transmissivity data (mean values) as summarized from SAWAS, 1996

Aquifer	Transmissivity [m^2/day]	Saturated Thickness [m]	EstimatedPermeability [m/day]
Alluvial	27.9	53.9	3.5
The Tertiary Volcanics	45.8	80.5	3
The Cretaceous Sandstone	280.3	163.3	2 (0.13 at Al-Sabeen well, 850m deep)
The Jurassic Limestone	25.6	40.3	2.2

The data presented in Table 2.7 indicate that:

The Amran limestone and Quaternary Alluvial sediments have the lowest average transmissivity (< 30 m^2/d) by comparison with the Tertiary Volcanics (46 m^2/d) and the Tawilah Sandstones (280 m^2/d).

The low transmissivity values of the Alluvial sediments are mainly due to interconnectivity of pore spaces (i.e. primary permeability), while flow in the other aquifers occurs through both pore spaces (primary permeability), as well as fractured and faulted zones (secondary permeability).

Secondary permeability appears to be much more significant in contributing to the higher T-values of Tertiary Volcanics and Tawilah Sandstones as compared with primary permeability. The higher T-values in the Tertiary Volcanics and Tawilah Sandstones result from increased aquifer thickness rather than true higher permeability (WEC, 2001).

The overall low permeabilities of the Tertiary Volcanics and Tawilah Sandstones, in spite of the very high transmissivity 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 (WEC, 2001).

The extremely low permeability (0.13 m/d) of the deepest borehole with available data (Al-Sabeen well, 850 m deep) with a T-value of a magnitude lower than the average suggests that the Sandstone transmissivity in the NWSA southern well-field may be significantly lower than what has been recorded from the western and eastern well-fields.

1.4.1.1 The Hydraulic Parameters of the Quaternary Volcanic Aquifer

There are no boreholes that have penetrated the full thickness of the Quaternary Volcanics. A pumping test was performed in only one borehole, whereby an average T-value of 51 m^2/day was determined (Foppen, 1996). The basalts are highly permeable because of fracturing and the hydrogeological properties are generally described as good. In some places even permanent springs are reported (Jungfer 1987). In some parts, these springs are in hydraulic contact with the underlying Amran limestones and marls, or Tawilah Sandstone, or the Tertiary Volcanics and the Alluvial (Naaman, 2004).

1.4.1.2 The Hydraulic Parameters of the Quaternary Alluvium Aquifer

The Alluvium Aquifer can locally be semi-confined and the recharge into the coarse grained material along the wadis and the base of hills (SAWAS, 1996) is expected to be mainly indirect. The aquifer is in hydraulic contact with the underlying units and is assumed to feed the Tawilah Sandstone (Naaman, 2004). According to 12 pumping tests given, the average T-value of the Quaternary Alluvial is 31.5 m^2 /day. The average permeability of this aquifer as computed from the pumping tests is in the order 0.5 to 2 m/day.

In one borehole (SE5), Italconsult, 1972 determined the storativity of the Alluvium Aquifer as 4.6E^{-4}. Selkhozpromexport, 1986 determined the porosity of sand, sandy loam and loam. The values of these sediments ranged between 24% and 47% (Foppen, 1996).

Based on a review of the previous studies, the hydraulic parameters of the Quaternary Alluvium Aquifer are summarized in Table 2.8.

Table 2-8 Hydraulic parameters of the Quaternary Alluvium Aquifer

Porosity	Average Permeability	Storativity	Average Transmissivity	Aquifer
Quaternary Alluvial	31.5 m^2 /day (Based on 12 Pumped Wells)	4.6E-4 (From one Borehole)	0.5 to 2 m/day. (Based on 12 Pumped Wells)	24% & 47%
Source of	Italconsult, 1973	Italconsult, 1973	Italconsult, 1973	Selkhozpromexport, 19

Data				86

1.4.1.3 The Hydraulic Parameters of the Tertiary Volcanics Aquifer

The Tertiary Volcanic seems to be significant as an aquifer only where unconsolidated deposits in the vicinity of Sana'a and the plain to the south overlie them. Fifteen pumping tests were carried out in this aquifer. The transmissivity values range from less than 1 m^2/day to 200 m^2/day. Selkhozpromexport, 1986 gave two average values: one T-value of the basalt in the fault zones and one T-value in a fractured zone. The T-value in the fault zone is ten times higher than in fractured zones. The estimated average permeability ranges from 0.5 to 1.5 m/day. Selkhozpromexport, 1986 estimated a porosity of 6.3%. SAWAS-2 (1990) estimated the average porosity for the alluvials and volcanics as a whole to be in the order of 1%, based on water budget calculations (Foppen, 1996).

1.4.1.4 The Hydraulic Parameters of the Tawilah Sandstone Aquifer

The Tawilah Sandstone Aquifer is characterized by both primary and secondary permeability. The first type, which is given by the pore space presented by the interstices between the grains of sand, is not great, but the second, given by fractures of variable density, provides channels of high permeability. The yield from well to well is thus very variable. According to the pumping test carried out previously in the Sabeen well, the transmissivity and storativity are about 400 m^2/d and 7 x 10^4, respectively. The piezometric level measured in the well in 1992 was 163 m below ground surface (WEC, 2001).

1.4.2 Transmissivity Maps of the Cretaceous Tawilah Aquifer (Foppen, 1996)

About 60 pumping tests were carried out in this aquifer. According to Selkhozpromexport, 1986, the average T-value in the fault zone is about 400-2000 m^2/day while, in undisturbed zones, the average T-value is about 50-100 m^2/day. The estimated average permeability ranges from 0.5 to 3 m/day. Italconsult, 1973 determined the storativity in five boreholes (SE-1, SE-2, SE-3, SE-7 and ST-7). From this and the saturated thickness, the average specific storage of the Cretaceous Tawilah Sandstone is determined as about 4.5E -6 m^{-1}. The specific yield of Cretaceous Tawilah Sandstone has been determined by Selkhozpromexport, 1986 at two locations. Values of 1% and 22% are given for boreholes SE-7 and D respectively. Van Dalfsen, 1996 estimated the water-saturated porosity of the sandstone at the Sabaeen well at 19% (Foppen,1996). Detailed information and review is presented in Technical Note 1.

Dar El-Handasa (1997) generated a map showing the variation in transmissivity of the Tawilah Sandstone Aquifer based on the estimated values from previous aquifer tests (SAWAS, 1996). This map indicates high values of transmissivity (900 m^2/day) that can be seen in the east-central part of the basin. This could be attributed to high fracturing in the Tawilah Sandstone Aquifer and/or presence of wells penetrating a maximum thickness of Tawilah Aquifer compared to others. Detailed information and review is presented in the Technical Note 1.

Based on our review of previous studies, the hydraulic parameters of the Tawilah Sandstone can be summarized in Table 2.9

Table 2-9 The hydraulic parameters of the Tawilah Sandstone Aquifer

Aquifer	Average Transmissivity *	Average * Hydraulic Permeability	Specific yield **	Specific Storage ***	Porosity ****
Tawilah Sandstone	400-2000 m^2/day (faulted Zone) 50-100 m^2/day (undisturbed zones)	0.5 to 3 m/day	1% and 22%	$4.5E^{-6}m^{-1}$	19%

* T and Hydraulic Permeability Values: Based on 60 Pumped Wells, Selkhozpromexport, 1986)

** The specific yield has been determined at two locations, Selkhozpromexport, 1986

*** (at 5 boreholes) Italconsult , 1973

**** Porosity of the sandstone determined at Al-Sabaeen well, Foppen,1996

1.5 Well inventory data

Several well inventory surveys were carried out in the Sana'a Basin. These surveys range from as old as the survey conducted by Italconsult in 1973 to the latest well inventory survey carried out by WEC, 2001. In 1989, 1990, 1992, 1993 and 1995, the SAWAS project made four well inventories and the Japanese team (JICA 1992) made one survey. The well inventory carried out by WEC (2001) covered larger areas than those performed by the previous surveys and covered about 13,425 water points. For the purpose of this project, the well inventory data were collected from several sources i.e. Italconsult, 1973, Mosgiprovodkhoz, 1986, SAWAS Project 1990-1995, JICA, 1992 and WEC, 2001.

Some details about those well inventory surveys are described briefly in Table 2.10.

Table 2-10 A summary of previous well inventory surveys carried out on the Sana'a Basin

Project / Date	Inventoried area	Wells/Water points Inventoried	Project/Report
Italconsult (1973)	Central plain areas around the city of Sana'a. (1200 km^2)	173	Italconsult
Mosgiprovodkhoz (1986)	(Presumably all Basin)	4000	Mosgiprovodkhoz
SAWAS – GDH (1990)	East of Shibam NW, Sana'a	211	SAWAS T.R- 4
SAWAS – GDH (1989-90)	Sana'a South	506	SAWAS T.R- 3
Jica , 1992	Southeastern part of Sana'a	241	JICA
SAWAS-3 (1992/93)	Sana'a North	3567	SAWAS T.R- 5 (V.VI)
SAWAS-3 (1995)	Sana'a City	254	SAWAS T.R- 5 (V.VI)
WEC (2001)	Entire Sana'a Basin	13,425	WEC

1.5.1 Recent well inventory (WEC, 2001)

The well inventory conducted by WEC, 2001 is the most reliable and recent survey. It covered most of the basin and all aquifer systems; however, a relatively small number of wells were inventoried in the northern, north-eastern and north-western parts of the basin.

1.5.2 Wells inventoried and aquifer types

Of the total number of wells inventoried, 20% are located in the Alluvium Aquifer, 42% in the Volcanic Aquifer, 26% in the Sandstone Aquifer and 8% in the limestone aquifer. It is not known which of these four aquifers represents the remaining 4% of the wells (WEC, 2004).

The distribution of well type over the different aquifers can be summarized in Table 2.11.

Table 2-11 Type of Wells in each aquifer type(WEC, 2001)

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

1.5.2.1 The Wells Tapping Alluvium Aquifer

From the well inventory data (WEC, 2001) a 2619 wells were present on the Alluvium Aquifer. The majority of the wells inventoried are mainly concentrated at Sana'a plain. The distribution density of these wells over Sana'a Basin is summarized in Table 2.12).

Table 2-12Distribution density of the wells tapping the Alluvium Aquifer (WEC, 2001)

Sr. No.	Sub-Basin	No. of Wells	%
1	Wadi Bani Huwat (sub-basin 9)	857	32.72
2	Wadi Sawan (sub-basin 17)	391	14.93
3	Wadi As'Sirr (sub-basin 11)	359	13.71
4	Wadi Al-Mawrid (sub-basin 16)	261	9.95
5	Wadi Shahik (sub-basin 18)	164	6.26
6	Wadi Al-Furs (sub-basin 12),	161	6.15
7	Wadi Dhar & Al-Ghail (sub-basin 14)	105	4.00
8	Wadi Ghaiman (sub-basin 19)	60	2.30
9	Wadi Thumah (sub-basin 10),	56	2.14

Sr. No.	Sub-Basin	No. of Wells	%
10	Wadi Al Mulaiky (sub-basin 20)	43	1.64
11	Wadi Al-Huqqah (sub-basin 8)	35	1.34
12	Wadi Hizyz (sub-basin 21)	30	1.15
13	Wadi Al-Maadi (sub-basin 4)	25	0.95
14	Wadi Asir (sub-basin 5)	19	0.73
15	Wadi Ahwar (sub-basin, 22)	18	0.69
16	Wadi Khulaqqah (sub-basin, 6)	15	0.57
17	Wadi Al-Kharid (sub-basin, 3)	8	0.31
18	Wadi Kasabah (sub-basin, 7)	6	0.23
19	Rest of wadis (sub-basins, 15, 13, 2 & 1)	6	0.23
Total		2619	100

1.5.2.2 The Wells Tapping the Volcanic Aquifer

From the well inventory data (WEC, 2001), 5587 wells were on the Volcanic Aquifer. The majority of the wells inventoried are mainly concentrated in the southern, eastern and western parts of the Sana'a Basin. The distribution density of these wells over Sana'a Basin is summarized in Table 2.13.

Table 2-13 Distribution density of the wells tapping the Volcanic Aquifer (WEC, 2001)

Sr. No.	Sub-Basin	No. of Wells	%
1	Wadi Shahik (18)	1412	25.27
1	Wadi Shahik (18)	1412	25.27
2	Wadi As'Sirr (11)	856	15.32
3	Wadi Sawan (17)	594	10.63
4	Wadi Ghaiman (19)	538	9.62
5	Wadi Dhar & Ghail (14)	445	7.96
6	Wadi Al-Mawrid (16)	321	5.74
7	Wadi Ahwar (22)	239	4.30

Sr. No.	Sub-Basin	No. of Wells	%
8	Wadi Hizyz (21)	236	4.22
9	Wadi Al-Huqqa (8)	220	3.93

1.5.2.3 The Wells Tapping Tawilah Sandstone Aquifer

From the well inventory data (WEC, 2001) 3500 wells were in the Tawilah Sandstone Aquifer. The majority of the wells inventoried are mainly concentrated at the Tawilah Sandstone outcrop areas of Nihm, Bani Hushiesh and Hamdan in the eastern and western areas of the basin. The rest of these wells are scattered over several sub-basins in the eastern and western parts of the basin. The distribution density of these wells over Sana'a Basin can be summarized in Table 2.14):

Table 2-14 Distribution density of the wells tapping the Tawilah Sandstone Aquifer (WEC, 2001)

Sr. No.	Sub-Basin	No. of Wells	%
1	Wadi As' Sirr (sub-basin 11)	991	28.33
2	Wadi Bani Huwat (sub-basin 9)	958	27.38
3	Wadi A' sir (sub-basin 5)	363	10.38
4	Wadi Al-Ghiras (sub-basin 12)	257	7.35
5	Wadi Al' Iqbal (sub-basin 13)	162	4.63
6	Wadi Dhar & Al-Ghail (sub-basin 14)	155	4.43
7	Wadi Thumah (sub-basin 10)	133	3.80
8	Wadi Al-Mawrid (sub-basin 16)	120	3.43
9	Wadi Sawan (sub-basin 17)	95	2.72
10	Wadi Hamdan (sub-basin 15).	84	2.40
11	Wadi al Maadi (sub-basin 4)	82	2.34
12	Wadi Khulaqqah (sub-basin 6)	46	1.32
13	Wadi Al Huqqah (sub-basin 8)	34	0.97
14	Wadi Shahik	18	0.51
Total		3498	100

1.5.2.4 Wells Tapping the Amran Limestone Aquifer

According to the well inventory data (WEC, 2001), 1083 wells were present at the Jurassic Amran Limestone Aquifer. The majority of the wells inventoried are concentrated at the northern part of Sana'a Basin. The rest of these wells are scattered over several sub-basins in the eastern and northern parts of the basin. The distribution density of these wells over Sana'a Basin can be summarized in the following Table 2.15.

Table 2-15 Distribution density of the wells tapping the Amran limestone aquifer (WEC, 2001)

Sr. No.	Sub-Basin	No. of Wells	%
1	Wadi Bani Huwat (sub-basin 9)	231	21.33
2	Wadi Al Maadi (sub-basin 4)	193	17.82
3	Wadi A' sir (sub-basin 5)	175	16.16
4	Wadi Thumah (sub-basin 10)	162	14.96
5	Wadi Al Kharid (sub-basin 3)	144	13.30
6	Wadi Al-Madini (sub-basin 2)	74	6.83
7	Wadi Khulaqah (sub-basin 6)	70	6.46
8	Wadi Al-Mashamini (sub-basin 1)	26	2.40
9	Wadi Qasabah (sub-basin 7)	3	o.28
10	Wadi As'Ssir (sub-basin 11)	3	0.28
11	Wadi Iqbal (sub-basin 10)	1	0.092
12	Wadi Ghaiman (sub-basin 10)	1	0.092
Total		1083	100

A detailed review of the previous well inventory surveys has been performed. The most important conclusion drawn from this review was that the WEC well inventory represents the comprehensive survey covering most of the Sana'a Basin. A summary of the main findings of WEC well inventory survey, 2001 is listed below:

A. In total, 13425 water points were recorded across the Sana'a Basin during this well inventory.

B. Up to 97 wells/km^2 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, which also have a high density of wells per km^2.

C. The highest number of wells were found in Wadi As-Sirr (sub-basin 11 - Bani Hushaish) and Wadi Bani Huwait (sub-basin 9 - Bani al Harith).

D. Totals of 2288 and 2256 wells were recorded in the Bani Hushaish and Bani Al Harith respectively, which means that about 40% of the total number of wells occur in these two sub-basins.

E. Recent drilling activities are mostly concentrated in the above-mentioned two sub-basins. Since 1995, 432 and 374 boreholes have been drilled in the two sub-basins respectively, indicating that there is an over-pumping of deep groundwater in Bani Hushaish and Ban al Harith. Unfortunately, most of these boreholes are private and were drilled by local companies, therefore no documented reports are available for these wells.

F. According to WEC report, 2002, the general trend of groundwater flow obtained from both dug wells and boreholes is very similar, since the 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.

1.6 Recharge of the aquifers

Al-Hamdi (2000) reported that estimates for the natural recharge in the Sana'a Basin vary between 28 and 60 MCM/y. He stated that much of the recharge is derived from the intermittent runoff along the wadi courses discharging to Sana'a plain. He explained that direct recharge from rainfall is limited due to low rainfall, high soil moisture deficit and thick unsaturated zone. Many estimates of groundwater recharge have been carried out through flow calculation and estimates of infiltration as proportion of precipitation.

Italconsult (1973), in their report, made a rough calculation of the amount of recharge. Over an area of 2400 km^2, they calculated a recharge figure of 25E6 M^3/y. Since the area of the catchment is 3200 km^2, it can be extrapolated that the basin-wide recharge will be around 30E6 M^3/y.

Foppen (1996) mentioned that Charalambous (1982) estimated a recharge of about 30E6 M^3/y, while Jungfer (1987) estimated, after analyzing isotope data of groundwater in the Sana'a Basin, that the amount of recharge is minimal.

Selkhozpromexport, 1986 estimated a recharge figure of about 60E6 M^3/y. They divided the basin into 66 regions of between 0.8 and 200 km^2 depending on topography, geology and rainfall. Infiltration and groundwater use were allocated to each area. Infiltration rates were calculated as percentage of total annual rainfall, varying from 5% on the alluvial plain to 9% in the fault zones.

Al-Derwish and Dottridge (1998) made an estimate of recharge in Sana'a Basin using an indirect method for defining wadi flow, during a field session in 1993; detailed observations were made of two streams, Wadi Dhar and Wadi As-Sir, including measurements of flood duration, extent and maximum stage, groundwater levels in observation wells and estimate of flows. These data were used to calibrate a rainfall-runoff model (SCS curve number method) and to derive infiltration rates by two independent approaches: a daily water balance calculation for the channel, and a groundwater model for the Alluvium Aquifer along the same stretch. Consistent results were obtained from both methods. This result was extrapolated to other years and wadis through the development of regression equation relating recharge to run-off from the up-land and total catchment areas. The total annual recharge from all 12 major wadis in the Sana'a Basin varies widely, from 3 to 129 M^3/y, with an average of 39 M^3/y, equivalent to 4.5% of the average annual rainfall. However, wadi recharge is not related to annual rainfall, but depends on the distribution, intensity and duration of individual storms, which determine the run-off from the mountain (Al-Derwish and Dottridge, 1998).

SAWAS-2 calculated inflow in the southern part of the Sana'a Basin. They calculated a total inflow of 3.9E6 M^3/y. From this, SAWAS-2 calculated that the recharge is in the order of 6.5 mm per year. If this were applicable to the whole area, then 35E6 M^3/y would be the figure of the recharge (Foppen, 1996).

There are two other sources of recharge into the Quaternary Alluvium Aquifer other than precipitation. These sources are infiltration of domestic sewage in the urban areas of Sana'a and irrigation return flow.

Al-Hamdi (2000) estimated the infiltration of domestic sewage to be 12.5E6 M^3/y. Urban recharge from main leakage and seepage through septic tanks was estimated from a well inventory, water supply records and usage rates as 59% of the water supplied (Al-Derwiah and Dottridge, 1998). An amount of 75% of supplied and abstracted water in the urban area was considered by (Naaman, 2004) as infiltration in the same area, giving 15E6 M^3/y in 1995.

Data on irrigation return flow is very limited. Al-Derwiah and Dottridge, (1998) made an estimate of irrigation return flow derived from measurements of the soil moisture and matric potential for the three most extensive crops (Qat, grapes and apples). They estimated the amount of irrigation return flow to be 20-40% of the water applied, giving some 30E6 M^3/y. SAWAS-2 assumed that 25% of the abstracted amount of groundwater would eventually infiltrate the Alluvium Aquifer (Foppen, 1996). A 25% of the abstracted amount was considered as irrigation return flow, giving 50.8E6 M^3 in1995 (Naaman, 2004).

In conclusion, it is important to mention that the estimates of the total underground water resources and of their recharge even within the area of the Tawilah-Madj-Zir sandstones alone, as made by "Italconsult" (1973), "Howard Humphreys" (1977,1980,1983), Charalambous (1982), can only be regarded as tentative because nobody, so far, has ever conducted a complete survey of all hydrological and hydrogeological conditions for such an assessment. Having presented their calculations of the underground water recharge for the Tawilah-Majd-Zir sandstones in their 1983 report, the experts from "Humphreys" emphasized that the value of the recharge remained unknown. It should be stressed that all the researchers agreed as to the reason behind the decline in the underground water levels. They argued that the lowering of the underground water level clearly indicated the excess of water intake over water recharge. As to the hydrogeological parameters for the area of the Sana'a Basin, they have been identified mainly over the territory of western and eastern well-fields involved in the construction of boreholes.

The study of the Satellite Imagery/Data Analysis Study along with Ground Truth and Meteorological Monitoring carried out by GAF, 2005 produced a potential infiltration map (Figure 50) at a scale of 1:100,000. It includes morphological and hydrogeological information derived from remote sensing data and geological maps. The potential infiltration map (Figure 50) shows the geomorphologic and hydrological features in the Sana'a Basin relevant for infiltration. Infiltration can be defined as downward movement of water into soil or porous rock; it can be either of natural origin or human-induced by the construction of dams, terraces or infiltration wells.

The following list resumes the relevant map features concerning potential infiltration in Sana'a Basin:

- Main infiltration is assumed to take place through the wadi bed during flood events (SAWAS 1996).
- Significant infiltration is also presumed in areas where alluvial deposits build up the surface. Though the hydrogeological properties of the alluvial are regarded as limited, the extensive area contributes quantitatively to groundwater recharge.
- Surface roughness classification indicates potentially better infiltration in the south and along the borders of the Alluvium Aquifer to the hills. This is in line with published data, which presumes recharge mainly in the transition from the foot of the slope to the basin. At the basin margins, the hydrogeological properties are generally better due to coarser material.
- Poor infiltration or none at all is assumed along the hill slopes. The Tawilah Sandstone and the Basal Basalts, however, often crop out as significant slopes or escarpments and the recharge can here be regarded as limited.
- Flat areas, as present in the west, provide good infiltration conditions, and can be of importance locally. On a more regional scale, the recharge depends on the hydraulic connection to the Tawilah Sandstone Aquifer.

1.6.1 Evidence of Recharge

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

- The first groundwater study in the basin showed a water level rise in the Quaternary Alluvium Aquifer, Tertiary Volcanics, and the Cretaceous Tawilah Sandstones. It ranged from 0.42-1.13 m (south of the city) and 0.13-0.55 m (north of the city) for the period between 1965 and 1972 (Italconsult, 1973). This rise was occurring when the central part of the plain had already become subject to considerable overdraft as mentioned earlier, i.e. Replenishment has been masked by overexploitation in this part.

- Between 1980 and 1990, a considerable number of water level records became available, including monthly values and hydrographs for NWSA observation wells. Laes and Bamatraf (1991) reviewed these data for the purpose of detecting water table fluctuations and estimating annual groundwater level declines. Unfortunately, not enough attention was paid to seasonal changes, which normally serve as the first signs of rainfall percolation as a recharge component to the aquifer system. Reanalyzing these data shows clear evidence of “water mound” following rainy seasons, which eventually disappears as the additional volume of water spreads across the aquifers.

The NWSA monitoring program was discontinued after completion of the SAWAS project, but NWRA has just started a new program. The limited data that have become available so far also show evidence of recharge.

Participants in stakeholder meetings arranged during this study (2006) have reported on a number of cases where the water table has risen significantly due to the construction of small dams in Bani Hushaish (Mukhtan), Bani Bahloul (Al Lujama), and Sanhan (Hajrat al Dhabyani). Site visits to some of these dams and discussions with locals have confirmed the occurrence of induced recharge in existing wells nearby.

1.6.2 Evidence from Environmental Isotopes

A systematic reconnaissance-level survey of the environmental isotope composition of Sana’a Basin groundwater has been carried out at the initiative of the IAEA-HIS over the past few years. Although interpretation is constrained as a result of the sampling limitations imposed by using water wells of uncertain and inadequate construction, the results of this work (Aggarwal, Wallin and Stichler, 2003) provide some important insights into the dynamics of aquifer recharge:

Figure 2.7 shows that the Sana’a Basin possesses a Quaternary Alluvium Aquifer (with clear isotopic evidence of some contemporary recharge from storm runoff) locally overlaying deep Cretaceous Sandstone Aquifer for which there is no evidence of significant recharge and presently contains mainly palaeo-ground water (Agrrarwal, et al, 2002). In the absence of regulation, some 13,000 water wells were constructed for urban and rural water-supply and to irrigate some 23,000 ha. These extract groundwater in part from the deeper aquifer and its ground water levels are falling by 3-5 m/a as a result of the imbalance between groundwater extraction and recharge (Foster, 2003).

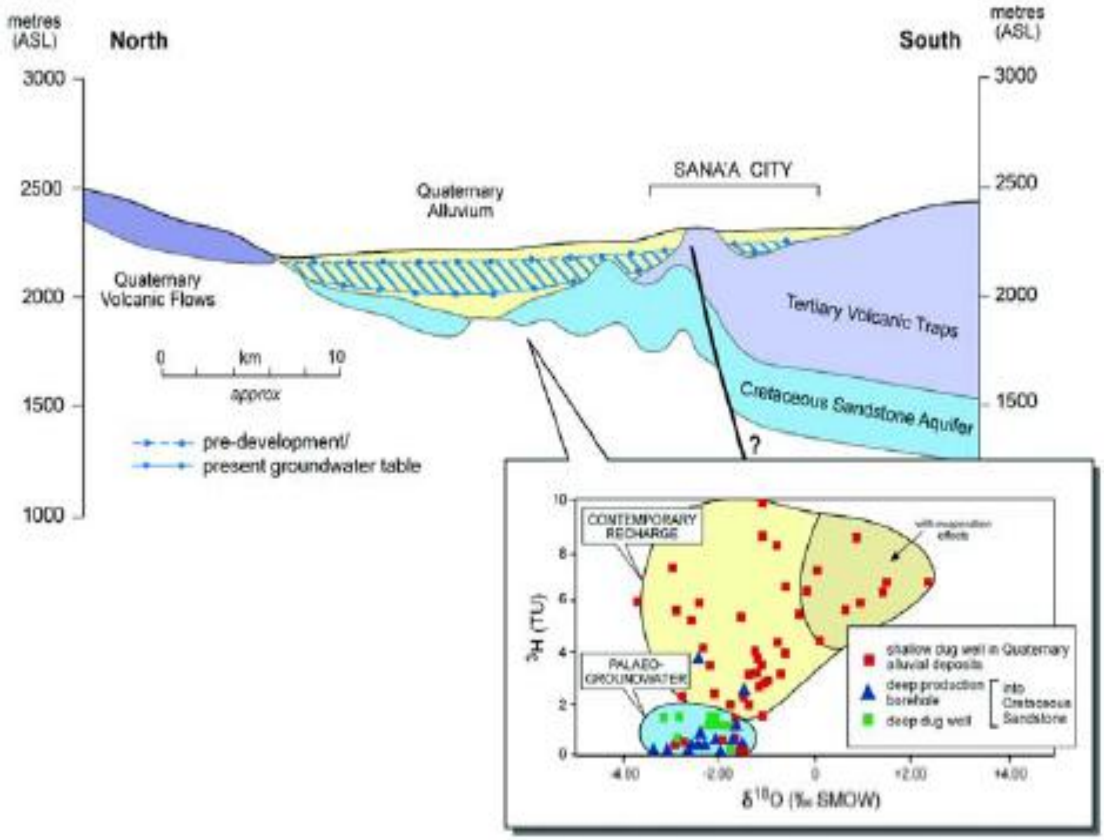

Figure 2-7 Characterization of Sana'a Basin Groundwater by their Isotopic Composition (Samples from Sana'a Basin sub-catchments 9, 14, 15, 16, 17 and 19) (After Foster et al, 2003)

1.7 Discharge of the aquifers

1.7.1 Groundwater Abstraction from Tawilah Sandstone Aquifer

Abstractions from the Tawilah Sandstone Aquifer date back to the late 1960s-early 1970s when, according to Italconsult 1973, some 66 l/s were abstracted for irrigation from Wadis Dhahr, Rijam and other smaller wadis. Howard Humphreys, 1977, estimated that abstraction from these "ancient" boreholes was somewhat higher, amounting to approximately 115 l/s; of this, 100 l/s were derived from the western well-field (mainly wadi Dhahr) and the remainder from the eastern well-field.

In 1979, Howard Humphreys re-estimated abstractions from the well-field areas (Table 2.16), but excluded the areas north of Wadi Dhahr in the western well-field and North of Wadi Sarf in the eastern well-field and found that these have increased to approximately 510 l/s.

Table 2-16 Re-estimated abstractions from the well-field areas (Howard Humphreys 1979)

Well-field	Area of Abstraction	l/s
Western well-field	Sana'a Water Supply (Boreholes ST1, ST5, ST6, ST7)	45
	Local Irrigation/Domestic/Other	300
Eastern well-field	Local Irrigation/Domestic/Other.	165
Total Abstraction (1979)		510

Thus, in a period of about 10 years, abstraction in the well-field areas has increased by almost five times. Increases in abstraction outside the well-field areas must have been considerable also, although these have never been estimated. However, it is known that, since 1979, a considerable number of private boreholes have been drilled, particularly in the eastern well-field area. It is tentatively considered, therefore, that local abstraction may now be as high as 1000 l/s, of which 400 l/s are thought to be abstracted from the western well-field and 600 l/s from the eastern well-field (Howard Humphreys, 1979).

In conclusion, tentative estimates indicate that at present that Tawilah Sandstone Aquifer is exploited at a rate of 37.84 Mm^3/a (1200 l/s) of which only 6.3 Mm^3/a (200 l/s) is used for the water supply of Sana'a City. Clearly, more reliable estimates of abstraction can only be obtained by a detailed inventory of all boreholes exploiting the Sandstone Aquifer (Howard Humphreys 1979).

According to Mosgiprovodkhoz, 1986, abstraction figures for both western and eastern well-fields are shown in Table 2.17.

Table 2-17 Abstraction in the western and eastern well-fields (m^3/day), (Mosgiprovodkhoz, 1986)

YEAR	Western Well-field			Eastern Well-field		
	NWSA	Private	Total	NWSA	Private	Total
1972	2800	4942	7742	3456	3456	
1973	2800	5720	8520	3742	3742	
1974	2800	6575	9375	4027	4927	
1975	2800	7517	10317	4313	4313	
1976	2800	8545	11345	4599	4599	
1977	2800	9081	11881	4884	4884	
1978	2800	9644	12444	5170	5170	
1979	5400	9644	15044	5456	5456	
1980	10400	9644	20044	5742	5742	

YEAR	Western Well-field			Eastern Well-field		
	NWSA	Private	Total	NWSA	Private	Total
1981	14200	9644	23844	6027	6027	
1982	17300	9644	26944	6027	6027	
1983	19300	9644	28944	6027	6027	
1984	14100	9644	23744	12960	6027	18987
1985	14600	9644	24244	11299	6027	17326

The figures for 1986 (15 M m^3/year) are equivalent to annual abstractions of respectively 8.8 Mm^3 in the western well-field and 6.3 Mm^3 in the eastern well-field. It is not clear whether that the sum of these amounts (15 Mm^3 /year) represents an estimate of the total groundwater abstraction from the Tawilah Sandstone Aquifer. If not, it is unlikely that additional abstractions add up to an amount of comparable magnitude (Mosgiprovodkhoz, 1986).

Groundwater, however, is not only abstracted from the Tawilah Sandstone Aquifer, but also from other geological units in the Sana'a Basin. An example is the abstraction by private wells in Sana'a - mainly from alluvial deposits and volcanic rocks – which, in 1985, was some 24,800 m^3/day or nearly equal to NWSA's abstraction at both well-fields combined. For total groundwater abstraction in 1984 in the Sana'a area, a figure of 48 M m^3 was mentioned by the Mosgiprovodkhoz, 1986. Differentiated according to water user sectors, this volume is composed of 26 millions for irrigation, 18 millions for consumption in Sana'a and 4 millions for rural water supply (Mosgiprovodkhoz, 1986).

According to SAWAS study (1993), exploitation of the Tawilah Sandstone Aquifer occurs mainly in two belts, a few kilometers wide, that run parallel to the sandstone outcrops bordering the plain north of Sana'a. These zones represent respectively the western well-field and the eastern well-field of the Sana'a public water supply. This Tawilah Sandstone Aquifer is heavily over-pumped, 80-90% of the pumped water being abstracted by the agricultural sector. The amount pumped annually is in the order of 200 M m^3, while the annual average recharge from precipitation is only 3.5 M m^3. About 25% of the groundwater abstracted for irrigation percolates as return flow to the aquifer.

According to the most recent data obtained from the well inventory performed by WEC 2001, the estimated groundwater abstracted from the Tawilah Sandstone Aquifer is 118.4 M m^3/year. This estimation, at the time of the well inventory, was based on interviews which were conducted with the well-owners, on the average number of daily pumping hours and on measurements of well discharge.

1.7.2 Groundwater Abstraction from Alluvium Aquifer

Most of the Ghayls stopped flowing before 1980, while the Ghayls Aylaf stopped flowing probably in 1983. The reduction of the Ghayl flow was caused by the decline of groundwater levels. During 1973, the total abstraction of groundwater was estimated to be 3.47 M m^3, composed of 2.5 M m^3 from dug wells, 0.07 M m^3 from pumped bore holes and 0.90 M m^3 from Ghayls. The total abstraction, minus some 25% return flow (figure has not been based on any measurements), is slightly higher than the difference between inflow and outflow; hence, the figure already suggests a beginning of over-exploitation in 1973, (Italconsult, 1973).

In the past, most dug wells abstracted water from the Alluvium Aquifer unit. Groundwater abstractions during the last two decades have largely drained this formation and further development of groundwater from this aquifer will yield only small quantities of water for a relatively short time. Numerous wells that tap the Alluvium Aquifer have gone dry in recent years (WEC, 2001).

According to the most recent data from the last well inventory, carried out by WEC 2001, the total groundwater abstracted from the Alluvium Aquifer is 13.3 M m^3 /year. This estimation of groundwater abstraction at the time of the well inventory was based on interviews conducted with well-owners on the average number of daily pumping hours and on measurements of well discharge (WEC, 2001).

1.7.3 Private abstraction

In 1989, 1990, 1992, 1993 and 1995, the SAWAS project performed four well inventories and a Japanese team (JICA) one. In 2001, WEC performed a major well inventory covering a larger area than that by the previous inventory. The data on all water points (about 13,426 points) was used to obtain an estimate of abstraction by private wells in Sana'a Basin.

To obtain in time a reasonable estimate of the total amount of water abstracted, the data had to be manipulated.

1.7.4 Abstraction by industry

The High Water Council estimated the industrial water use in 1990 to be 4.7E6 m^3/yr and in 1995 to be 6.2E6 m^3/yr.

During the well inventory of Sana'a town by Foppen and Siddiq (1995), seven wells belonging to factories were visited. In August 1995, an additional 10 major factories, comprising a total number of 17-19 wells, were visited.

Assuming an abstraction rate of 10 l/s and an average pumping duration of 12 hours per day, the total abstracted amount of water is 5.7E6 m^3/yr. This is in the same range as the estimation of the High Water Council (Foppen, 1996).

II. PROCESSING AND INTERPRETATION OF ALL DATA AND INFORMATION REVIEWED

After concluding the inventory and reviewing previous data, an attempt has been made to produce a provisional version of several maps and geological cross-sections as has been described in the inception report, with the help of GIS software.

1.8 Outputs of the Processing and interpretation of all data

After processing of previously collected data, professional versions of GIS maps and sub-surface geological cross-sections have been obtained. A brief description of these outputs is given below. Four types of GIS maps were constructed. These maps are:

- MAPS and cross-sections of aquifer geometry showing the aerial extent, upper and lower boundaries of the different aquifers.
- Potentiometric/groundwater elevation maps showing a regionalized groundwater flow (SWL) in the Quaternary Alluvial and the Cretaceous Tawilah Sandstone Aquifers,
- Historical groundwater elevation maps showing approximate groundwater level since 1970,
- Maps of hydraulic aquifer parameters showing transmissivity variations.

1.8.1 Aquifer Geometry Maps and Cross-sections

Aquifer geometry involves the study and identification of geological units, aerial extent, thickness and geological structures.

1.8.1.1 Alluvium Aquifer Geometry

Alluvium Aquifer geometry has been studied based on the aquifer geometry maps constructed. Two maps were constructed based on data collected from the previous driller logs, geophysical data and the well inventory of WEC, 2001. A brief description of these maps is given below (more details given in Technical Note 1):

1.8.1.1.1 Surface distribution map of the Quaternary Alluvium Aquifer

This map (Figure 2.8) shows the surface distribution of the Alluvium Aquifer throughout the basin. It is clear from this map that this aquifer is confined to Sana'a plain and wadi beds. The Sana'a plain is mostly covered by the Alluvium Aquifer.

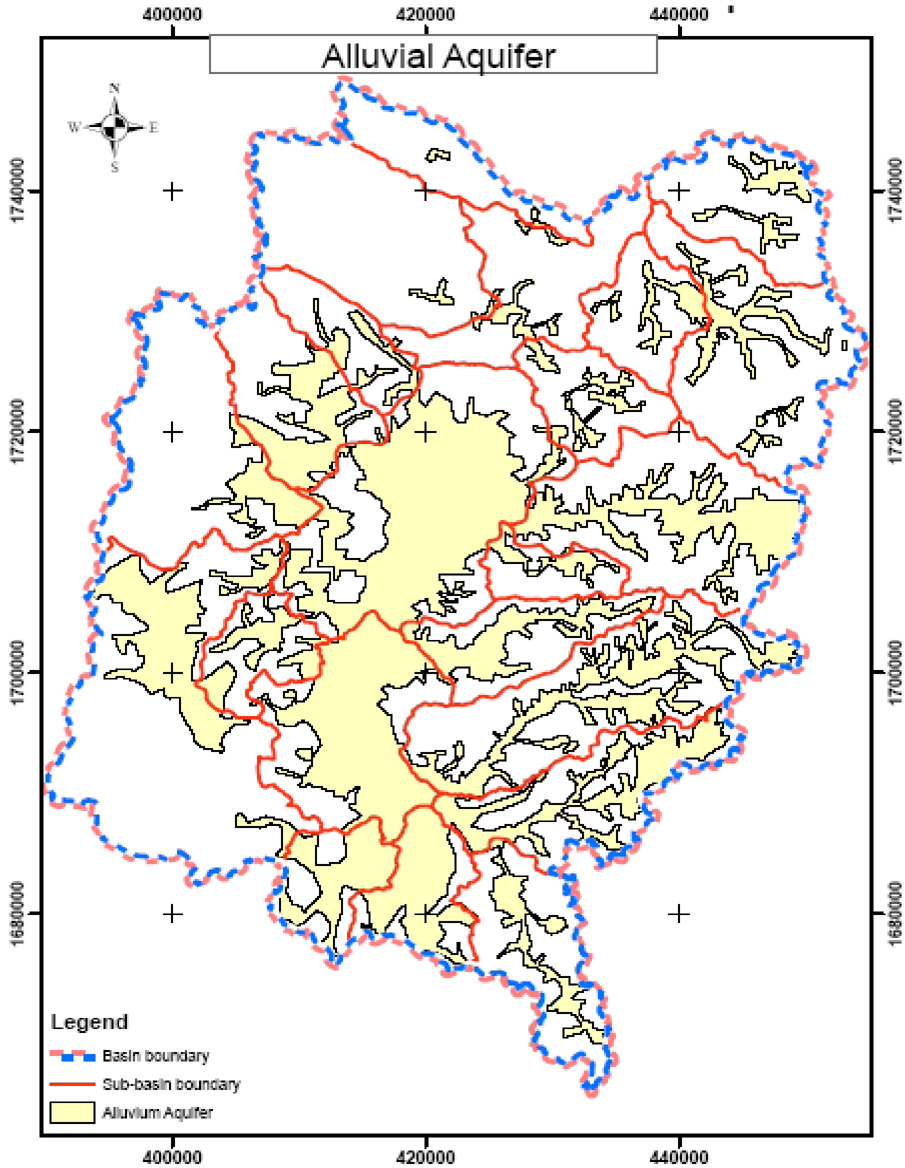

Figure 2-8 Map Showing the Surface Distribution of the Quaternary Alluvium Aquifer of Sana'a Basin

1.8.1.1.2 Alluvium Aquifer Thickness Map

This map (Figure 2.9) shows the variation of Alluvium Aquifer thickness over the entire basin. The alluvial deposits form about three depositional small basins. The deepest one is more than 300 m in depth and is located in the area between Al-Rawdah and Sana'a airport. The other two small basins are located to the south and northeast of Sana'a Basin.

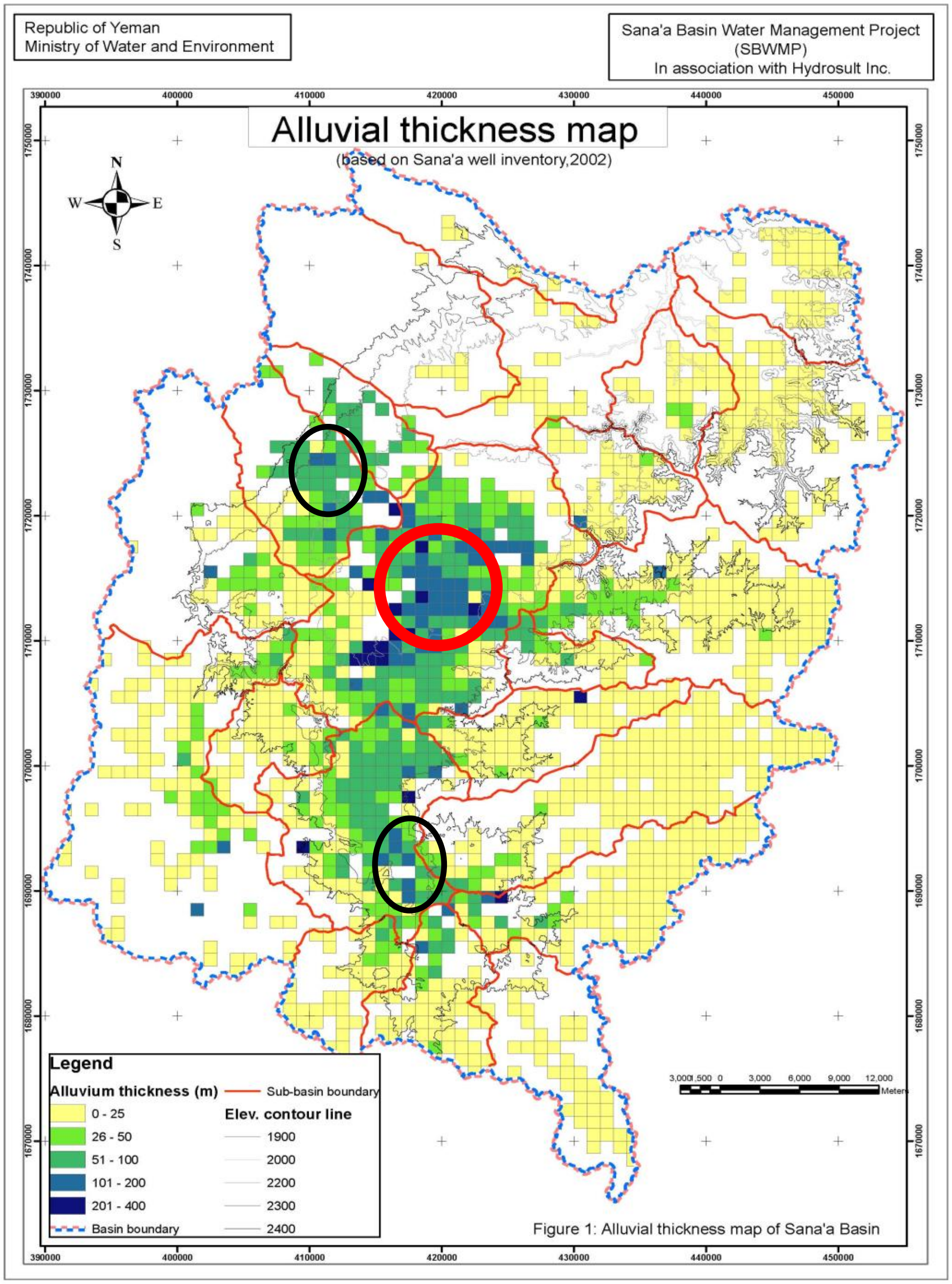

Figure 2-9 Map Showing the Quaternary Alluvial Thickness Map of Sana'a Basin

1.8.1.2 The Volcanic Aquifer (Quaternary & Tertiary) Geometry Maps

The Volcanic Aquifer geometry has been studied based on the aquifer geometry maps constructed. Three maps were constructed based on the data collected from the driller logs, geophysical data, the well inventory of WEC, 2001 and data from several previous projects. A brief description of these maps is given below (more details given in Technical Note 1):

1.8.1.2.1 Surface & Sub-surface Distribution of the Volcanic Aquifer

This map (Figure 2.10) shows the distribution of the Volcanic Aquifer in both surface outcrops and sub-surface. The volcanics are mainly outcropped to the west, east and south of Sana'a Basin. In the central plain, the Volcanic Aquifer is presented on subsurface overlain by the Quaternary Alluvium Aquifer.

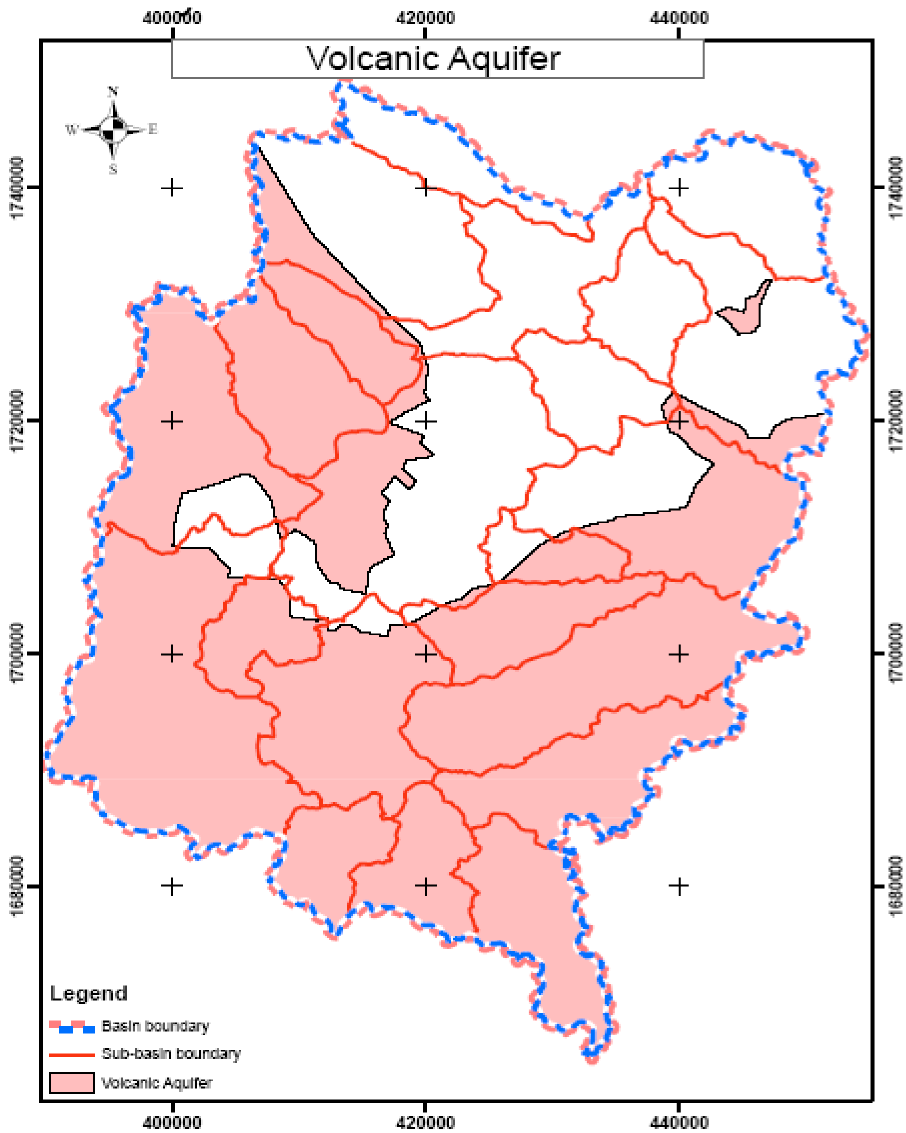

Figure 2-10 Map Showing the Surface and Sub-Surface distribution of the Volcanic Aquifer of Sana'a Basin

1.8.1.2.2 Upper Boundary of Volcanic Aquifer (m amsl)

This map (Figure 2.11) shows the upper surface of the Volcanic Aquifer. It is clear from this map that the Volcanic Aquifer is present at lower elevation (amsl) in two areas i.e. The northwest Area and the south-central area (more details are given in Technical Note 1).

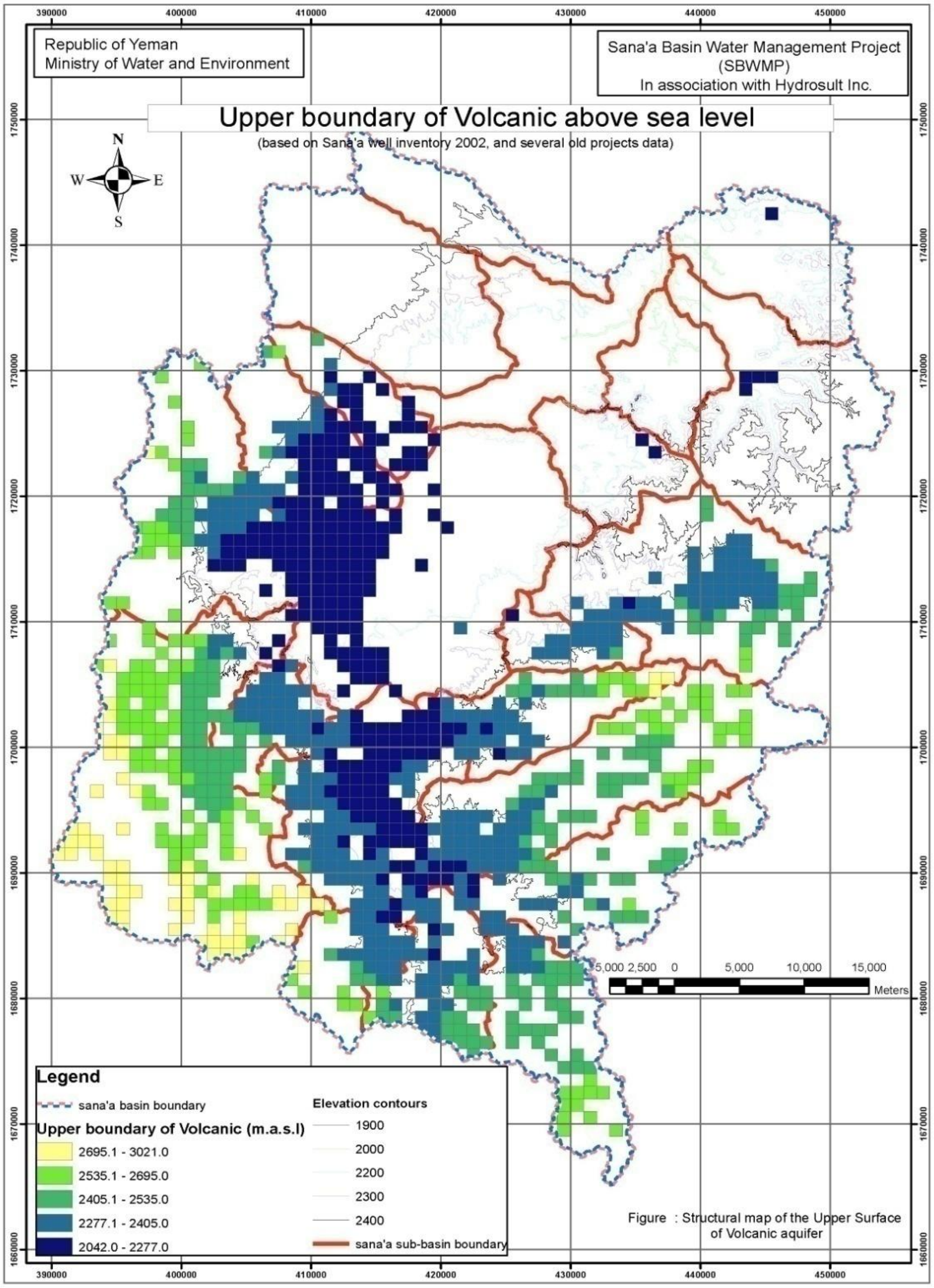

Figure 2-11 Structural Map of the Upper Boundary of the Volcanic Aquifer of Sana'a Basin (amsl)

1.8.1.2.3 Lower Boundary of Volcanic Aquifer in m (amsl)

This map (Figure 2.12) shows the lower surface of the Volcanic Aquifer. It is clear from this map that the Volcanic Aquifer is present at lower elevation (amsl) in two areas i.e. the northwestern area and the south-central areas (more details are given in Technical Note 1).

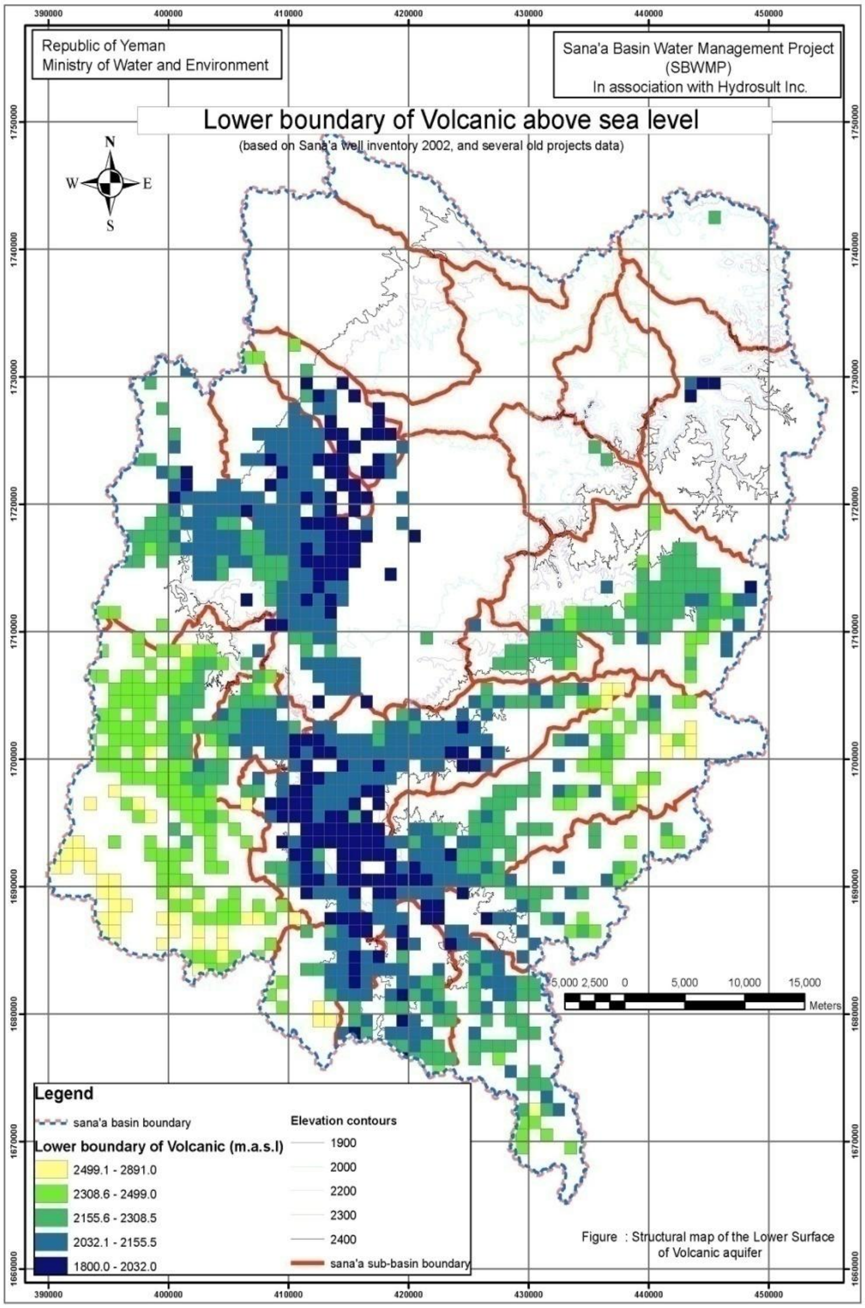

Figure 2-12 Structural Map of the Lower Boundary of the Volcanic Aquifer of Sana'a Basin (amsl)

1.8.1.3 The Tawilah Aquifer Geometry Maps

The Tawilah Aquifer geometry has been studied based on the aquifer geometry maps constructed. Three maps were constructed based on data collected from the driller logs, geophysical data, the well inventory of WEC, 2001 and data from several previous projects. A brief description of these maps is given below:

1.8.1.3.1 Surface distribution of the Tawilah Sandstone Aquifer

This map (Figure 2.13) shows the surface distribution of the Tawilah Sandstone in the outcrop areas. The Tawilah Sandstone outcrops extend as a narrow band from east to west. It is mainly outcrops northeast (Nihm), east (Bani Hushaish) and west of Sana'a Basin (Hamdn area). It outcrops over an area of about 15% of the basin (more details given in Technical Note-1).

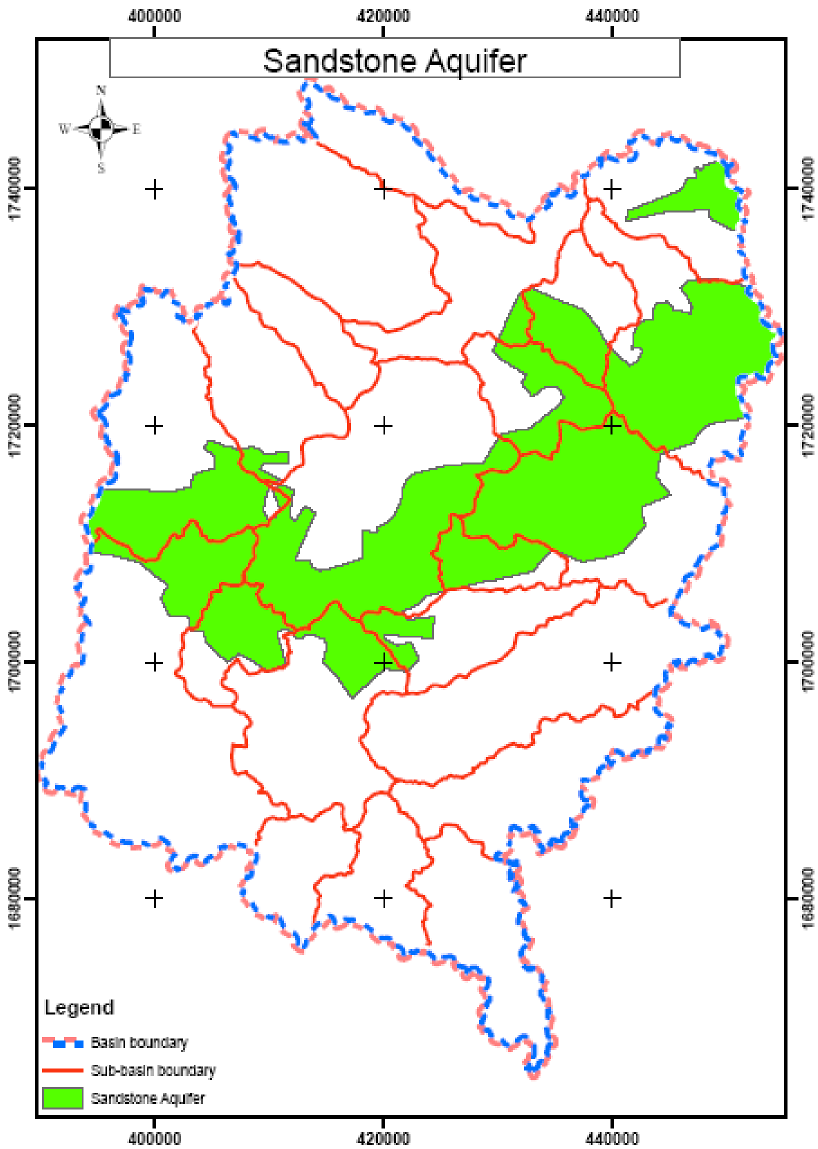

Figure 2-13 Map Showing the Surface distribution of the Tawilah Sandstone Aquifer of Sana'a Basin

1.8.1.3.2 Depth to Upper Surface of Tawilah Aquifer (in m bgl)

This map (Figure 2.14) shows the upper surface of the Tawilah Sandstone Aquifer. It is clear from this map that the Tawilah Aquifer is outcropped on the northeast and northwest areas of the basin or is present at shallow depths. Towards the south, the upper surface of this aquifer presents deeper depths (bgl). Presence of the Tawilah Aquifer at two different elevations (amsl) confirms the presence of a major fault affecting the Tawilah Aquifer in the southern part of the basin (Al-Sabeen Area).

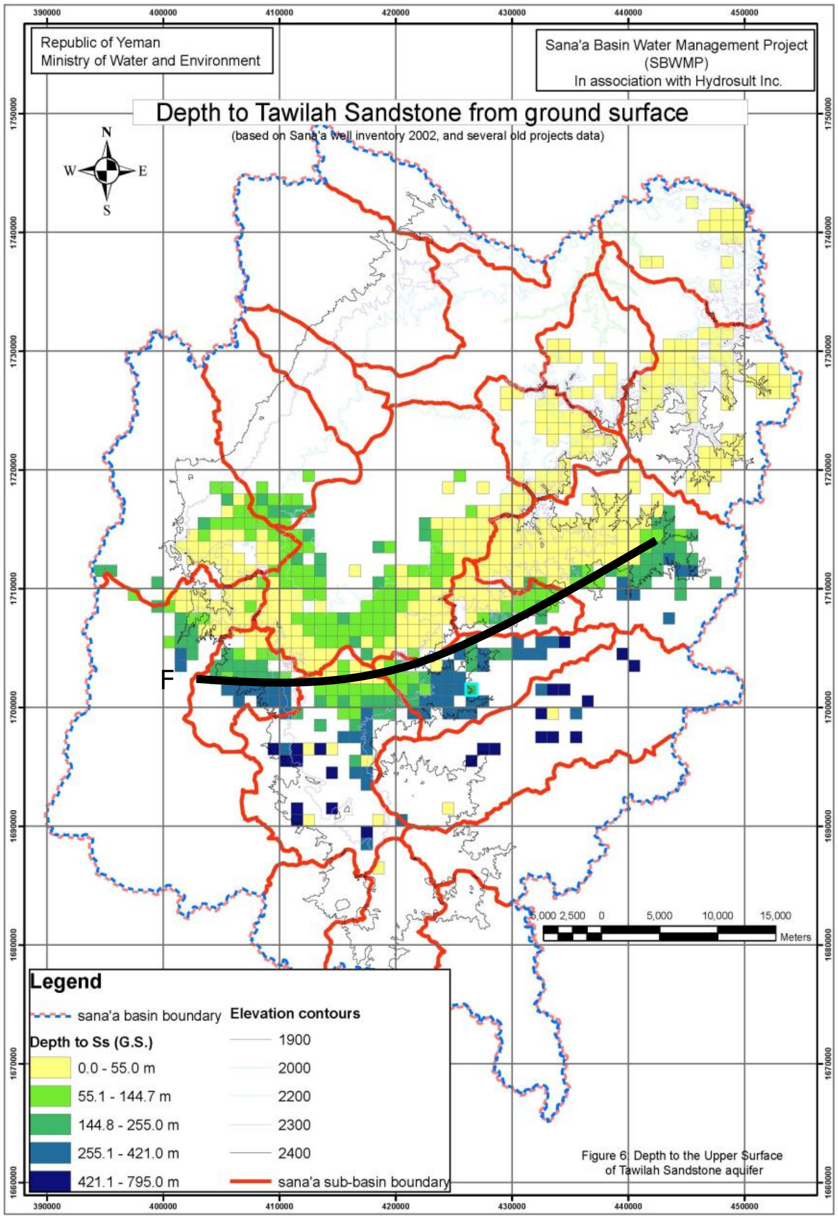

Figure 2-14 Map Showing Depth of the Upper Surface of the Tawilah Sandstone Aquifer below Ground Level

1.8.1.3.3 Upper Boundary of Tawilah Aquifer in m (amsl)

This map (Figure 2.15) shows the upper surface of the Tawilah Aquifer. It is clear from this map that the Tawilah Aquifer presents a lower elevation (amsl) as we go toward south. This confirms the presence of a major fault to the south of Sana'a City. This fault results in the disappearance of Tawilah Sandstone Group at the southern part of the basin.

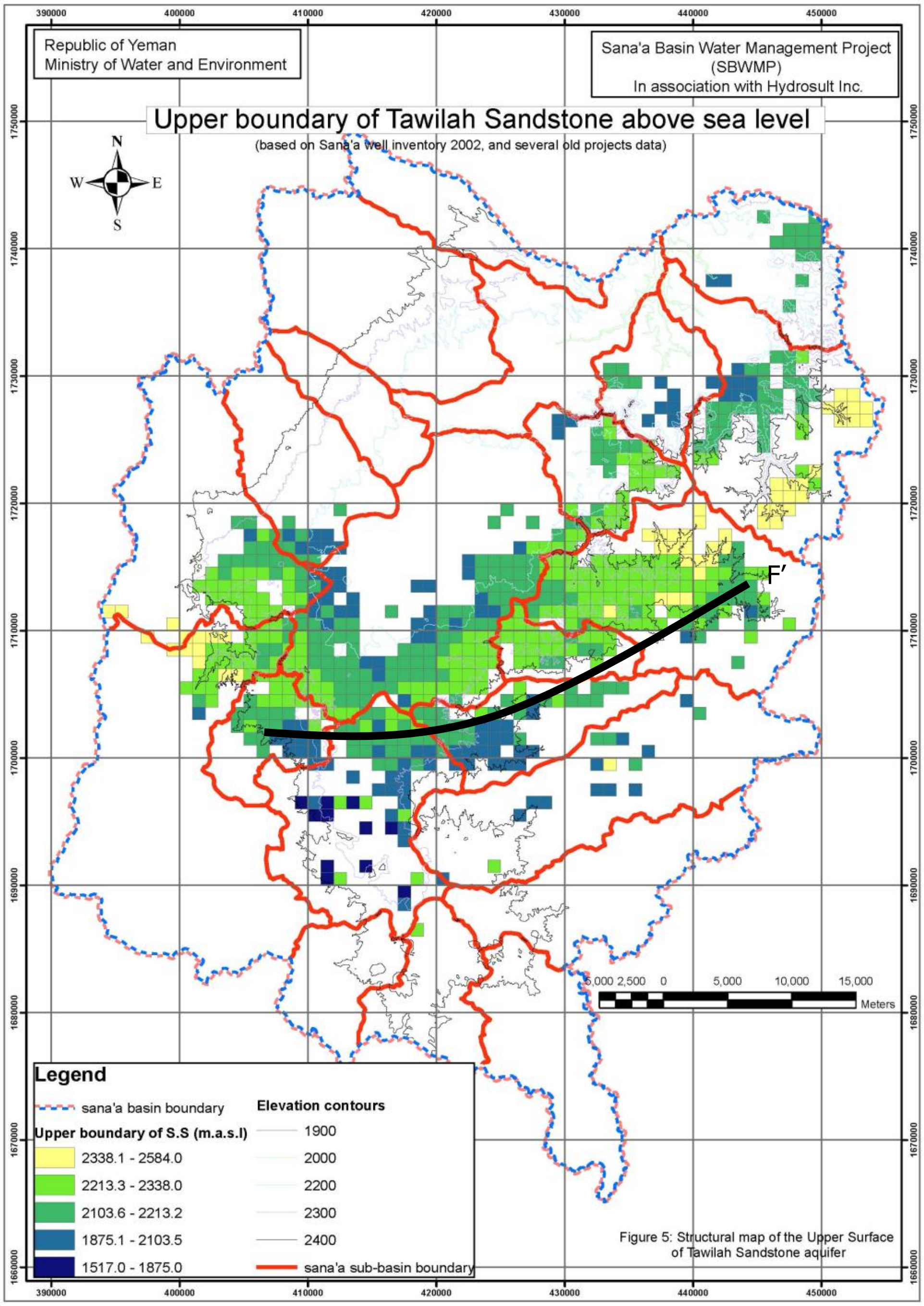

Figure 2-15 Map Showing Upper Boundary of the Tawilah Sandstone Aquifer Above Mean Sea Level

1.8.1.3.4 Lower Boundary of Tawilah Aquifer in m (amsl)

This map (Figure 2.16) shows the lower surface of the Tawilah Aquifer. It is clear from this map that the Tawilah Aquifer presents a lower elevation (amsl) as we go towards the south. It is important to mention here that only a very limited number of wells have encountered the lower surface, such as the wells drilled by SAWAS (DSI & DS2) and the average thickness of this Tawilah Aquifer is assumed to be 350 m, based on review of the subsurface seismic cross-sections and data.

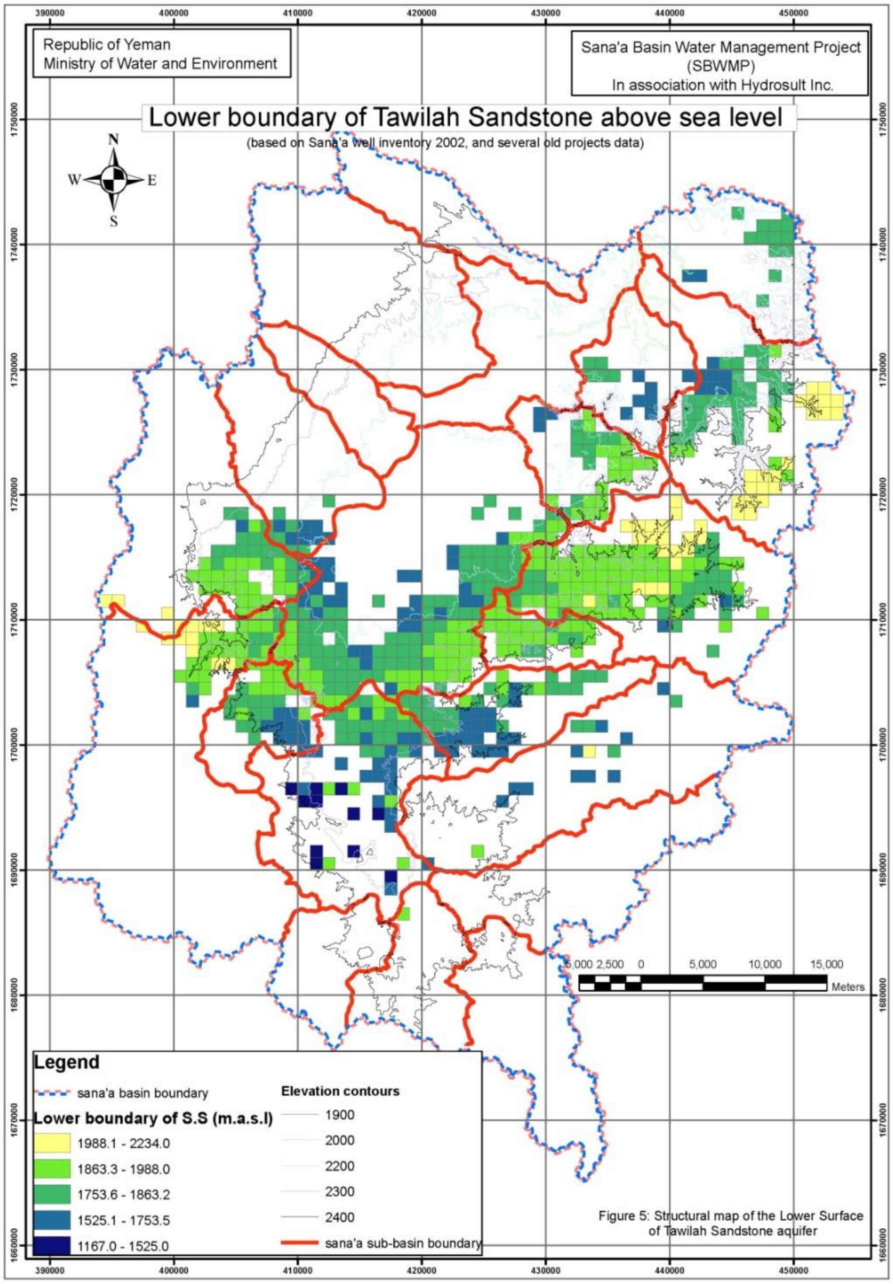

Figure 2-16 Map Showing Lower Boundary of the Cretaceous Tawilah Sandstone Aquifer of Sana'a Basin asl

1.9 Sub-surface Geological Cross-Sections

The subsurface geological cross-sections are useful in delineating, the lateral and vertical boundaries of the aquifers and the subsurface structures controlling the groundwater flow. In order to delineate aquifer geometry, 136 technical drilling reports of deep boreholes drilled in Sana'a Basin were collected and used. The majority of these wells are located in Sana'a plain. They were drilled by several foreign and local drilling companies. Table 2.18 gives the number of wells that were drilled in Sana'a Basin and the foreign and local drilling companies involved.

Table 2-18 Names of the Drilling Companies, Names and Number of Drilled Wells

Company	No. of wells drilled
Howard Humphery (1981-82)	32
Italconsul (1973)	16
NWSA (1984-2001)	27
Dar Al-Handasah (1980)	07
SAWAS (1990-1995)	02
Mosgiprovodkhoz (1986)	14
Other local companies	38
Total	136

Using the above-mentioned data, two previous subsurface geological cross-sections (Italconsult, 1973) were studied again and modified. The modification was based on the new collected well log data and the geophysical resistivity data. A brief description of these modified cross-sections is given below:

1.9.1.1.1 Cross-section a-a'

The sub-surface geological cross-section (Figure 2.17) extends from Hamdan to Bani Hushaish along the northern part of the basin. It was constructed based on additional new data (well logs and Seismic data). The Alluvium Aquifer reached its maximum thickness in the area of Al-Rawdah. It is evident that no structural elements were detected along this cross-section. The Tawilah Aquifer is of approximately uniform thickness. This aquifer can be considered as unconfined aquifer in the northern part of the basin.

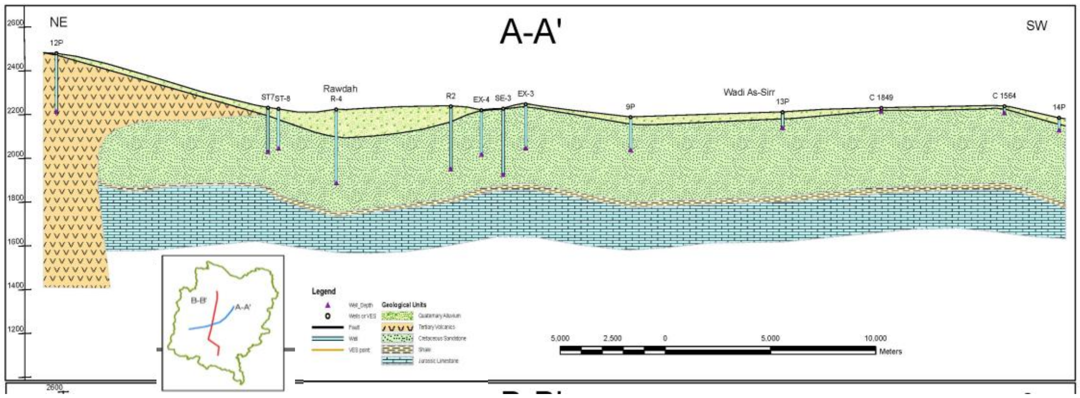

Figure 2-17 Sub-Surface Geological Cross-Sections A-A' (Modified after, Italconsult, 1973)

1.9.1.1.2 Cross-Section B-B'

This cross-section (Figure 2.18) extends from Jabal As-Sama (Arhab) to Sawad Hizyz. It was constructed based on additional new data (well logs, electrical resistivity and seismic data). The Alluvium Aquifer has been deposited unconformably overlying the Jurassic Amran limestone and reaches its maximum thickness north of Al-Rawdah. In this particular area, the Tawilah Sandstone has been completely eroded. Along this cross-section, three normal faults were detected. It is clear from the figure that the Tawilah Aquifer is dipping towards the south and is under considerable thickness of the volcanic and Alluvial lithostratigraphic units.

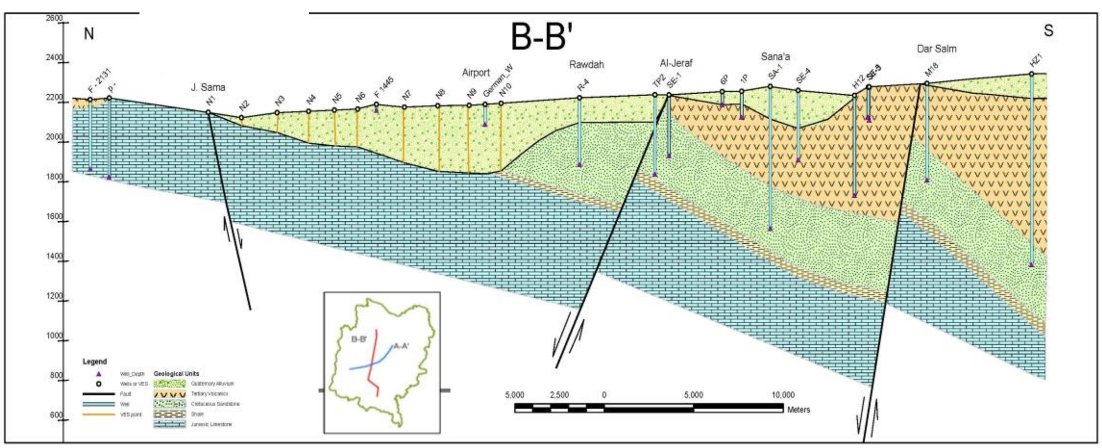

Figure 2-18 A sub-Surface Geological Cross-Sections B-B' (Modified after, Italconsult, 1973)

1.10 Groundwater Elevation Maps

The main purpose of groundwater elevation maps is to determine the principle groundwater flow paths in the aquifer and to understand the ground water aquifer system.

These maps were constructed based on recent well inventory data of WEC, 2001 that covers the Sana'a Basin. Special attention has been given to constructing the groundwater elevation maps related to the Quaternary Alluvial and Cretaceous Tawilah Aquifers. A brief description of the maps related to these two aquifers is given below.

1.10.1 Groundwater Elevation Maps Based on WEC Data

1.10.1.1 Groundwater Elevation of the Alluvium Aquifer (amsl)

The elevation map of the Alluvium Aquifer (Figure 2.19) has been constructed based on well inventory data of WEC, 2001. The map shows that the general trend of groundwater flow is from the south and from both eastern and western sides of the plateaux towards the northern side of the basin where Wadi Al-Kharid is acting as the outlet of groundwater flow. It is clear also from this map that the highest value of water elevation (2700 m amsl) is measured at the eastern part of the basin, whereas, the lowest value (2050 m amsl) is measured at the outlet of Wadi Al-Kharid.

The closeness of the water elevation contour lines at the north-eastern part (Nihm area i.e. Wadi Kulaqah and Wadi A'sir sub-basins) and the eastern part (Wadi Sawan sub-basin) of this map are also up normal and did not match with the normal hydrogeological regime (groundwater flow system) of Sana'a Basin (i.e. generally from south to north), in which Wadi Al Kharid acts as an outlet for the groundwater flow. This situation may have arisen due to the presence of local reverse groundwater flow in those particular areas, which resulted from over-exploitation of the groundwater. This agrees with the conclusions of the above-mentioned well inventory survey, which revealed that those sub-basins are experiencing excessive abstraction of groundwater through a large number of wells.

As shown from the map, the groundwater contour lines cover a large area beyond the lateral extent of the Alluvium Aquifer, especially in the northern and eastern parts of the basin. This is because a rather large number of wells tapping the Alluvium Aquifer are located along the main courses of wadis that give onto the Sana'a plain.

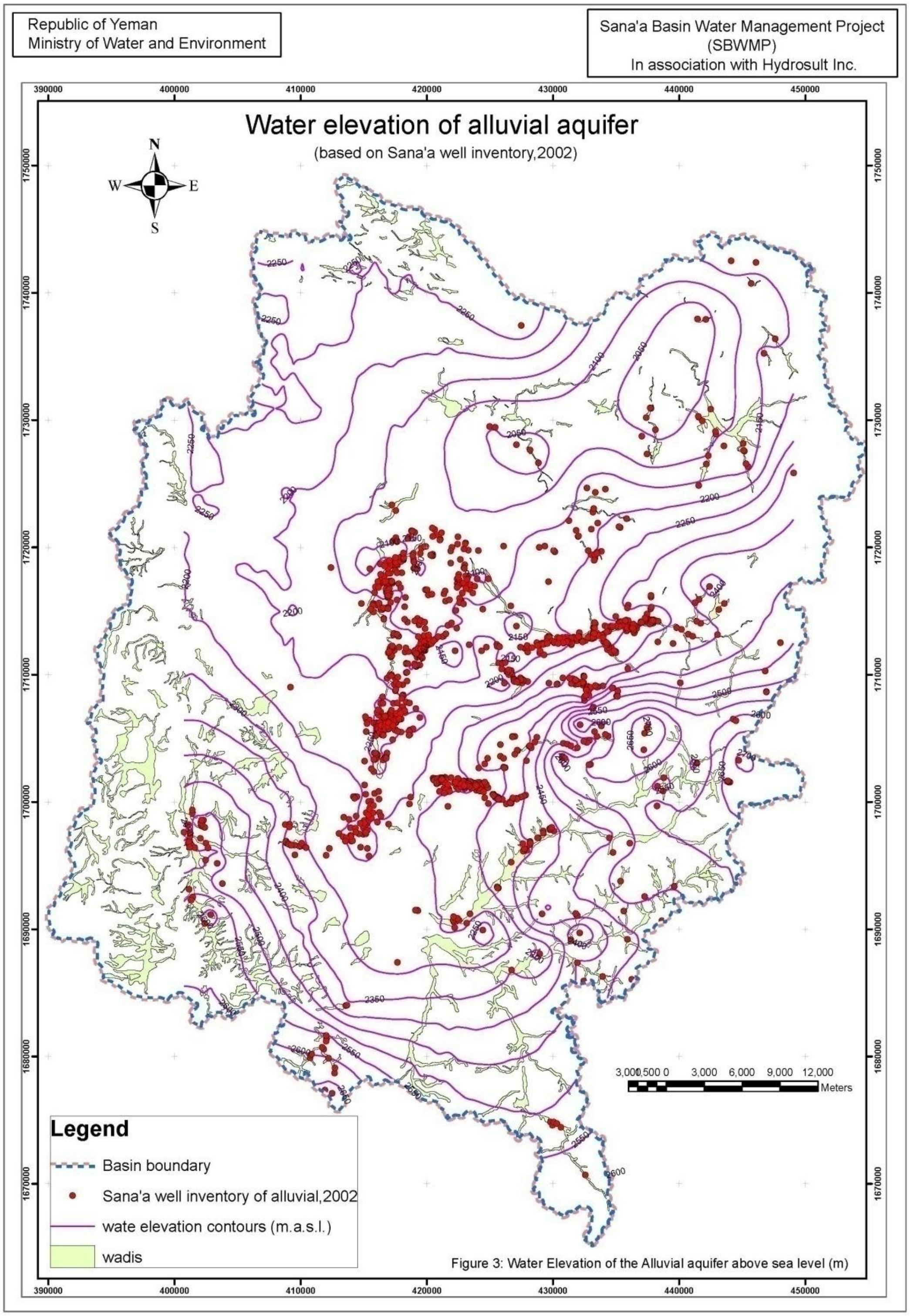

Figure 2-19 Water Elevation Contour map of the Alluvium Aquifer in (m)

1.10.2 The Groundwater Elevation Maps of the Tawilah Sandstone Aquifer

Three groundwater elevation maps (Figure 2.20) have been constructed by SBWMP in association with Hydrosult Inc. (2006), based on well inventory data of WEC, 2001. In these maps, the data from dug wells, bore wells and the dug/boreholes were used. Table 2.19 gives number of operating wells tapping the Tawilah Aquifer which were used to construct the above-mentioned maps.

Table 2-19 Operating wells tapping the Tawilah Sandstone Aquifer (WEC 2001)

Sr. No.	Map No.	Well Type used	No. of Operating Wells
1	Map 1	Dug wells	694
2	Map 2	Bore holes	715
3	Map 3	Total	1409

The first map constructed is based on water elevation data collected from both operating dug wells and boreholes, the second is based on data collected from operating boreholes only and the third is based on data collected from operating dug wells. The consultant prefers the second constructed map based on data of boreholes only because it is relatively more accurate than the others.

The second map provides quite sufficient information about the hydrogeological regime in the western, eastern and northern parts of the basin. It is shown from the second map also (based on boreholes data) that the trend of groundwater flow within the Tawilah Sandstone Aquifer is from both eastern and western banks of the plateaux (outcrops of Tawilah group) towards the central part of the basin. There is also a general trend of flow from south to north. The highest value of water elevation (2520 m) is shown at both eastern and western sides of the basin, whereas the lowest value (1920 m) is detected in the central part of the Sana’a Basin, which indicates the existing of pumping zone. Some closeness of contours may be attributed to over-exploitation of groundwater at those locations.

In general, the water elevations of the Tawilah Sandstone Aquifer are at higher levels in the south, west, and east with respect to the levels present at the central part of the basin. This situation gives rise to a general groundwater flow from south to north. The Tawilah Sandstone piezometric levels also are generally below the levels of the groundwater in the overlying Tertiary Volcanic Aquifer.

The third map (based on dug wells data) indicates that most of the dug wells are concentrated in the north-eastern part of the basin where the Tawilah Sandstone outcropping (i.e Nihm and Bani Hushaish areas) is found.

The hydrogeological regime in the western and southern areas of the basin was not reflected clearly in this map due to the presence of deep boreholes tapping only the deep Tawilah Sandstone Aquifer.

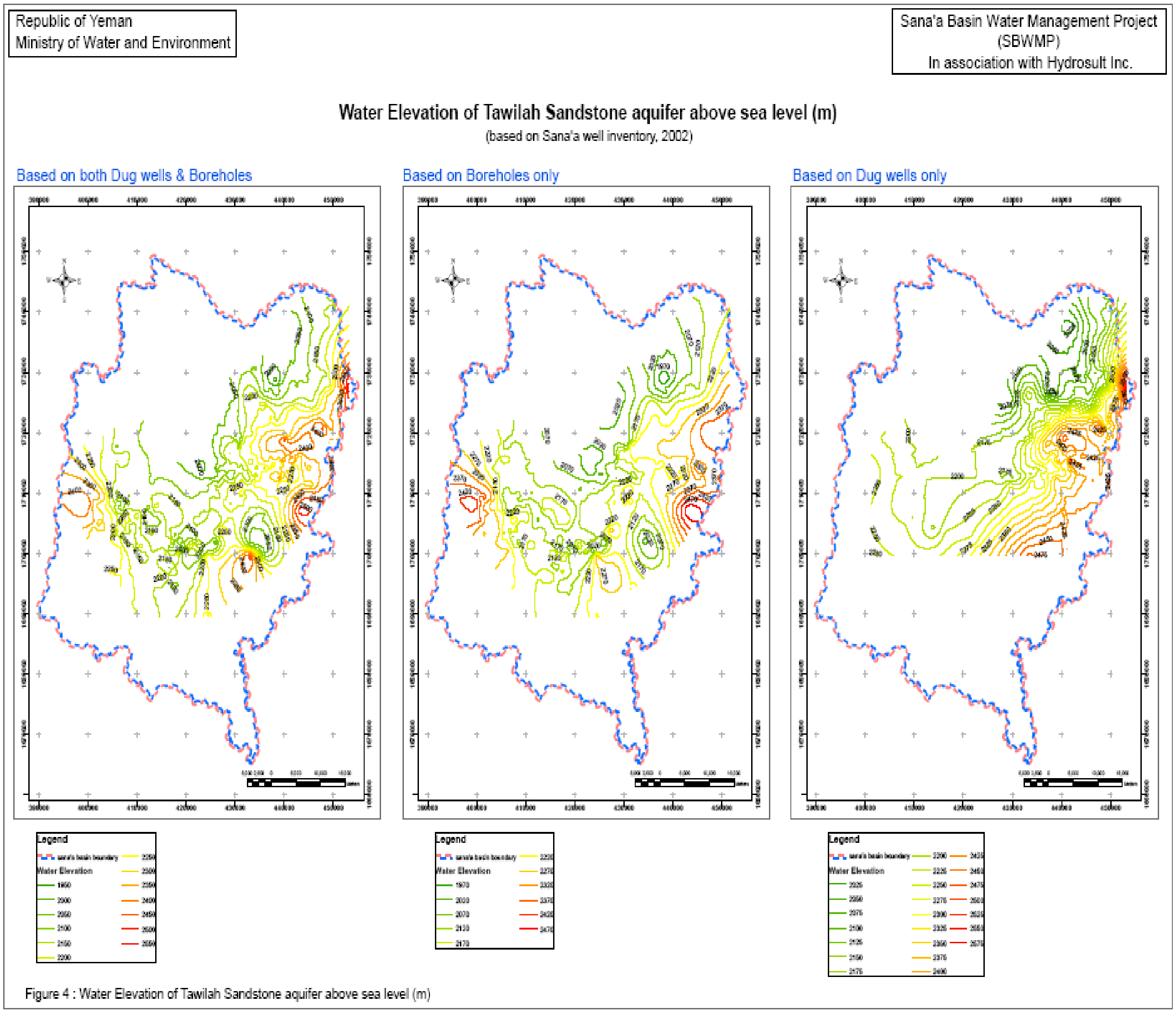

Figure 2-20 Water Elevation Maps of Tawilah Aquifer, (Hydrosult, 2006)

1.11 Historical Groundwater Elevation Maps

The review of ground water monitoring indicated that the measurements of water level fluctuation were usually made at irregular intervals. Each project/authority has its own monitored wells. There was no continuity in the well hydrograph records in the majority of the monitored wells. Several groundwater level measurements were made in the Alluvial, Tawilah Sandstone and Volcanic (Quaternary and Tertiary) aquifers. Previous data of groundwater elevation were collected from different sources. Table 2.20 provides information about the different international projects studied in Sana'a Basin and water level measurements performed. It also provides information about aquifer type, number of monitored wells and dates of measurements.

Table 2-20 A summary of water levels monitored in the aquifers of Sana'a Basin

Firm	Aquifer type	No. of monitoring wells	Date of measurements
Italconsult	Alluvial	295	1972
Selkhozpromexport	Alluvial	135	1984
Selkhozpromexport	Volcanic (Quaternary & Tertiary)	277	1984
SAWAS	Alluvial	611	1993
SAWAS	Tawilah Sandstone	69	1993
SAWAS	Volcanic	84	1993
WEC	Entire Sana'a Basin	13425	2002

Using the above-mentioned water level data; several groundwater level maps of the different aquifers in the Sana'a Basin were constructed covering the last thirty years. A brief description of these maps is given below:

1.11.1 Historical Ground Water Elevation Map of the Alluvium Aquifer

Three groundwater elevation maps of the Alluvium Aquifer were constructed by the Hydrousult Inc, 2006 team. A brief description of these maps is given below.

1.11.1.1 Water Elevation Map of the Alluvium Aquifer (Italconsult, 1972)

This map was constructed by SBWMP in association with Hydrosult Inc., (2006) based on data concerning the Alluvium Aquifer which were collected by Italconsult, 1973 (Figure 2.21). It is clear from the map that the highest contour line value of water elevation is 2550 m amsl, presented in the south-western part of this map, whereas the lowest value (2125 m amsl) is presented in the northern part. It is also clear that the groundwater flow in the aquifer system is from south to north and from the surrounding mountains into the alluvial plain.

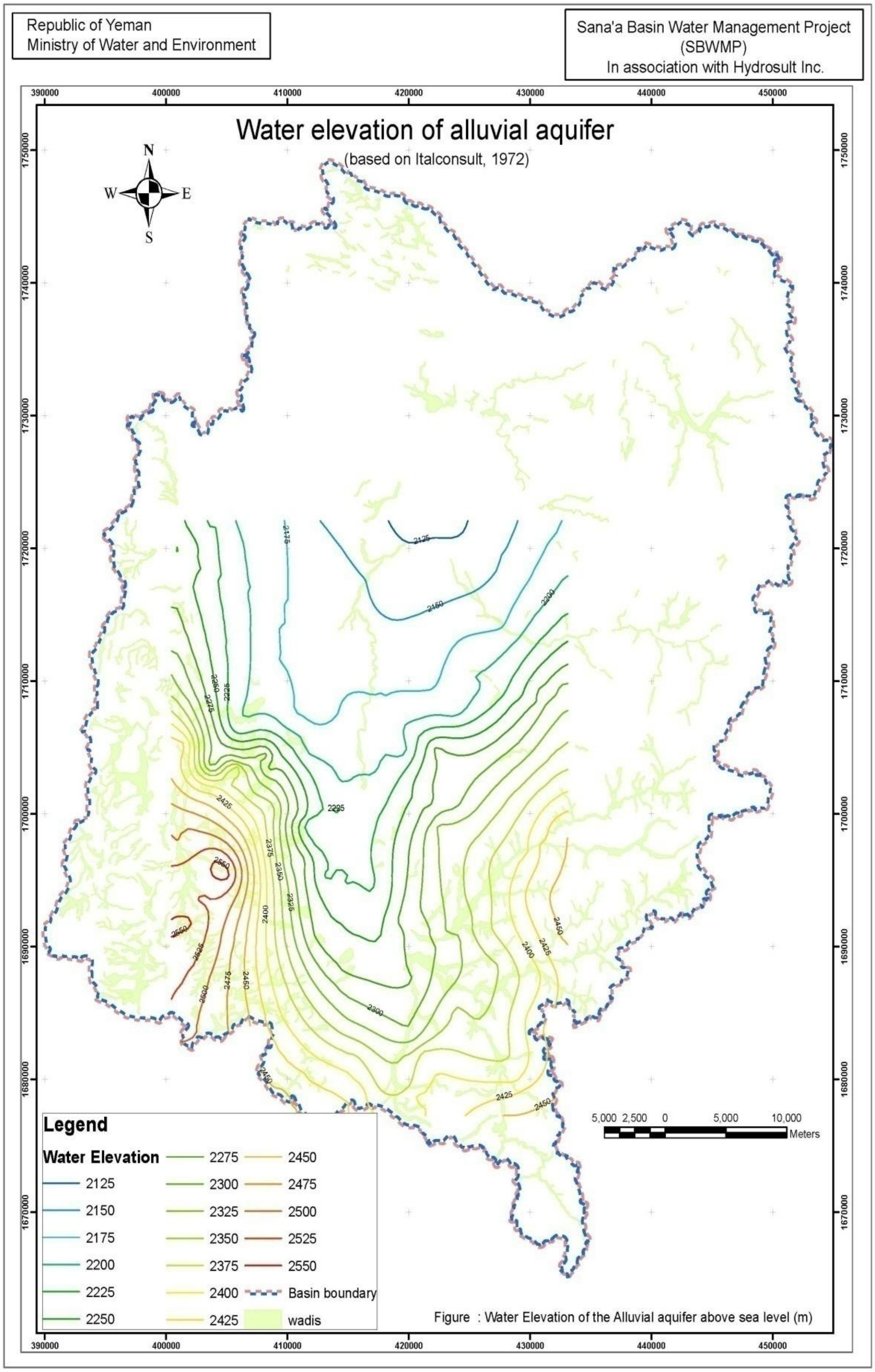

Figure : Water Elevation of the Alluvial aquifer above sea level (m)

Figure 2-21 Groundwater Elevation Map of the Alluvium Aquifer (based on Italconsult, 1972)

1.11.1.2 Groundwater Elevation Map of the Alluvium Aquifer (Solkovpromexport 1986)

This map was constructed based on data concerning the Alluvium Aquifer which were collected by the Russian team, 1985 (Figure 2.22). It is clear from this map that the data are concentrated at the Sana'a plain. It shows the sites of over-exploitation in the Alluvium Aquifer at that time of surveying and covering most of the aerial Alluvium Aquifer. The highest contour line value of water elevation is 2375 m amsl is presented in the south-eastern part of this map, whereas the lowest value (2125 m) is presented in the northern part. It is also clear that the groundwater flow pattern is dominantly in a northerly direction. The contour lines pattern indicates that the ground water abstraction at that time was uniformly distributed without any stress on the Alluvium Aquifer.

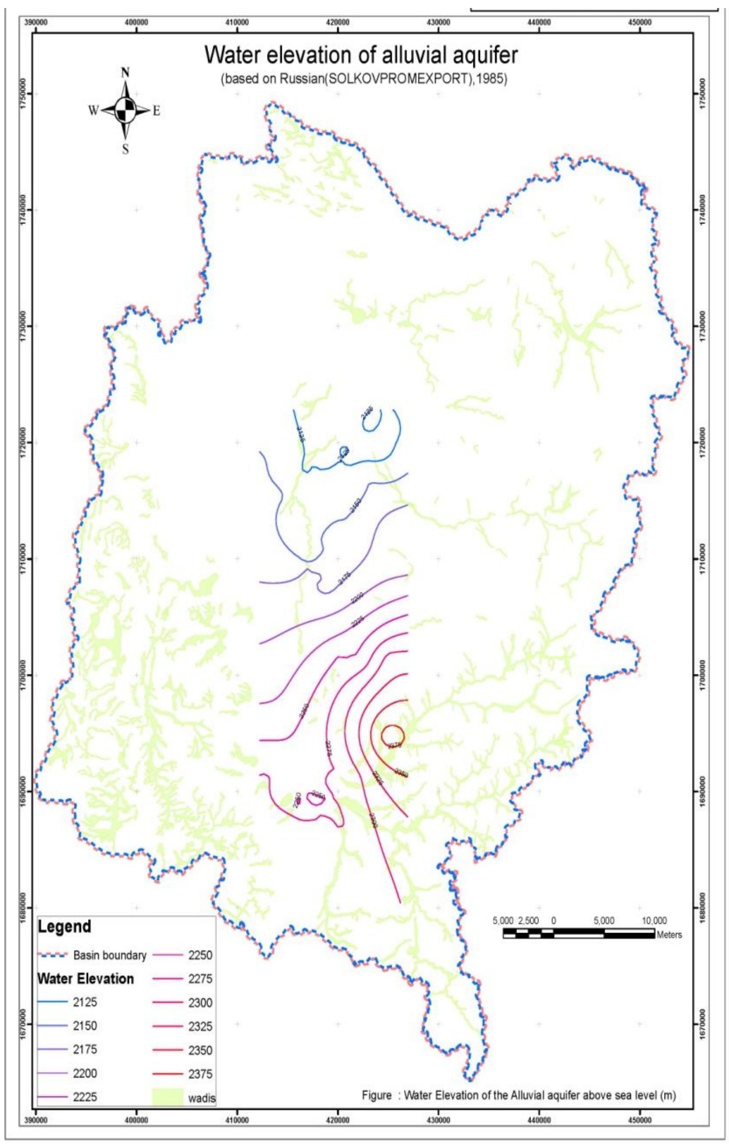

Figure 2-22 Groundwater Elevation Map of the Alluvium Aquifer (based on Solkovpromexport, 1985)

1.11.1.3 Water Elevation Map of the Alluvium Aquifer (SAWAS, 1993)

This map was constructed based on water elevation data of the Alluvium Aquifer collected by SAWAS Project team, 1993 (Figure 2.23). It is clear from this map that there are two directions of groundwater flow. The major one is from south to north, whereas the minor direction flow is from both eastern and western sides to the central part of the basin. A local trend of groundwater flow can be traced in the southern part of the basin. This local phenomenon can be attributed to over-exploitation of groundwater at this particular site. Two groundwater mounds are located in the eastern part of the basin. At these particular points, the groundwater flow is directed to all direction around these two mounds. The highest contour line value of water elevation is 2650 m amsl shown in the eastern part of the map (at the two mounds) whereas the lowest value (2100 m) is detected in the most northern part of the basin.

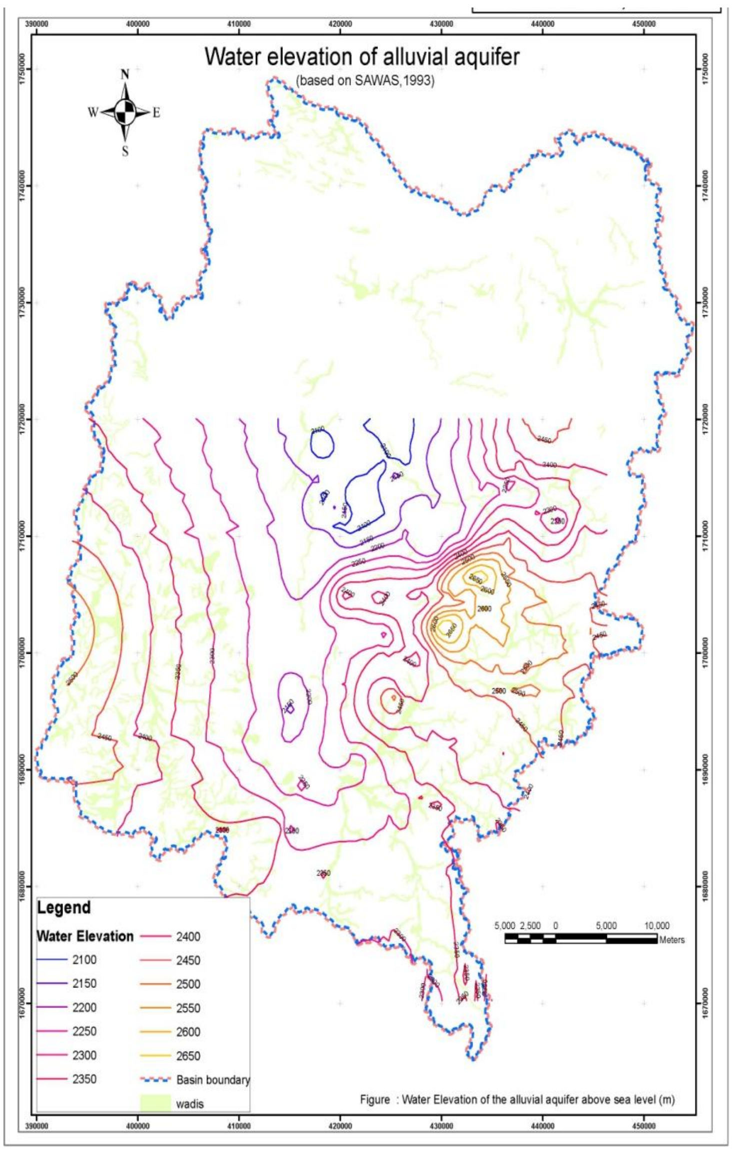

Figure 2-23 Groundwater Elevation Map of the Alluvium Aquifer (based on SAWAS, 1993)

1.11.1.4 Historical Ground Water Elevation Maps of the Tawilah Sandstone Aquifer

One historical groundwater elevation map of the Tawilah Aquifer was constructed by the Hydrosult Inc., 2006 Team.

1.11.1.4.1 Water elevation Map of the Tawilah Aquifer (SAWAS, 1993)

This map was constructed based on water elevation data from the Tawilah Aquifer, which were collected by SAWAS Project team, 1993 (Figure 2.24). The groundwater contour lines are concentrated on the central and eastern parts of the map where the wells tapping the Tawilah Aquifer are located. It is obvious, at this time (1993), that there was no over-exploitation of the groundwater from this aquifer in the southern part of the basin and, hence, no previously documented water level data were available. The main groundwater flow direction is from both eastern and southern parts northward. The highest water elevation value (2375 m amsl) is seen at the south-eastern part of the map, whereas the lowest value (2025 m amsl) is seen at the north-western part of the map. A local depression of the groundwater level is presented around the NWSA western well-field due to over-exploitation of the aquifer. This may also be attributed to the presence of many wells in a restricted area with closed spacing.

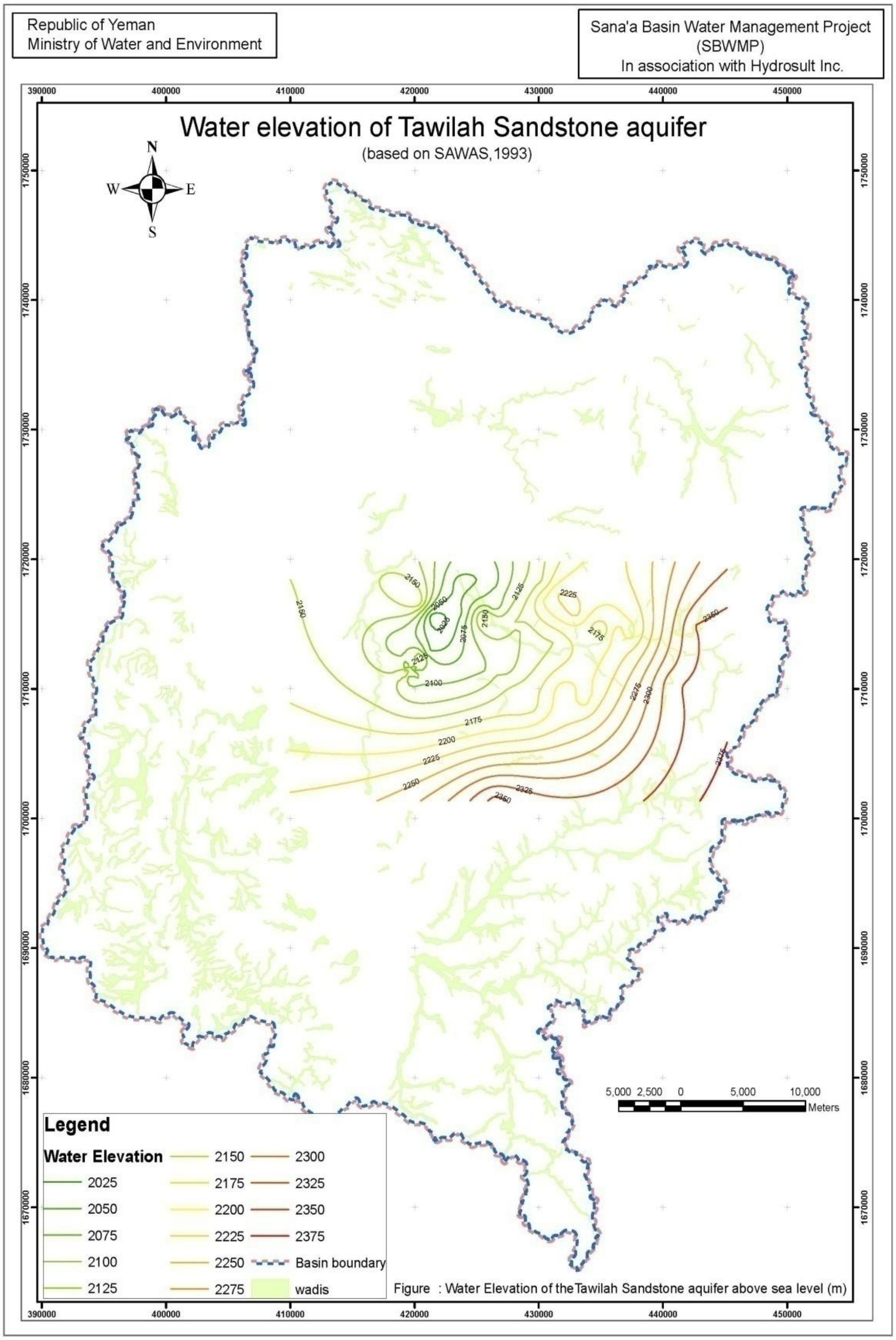

Figure 2-24 Groundwater Elevation Map of the Tawilah Sandstone Aquifer (SAWAS, 1993)

1.11.2 Hydraulic Aquifer Parameters Maps

1.11.2.1 Hydraulic Parameters of the Quaternary Alluvium Aquifer

It was not possible to draw hydraulic parameter maps of the Quaternary Alluvium Aquifer due to lack of sufficient data. According to the 12 pumping tests carried out by Italconsult, 1973, the average Transmissivity value is 31.5 m^2/day. The average permeability from the pumping tests is in the order of 0.5 to 2 m/day. In one borehole Italconsult determined the storativity (SE5; 4.6E-4). It is not clear how the porosities were determined and whether they are effective porosities (Foppen, 1996). It is in hydraulic contact with the underlying units and is assumed to feed the Tawilah Sandstone (SAWAS, 1996).

1.11.2.2 Hydraulic Parameters of the Quaternary Volcanic Aquifer

It was also not possible to draw hydraulic parameter maps of the Quaternary Alluvium Aquifer due to lack of sufficient data. Only in one borehole was a pumping test performed. The average Transmissivity value was 51 m^2/day (Foppen, 1996). They are in some parts in hydraulic contact with the underlying Amran limestone and marls, Tawilah Sandstone, the Tertiary Volcanics and the Alluvium Aquifers.

1.11.2.3 Hydraulic Parameters of the Tertiary Volcanics Aquifer

It was also not possible to draw hydraulic parameter maps of the Quaternary Alluvium Aquifer due to lack of sufficient data. The transmissivity values of this aquifer range from less than 1 m^2/day to 200 m^2/day. Selkhozpromexport gave two average values: one T-value of the basalt in the fault zones and one T-value in fractured zone. The T-value in the fault zone is ten times higher than in fractured zones.

1.11.2.4 Hydraulic Parameters of the Tawilah Sandstone Aquifer

A new Transmissivity map of Tawilah Sandstone Aquifer was constructed by the Hydrosult Inc. (2006) team, based on values of pumping tests collected from previous studies (Italconsult, 1973, Howard Humphry, 1979-1982, NWSA & SWEP 2001 and NWSA 1981-2005) (Figure 2.25). The map shows the average values of transmissivity for the Tawilah Sandstone Aquifer in m^2/day/km^2. The highest average transmissivity value (1300-3378 m^2/day) can be seen in the central part of Sana'a plain, whereas the lowest average value (2-141 m^2/day) can be seen towards the north of Sana'a plain. The highest and lowest values of transmissivity are related to wells that penetrate the maximum and minimum thickness of the Tawilah Sandstone Aquifer respectively. It is important to mention that the transmissivity data (Tawilah Sandstone Aquifer) of the pumping test conducted by Selkhospromexport, 1986 have not been used to re-construct a transmissivity map of the Tawilah Sandstone Aquifer. The main obstacle presented was the unavailability of well coordinates either in UTM or in Degree.

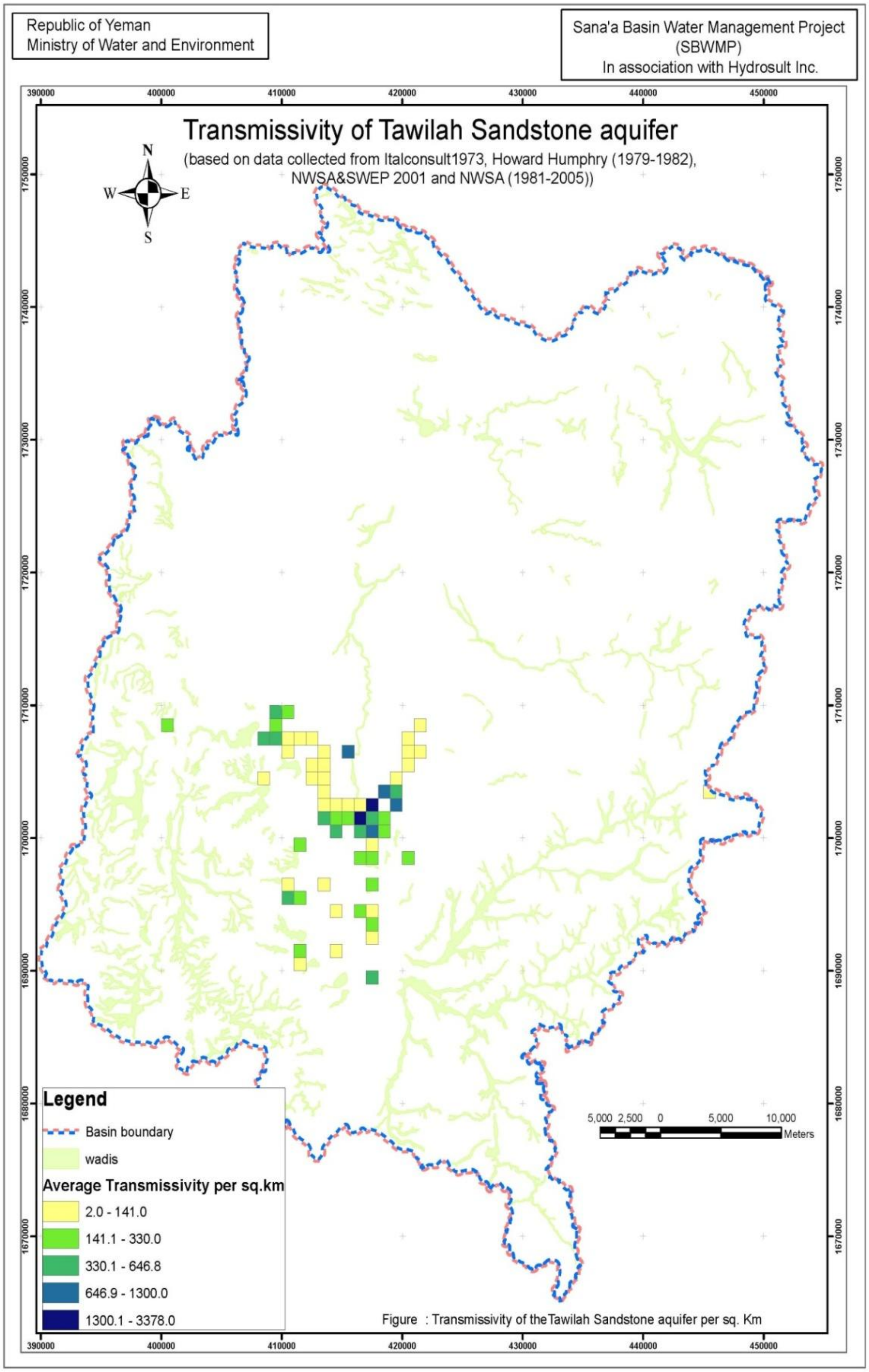
Republic of Yemen
Ministry of Water and Environment
Sana'a Basin Water Management Project
(SBWMP)
In association with Hydrosult Inc.
Transmissivity of Tawilah Sandstone aquifer
(based on data collected from Italconsult1973, Howard Humphry (1979-1982), NWSA&SWEP 2001 and NWSA (1981-2005))
N
W
E
S
Legend
Basin boundary
wadis
Average Transmissivity per sq.km
2.0 - 141.0
141.1 - 330.0
330.1 - 646.8
646.9 - 1300.0
1300.1 - 3378.0
5,000 2,500 0 5,000 10,000
Meters
Figure : Transmissivity of the Tawilah Sandstone aquifer per sq. Km

Figure 2-25 Map showing Transmissivity of the Tawilah Sandstone Aquifer, (Hydrosult2006)

III. IDENTIFICATION OF MAIN INFORMATION GAPS

With the results of all preceding steps at hand, and with a clear view of what the outcomes of Activity 1 should be, it will be easy to identify the main gaps in information. Knowledge of these gaps and assessment of the feasibility of possible actions to fill these gaps will provide guidance on how to focus and/or modify the planned field activities. More details about the results of this step and the preceding one have been presented together in Technical Notes 1 and 2. A brief description of these gaps is presented below:

1.12 Gaps related to Delineation of Aquifer Geometry

The main important gaps identified during the course of review and processing of previous data related to the aquifer geometry can be listed below:

- Verify extent of aquifer system at the outcrops;
- Study variations in aquifer thickness (If data available);
- Collect borehole log data from drilling companies to fill in gaps related to the lower surface of Tawilah Sandstone Aquifer (if data available);
- Construct typical subsurface geological cross-sections in representative sub-basins, especially at the outcrops of Tawilah Sandstone.

1.12.1 Gaps related to Delineation of structural elements controlling regional groundwater flow

The main important gaps identified during the course of reviewing and processing of the previous data which related to the structural elements can be listed below:

- Delineation of the main structural barriers controlling the groundwater flow, such as faults, etc.;
- Delineation of low-permeability units (clay beds, lenses) found between the Cretaceous Tawilah Group;
- Delineation of the rock boundaries all over the basin.

1.12.2 Gaps related to Capacity of the Aquifers

The main important gaps identified during the course of review and processing of the previous data related to the capacity of the aquifer can be listed below:

- Hydraulic continuity across boundaries of the basin (east, west, north and south);
- Nature of the hydraulic continuity between the Tawilah Sandstone Aquifer and the overlying Volcanic and/or Alluvial layers;
- Effective porosity of the Tawilah Sandstone Aquifer;
- Saturated thickness of the aquifers;
- Identifying representative boreholes of appropriate depth etc., to perform pumping tests in order to obtain data on aquifer properties;
- Quantifying the storage of Alluvium and Tawilah Sandstone Aquifers.