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Chapter 4. AQUIFER GEOMETRY IN SANA'A BASIN

EXECUTIVE SUMMARY

The description of groundwater and surface water conditions considers 22 sub-basins which were identified according their surface water drainage system. Aquifers are not restricted to these zones; the aquifers extend even beyond the Sana'a Basin boundary. The zones serve to analyze from which aquifer the population uses groundwater.

The aquifers in the Sana'a Basin are:

- The Kohlan sandstone aquifer: not exploited within Sana'a Basin,
- The Jurassic Amran limestone Aquifer: poor aquifer but exploited from fractures,
- The Cretaceous Tawilah sandstone aquifer: the main aquifer in the Basin,
- The Tertiary Volcanics Aquifer: exploited in weathered zones and fractures,
- The Quaternary Basalt Aquifer: highly productive where containing water,
- The unconsolidated Quaternary Alluvial Deposits Aquifer: poor aquifer but heavily exploited.

The geological map was prepared based on the map prepared from satellite imagery by GAF (2005) and the field work carried out by the project. The map shows the areal extent on the surface of the geological formations. The geometry of the aquifers and structural elements are shown through three regional and twelve local cross-sections (in Nihm, Bani Hushaish, Arhab and Hamdan sub-basins) and one fence diagram.

The depth and thickness of the aquifers was determined using a GIS and these are presented in ten contour maps.

4.1 Surface water system

The general drainage pattern in the Sana'a Basin is ephemeral centripetal (Davison et al 1994). There is significant variation in altitude both east-west and north-south. The highest point in the basin is in the southwest end (Jabal An Nabi Shu'ayb) with an elevation of almost 3700 m amsl. The lowest (about 1900 m amsl) is in the northern extremity where the Wadi Al-Kharid is located. The predominant climate is arid, although semi-arid conditions prevail in localized areas, particularly along the western highlands. Significant local differences, however, are observed within. Such differences are mainly due to the complexity of the geological history of the basin and its location across three different physiographic regions with variable climatic conditions.

On the basis of these differences, the basin was divided into separate hydrological units which, in turn, were divided into several groundwater zones, depending on the effective groundwater source or sources that commonly serve local populations. Within each groundwater zone, major wadi catchment zones were delineated. These are expected to serve as water management zones either individually or through combined zones if necessary (WEC, 2001).

Hydrologically, the Sana'a Basin can be divided into two units, i.e. an upper (northern) unit and a lower (southern) one. These units are referred to as the *Wadi Al-Kharid Hydrological Unit* and the *Musyareka Hydrological Unit*, respectively (WEC, 2001), (Figure 4-1).

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

The general pattern of the surface drainage is along the numerous faults and fracture system, which develop on the exposed limestone formations. However, significant local differences are caused by the presence of uplifted basement and the Amran down-faulted trough along the eastern and western boundaries of the Basin, respectively (WEC, 2001).

The **Musayreka Hydrologic Unit** is on the northeastern edge of the high ground where large flood volcanic provinces developed due to the piling up of thick volcanic flows coupled with enhanced heat flow (Davison et al, 1994). It covers a total area of more than 50% of the Basin approximately, extending across the southern volcanic provinces and the central alluvial plain surrounded by some sandstone outcrops. The watershed areas of this catchment are characterized by a significant contrast in the geological outcrops and climatic conditions which result in important variations in surface characteristics (landform features, soil properties, vegetation cover, rock permeability, etc.), hence the development of local differences in the drainage system. This part of the basin constitutes a hydrologically closed system with an ephemeral centripetal drainage pattern. Runoff water descending along a fairly well developed wadi drainage system of dendritic to trellis pattern (mainly from the southern and eastern watershed zones), sinks into the lowland areas extending from Sana'a City to *Jabal Aş Şama'*. Almost no surface water flows past this east-west mountain, which forms a pronounced structure across the plain, except perhaps during unusually wet conditions when extremely heavy flooding may result in some flow past the west end of this structure (WEC, 2001).

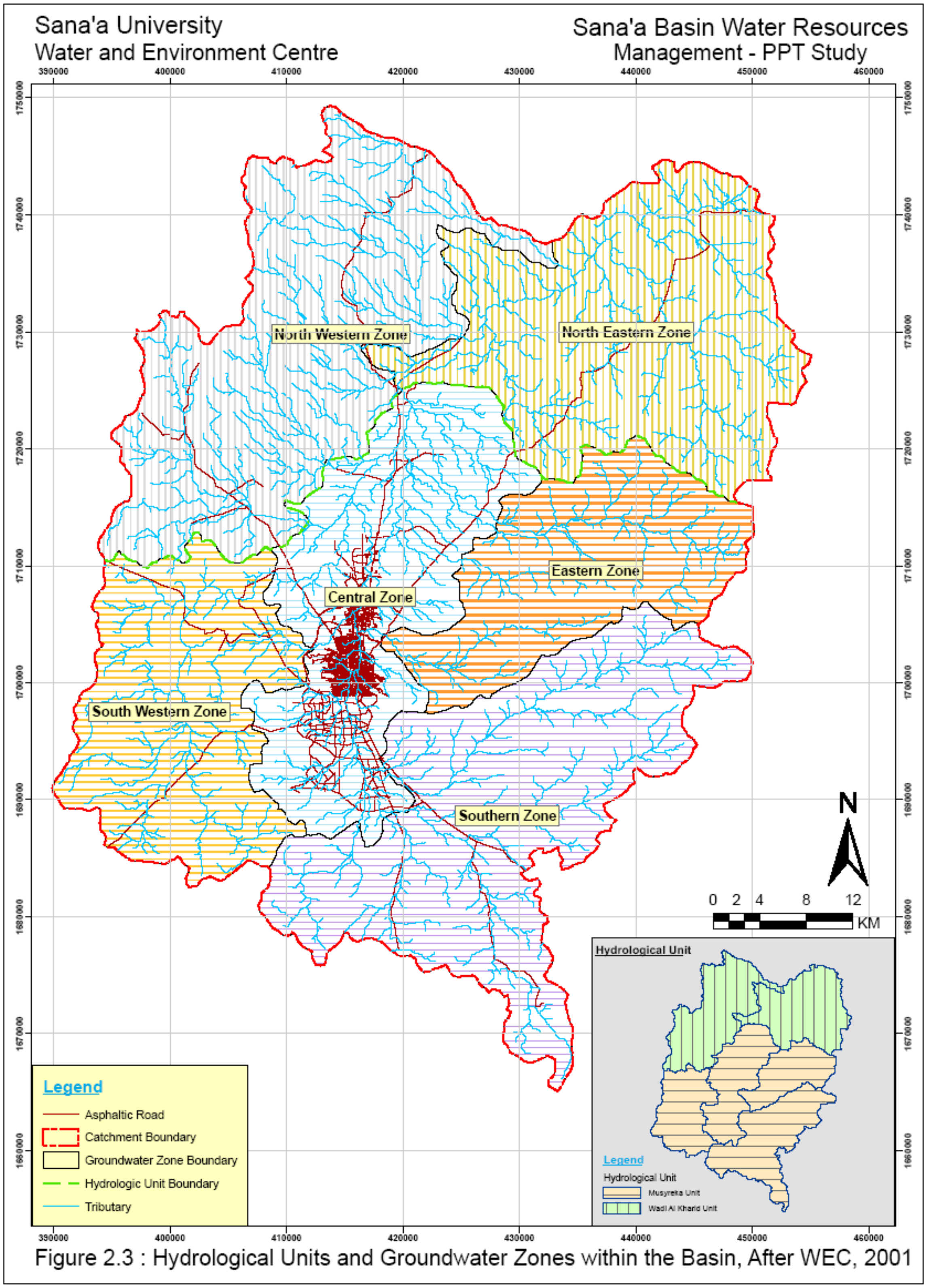

Figure 4-1 Hydrological units and groundwater zones within the Basin (after WEC, 2001)

4.2 Groundwater zones

The occurrence of various aquifer systems throughout the basin signifies differences in groundwater use across the region. Most likely, some of these aquifers extend outside the basin surface boundaries, particularly the regional ones such as the Cretaceous Tawilah sandstones. In theory, groundwater provinces within the basin cannot be delineated without adequate knowledge of the sub-surface configuration of the aquifers. However, it is important to determine which aquifer or aquifers are serving most of the population in any one region. Using this 'common water use' criterion, WEC, 2001 identified six groundwater zones (Figure 4-1): two in Al-Kharid Hydrological Unit (Northwestern and North-eastern) and four in the Musayreka Hydrological Unit (Eastern, Southeastern, Southwestern, and Central) (WEC, 2001). These zones are divided further into 22 sub-basins.

4.3 Sub-catchment (major wadi) boundaries

On the basis of surface water drainage systems and topography, a total of 22 sub-basins have been identified. These are shown in Figure 4-2. While local populations share the groundwater resources in an aquifer system that may extend beyond their wadi boundary, use of surface water flowing in the wadi is fully under local control. Such use, in turn, affects the amount of recharge percolating into the shared groundwater resources (WEC, 2001).

4.4 Use of surface water

Surface water is used for recharge, irrigation and domestic purposes through 44 surface dams, 24 dams/pools and 145 springs within Sana'a Basin. Most of the dams have been built to recharge groundwater. While 15 dams are also used for irrigation, only three dams are used for domestic purpose. The 15 dams, which may be small-scale reservoirs constructed by rural people, are mainly used for irrigation purpose.

Concerning springs, 51 of the 145 springs (35%) are used for irrigation, 43 springs (30%) for animals or livestock, and 49 springs (34%) for domestic water use in rural areas. The total yield from springs is estimated to be 17.2 M m^3 annually. The volume, however, is not likely an actual annual yield amount, because the yield of the spring fluctuates seasonally. One third to one half of the amount, about 6 to 9 M m^3 may be an acceptable figure (JICA, 2007).

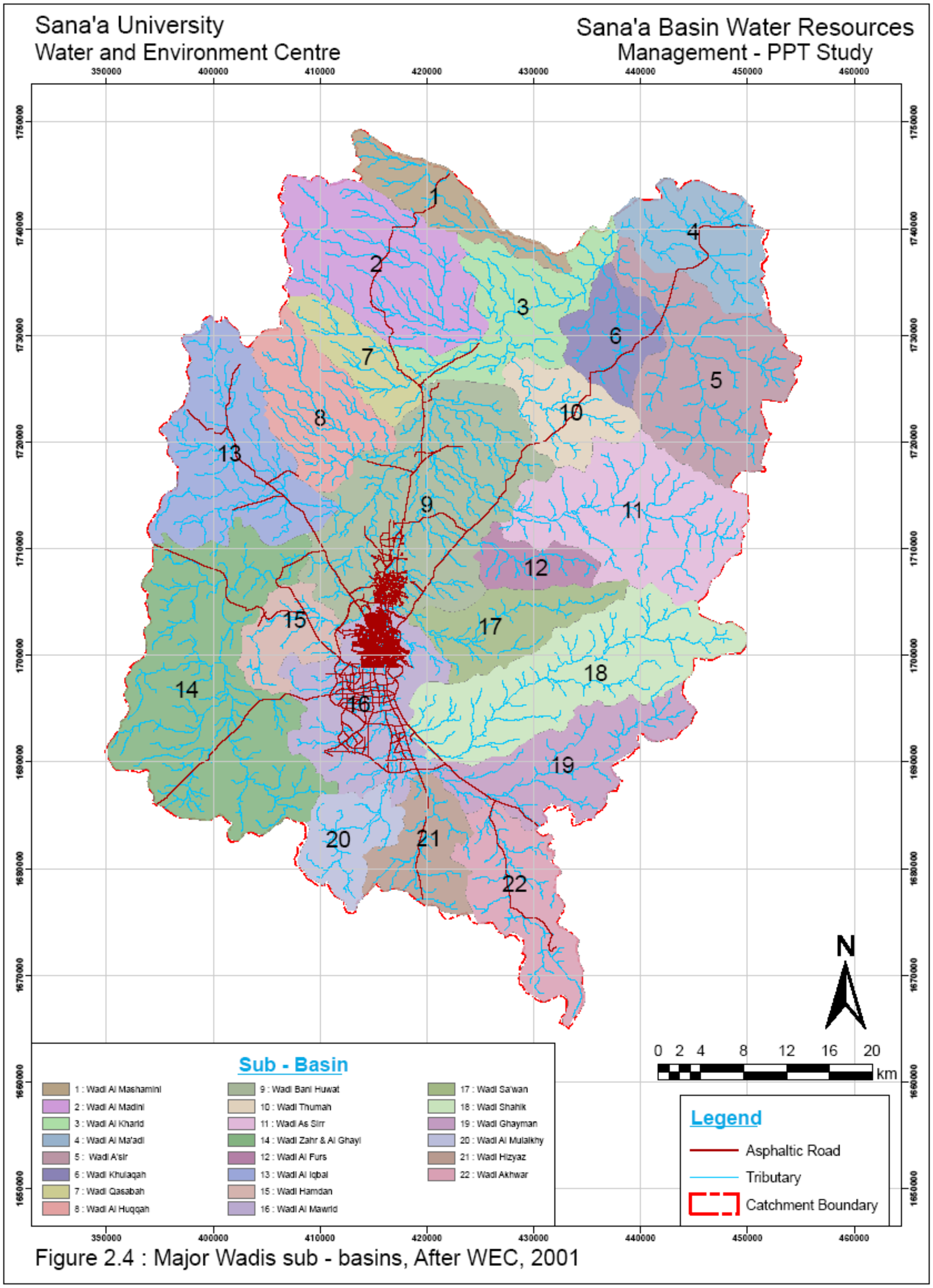

Figure 4-2 Major Wadi sub-basins (after WEC, 2001)

4.5 Hydrogeology

The hydrogeological setting of Sana'a Basin is complex, as it is rare for any single aquifer unit to exist in isolation. Through a combination of existing stratigraphy and structural features, each aquifer is often seen to be in lateral or vertical hydraulic continuity with another (Italconsult, 1973). The geological map (Figure 4-3) shows the spatial distribution of the aquifer system in Sana'a Basin. In the basin, both low and moderate to high productivity aquifers occur given the situation of recharge through rainfall whose annual amount and volume is low, whereas the Wadi-filled alluvial contains shallow, unconfined groundwater. The alluvial-filled area in central Sana'a Basin contains both unconfined and semi-confined aquifers. The main types of aquifers and their characteristics are presented in Table 4-1. The volcanics and the underlying Tawilah sandstone aquifers are deep and confined. The characteristics of the different lithostratigraphic units in Sana's Basin are described in terms of aquifer type, nature and productivity as shown in Table 4-1.

Table 4-1 Aquifers of Sana'a Basin

S. No.	Lithostratigraphic Units	Aquifer Type	Nature	Productivity
1.	Wadi in-filled valley aquifers	Shallow unconfined	Porous but with limited aquifer volume	Highly productive
2.	Quaternary Alluvial	Generally unconfined but locally also semi-confined	Porous	Moderately productive
3.	Tertiary Volcanics / Basaltic Rocks	Semi-confined to confined	Fissured flow dominant	Highly productive in South of Sana'a; generally low to moderately productive
4.	Cretaceous Tawilah sandstone	Confined	Porous and fissured flow	Productive

Table 4-2 Geohydrological characteristics of the lithostratigraphic sequences of Sana'a Basin (Adopted from Italconsult, 1973 by Naaman, 2004)

System	Series	Formation	Geohydrological Units	Description
QUATERNARY	PLEISTOCENE - RECENT	Alluvial	Valley-fill Aquifer	Loose, sandy clay with gravel and boulders. Coarse terrace gravel
		Basalt	Basalt Aquifer	Basalt cones and lava flows
TERTIARY	EOCENE TO MIOCENE	Tertiary Volcanic Group: Chaotic and Stratoid Rocks	Aquitard	Well stratified ignembrites and tuffs with some lava flows. Black basalt and light colored rhyolite. Lava flows chaotically intermingled

<table>
<tr><th>System</th><th>Series</th><th colspan="2">Formation</th><th>Geohydrological Units</th><th>Description</th></tr>
<tr><td rowspan="3"></td><td rowspan="2"></td><td rowspan="2"></td><td>Stratoid Rocks</td><td>Aquitard</td><td>Well stratified tan, red and green ignembrites and tuffs with interbedded fluvio-lacustrine layers</td></tr>
<tr><td>Basal Basalt</td><td>Trap basal basalt Aquitard</td><td>Greenish black basalt with a few trachyte lenses. Frequent quartz geodes in some horizons</td></tr>
<tr><td>Paleocene</td><td rowspan="2">Tawilah Group</td><td>MEDJ-ZIR</td><td rowspan="2">Cretaceous sandstone aquifer</td><td>Tan to reddish fine-grained sandstone with inter-bedded siltstone clay and weathered volcanic tuffs, Basalt dykes</td></tr>
<tr><td rowspan="2">CRETACEOUS</td><td rowspan="2">Lower to Upper</td><td>AL-GHIRAS</td><td>Tan to reddish fine to coarse-grained sandstone with inter-bedded siltstone and ironstone Basalt dykes</td></tr>
<tr><td colspan="2">UNNAMED</td><td></td><td>Grey clay and shale with fine-grained sandstone beds, lignite layers and gypsum lenses
Black pyretic shale and limestone Basalt dykes</td></tr>
<tr><td rowspan="2">JURASSIC</td><td>MIDDLE TO UPPER</td><td colspan="2">AMRAN</td><td>Amran limestone Aquitard</td><td>Grey to tan fossiliferous limestone and calcareous shale, basalt dykes</td></tr>
<tr><td>LIAS</td><td colspan="2">KOHLAN</td><td>Kohlan sandstone aquifer</td><td>Sandstone and Sahle</td></tr>
</table>

A brief description of the aquifers in Sana'a Basin is given below.

4.5.1 Kohlan sandstone aquifer

This group is the oldest sedimentary unit in Sana'a Basin. It consists of green shale with sandstone and conglomerate bands in the lower parts and sandstone and conglomerates in the upper parts, (Naaman, 2004). It is exposed at Jabal Salab in the Nihm area and recorded in the Sana'a Basin from sub-surface data only such as in Arhab and Al-Hatarish deep wells. It has a maximum thickness of about 45-50 m (Kruseman and Vasak, 1996). The age of this rock unit is wide-ranging, from Lower to Middle Jurassic (Beydoun, 1982, Diggens, et al, 1988).

This aquifer has not been exploited in the Sana'a region and its potential in terms of distribution, possible yield, quantity of water in storage and quality of water is unknown. A pump test in the sandstone borehole DS1 of SAWAS, 1996 indicated a permeability and porosity comparable to the Tawilah sandstone aquifer.

Towards the north and north-west, there are indications of good groundwater potential for the Kohlan group, which gives rise to a number of high-yield springs (Italconsult, 1970). In the Al-Ghiras and Bani Jermouz areas, the Kohlan sandstones group could be reached at a depth of about 500-700 m according to information obtained through formal interview with local people in those particular areas.

4.5.2 Jurassic Amran limestone aquifer

It is generally considered to be a poor aquifer, although supplies can be obtained from zones of secondary permeability. Karst features, however, are poorly developed. The depth to water is over 100 m in the plateau area in the northwest of the basin and groundwater is abstracted mainly by means of dug wells. The unnamed formation is believed to act as an aquiclude although the regional permeability may be similar to the Amran limestones (WEC, 2001). From information collected to the north of the Sana'a Basin, the formation may be water-bearing due to fracturing. However, data presently available generally indicate poor water-bearing properties (Italconsult, 1970).

4.5.3 Cretaceous Tawilah sandstone aquifer

It forms the main aquifer in the region. It has low regional permeability but, locally, higher permeabilities are found in weathered and fractured zones. It is heavily exploited to the northeast and northwest of Sana'a where it either outcrops or occurs beneath an unconsolidated cover of up to 50 m thickness. In the south of the basin, the sandstone is confined beneath several hundreds of meters of Tertiary volcanics (WEC, 2001).

The Tawilah group constitutes the most important groundwater reservoir so far discovered in Sana'a Basin. The considerable lateral extension and its notable thickness mean that the water-bearing volume is large. In addition, favorable hydraulic characteristics ensure that the group becomes the main groundwater collector in the basin.

4.5.4 Tertiary volcanic aquifer

The basalt flows and stratoid sequences of the Tertiary volcanics act as aquicludes, except where fractured or where primary permeability occurs in sediments between flows. The mixed basalt and rhyolite flows at the top of the sequence are more highly fractured and contain perched aquifers which supply dug wells and feed high level springs. The upper layers of the volcanics are highly weathered and relatively permeable where they underlie the unconsolidated Quaternary deposits in the south of the basin. Here, they are exploited together with the unconsolidated aquifer by dug and drilled wells (WEC, 2001).

4.5.5 Quaternary basalt aquifer

The Quaternary basalts are highly permeable due to fracturing and to the presence of clastic deposits between flows. Where the formation is saturated, it provides an unconfined aquifer.

4.5.6 Unconsolidated Quaternary alluvial deposits aquifer

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

The hydraulic parameters of the Quaternary alluvial aquifer vary considerably depending on their fine-grained particle content. Italconsult, 1973, and Howard Humphreys, 1983 reported that these Quaternary deposits of the Sana'a plain are generally considered to be a poor aquifer, and tend to have transmissivity values in the order of 100 m^2/d. The reported permeability is 0.9 m/d, which is indicative, according to Freeze and Cherry, 1979, of silty sand moderate permeability aquifer material. Other values of permeability for each horizon within the aquifer were given by Mosgiprovodkhoz, 1986. For the clean, coarse-grained (gravelly) horizons within the aquifer, permeability varies from 10 to 35 m/day, for "dirty" coarse-grained horizons that are filled with silt and clay, it is 1.1 m/day and, for the sandy loam horizons, the value is 0.7 m/d. The suggested average transmissivity for this aquifer was 35 m^2/d (range from 3.6 to 82 m^2/d) (Mosgiprovodkhoz, 1986). The average hydraulic conductivity is in the order of 0.5 to 2 m/day. The specific yield is in the order of 0.01 (SAWAS TR-05). In spite of their large extent and volume, their high clay content and lack of thick sand layers make them poorly productive and not suitable for large-scale exploration (Howard Humphrey, 1983).

The porosity also varies, depending upon the material within the horizon. Porosity for the sandy gravel deposits varies from 11.6-24.7%, for sandy loams 44-48%, and the average porosity for loam is 47%. The average specific yield was reported as 2% by Mosgiprovodkhoz, 1986, whereas, in the southern part of Sana'a plain, from the water balance and change in storage, the SAWAS team estimated it to be 1%. Results from a pumping test in the southern part of the plain, SE-5, gave a storage coefficient of 4.1×10^{-4}, which indicates semi-confined conditions due to the fine-grained nature of the deposits (Italconsult, 1973).

4.6 Aquifer geometry

Several hydrogeological studies were carried out in Sana'a Basin (Italconsult, 1973, Mosgiprovodkhoz, 1986, SAWAS, 1996 and WEC, 2001), but no comprehensive study until now has investigated the lithostratigraphic units (aquifers) to delineate their geometry in the Basin.

In the present study, the delineation of aquifer geometry in Sana'a Basin involves the study and identification of the different lithostratigraphic units, their areal extent, top and bottom of these units above mean sea level, their thickness, lateral boundaries and the main geological structures controlling the groundwater flow.

The geology and geometry of rocks and sediments control the behavior of groundwater. The aquifer geometry mainly involves surface geological mapping of the aquifers, which requires a search for:

- Delineation and definition of aquifer units,
- Lateral extent (spatial distribution of the aquifer rock units),
- Sub-surface geological cross-sections.

The incorporation of geophysical data and well logs is very important in order to determine:

- Aquifer depth from the ground surface
- Aquifer thickness
- Top and bottom surfaces of the aquifers with respect to the mean sea level.

4.6.1 Areal distribution of the lithostratigraphic units

Based on identification of the main information gaps related to the surface extent and distribution of the different lithostratigraphic units (aquifers) in Sana'a Basin, intense geological fieldwork was carried out in order to bridge these gaps. As mentioned in chapter 3, the total number of ground-truthing stations (GPS points) used to delineate surface distribution as well as structural features are 855 points. Of these, 181 points are within the Nihm area, 82 points in the Bani Hushaish and 592 points in the Hamdan area and the rest of the basin. These GPS points have been plotted on topographical, geological and satellite image maps for the purpose of comparison and to ensure reliable results. Based on these data, the recent geological map of Sana'a Basin (Figure 4-3) was prepared by Hydrosult, 2007 (modified after GAF, 2005).

The new geological map indicates that the Quaternary alluvial unit has less areal extent, whereas the Quaternary, Tertiary volcanics, Cretaceous Tawilah sandstone group and the Jurassic Amran limestone group have more areal distribution than that which was reflected by the geological map compiled by GAF, 2005. The areal distribution of each lithostratigraphic unit was calculated with the help of GIS software and is presented in Table 4-3.

Table 4-3 Surface area calculated for each aquifer based on the geological maps of GAF, 2005 and Hydrosult, 2007

GAF (2005)			**Hydrosult (2007)**		
Lithostratigraphic Units	**Area (km^2)**	**% of Area**	**Lithostratigraphic Units**	**Area (km^2)**	**% of Area**
Quaternary Alluvial	661.22	20.43	Quaternary Alluvial	504.9588	15.6
Quaternary and Tertiary Volcanics	1883.7	58.199	Quaternary Volcanics	56.54583	1.7
			Tertiary Volcanics	1867.779	57.7
Cretaceous Tawilah sandstone	248.33	7.67	Cretaceous Tawilah sandstone	270.9687	8.4
Jurassic Amran limestone	443.42	13.7	Jurassic Amran limestone	536.7322	16.6
Total Area of Sana'a Basin	3236.67	100	Total Area of Sana'a Basin	3236.985	100

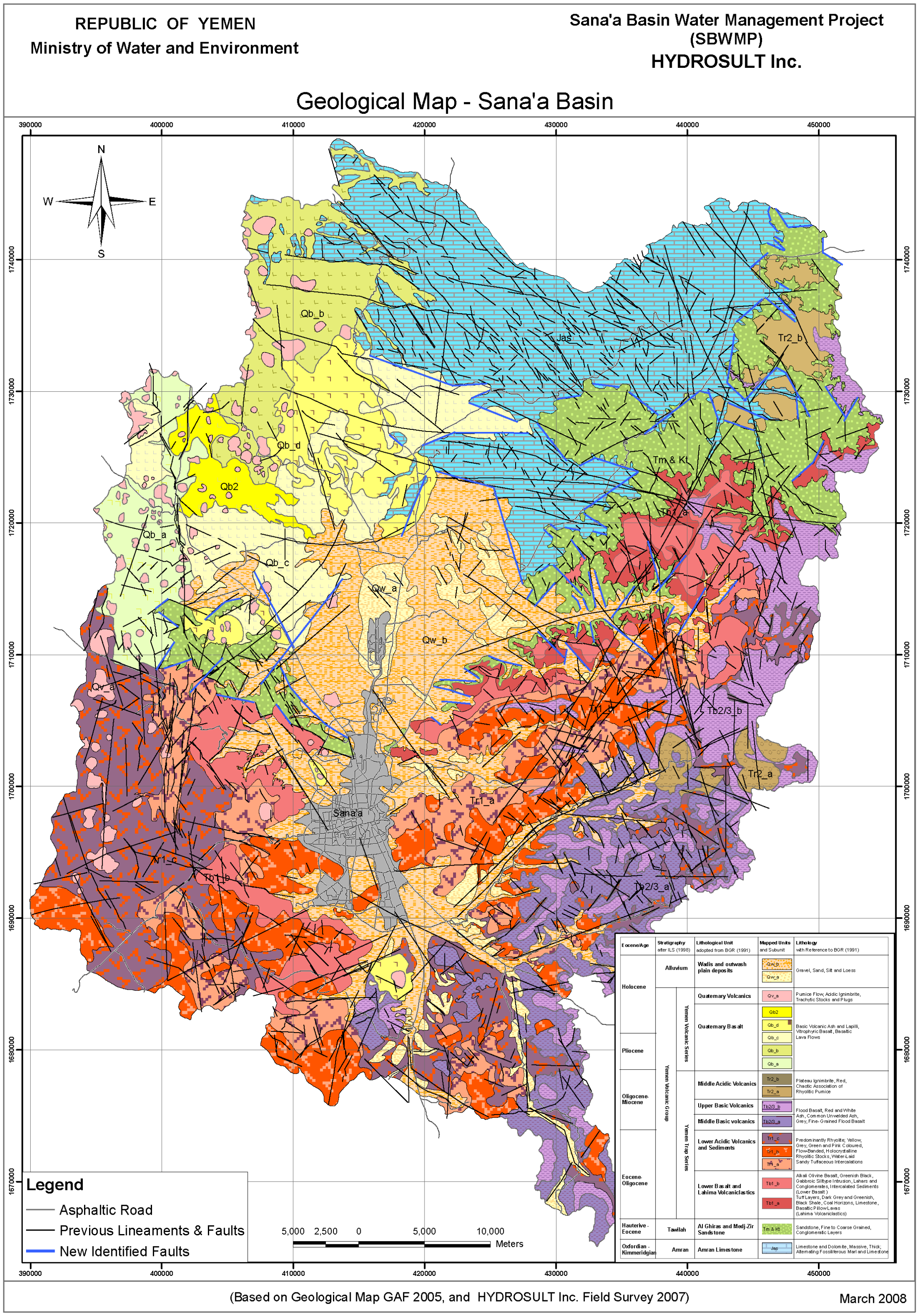

Figure 4-3 Geological map of Sana’a Basin (after GAF, 2005)

4.6.2 Regional sub-surface geological cross-sections

Three sub-surface geological cross-sections were modified and updated after (Mosgiprovodkhoz, 1986). The modifications include the utilization of new drill logs, geophysical seismic data and correlation with the top and bottom boundaries of the different lithostratigraphic units. One of these cross-sections has a north-south direction whereas the other two have east-west directions. The locations of these sub-surface geological cross-sections are shown in the geological map (Figure 4-4). A summary of these cross-sections is given in Table 4-4.

Table 4-4 Summary Information related to the regional sub-surface geological cross-sections

No.	Name of cross-section	Location	Direction	No. of wells covered	Aquifers encountered through the cross-section	Geological structures
1	A-A'	Sana'a Basin	North-South	42	Quaternary alluvial Tertiary volcanic Cretaceous Tawilah sandstone Unnamed formation (Shale) Jurassic Amran limestone	Five normal faults are encountered forming graben and horst structures
2	B-B'	Sana'a Basin	East-West	20	Quaternary alluvial Tertiary volcanics Cretaceous Tawilah sandstone Unnamed formation (Shale) Jurassic Amran limestone	Five normal faults are encountered forming graben and horst structures
3	C-C'	Sana'a Basin	North-South	22	Quaternary alluvial Tertiary volcanics Cretaceous Tawilah sandstone Unnamed formation (Shale) Jurassic Amran limestone	Two normal faults are encountered forming a graben structure

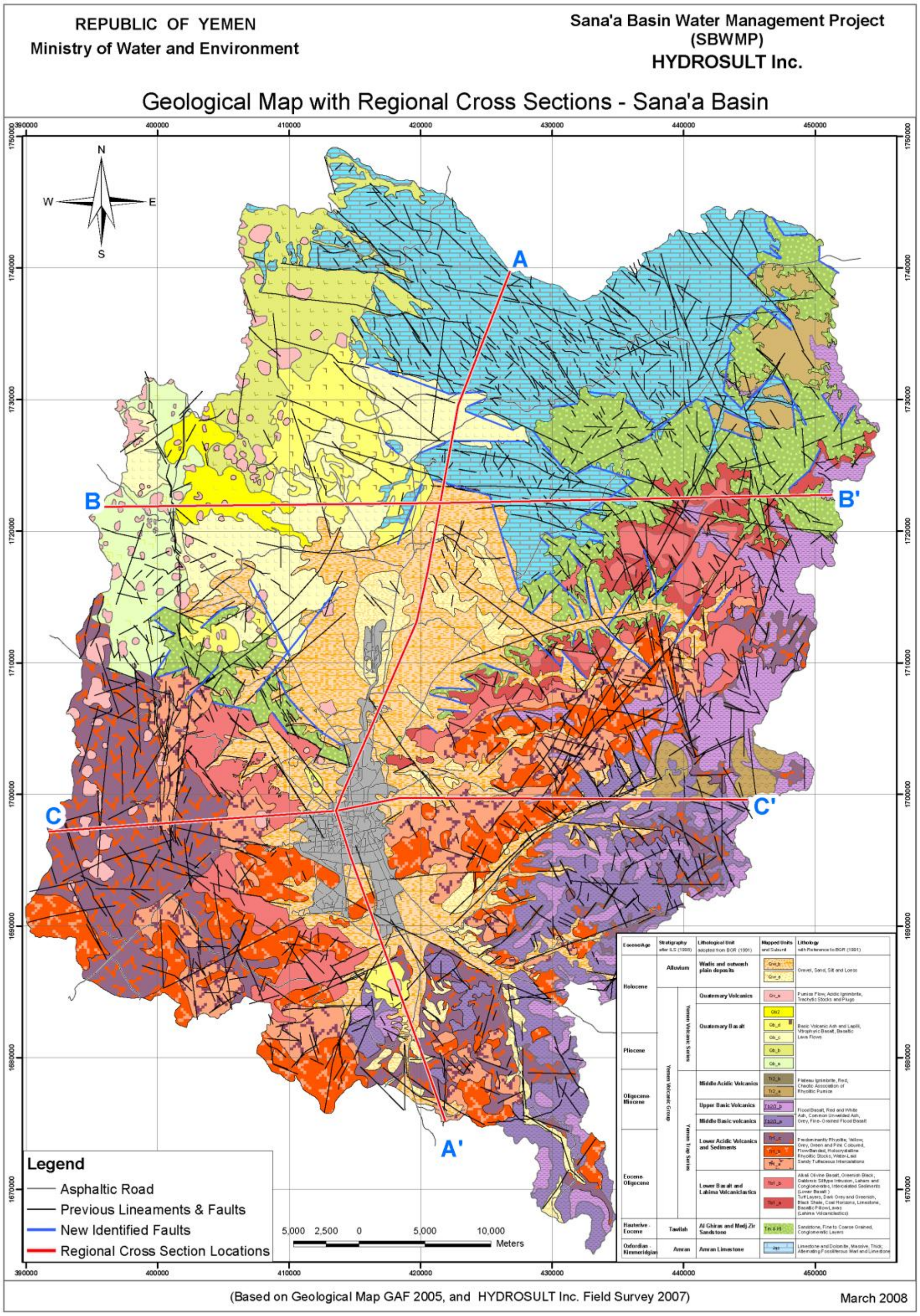

Figure 4-4 Geological map of Sana’a Basin showing location of regional geological cross-sections

4.6.3 Regional sub-surface geological cross-section A-A' (N-S)

This cross-section was first constructed by Mosgiprovodkhoz, 1986 and recently modified and updated by Hydrosult, 2007 based on new data of well lithology and geophysical seismic data (EXXON, 1986 and WEC, 2001). The lithological data of forty-two wells was used to update this cross-section. These data were used to modify and confirm the extent of the different lithostratigraphic units, vertically as well as horizontally. Data related to these wells are presented in Table 4-5. The cross-section extends from north (Arhab) to south (Jabal Jada) of Sana'a Basin (Figure 4-5). It provides a regional picture of the sub-surface extent of the lithostratigraphic units. It is clear from this cross-section that Jurassic Amran limestone is present at the base, followed by Cretaceous Tawilah sandstone. The unnamed formation (shale) is present as a sandwich between the two lithostratigraphic units mentioned above. The Cretaceous Tawilah sandstone is overlain by Tertiary volcanics. The Quaternary alluvial is present at ground surface. Five normal faults are encountered across this cross-section. These faults have a more or less east-west directions. One horst (Jabal As-Sama) and two graben structures were detected along the section. The two grabens are located to the north and south of the Jabal As-Sama horst structure. It is clear from this cross-section that the Quaternary alluvial attains its maximum thickness at Sana'a airport. In this particular location, the Quaternary alluvial overlays unconformably the Jurassic Amran limestone. The data of well lithology (A-1837, A-1923, A-2046, C-2363, C-2287 and C-22223) have confirmed that the Cretaceous Tawilah sandstone has been completely eroded and that the Quaternary alluvial was deposited unconformably overlaying the Jurassic Amran limestone.

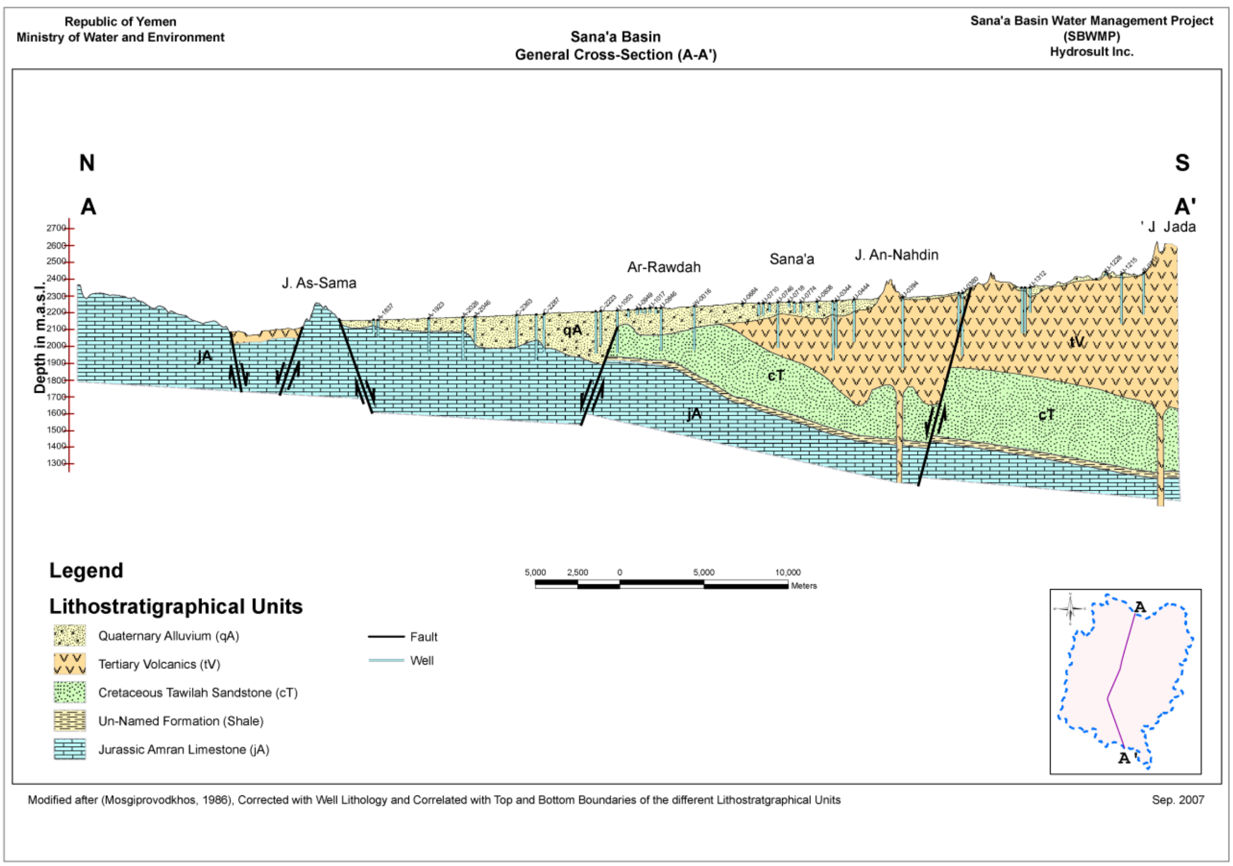

Figure 4-5 Regional sub-surface geological cross-section A-A' across Sana'a Basin

Table 4-5 Well data of the regional geological cross-section A-A'

W-ID	UTM-N	UTM-E	Well Type	DEM Altitude	No. Layers	TD (m)	Layer 1		Layer 2		Water Level
							Thickness (m)	Lithology	Thickness (m)	Lithology	
F-2042	1729481.0	423857.0	Dug	2067	2	37.00	2.0	Alluvial	35.0	Limestone	19.00
F-2045	1729007.0	423887.0	Dug	2082	2	20.00	10.0	Alluvial	10.0	Limestone	15.00
A-1835	1722311.0	421824.0	dug/bor	2152	2	80.00	34.0	Alluvial	46.0	Limestone	0.00
A-1923	1719035.0	420877.0	Bor	2163	2	210.00	80.0	Alluvial	30.0	Limestone	119.00
A-2026	1717016.0	420484.0	Bor	2170	2	250.00	80.0	Alluvial	170.0	Volcanic	0.00
A-2046	1716299.0	420409.0	Bor	2174	1	150.00	150.0	Alluvial	0.0	-	70.00
C-2363	1713823.0	419843.0	dug/bor	2182	2	200.00	190.0	Alluvial	10.0	Limestone	0.00
C-2345	1712651.0	419498.0	Bor	2186	2	275.00	150.0	Alluvial	125.0	Limestone	0.00
C-2287	1712204.0	419212.0	Bor	2188	2	230.00	200.0	Alluvial	30.0	Limestone	0.00
C-2272	1709104.0	417867.0	Bor	2204	1	250.00	250.0	Alluvial	0.0	-	0.00
C-2223	1708837.0	417958.0	Bor	2207	1	200.00	200.0	Alluvial	0.0	-	0.00
U-1053	1707844.0	417423.0	Bor	2208	2	250.00	100.0	Alluvial	150.0	Sandstone	0.00
U-1036	1707197.0	417177.0	Dug	2213	1	45.00	45.0	Alluvial	0.0	-	30.00
U-0949	1706671.0	416893.0	Dug	2216	1	31.00	31.0	Alluvial	0.0	-	28.00
U-1041	1706456.0	416729.0	Dug	2218	1	25.00	25.0	Alluvial	0.0	-	0.00

W-ID	UTM-N	UTM-E	Well Type	DEM Altitude	No. Layers	TD (m)	Layer 1 Thickness (m)	Layer 1 Lithology	Layer 2 Thickness (m)	Layer 2 Lithology	Water Level
U-0961	1706213.0	416775.0	Dug	2221	1	30.00	30.0	Alluvial	0.0	-	22.00
U-1017	1705912.0	416540.0	Dug	2222	1	25.00	25.0	Alluvial	0.0	-	21.00
U-0858	1705548.0	416432.0	Dug	2223	1	30.00	30.0	Alluvial	0.0	-	0.00
W-0016	1703280.0	415341.0	Bor	2234	2	260.00	125.0	Alluvial	135.0	Sandstone	155.00
U-0684	1700424.0	414183.0	Dug	2249	1	9.50	9.5	Alluvial	0.0	-	8.00
U-0692	1699441.0	413863.0	Dug	2252	1	70.00	70.0	Alluvial	0.0	-	0.00
U-0710	1699169.0	413768.0	Dug	2252	1	70.00	70.0	Alluvial	0.0	-	0.00
U-0820	1698796.0	413401.0	Dug	2257	1	50.00	50.0	Alluvial	0.0	-	37.00
U-0746	1698302.0	413648.0	Bor	2257	2	270.00	70.0	Alluvial	200.0	Volcanic	0.00
U-0718	1697658.0	413871.0	Dug	2260	1	30.00	30.0	Alluvial	0.0	-	0.00
U-0774	1696946.0	414121.0	Dug	2257	1	60.00	60.0	Alluvial	0.0	-	50.00
U-0808	1695988.0	414391.0	Dug	2263	1	66.00	66.0	Alluvial	0.0	-	0.00
U-0347	1695029.0	414711.0	Bor	2267	2	350.00	80.0	Alluvial	270.0	Volcanics	0.00
U-0344	1694844.0	414817.0	Bor	2267	2	280.00	90.0	Alluvial	190.0	Volcanic	115.00
U-0444	1693785.0	415105.0	Bor	2275	2	250.00	70.0	Alluvial	180.0	Volcanic	0.00
U-0394	1690893.0	416138.0	Bor	2292	2	420.00	10.0	Alluvial	410.0	Volcanic	0.00

W-ID	UTM-N	UTM-E	Well Type	DEM Altitude	No. Layers	TD (m)	Layer 1		Layer 2		Water Level
							Thickness (m)	Lithology	Thickness (m)	Lithology	
U-0378	1687554.0	417413.0	Bor	2315	2	250.00	10.0	Alluvial	240.0	Volcanic	0.00
U-0380	1687350.0	417588.0	Bor	2318	2	370.00	30.0	Alluvial	340.0	Volcanic	0.00
U-1310	1683797.0	418760.0	Bor	2345	2	270.00	20.0	Alluvial	250.0	Volcanic	0.00
U-1311	1683621.0	418932.0	Bor	2344	2	270.00	20.0	Alluvial	250.0	Volcanic	0.00
U-1312	1683324.0	418953.0	Bor	2348	2	150.00	60.0	Alluvial	90.0	Volcanic	0.00
U-1215	1677890.0	420917.0	Bor	2424	2	300.00	6.0	Alluvial	294.0	Volcanic	0.00
B-0715	1676587.0	421350.0	Bor	2439	2	250.00	6.0	Alluvial	244.0	Volcanic	0.00
U-0846	1705254.0	416279.0	Bor	2224	2	250.00	160.0	Alluvial	90	Sandstone	
U-1238	1679392.0	420441.0	Dug	2396	1	5.00	5.0	Alluvial	-	-	
U-0768	1697307.0	413968.0	Dug	2256	1	60.00	60.0	Alluvial	-	-	
U-1228	1678822.0	420659.0	Dug	2460	2	25.00	11.0	Alluvial	14.0	Volcanic	

4.6.4 Regional sub-surface geological cross-section B-B' (W-E)

This cross-section was first constructed by Mosgiprovodkhoz, 1986 and was recently modified and updated by Hydrosult, 2007 based on new data of well lithology and geophysical seismic data (EXXON, 1987, WEC, 2001). The lithological data of twenty wells was used to update this cross-section to modify and confirm the extent of the different lithostratigraphic units, vertically as well as horizontally. Data related to these wells are presented in Table 4-6. The cross-section extends from the west (Jabal Al-Hamra region) to the east (Jabal Al-Qarb) of Sana'a Basin (Figure 4-6). It provides a regional picture of the sub-surface extent of the different lithostratigraphic units. It is clear from this cross-section that the Jurassic Amran limestone is present at the base, followed by the Cretaceous Tawilah sandstone in the eastern part of this section. The unnamed formation (shale) is sandwiched between the two lithostratigraphic units mentioned above. The Tertiary volcanic is outcropped in the eastern and western parts of this cross-section conformably overlying the Cretaceous Tawilah sandstone in the east and unconformably the Jurassic Amran limestone in the west. The Quaternary alluvial is present at the surface in the central part of this cross-section. Five normal faults are encountered along this cross-section forming two horst and two graben structures. These faults lie in more or less north-south directions. It is clear from this cross-section that the Quaternary alluvial attains its maximum thickness at the Sana'a airport. In this particular area, the Quaternary alluvial overlays unconformably the Jurassic Amran limestone. The data of well lithology (A-1824, A-1833, A-1836, C-1479 and C-1411) have confirmed that the Cretaceous Tawilah sandstone has been completely eroded in this particular location and that the Quaternary alluvial was deposited unconformably overlaying the Jurassic Amran limestone.

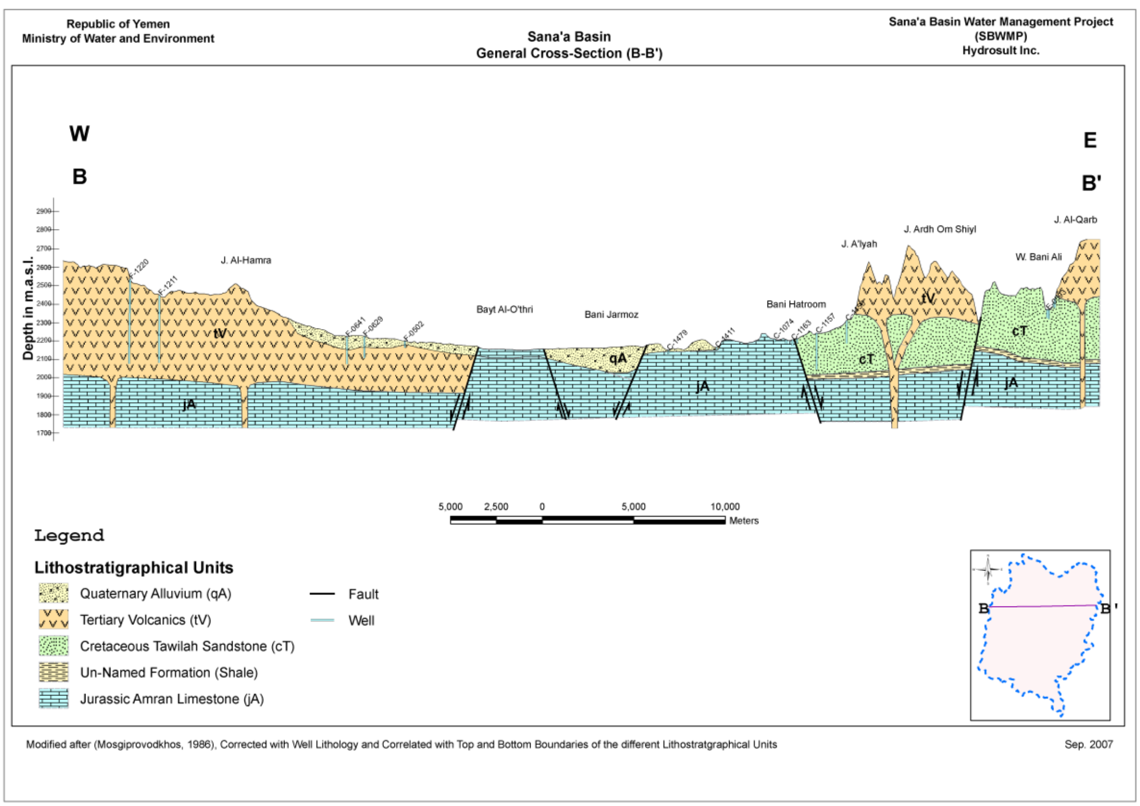

Figure 4-6 Regional sub-surface geological cross-section B-B' across Sana'a Basin

Table 4-6 Well data of the regional geological cross-section B-B'

W-ID	UTM-N	UTM-E	Well Type	DEM Altitude	TD (m)	No. Layers	Layer 1		Layer 2		Water Level
							Thickness (m)	Lithology	Thickness (m)	Lithology	
F-1220	1722093.0	399301.0	Bor	2515	460.00	1	460.0	Volcanic	0.0	-	0.00
F-1211	1721843.0	400958.0	Bor	2441	370.00	1	370.0	Volcanic	0.0	-	318.00
F-0629	1721920.0	412152.0	Bor	2222	120.00	2	60.0	Alluvial	60.0	Volcanic	0.00
F-0502	1722088.0	414369.0	Dug	2197	35.00	2	18.0	Alluvial	17.0	Volcanic	0.00
A-1824	1722086.0	420136.0	Dug	2149	47.50	2	45.0	Alluvial	2.0	Limestone	45.00
A-1833	1722225.0	420807.0	dug/bor	2150	140.00	2	40.0	Alluvial	100.0	Limestone	104.00
C-1479	1722084.0	428728.0	Dug	2154	21.30	2	5.4	Alluvial	15.9	Limestone	17.00
C-1411	1722309.0	431367.0	Dug	2161	12.00	1	12.0	Alluvial	0.0	-	0.00
C-1074	1722469.0	434524.0	Dug	2200	17.00	2	4.0	Alluvial	13.0	Limestone	16.00
C-1085	1722433.0	435159.0	Dug	2200	22.00	2	3.0	Alluvial	19.0	Limestone	16.00
C-1163	1722481.0	435509.0	Dug	2205	34.00	2	2.0	Alluvial	32.0	Limestone	33.00
C-1159	1722510.0	435759.0	Dug	2213	21.85	1	21.9	Sandstone	0.0	-	19.00
C-1157	1722405.0	436825.0	Bor	2229	200.00	1	200.0	Sandstone	0.0	-	27.00
C-1150	1722482.0	438450.0	Bor	2301	120.00	1	120.0	Sandstone	0.0	-	0.00
E-0593	1722680.0	449401.0	Dug	2349	29.00	2	2.0	Alluvial	27.0	Sandstone	16.00

W-ID	UTM-N	UTM-E	Well Type	DEM Altitude	TD (m)	No. Layers	Layer 1		Layer 2		Water Level
							Thickness (m)	Lithology	Thickness (m)	Lithology	
F-0641	1722012.0	411196.0	Bor	2221.0	150.0	2.0	70.0	Alluvial	80.0	Volcanic	-
A-1836	1722049.0	421773.0	Bor	2153.0	250.0	2.0	45.0	Alluvial	205.0	Limestone	-
E-0590	1722742.0	449494.0	Dug	2357.0	42.0	2.0	3.0	Alluvial	39.0	Sandstone	-
E-0588	1722744.0	449780.0	Dug	2398.0	9.0	1.0	9.0	Sandstone	-	-	-
E-0589	1722754.0	449832.0	Dug	2436.0	10.0	1.0	10.0	Sandstone	-	-	-

4.6.5 Regional sub-surface geological cross-section C-C' (W-E)

This cross-section was first constructed by (Mosgiprovodkhoz, 1986) and recently modified and updated by Hydrosult, 2007 based on new data of well lithology and geophysical seismic data (EXXON, 1987 and WEC, 2001). Along this cross-section, the lithological data of twenty-two wells was used to modify and confirm the extent of the different lithostratigraphic units, vertically as well as horizontally. Data related to these wells are presented in Table 4-7. The cross-section extends from west (Raishan) to east (Jabal Allwz) of Sana'a Basin (Figure 4-7). It provides a regional picture of the sub-surface extent of the different lithostratigraphic units. It is clear from this cross-section that the Jurassic Amran limestone is present at the base, followed by the Cretaceous Tawilah sandstone. The unnamed formation (shale) is sandwiched between the two lithostratigraphic units mentioned above. The Cretaceous Tawilah sandstone is overlain by Tertiary volcanics which outcrop at ground surface in eastern and western parts of this cross-section. The Quaternary alluvial is present at the surface in the central part of this cross-section. Two normal faults are encountered along this cross-section, forming a graben structure. These two faults have more or less north-south directions. It is clear from this cross-section that the Quaternary alluvial attains its maximum thickness at the central part, which is affected by the graben structure.

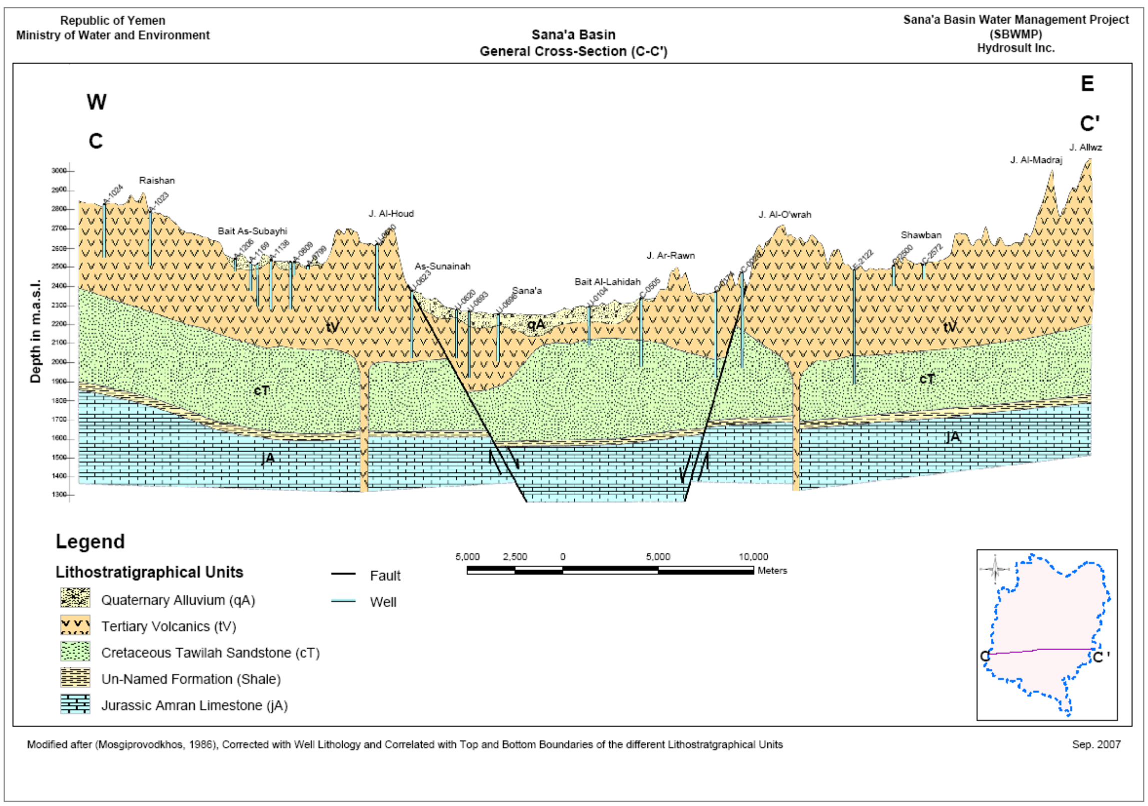

Figure 4-7 Regional sub-surface geological cross-section C-C' across Sana'a Basin

Table 4-7 Well data of the regional geological cross-section C-C'

W-ID	UTM-N	UTM-E	Well type	DEM altitude	TD (m)	No. Layers	Layer 1		Layer 2		Layer 3		Water Level
							Thickness (m)	Lithology	Thickness (m)	Lithology	Thickness (m)	Lithology	
A-1024	1696705.0	393087.0	Bor	2826	280.00	2	2.0	Alluvial	278.0	Volcanic	0.0	-	174.00
A-1023	1697495.0	395482.0	Bor	2796	280.00	1	280.0	Volcanic	0.0		0.0	-	200.00
A-1206	1697750.0	399949.0	Bor	2542	65.00	2	48.0	Alluvial	17.0	Volcanic	0.0	-	48.00
A-1169	1697853.0	400766.0	Bor	2516	150.00	1	150.0	Volcanic	0.0	-	0.0	-	75.00
A-1131	1697806.0	401135.0	Bor	2513	220.00	1	220.0	Volcanic	0.0	-	0.0	-	192.00
A-1138	1697931.0	401819.0	Bor	2546	260.00	2	5.0	Alluvial	255.0	Volcanic	0.0	-	237.00
A-0803	1697966.0	402845.0	Bor	2528	250.00	2	40.0	Alluvial	210.0	Volcanic	0.0	-	240.00
A-0809	1697970.0	403054.0	Dug	2524	70.00	2	5.0	Alluvial	65.0	Volcanic	0.0	-	54.00
A-0799	1698017.0	403771.0	Dug	2507	18.80	2	6.7	Alluvial	11.3	Volcanic	0.0	-	0.00
U-0610	1698107.0	407402.0	Bor	2599	350.00	2	5.0	Alluvial	345.0	Volcanic	0.0	-	0.00
U-0623	1698293.0	409225.0	Bor	2371	350.00	2	4.0	Alluvial	346.0	Volcanic	0.0	-	0.00
U-0620	1698637.0	411571.0	dug/bor	2274	255.00	2	40.0	Alluvial	215.0	Volcanic	0.0	-	0.00
U-0693	1698653.0	412233.0	Bor	2264	350.00	2	80.0	Alluvial	270.0	Volcanic	0.0	-	0.00
U-0696	1698813.0	413753.0	Bor	2254	250.00	2	60.0	Alluvial	190.0	Volcanic	0.0	-	0.00

W-ID	UTM-N	UTM-E	Well type	DEM altitude	TD (m)	No. Layers	Layer 1		Layer 2		Layer 3		Water Level
							Thickness (m)	Lithology	Thickness (m)	Lithology	Thickness (m)	Lithology	
U-0112	1699562.0	417568.0	Bor	2276	350.00	2	180.0	Volcanic	170.0	Sandstone	0.0	-	0.00
U-0104	1699783.0	418525.0	Bor	2289	200.00	3	80.0	Alluvial	90.0	Volcanic	30.0	Sandstone	0.00
C-0505	1699790.0	421256.0	Bor	2334	358.00	3	6.0	Alluvial	214.0	Volcanic	138.0	Sandstone	242.00
C-0174	1699771.0	425160.0	Bor	2371	450.00	2	350.0	Volcanic	100.0	Sandstone	-	-	-
C-0026	1699889.0	426554.0	Bor	2394	500.00	2	300.0	Volcanic	200.0	Sandstone	-	-	-
E-2122	1699590.0	432451.0	Bor	2480	600.00	3	3.0	Alluvial	447.0	Volcanic	150.0	Sandstone	0.00
C-2500	1699645.0	434517.0	dug/bor	2507	110.00	2	6.0	Alluvial	104.0	Volcanic	0.0	-	0.00
C-2572	1699612.0	436072.0	dug/bor	2513	80.00	2	8.0	Alluvial	72.0	Volcanic	0.0	-	0.00

4.6.6 Local sub-surface geological cross-sections

The local cross sections were constructed by Hydrosult, 2007. They are mainly concentrated across the areas where the Cretaceous Tawilah sandstone outcrops at ground surface. These areas are represented by Nihm, Bani Hushaish and Hamdan. The main objectives of constructing these sections are:

- To determine the areal sub-surface extent of the different lithostratigraphic units;
- To determine the upper and lower boundaries of each unit; and
- To locate the different structural elements affecting these units.

Twelve local sub-surface geological cross-sections were constructed for Nihm, Ban Hushaish, Hamdan (for the first time) and Arhab areas. Figure 4-8 shows the locations and directions of these cross-sections. In addition, summarized information of these cross-sections is provided in Table 4-8.

Table 4-8 Summary Information related to local sub-surface geological cross-sections

No.	Name of cross-section	Location	Direction	No. of wells covered	Aquifers encountered	Structures
1	D-D'	Nihm	SW-NE	17	Quaternary alluvial Cretaceous Tawilah sandstone Jurassic Amran limestone	Six normal faults forming graben and horst structures
2	E-E'	Nihm	W-E	15	Quaternary alluvial Cretaceous Tawilah sandstone Jurassic Amran limestone	Two normal faults forming a horst structure
3	F-F'	B. Hushaish	W-E	20	Quaternary alluvial Tertiary volcanics Cretaceous Tawilah sandstone	Four normal faults, two of them forming a horst structure
4	G-G'	B. Hushaish	N-S	16	Quaternary alluvial Tertiary volcanics Cretaceous Tawilah sandstone	Two normal faults forming a graben structure
5	H-H'	B. Hushaish	N-S	13	Quaternary alluvial Tertiary volcanics Cretaceous Tawilah sandstone	One normal fault
6	I-I'	Arhab	N-S	19	Quaternary alluvial Tertiary volcanics Cretaceous Tawilah sandstone Unnamed formation (Shale) Jurassic Amran limestone	Four normal faults, two of them forming a graben structure
7	J-J'	Arhab	W-E	22	Quaternary alluvial Tertiary volcanics Cretaceous Tawilah sandstone Jurassic limestone	Four normal faults forming graben and horst structures
8	K-K'	Hamdan	N-S	75	Quaternary alluvial Tertiary volcanics Cretaceous Tawilah sandstone	Two normal faults forming a horst structure
9	L-L'	Hamdan	N-S	46	Quaternary alluvial Tertiary volcanics Cretaceous Tawilah sandstone	Two normal faults forming a horst structure

No.	Name of cross-section	Location	Direction	No. of wells covered	Aquifers encountered	Structures
10	M-M'	Hamdan		42	Quaternary alluvial Tertiary volcanics	-----------
11	N-N'	Hamdan		41	Quaternary alluvial Tertiary volcanics Cretaceous Tawilah sandstone	Three normal faults, forming graben and horst structures
12	O-O'	Hamdan		29	Quaternary alluvial Tertiary volcanics Cretaceous Tawilah sandstone	Two normal faults forming a horst structure

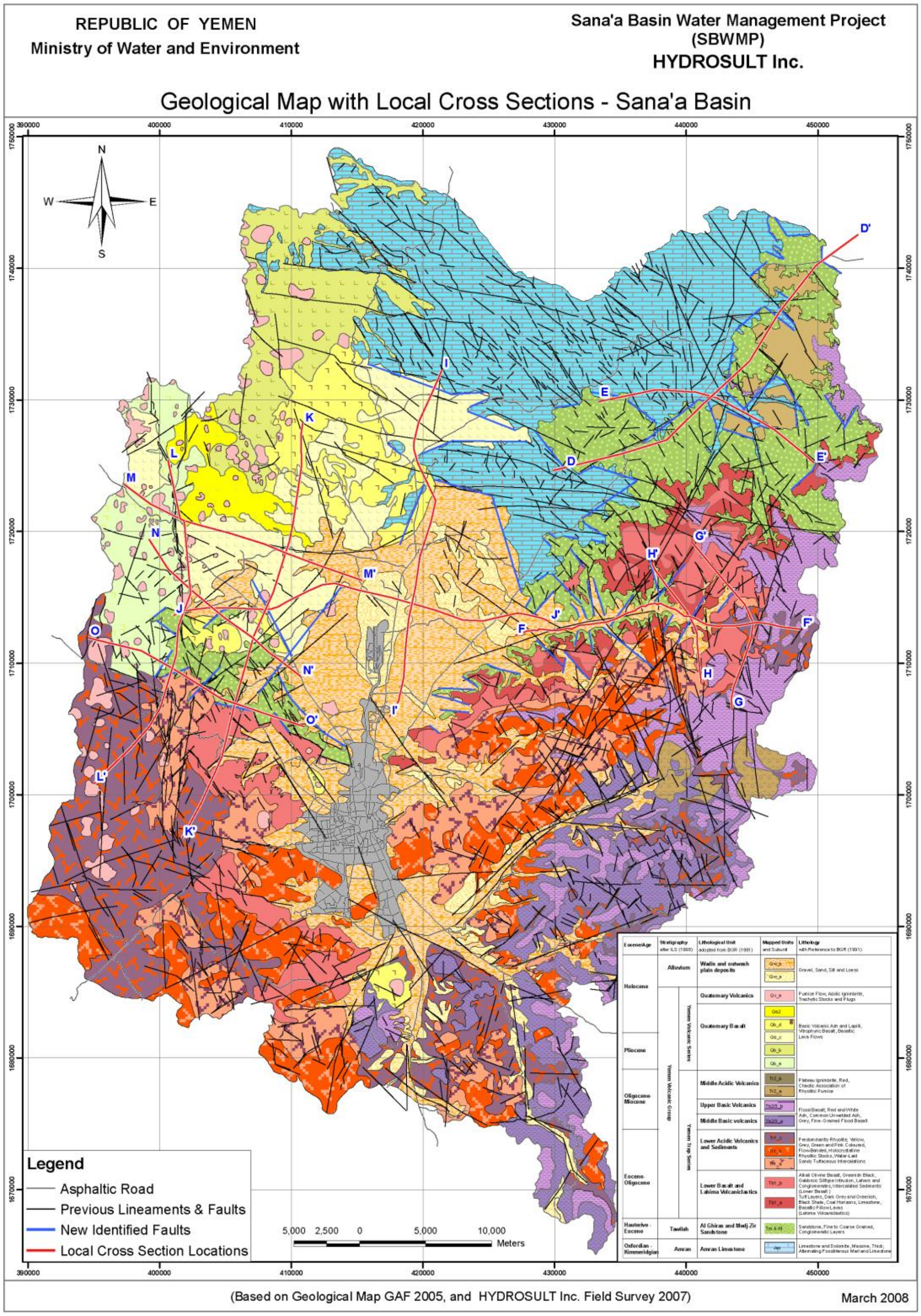

Figure 4-8 Geological map of Sana'a Basin showing location of the local sub-surface cross-sections

4.6.7 Local sub-surface geological cross-sections at Nihm area

Two geological cross-sections of northeast-southwest (D-D') and northwest-southeast (E-E') directions (Figure 4-8) were constructed by Hydrosult Inc. (2007). These cross-sections were constructed using data collected from the field survey conducted in this area and previous lithological data collected by WEC, 2002. A brief description of these geological cross-sections is given below.

4.6.8 Sub-surface geological cross-section D-D' (SW-NE)

This cross-section has a northeast-southwest direction and is constructed based on data from well logs (HS-28, C-1198, C-1199, F-10001, F-0008, F-0131, E-0030, F-0008, E-0026, E-0326, F-0202, F-0214, F-0220, F-0350, F-0300, F-0310, and HS-09) (Figure 4-9). Data related concerning these wells (17 wells) are presented in Table 4-9. The cross-section extends from outside the basin, from Al-Salda and Jabal Al-Hawl in the Barran area in the north-east, to the upper catchment of Wadi Shera'a located in the Arhab area. It shows the lithostratigraphic sequence of geological units from the Jurassic Amran limestone at its base, followed by the Cretaceous Tawilah sandstone, and Quaternary alluvial deposits at the top. The salient features that can be drawn from this cross-section are:

1. The Jurassic Amran limestone is clearly outcropped, covering a large area in the central and southwestern parts of this cross-section. This type of lithology has been uplifted to the surface through three normal structural faults.
2. The Cretaceous Tawilah sandstone aquifer is outcropped in the southwestern part of this cross-section i.e. at Naqil bin Gailan (located in the vicinity between Khulaqah, Arisha and Al-Mahajir villages, at wells nos. C-1198, C-1199, F-10001, F-0008, F-0131). The Tawilah sandstone has been subjected to intense faulting, forming a graben structure. It also outcrops towards the northeastern part i.e. outside the boundary of the basin where it has been subjected to intense tectonic processes in the Al-Madarej and Jabal Al-Hawl area.
3. The alluvial aquifer is present as an isolated layered aquifer of very small thickness. It attains its maximum thickness (100 m at well no. F-0131) in the southwestern part of this cross-section.
4. Six normal faults approximately northwest-southeast direction were inferred from this cross-section. Three graben and two horst structures were encountered along this cross-section.

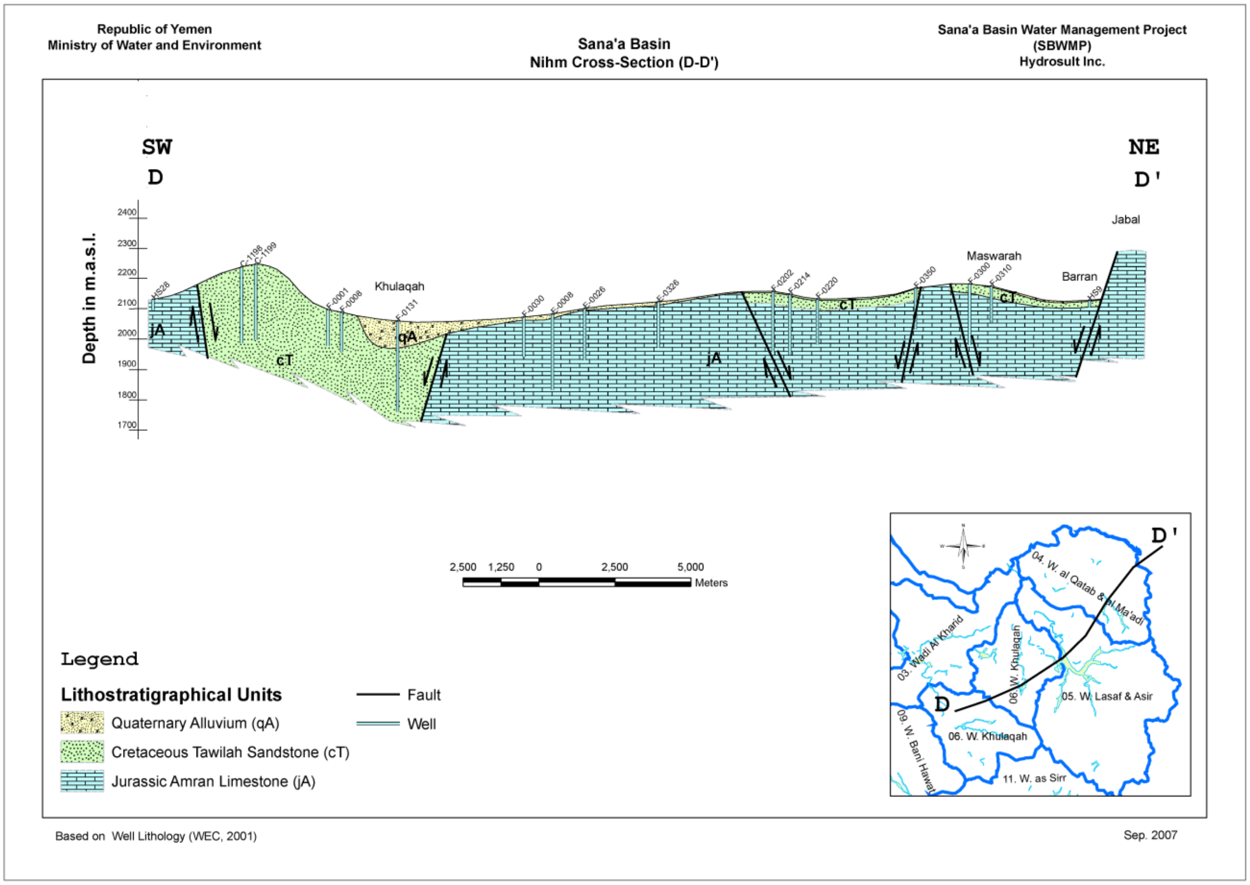

Figure 4-9 Sub-surface geological cross-section (D-D') across the Nihm area

Table 4-9 Well data of the geological cross-section D-D' in the Nihm area

WPID	UTM NORTH	UTM EAST	Elev.	Total dept.	Thickness (m)	LY1 LITHOL	Thickness (m)	LY2 LITHOL	Thickness (m)	LY3 LITHOL
HS28	1724836	430758	2127	35	35	Limestone	-	-	-	-
C-1198	1725691	433554	2234	250	250	Sandstone	-	-	-	-
C-1199	1725924	433960	2244	250	250	Sandstone	-	-	-	-
F-0001	1726488	436278	2094	120	120	Sandstone	-	-	-	-
F-0008	1726772	436620	2085	130	130	Sandstone	-	-	-	-
F-0131	1727909	438078	2056	300	90	Alluvial	210	Sandstone	-	-
F-0030	1730316	441481	2069	130	10	Alluvial	120	Limestone	-	-
E-0008	1730585	442390	2079	250	15	Alluvial	235	Limestone	-	-
E-0026	1731324	443142	2097	170	5	Alluvial	165	Limestone	-	-
E-0326	1732830	445059	2119	150	12	Alluvial	138	Limestone	-	-
F-0202	1736122	446918	2154	200	5	Alluvial	195	Limestone	-	-
F-0214	1736661	447068	2145	200	4	Alluvial	196	Limestone	-	-
F-0220	1737571	447024	2129	150	5	Alluvial	145	Limestone	-	-
F-0350	1740730	447732	2164	135	2	Alluvial	133	Limestone	-	-
F-0300	1741531	449329	2178	200	30	Sandstone	170	Limestone	-	-
F-0310	1742050	449823	2171	120	4	Alluvial	40	Sandstone	76	Limestone
HS9	1742545	453019	2124	22	3	Alluvial	19	Sandstone	-	-

4.6.9 Sub-surface geological cross-section E-E' (W-SE)

This cross-section has a west-southeast direction and was constructed based on data from well logs (F-0129, F-0115, F-0081, F-0079, F-0080, F-0138, E-0008, E-0012, E-0024, E-0042, HS-30, E-0261, E-0254, E-0466 and HS-31) (Figure 4-10). Data related to these wells (15 wells) are presented in Table 4-10. The cross-section extends from Al-Mai'nah village in the south-eastern part of the Nihm area to south of Bait Shabana. It shows the lithostratigraphic sequence of the geological units from Jurassic Amran limestone at its base, followed by Cretaceous Tawilah sandstone, and Quaternary alluvial deposits at the top. The salient features that can be drawn from this cross-section are:

1. The Jurassic Amran limestone has been uplifted and outcropped at ground surface in the central part of this cross-section, forming a horst structure at wells no. F-0079, F-0080, F-0138, E-0004, E-0008, E-0012, E-0024, E-0042, E-0183, HS-30 (i.e. in the Bani Zeter, Al-Hayathem and Al-Hodowd areas).
2. The Tawilah sandstone aquifer is present at both ends of this cross-section (at Jabal Ghawlat Assem to the east and Jabal Arisha to the west of the Nihm area.)
3. Two major faults forming a horst structure of approximately northwest-southeast direction have been inferred from this cross-section.
4. The alluvial aquifer has a relatively small thickness and is outcropped in the central part of the cross-section, overlying both the Cretaceous Tawilah sandstone and the Jurassic Amran limestone aquifers.
5. The area has been subjected to intense tectonic processes which have affected the hydrogeological regime.

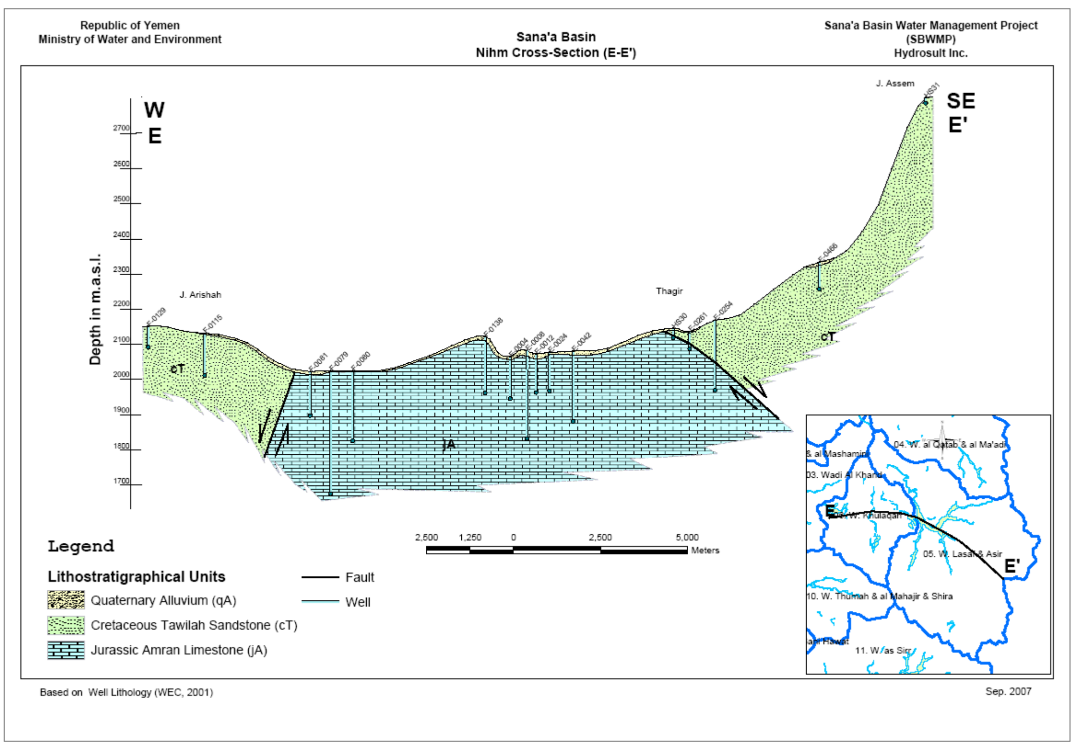

Figure 4-10 Sub-surface geological cross-section (E-E') across the Nihm area

Table 4-10 Well data of geological cross-section E-E' in the Nihm area

W-ID	UTM-N	UTM-E	Elevation	No. Layers	TD (m)	Layer 1		Layer 2		Layer 3	
						Thickness (m)	Lithology	Thickness (m)	Lithology	Thickness (m)	Lithology
F-0129	1730110	433321	2148	1	60	60	Sandstone			0	-
F-0115	1729818	434894	2128	2	120	3	Alluvial	117	Sandstone	0	-
F-0081	1730792	437725	2019	2	125	9	Alluvial	116	Limestone	0	-
F-0079	1731322	437958	2022	2	350	3	Alluvial	347	Limestone	0	-
F-0080	1730747	438200	2022	2	200	3	Alluvial	197	Limestone	0	-
F-0138	1731478	441885	2119	2	160	12	Alluvial	148	Limestone	0	-
E-0008	1730585	442390	2079	2	250	15	Alluvial	235	Limestone	0	-
E-0012	1730439	442599	2070	2	110	15	Alluvial	95	Limestone	0	-
E-0024	1730085	442749	2074	2	110	6	Alluvial	104	Limestone	0	-
E-0042	1729526	443127	2078	2	200	12	Alluvial	188	Limestone	0	-
HS30	1728333	445697	2142	3	26	4	Alluvial	20	Sandstone	2	Limestone
E-0261	1728010	446035	2134	3	50	4	Alluvial	35	Sandstone	11	Limestone
E-0254	1727745	446702	2166	2	200	120	Sandstone	80	Limestone	0	-
E-0466	1725836	448972	2331	2	77	9	Alluvial	77	Sandstone	0	-
HS31	1723827	451212	2799	1	15	15	Sandstone	0		0	-

4.6.10 Sub-surface geological cross-sections in the Bani Hushaish area

Three sub-surface geological cross-sections of east-west (F-F') and northwest-southeast (G-G' and H-H') directions (Figure 4-8) were constructed by Hydrosult Inc. (2007). These sections were constructed using data collected from the geological field survey conducted in this area and lithology data collected by WEC, 2001. A brief description of these cross-sections is given below.

4.6.11 Sub-surface geological cross-section F-F' (W-E)

This cross-section is east-west in direction and was constructed based on data from well logs (E-1555, E-1535, E-1464, E-1392, HS-44, E-0735, E-1270, E-1150, E-0885, E-0869, E-0949, E-0940, BS-1200, BS-0925, BS-0775, BS-0733, BS-0704, BS-0484, BS-O353 and BS-0354) (Figure 4-11). Data related to these wells (20 wells) are presented in Table 4-11. The cross-section covers a distance of 18.5 km. It extends from the area located east of Ash-shariah village in the west, to the village of Bani Dawood in the east. It shows the lithostratigraphic sequence of the geological units from Cretaceous Tawilah sandstone at its base, followed by the Tertiary volcanic group and Quaternary alluvial deposits at the top. The salient features that can be drawn from this cross-section are:

1. The Tawilah sandstone aquifer is present under a thick layer of Tertiary volcanic group in the eastern part and Quaternary alluvial deposits in the western part. It outcrops on the surface in the central and eastern parts of this cross-section.
2. The Tertiary volcanic group is clearly outcropped in the eastern part of the Bani-Hushaish area, located in the eastern part of Sana'a Basin where it reaches its maximum thickness. It has been subjected to tectonic movement (horst structure) in which the Tertiary volcanic group has been uplifted and outcropped at ground surface.
3. The thickness of the alluvial aquifer increases from east to west and attains its maximum thickness in the western part at Ash-Shariah village, with a thickness of 85 meters (well no. E-1392).
4. Four faults approximately north-south in direction have been inferred from this cross-section. In the eastern part of the cross-section, a horst structure has been inferred due to the effect of two normal faults. Towards the west, step faults have been inferred, giving rise to an accumulation of Quaternary alluvial deposits towards the west.

The cross-section shows the following aquifer system:

Aquifer 1: Quaternary alluvial deposits

In the central and eastern parts, the alluvial deposits are present as isolated, very thin layers overlaying both Tertiary volcanic rocks and Cretaceous Tawilah sandstone. The Alluvial aquifer reaches a uniform and maximum thickness of 85 m towards the western part of this cross-section.

Aquifer 2: Tertiary volcanics

This aquifer is predominant towards the east of the cross-section, where it reaches its maximum thickness.

Aquifer 3: Cretaceous Tawilah sandstone

The Tawilah sandstone aquifer is dominantly present with appreciable thickness towards the western part of the cross-section. It is outcropped in the central and western parts of this section. It is subject to several normal faults, as can be seen from Figure 4-11. This cross-section confirms that:

- The alluvial aquifer attains its maximum thickness in the western part.
- The area has been subjected to intense tectonic processes affecting the hydrogeological regime.
- The geological sequence of Bani Hushaish is intruded by volcanic rocks in the eastern part of this section.
- The Cretaceous Tawilah aquifer is present in the central and western part of the area, where it has been subjected to excessive pumping.

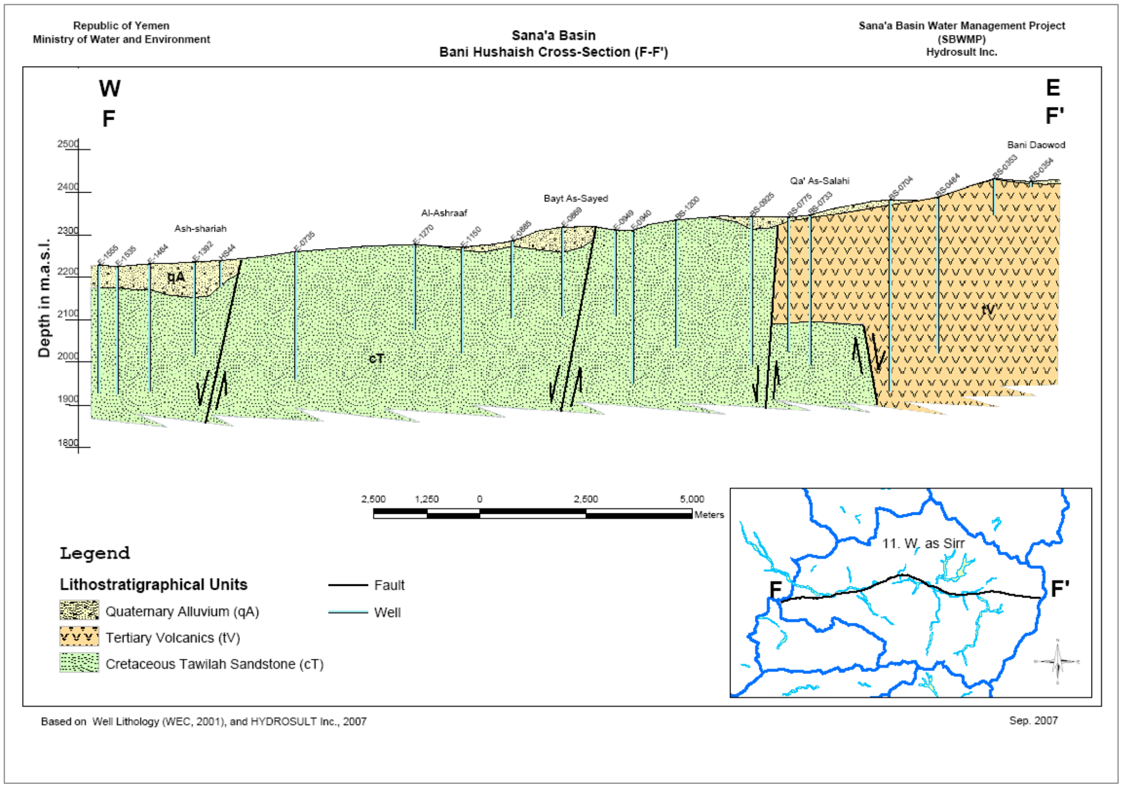

Figure 4-11 Sub-surface geological cross-section (F-F') across the Bani Hushaish area

Table 4-11 Well data of the geological cross-section F-F' in the Nihm area

W-ID	UTM-N	UTM-E	Average Elevation	No. Layers	TD (m)	Layer 1		Layer 2		Layer 3	
						Thickness (m)	Lithology	Thickness (m)	Lithology	Thickness (m)	Lithology
E-1555	1712513	428410	2225	2	300	54	Alluvial	246	Sandstone	0	-
E-1535	1712607	428819	2222	2	300	50	Alluvial	250	Sandstone	0	-
E-1464	1712508	429571	2228	2	300	60	Alluvial	240	Sandstone	0	-
E-1392	1712562	430621	2233	2	220	84	Alluvial	136	Sandstone	0	-
HS44	1712590	431249	2236	1	60	60	Alluvial	0	-	0	-
E-0735	1714319	431603	2257	1	300	300	Sandstone	0	-	0	-
E-1270	1712471	433702	2274	1	200	200	Sandstone	0	-	0	-
E-1150	1713296	434468	2268	2	250	8	Alluvial	142	Sandstone	0	-
E-0885	1713802	435532	2282	2	180	12	Alluvial	168	Sandstone	0	-
E-0869	1714306	436610	2315	2	210	60	Alluvial	150	Sandstone	0	-
E-0949	1714472	437819	2308	1	200	200	Sandstone	0	-	0	-
E-0940	1714435	438231	2307	1	360	360	Sandstone	0	-	0	-
BS-1200	1714069	439207	2332	1	300	300	Sandstone	0	-	0	-
BS-0925	1713187	440729	2340	2	350	30	Alluvial	320	Sandstone	0	-

W-ID	UTM-N	UTM-E	Average Elevation	No. Layers	TD (m)	Layer 1		Layer 2		Layer 3	
						Thickness (m)	Lithology	Thickness (m)	Lithology	Thickness (m)	Lithology
BS-0775	1712926	441574	2338	3	315	9	Alluvial	241	Volcanic	65	Sandstone
BS-0704	1712851	443954	2379	2	450	12	Alluvial	438	Volcanic	0	-
BS-0733	1712846	442057	2343	3	353	6	Alluvial	244	Volcanic	103	-
BS-0484	1712589	445027	2385	1	360	160	Volcanic	0	-	0	-
BS-0353	1712984	446314	2429	2	86	2	Alluvial	84	Volcanic	0	-
BS-0354	1712775	447143	2422	2	12	5	Alluvial	7	Volcanic	0	-

4.6.12 Sub-surface geological cross-section G-G' (W-E)

This cross-section has a north-south direction and is constructed based on data from well logs (E-1035, E-1022, BS-1027, BS-0956, BS-0935, BS-0502, BS-0467, BS-470, BS-0484, BS-0682, BS-0661, BS-0672, BS-0654, BS-0629, BS-0605 and BS-0564) (Figure 4-12). Data related to these wells (16 wells) are presented in Table 4-12. The cross-section extends from the village of Jawj on the south for a distance of 7 km to Bani Rasam village in the north. It shows the lithostratigraphic sequence of the geological units from the Cretaceous Tawilah sandstone group at its base, followed by the Tertiary volcanic group and Quaternary alluvial deposits at the top. Along this cross-section, the Tertiary volcanic flows are exposed on the ground surface in the northern and central part, and are hidden under a very small thickness of Quaternary alluvial aquifer in the southern part of this cross-section. Towards the north, Cretaceous Tawilah sandstone is present under a small thickness of Tertiary volcanic flows. It is present under a larger thickness of Tertiary volcanic group in the southern part of this cross-section.

Two normal faults of approximately east-west direction have been detected along this cross-section. It is clear from this cross-section that the Tawilah sandstone has moved upward in the northern and southern parts of this cross-section, whereas the Tertiary volcanics moved downward in the central part, forming a graben structure.

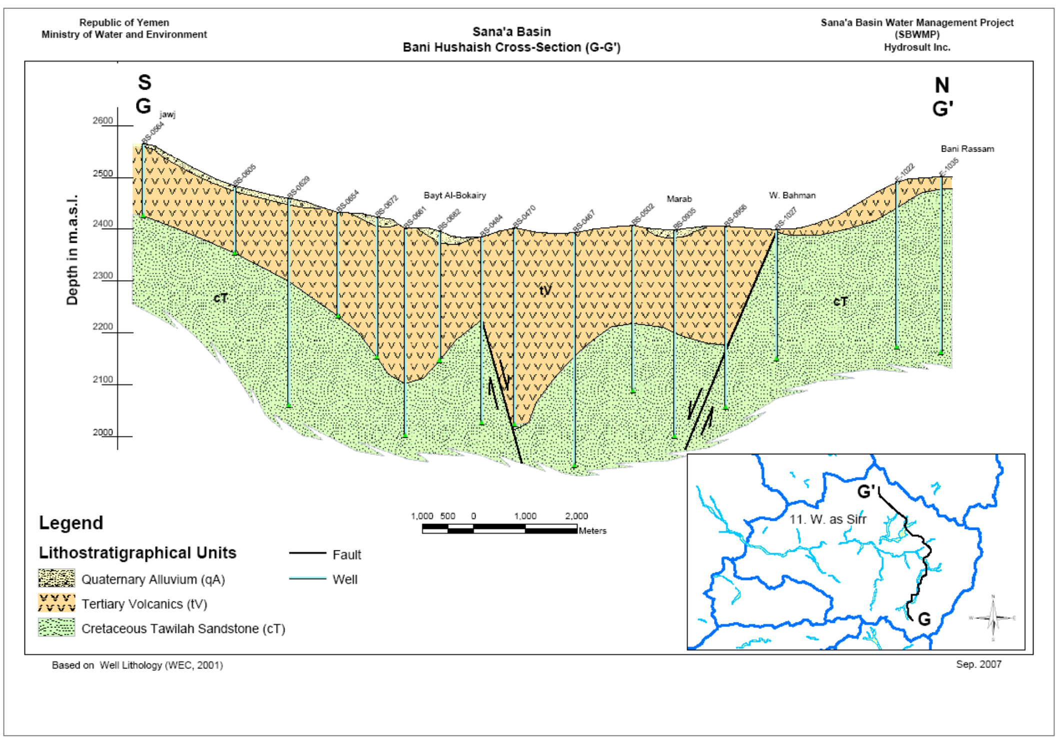

Figure 4-12 Sub-surface geological cross-section (G-G') across the Bani Hushaish area

Table 4-12 Well data of the geological cross-section G-G′ in the Nihm area

W-ID	UTM-N	UTM-E	Average Elevation	No. Layers	TD (m)	Layer 1		Layer 2		Layer 3	
						Thickness (m)	Lithology	Thickness (m)	Lithology	Thickness (m)	Lithology
BS-0564	1706576	443672	2565	2	140.00	6	Alluvial	134	Volcanic	0	-
BS-0605	1708328	443405	2483	2	130.00	10	Alluvial	120	Volcanic	0	-
BS-0629	1709061	444156	2459	3	400.00	12	Alluvial	148	Volcanic	340	Sandstone
BS-0654	1710013	444207	2432	1	200.00	200	Volcanic	0	-	0	-
BS-0672	1710688	444538	2423	2	270.00	18	Alluvial	225	Volcanic	0	-
BS-0661	1711118	444887	2401	2	400.00	300	Volcanic	100	Sandstone	0	-
BS-0682	1711778	444907	2396	2	250.00	24	Alluvial	226	Volcanic	0	-
BS-0484	1712589	445027	2385	2	360.00	160	Volcanic	200	Sandstone	0	-
BS-0470	1713107	445396	2402	1	380.00	380	Volcanic	0	-	0	-
BS-0467	1713927	444575	2393	2	450.00	240	Volcanic	210	Sandstone	0	-
BS-0502	1714572	443639	2407	2	320.00	190	Volcanic	130	Sandstone	0	-
BS-0935	1715145	443071	2398	3	400.00	15	Alluvial	200	Volcanic	185	Sandstone
BS-0956	1716135	443045	2405	2	350.00	230	Volcanic	120	Sandstone	0	-
BS-1027	1716715	442255	2399	2	250.00	5	Volcanic	245	Sandstone	0	-

W-ID	UTM-N	UTM-E	Average Elevation	No. Layers	TD (m)	Layer 1		Layer 2		Layer 3	
						Thickness (m)	Lithology	Thickness (m)	Lithology	Thickness (m)	Lithology
E-1022	1718292	440537	2491	2	320.00	50	Volcanic	270	Sandstone	0	-
E-1035	1719146	440484	2501	2	340.00	24	Volcanic	316	Sandstone	0	-

4.6.13 Sub-surface geological cross-section H-H' (N –S)

This cross-section has a north-south direction and is constructed based on data from well logs (E-1068, E-1067, E-1049, E-1002, BS-1170, BS-1149, BS-0865, BS-0883, BS-0869, BS-0821, BS-0870, BS-0841 and BS-0840) (Figure 4-13). Data related to these wells (Thirteen wells) are presented in Table 4-13. The cross-section extends from south of Jabal Roban village in the south to the northern part of Wadi As-Sir (Wadi Al-Higrah). It shows the lithostratigraphic sequence of the geological units from the Cretaceous Tawilah sandstone group at its base, followed by the Tertiary volcanic group and Quaternary alluvial deposits at the top. The Tertiary volcanic flows are exposed at ground surface in the southern part of this cross-section, whereas the Cretaceous Tawilah sandstone is exposed towards the north.

A normal fault of approximately east-west direction has been detected along this cross-section. It shows a downthrown side towards the southern part in which the Tertiary volcanic group moved downward. The Cretaceous Tawilah volcanic group occupies the southern part of this cross-section. Tawilah sandstone is outcropped on the ground surface in the central and northern part of the cross-section. A thin Quaternary alluvial deposit is present in the central part of this section along the main channel of Wadi As'Sir. The Tertiary volcanic group attains a maximum thickness of 300 m in the southern part of this section (wells no. BS-0840 and BS-0840).

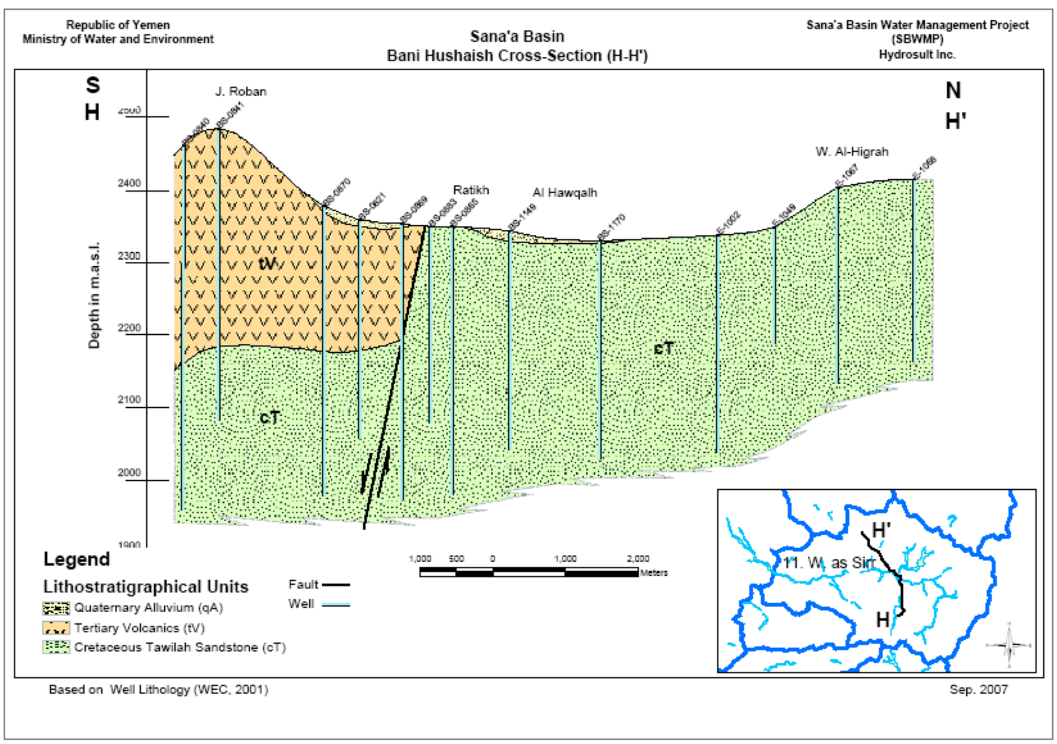

Figure 4-13 Sub-surface geological cross-section (H-H') across the Bani Hushaish area

Table 4-13 Well data of the geological cross-section H-H' in the Nihm area

W-ID	UTM-N	UTM-E	Average Elevation	No. Layers	TD (m)	Layer 1		Layer 2		Layer 3	
						Thickness (m)	Lithology	Thickness (m)	Lithology	Thickness (m)	Lithology
BS-0840	1709420	440454	2457	2	500.00	300	Volcanic	200	Sandstone	0	-
BS-0841	1709672	440857	2481	2	400.00	300	Volcanic	100	Sandstone	0	-
BS-0870	1711132	440830	2374	3	400.00	9	Alluvial	200	Volcanic	191	Sandstone
BS-0821	1711622	440814	2355	3	300.00	9	Alluvial	180	Volcanic	111	Sandstone
BS-0869	1712194	440825	2350	3	380.00	6	Alluvial	160	Volcanic	214	Sandstone
BS-0883	1712577	440729	2346	1	270.00	270	Sandstone	0	-	0	-
BS-0865	1712842	440601	2346	1	370.00	370	Sandstone	0	-	0	-
BS-1149	1713557	440240	2340	2	300.00	15	Alluvial	285	Sandstone	0	-
BS-1170	1714438	439385	2326	2	300.00	3	Alluvial	297	Sandstone	0	-
E-1002	1715831	438533	2334	1	300.00	300	Sandstone	0	-	0	-
E-1049	1716173	437849	2345	1	160.00	160	Sandstone	0	-	0	-
E-1067	1716981	437533	2400	1	270.00	270	Sandstone	0	-	0	-
E-1068	1717811	436867	2411	1	250.00	250	Sandstone	0	-	0	-

4.7 Sub-surface geological cross-sections in Bani Al-Harith - Arhab Area (central plain of Sana'a Basin)

Two geological cross-sections of north-south (F-F') and east-west (G-G') directions (Figure 3-3) were built by Hydrosult Inc. (2007). The cross-sections were constructed using data collected from the geological field survey conducted in this area and lithology data collected by WEC, 2002. A brief description of these geological cross-sections is summarized below.

4.7.1 Sub-surface geological cross-section I-I' (N-S)

This cross-section is north-south in direction and was constructed based on data from well logs (E-2140, HSA-37, HSA-38, F-0563, F-0567, F-0477, F-1234, F-1241, F-1248, F-1891, F-1895, A-2036, C-2397, C-2356, C-2276, C-2232, C-2229, U-0838 and U-0896) (Figure 4-14). Data related to these wells (19 wells) are presented in Table 4-14. The cross-section is 23 km long. It extends from Arhab (the village of Bawsan) in the north, to the village of Dar Salm in the south. It shows the lithostratigraphic sequence of the geological units from the Jurassic Amran limestone at its base, followed by Cretaceous Tawilah sandstone, the Tertiary volcanic group and Quaternary alluvial deposits at the top. The salient features that can be drawn from this cross-section are:

1. Jurassic Amran limestone is clearly outcropped in the northern part of this cross-section, located in the Arhab area to the north of Sana'a City.
2. The Amran group has been subjected to multiple step faults as shown in Figure 4-14.
3. Cretaceous Tawilah sandstone has been detected in the sub-surface towards the southern part of this cross-section (i.e. south of Al-Rawda), as indicated in Figure 4-14. The data from the German wells, the resistivity data (Vertical Electrical Soundings) and the wells (F-2344, A-2071, C-2388, C-2393 and C-2374) confirmed that the Tawilah sandstone has been completely eroded in the area between Al-Rawda and Jabal As-Samma to the north (Figures 4-14 and 4-15).
4. Quaternary and Tertiary volcanics were detected towards the north of this cross-section in a localized scale overlying Jurassic Amran limestone and Cretaceous Tawilah sandstone respectively.
5. The Quaternary alluvial aquifer outcropped over most of this cross-section, and attains its maximum thickness of 250 m in the central part of the cross-section.
6. Five normal step faults have been identified along this cross-section of approximately east-west direction, indicating that the downthrown blocks are towards the south. This confirms the disappearance of the Tawilah sandstone in the southern part of the basin and, hence, it is deeper in that particular area. A graben structure is present in the central part of the cross-section (at the airport and Al-Rawdah areas).

The cross-section shows the following aquifer system:

- Aquifer 1: Quaternary alluvial deposits,
- Aquifer 2: Tertiary volcanic,
- Aquifer 3: Cretaceous Tawilah sandstone, and
- Aquifer 4: Jurassic Amran limestone.

This sub-surface cross-section confirmed that:

- The alluvial aquifer attains its maximum thickness in the area between Al-Rawda and the Jabal Assama, where the Cretaceous Tawilah sandstone has been completely eroded.
- The area has been subjected to intense tectonic movement which has affected the hydrogeological regime.

- The lithostratigraphic units are dipping towards the south where the Cretaceous Tawilah sandstone aquifer is present under a thick layer of Quaternary alluvial and Tertiary volcanics in the southern part of the basin.

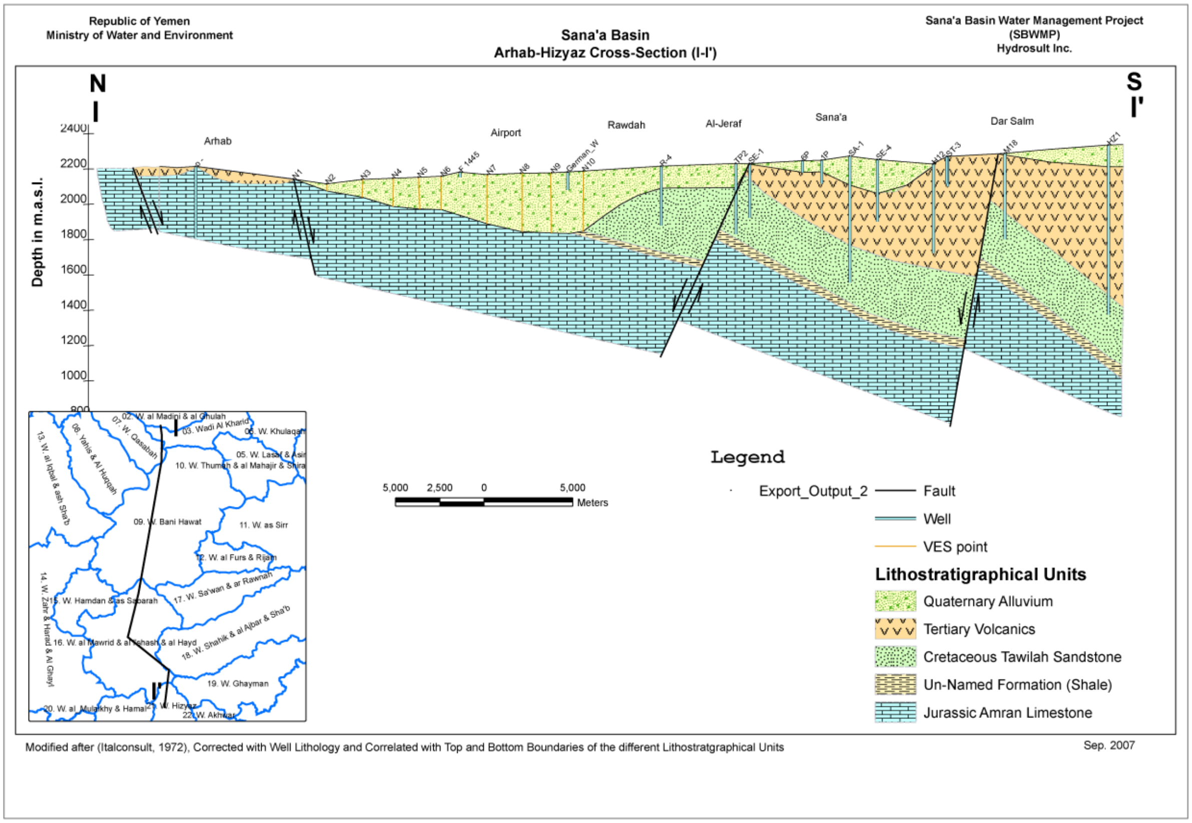

Figure 4-14 Sub-surface geological cross-section (I-I') across the Bani Al-Harith – Arhab area

Table 4-14 Well data of the local geological cross-section (I-I') in the Bani Hushaish area

W-ID	UTM-N	UTM-E	Av. Elev.	No. Layers	TD (m)	Layer 1		Layer 2	
						Thickness (m)	Lithology	Thickness (m)	Lithology
F-2140	1732304	421450	2139	2	150	3	Alluvial	147	Limestone
HSA37	1730184	421333	2130	1	100	100	Limestone	0	-
HSA38	1728959	417429	2206	1	100	100	Limestone	0	-
F-0563	1727213	417468	2211	2	245	30	Alluvial	215	Volcanic
F-0567	1725787	418229	2190	2	198	40	Alluvial	158	Volcanic
F-0477	1724976	419130	2162	2	120	20	Alluvial	100	Volcanic
F-1234	1722936	419305	2137	1	300	300	Alluvial	0	-
F-1241	1722363	419099	2119	1	210	210	Alluvial	0	-
F-1248	1721463	418945	2137	1	150	150	Alluvial	0	-
A-1891	1720758	419790	2157	2	380	100	Alluvial	280	Limestone
A-1895	1719846	419841	2159	2	300	40	Alluvial	260	Limestone
A-2036	1716346	419517	2174	1	200	200	Alluvial	0	-
C-2397	1714145	419379	2189	2	550	220	Alluvial	330	Limestone

W-ID	UTM-N	UTM-E	Av. Elev.	No. Layers	TD (m)	Layer 1		Layer 2	
						Thickness (m)	Lithology	Thickness (m)	Lithology
C-2356	1712956	418899	2189	2	250	200	Alluvial	50	Limestone
C-2276	1711445	418689	2197	2	450	210	Alluvial	240	Limestone
C-2232	1710489	418933	2200	2	400	200	Alluvial	200	Limestone
C-2229	1708883	418517	2218	2	250	150	Alluvial	100	Sandstone
U-0838	1707443	418613	2278	2	200	80	Alluvial	120	Sandstone
U-0896	1705927	417441	2286	2	300	50	Alluvial	250	Sandstone

4.7.2 Sub-surface geological cross-section J-J' (W-E)

This cross-section is east-west in direction and was constructed based on data from well logs (F-1087, F-1097, F-1099, F-1029, F-0867, F-0907, F-0924, F-0781, F-1483, F-1509, F-1550, F-2344, A-2071, C-2388, C-2393, C-2374, C-1832, C-1828, C-1767, C-1735 C-1806, and E-1441) (Figure 4-15). Data related to these wells (22 wells) are presented in Table 4-15. The cross-section covers a distance of 23 km. It extends from Bani Hushaish in the eastern part to Hamdan area in the western part. It shows the lithostratigraphic sequence of geological units from the Jurassic Amran limestone at its base, followed by Cretaceous Tawilah sandstone, Tertiary volcanic group and Quaternary alluvial deposits at the top. The salient features that can be drawn from this cross-section are:

1. The Cretaceous Tawilah sandstone group outcrops at ground surface in the western part of the cross-sections i.e. in the Hamdan area.
2. It has been subjected to faulting towards the central part of this cross-section.
3. It is clearly confirmed through this cross-section that the Tawilah sandstone has been totally eroded in the area of Bani Hawat to the north of Al-Rawdah where Quaternary alluvial deposit is unconformable overlying Jurassic Amran limestone. This was confirmed from the lithological data of the wells (F-2344, A-2071, C-2388, C-2393 and C-2374).
4. The Quaternary alluvial aquifer outcrops over most of this cross-section, and attains its maximum thickness of 250 m in the central part (wells no. A-2071 and C-2388).
5. The Tertiary volcanic group is present in the central part of this cross-section in the form of a graben structure due to the effect of two normal faults.
6. The Jurassic Amran limestone has been uplifted in the central part of the cross-section forming a horst structure.

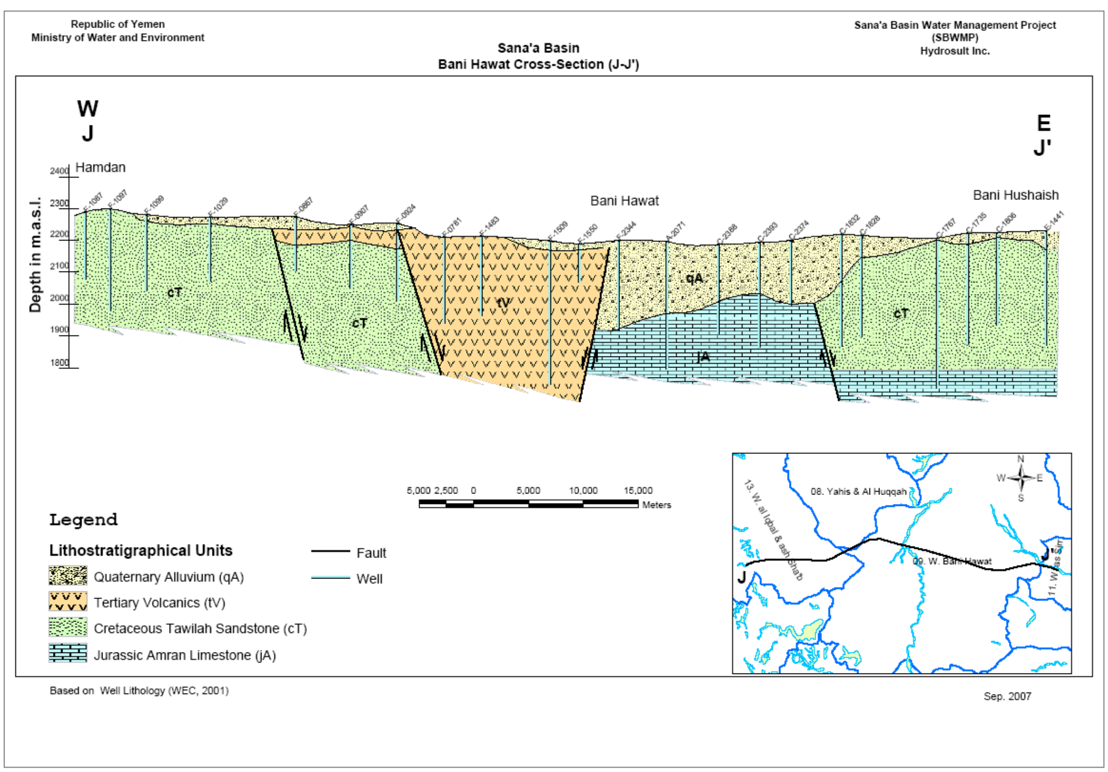

Figure 4-15 Sub-surface geological cross-section (J-J') across the Bani Hawat area

Table 4-15 Well data of the local geological cross-section (J-J) in the Bani Hushaish area

W-ID	UTM-N	UTM-E	Average Elev.	No. Layers	TD (m)	Layer 1		Layer 2		Layer 3	
						Thickness (m)	Lithology	Thickness (m)	Lithology	Thickness (m)	Lithology
F-1087	1713638	401070	2285	1	210	210	Sandstone	0	-	0	-
F-1097	1713961	401772	2295	1	320	320	Sandstone	0	-	0	-
F-1099	1714134	402903	2277	2	240	20	Alluvial	220	Sandstone	0	-
F-1029	1714186	404915	2269	2	200	20	Alluvial	180	Sandstone	0	-
F-0867	1714265	407607	2270	3	170	40	Alluvial	90	Volcanic	40	Sandstone
F-0907	1714452	409349	2246	3	200	4	Alluvial	50	Volcanic	146	Sandstone
F-0924	1715272	410568	2249	3	240	20	Alluvial	80	Volcanic	140	Sandstone
F-0781	1716210	411676	2206	1	270	270	Volcanic	0	-	0	-
F-1483	1716153	412852	2210	1	250	250	Volcanic	0	-	0	-
F-1509	1715593	414943	2195	2	450	30	Alluvial	420	Volcanic	0	-
F-1550	1715341	415845	2185	2	120	20	Alluvial	100	Volcanic	0	-
F-2344	1715353	417059	2196	1	280	280	Alluvial	0	-	0	-
A-2071	1714359	418241	2193	3	400	226	Alluvial	4	Shale	170	Limestone
C-2388	1714630	419830	2183	2	280	180	Alluvial	100	Limestone	0	-
C-2393	1714014	420954	2190	2	330	160	Alluvial	170	Limestone	0	-

W-ID	UTM-N	UTM-E	Average Elev.	No. Layers	TD (m)	Layer 1		Layer 2		Layer 3	
						Thickness (m)	Lithology	Thickness (m)	Lithology	Thickness (m)	Lithology
C-2374	1714066	421938	2196	1	200	200	Alluvial	0	-	0	-
C-1832	1713290	423334	2215	2	350	150	Alluvial	200	Sandstone	0	-
C-1828	1713073	423931	2212	2	320	70	Alluvial	250	Sandstone	0	-
C-1767	1713511	426298	2203	3	470	6	Alluvial	334	Sandstone	130	Limestone
C-1735	1713809	427193	2219	2	350	36	Alluvial	314	Sandstone	0	-
C-1806	1713631	428118	2220	2	290	15	Alluvial	275	Sandstone	0	-
E-1441	1713184	429559	2226	2	360	60	Alluvial	300	Sandstone	0	-

4.7.3 Sub-surface geological cross-sections in the Hamdan area

Five representative sub-surface geological cross-sections were selected in the Hamdan area. These were constructed based on lithological data from well data collected during geological field surveys and data from well logs collected by WEC, 2002. A brief description of these cross-sections is given below.

4.7.4 Sub-surface geological cross-section K-K' (N-S)

This cross-section has a north-south direction and is constructed based on data from more than 70 well logs (Figure 4-16). Data related to these wells (75 wells) are presented in Table 4-16. It extends from the area of Hazim in the north to Hisn Ar-Rassin in the south. This section shows the lithostratigraphic sequence of geological units from the Cretaceous Tawilah sandstone at its base, followed by the Tertiary volcanic group and Quaternary alluvial deposits at the top. The salient features that can be drawn from this cross-section are:

1. The Cretaceous Tawilah sandstone is uplifted and outcropped at ground surface in the central part of this section (Hamdan area). It has been uplifted to the surface through two normal structural faults forming a horst structure.
2. The Tertiary volcanic aquifer is outcropped in the northern and southern parts of this cross-section (Hamdan and Bani Matter areas respectively) and partially covered by Quaternary alluvial deposits.
3. The alluvial deposits are present as isolated layers with variable thickness. It attains a maximum thickness of 100 m in the southern part of this cross-section.
4. Two normal faults of approximately east-west direction were inferred along this cross-section.

The cross-section shows the following aquifer system:

- Aquifer 1: Quaternary alluvial deposits,
- Aquifer 2: Tertiary volcanics,
- Aquifer 3: Cretaceous Tawilah sandstone.

The cross-section confirmed that:

- The alluvial aquifer attains a maximum thickness of 100 m in the southern part of this cross-section.
- The area has been subjected to intense tectonic processes which affected the hydrogeological regime.
- The potential Cretaceous Tawilah aquifer was uplifted and outcropped at the surface in the central part of this cross-section (Hamdan Area).

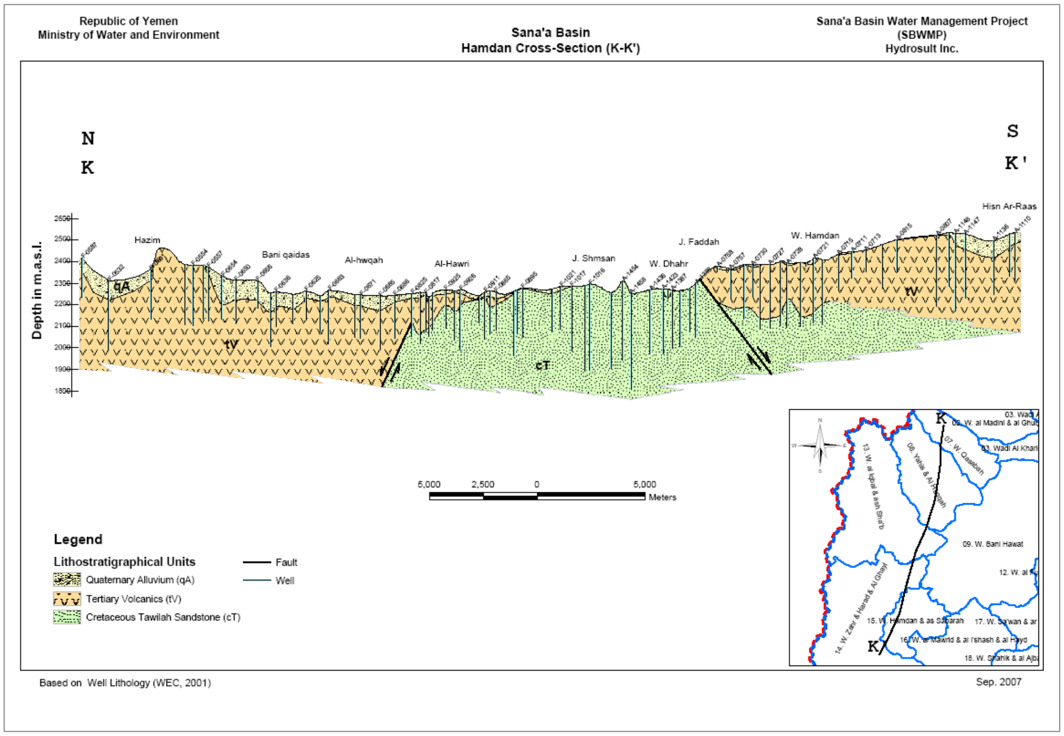

Figure 4-16 Sub-surface geological cross-section (K-K') across the Hamdan area

Table 4-16 Well data of the local geological cross-section (K-K') in the Hamdan area

W-ID	UTM-N	UTM-E	Well Type	Av.Elev.	TD (m)	No. Layers	Layer 1		Layer 2		Layer 3	
							Thickness (m)	Lithology	Thickness (m)	Lithology	Thickness (m)	Lithology
F-0587	1730766	411272	Bor	2412	180	2	60	Alluvial	120	Volcanic	0	-
F-0532	1729541	411467	Bor	2308	320	2	90	Alluvial	230	Volcanic	0	-
F-0591	1727855	410541	Bor	2360	230	2	50	Alluvial	180	Volcanic	0	-
F-0595	1727470	410744	Bor	2461	320	2	50	Alluvial	270	Volcanic	0	-
F-0555	1726452	410143	Bor	2383	280	1	280	Volcanic	0	-	0	-
F-0554	1726224	410383	Bor	2379	280	1	280	Volcanic	0	-	0	-
F-0556	1725745	410592	Bor	2381	250	1	250	Volcanic	0	-	0	-
F-0557	1725566	410520	Bor	2371	250	2	20	Alluvial	230	Volcanic	0	-
F-0654	1724948	410764	Bor	2328	200	2	130	Alluvial	70	Volcanic	0	-
F-0650	1724366	410920	Bor	2310	200	2	90	Alluvial	110	Volcanic	0	-
F-0656	1723416	411249	Bor	2309	130	2	90	Alluvial	40	Volcanic	0	-
F-0635	1722845	411412	Bor	2251	250	2	90	Alluvial	160	Volcanic	0	-
F-0636	1722689	411202	Bor	2256	160	2	70	Alluvial	90	Volcanic	0	-
F-0640	1721879	411021	Bor	2245	135	2	70	Alluvial	65	Volcanic	0	-
F-0625	1721427	410679	Bor	2260	135	2	30	Alluvial	105	Volcanic	0	-
F-0668	1720746	410483	Bor	2239	170	2	25	Alluvial	145	Volcanic	0	-
F-0663	1720645	410114	Bor	2264	250	2	30	Alluvial	220	Volcanic	0	-
F-0670	1719459	409807	Bor	2243	200	2	50	Alluvial	150	Volcanic	0	-
F-0671	1719206	409831	Bor	2242	200	2	50	Alluvial	150	Volcanic	0	-
F-0685	1718387	409551	Bor	2238	250	2	70	Alluvial	180	Volcanic	0	-
F-0686	1717727	409663	Bor	2240	200	2	30	Alluvial	170	Volcanic	0	-

W-ID	UTM-N	UTM-E	Well Type	Av.Elev.	TD (m)	No. Layers	Layer 1		Layer 2		Layer 3	
							Thickness (m)	Lithology	Thickness (m)	Lithology	Thickness (m)	Lithology
F-0825	1717155	409060	Bor	2248	200	3	20	Alluvial	110	Volcanic	70	Sandstone
F-0818	1716788	409067	Bor	2255	240	3	30	Alluvial	170	Volcanic	40	Sandstone
F-0817	1716543	409070	Bor	2251	180	3	10	Alluvial	160	Volcanic	20	Sandstone
F-0815	1716365	408996	Bor	2231	180	3	20	Alluvial	120	Volcanic	40	Sandstone
F-0816	1716191	408961	Bor	2251	170	3	15	Alluvial	115	Volcanic	55	Sandstone
F-0925	1715637	409006	Bor	2266	180	3	20	Alluvial	50	Volcanic	110	Sandstone
F-0919	1715399	408619	Bor	2261	230	3	8	Alluvial	87	Volcanic	135	Sandstone
F-0926	1715244	408415	Bor	2267	280	3	20	Alluvial	50	Volcanic	210	Sandstone
F-0913	1714379	408199	Bor	2241	130	3	15	Alluvial	5	Volcanic	110	Sandstone
F-0911	1714162	408107	Bor	2256	220	3	20	Alluvial	5	Volcanic	195	Sandstone
F-0866	1714082	407865	Bor	2262	200	3	30	Alluvial	50	Volcanic	120	Sandstone
F-0865	1713895	408004	Bor	2257	180	3	30	Alluvial	30	Volcanic	120	Sandstone
F-0892	1713031	408098	Bor	2259	300	3	2	Alluvial	6	Volcanic	192	Sandstone
F-0893	1712925	408152	Bor	2266	200	2	2	Alluvial	198	Sandstone	0	-
F-0895	1712694	408257	Bor	2275	230	2	3	Alluvial	227	Sandstone	0	-
F-1022	1711914	407069	Bor	2271	200	2	20	Alluvial	180	Sandstone	0	-
F-1021	1711550	406994	Bor	2282	200	2	20	Alluvial	180	Sandstone	0	-
F-1017	1711102	406824	Bor	2281	300	1	300	Sandstone	0	-	0	-
F-1015	1710811	406225	Bor	2287	400	1	400	Sandstone	0	-	0	-
F-1016	1710711	406052	Bor	2293	400	1	400	Sandstone	0	-	0	-
A-1452	1709759	405977	Bor	2253	350	1	350	Sandstone	0	-	0	-
A-1454	1709176	406006	Bor	2309	370	1	370	Sandstone	0	-	0	-

W-ID	UTM-N	UTM-E	Well Type	Av.Elev.	TD (m)	No. Layers	Layer 1		Layer 2		Layer 3	
							Thickness (m)	Lithology	Thickness (m)	Lithology	Thickness (m)	Lithology
A-1458	1708907	405784	Bor	2249	440	1	440	Sandstone	0	-	0	-
A-1436	1708034	406055	Bor	2267	300	1	300	Sandstone	0	-	0	-
A-1423	1707914	405491	Bor	2271	300	1	300	Sandstone	0	-	0	-
A-1388	1707742	405385	Dug	2269	48	2	40	Alluvial	8	Sandstone	0	-
A-1387	1707589	405228	Bor	2266	270	1	270	Sandstone	0	-	0	-
A-1386	1707249	405419	Bor	2263	260	2	2	Alluvial	258	Sandstone	0	-
A-1384	1706942	405698	Bor	2272	200	1	200	Sandstone	0	-	0	-
A-1383	1706625	405650	Bor	2297	250	1	250	Sandstone	0	-	0	-
A-0758	1705634	405823	Dug	2376	20	2	11	Alluvial	9	Volcanic	0	-
A-0757	1705146	406119	Bor	2363	140	2	5	Alluvial	135	Volcanic	0	-
A-0731	1704771	405574	Bor	2385	250	3	3	Alluvial	197	Volcanic	50	Sandstone
A-0730	1704424	405624	Bor	2382	150	2	10	Alluvial	140	Volcanic	0	-
A-0729	1704123	405812	Bor	2383	300	3	5	Alluvial	245	Volcanic	50	Sandstone
A-0727	1703741	405568	Bor	2383	290	2	250	Volcanic	50	Sandstone	0	-
A-0726	1703512	405079	Bor	2400	300	3	3	Alluvial	247	Volcanic	50	Sandstone
A-0728	1703395	405343	Bor	2390	300	3	10	Alluvial	155	Volcanic	135	Sandstone
A-0725	1703110	404779	Bor	2394	300	2	250	Volcanic	50	Sandstone	0	-
A-0724	1702853	404707	Dug	2393	16	2	10	Alluvial	6	Volcanic	0	-
A-0721	1702534	404625	Bor	2412	300	3	25	Alluvial	225	Volcanic	50	Sandstone
A-0716	1702500	404201	Bor	2406	300	2	200	Volcanic	50	Sandstone	0	-
A-0715	1702042	403686	Bor	2431	160	2	5	Alluvial	155	Volcanic	0	-
A-0711	1701872	403051	Bor	2442	120	2	5	Alluvial	115	Volcanic	0	-

W-ID	UTM-N	UTM-E	Well Type	Av.Elev.	TD (m)	No. Layers	Layer 1		Layer 2		Layer 3	
							Thickness (m)	Lithology	Thickness (m)	Lithology	Thickness (m)	Lithology
A-0713	1701487	403529	Bor	2450	100	1	100	Volcanic	0	-	0	-
A-0816	1701168	404223	Bor	2476	204	2	204	Volcanic	0	-	0	-
A-0815	1700528	404488	Bor	2499	150	2	1	Alluvial	149	Volcanic	0	-
A-0807	1699289	403095	Bor	2520	330	2	2	Alluvial	328	Volcanic	0	-
A-0806	1698802	402866	Bor	2531	250	2	10	Alluvial	240	Volcanic	0	-
A-1148	1698783	402572	Bor	2529	360	2	50	Alluvial	310	Volcanic	0	-
A-1147	1698319	402578	Bor	2526	300	2	70	Alluvial	230	Volcanic	0	-
A-1136	1697600	402159	Bor	2494	250	2	80	Alluvial	170	Volcanic	0	-
A-1112	1696953	401732	Bor	2527	200	2	60	Alluvial	140	Volcanic	0	-
A-1110	1696711	401695	Bor	2532	220	2	50	Alluvial	170	Volcanic	0	-

4.7.5 Sub-surface geological cross-section L-L' (N-S)

This cross-section is north-south in direction and is constructed based on lithological data of more than 45 wells (Figure 4-17). Data related to these wells (46 wells) are presented in Table 4.17. It extends from Al-Jaeif in the north to Bait Makharish in the south. This section shows the lithostratigraphic sequence of geological units from the Cretaceous Tawilah sandstone at its base, followed by the Tertiary volcanics group and Quaternary alluvial deposits at the top. The salient features from this cross-section are:

1. The Cretaceous Tawilah sandstone is clearly outcropped in the central part of the cross-section (Hamdan area). It was uplifted and outcropped on the surface through two normal structural faults forming a horst structure.
2. The Tertiary volcanic aquifer is outcropped in the northern and southern parts of this cross-section (Hamdan and Bani Matter areas respectively).
3. Along this cross-section, alluvial deposits form isolated small aquifer overlaying the Tertiary volcanics with a maximum thickness of approximately 200 m in the southern part.
4. Two normal faults of approximately east-west direction had formed a horst structure inferred from this cross-section.

The cross-section shows the following aquifer system:

- Aquifer 1: Quaternary alluvial deposits,
- Aquifer 2: Tertiary volcanic,
- Aquifer 3: Cretaceous Tawilah sandstone.

This geological cross-section confirmed that:

- The alluvial aquifer has attained its maximum thickness of approximately 200 m in the southern part of this cross-section.
- The area was subjected to intense tectonic processes which affected the hydrogeological regime.
- The Potential Cretaceous Tawilah aquifer outcrops in the central part of the cross-section (Hamdan Area).

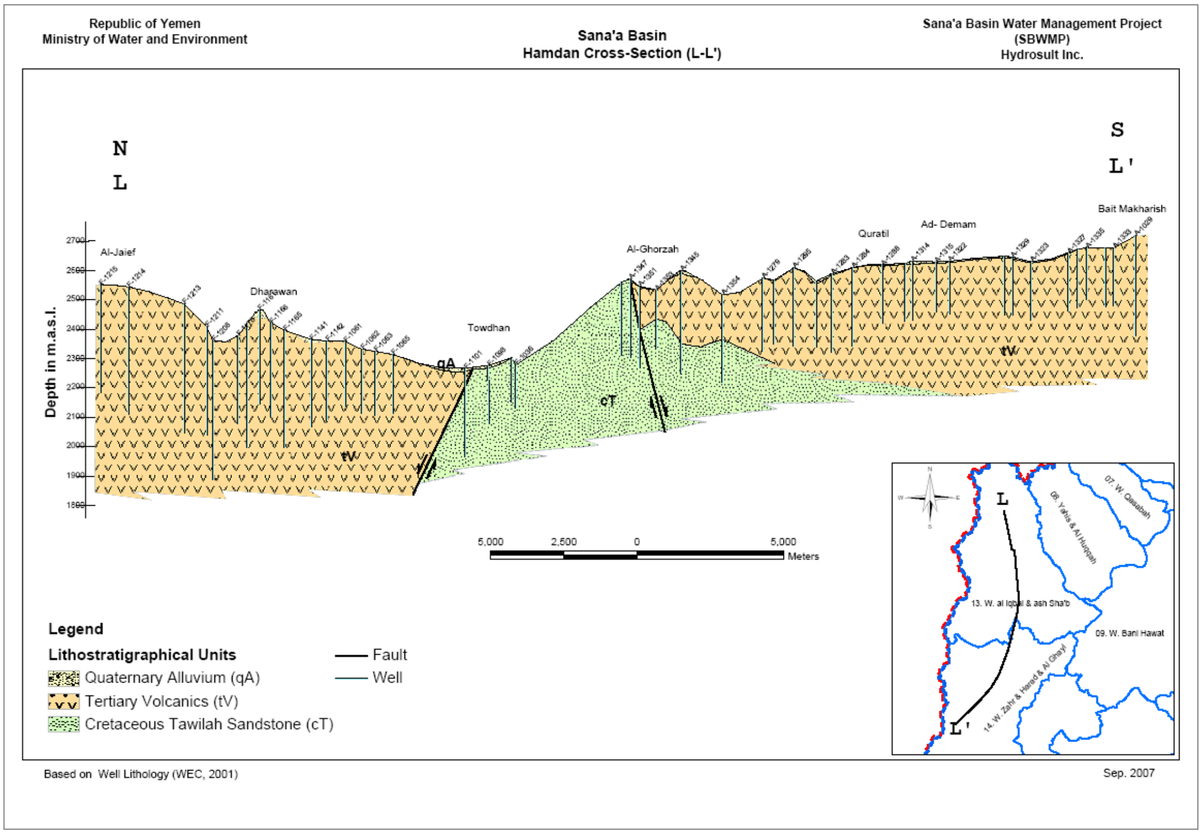

Figure 4-17 Sub-surface geological cross-section (L-L') across the Hamdan area

Table 4-17 Well data of the local geological cross-section L-L' in the Hamdan area

W-ID	UTM-N	UTM-E	Well Type	Av. Elev.	TD (m)	No-Layers	Layer 1		Layer 2		Layer 3	
							Thickness (m)	Lithology	Thickness (m)	Lithology	Thickness (m)	Lithology
F-1215	1725438	400621	Bor	2549	370	1	370	Volcanic	0			
F-1214	1724488	400558	Bor	2541	436	1	436	Volcanic	0			
F-1213	1722608	400757	Bor	2483	440	1	440	Volcanic	0			
F-1211	1721843	400958	Bor	2406	370	1	370	Volcanic	0			
F-1208	1721640	401025	Bor	2357	475	1	475	Volcanic	0			
F-1178	1720968	401545	Bor	2375	300	1	300	Volcanic	0			
F-1167	1720833	401842	Bor	2418	425	1	425	Volcanic	0			
F-1161	1720435	401905	Bor	2463	320	2	30	Alluvial	290	Volcanic		
F-1166	1720059	402041	Bor	2419	320	1	320	Volcanic	0			
F-1165	1719686	402330	Bor	2393	400	1	400	Volcanic	0			
F-1141	1718860	402675	Bor	2362	300	2	10	Alluvial	290	Volcanic		
F-1142	1718341	402855	Bor	2356	270	1	270	Volcanic	0			
F-1061	1717873	402468	Bor	2355	220	1	220	Volcanic	0			
F-1062	1717395	402815	Bor	2328	220	1	220	Volcanic	0			
F-1063	1716964	402680	Bor	2321	220	1	220	Volcanic	0			
F-1065	1716640	403170	Bor	2311	200	1	200	Volcanic	0			
F-1101	1714406	402481	Bor	2263	300	2	60	Volcanic	240	Sandstone		
F-1098	1713686	402151	Bor	2273	200	2	10	Alluvial	190	Sandstone		
F-1035	1712937	402386	Bor	2298	150	1	150	Sandstone	0			
F-1036	1712839	402500	Bor	2276	150	1	150	Sandstone	0			
A-1350	1709521	401135	Bor	2557	250	1	250	Sandstone	0			

W-ID	UTM-N	UTM-E	Well Type	Av. Elev.	TD (m)	No-Layers	Layer 1		Layer 2		Layer 3	
							Thickness (m)	Lithology	Thickness (m)	Lithology	Thickness (m)	Lithology
A-1347	1709313	400906	Bor	2569	270	1	270	Sandstone	0			
A-1351	1708992	400875	Bor	2543	280	3	3	Alluvial	147	Volcanic	130	Sandstone
A-1353	1708435	400760	Bor	2531	200	2	100	Volcanic	100	Sandstone		
A-1345	1708074	399978	Bor	2597	350	3	10	Alluvial	240	Volcanic	100	Sandstone
A-1354	1707414	401221	Bor	2514	300	2	150	Volcanic	150	Sandstone		
A-1279	1706981	399920	Bor	2571	250	1	250	Volcanic	0			
A-1280	1706623	400057	Bor	2565	220	2	2	Alluvial	218	Volcanic		
A-1295	1706373	399431	Bor	2607	270	2	2	Alluvial	268	Volcanic		
A-1281	1705934	400064	Bor	2562	228	2	10	Alluvial	218	Volcanic		
A-1283	1705450	399831	Bor	2586	270	1	270	Volcanic	0			
A-1284	1705162	399190	Bor	2607	270	2	2	Alluvial	268	Volcanic		
A-1288	1705108	398177	Bor	2616	200	1	200	Volcanic	0			
A-1313	1704406	397823	Bor	2622	200	2	5	Alluvial	195	Volcanic		
A-1314	1704347	397598	Bor	2628	200	2	10	Alluvial	190	Volcanic		
A-1315	1703557	397785	Bor	2626	170	1	170	Volcanic	0			
A-1322	1703130	397633	Bor	2628	180	2	5	Alluvial	175	Volcanic		
A-1328	1702915	395779	Bor	2645	200	1	200	Volcanic	0			
A-1329	1702901	396059	Bor	2643	200	2	6	Alluvial	194	Volcanic		
A-1323	1702877	396716	Bor	2627	200	2	5	Alluvial	195	Volcanic		
A-1327	1702798	395445	Bor	2658	200	2	3	Alluvial	197	Volcanic		
A-1336	1702533	395267	Bor	2669	200	1	200	Volcanic	0			
A-1335	1702323	395043	Bor	2676	180	1	180	Volcanic	0			

W-ID	UTM-N	UTM-E	Well Type	Av. Elev.	TD (m)	No-Layers	Layer 1		Layer 2		Layer 3	
							Thickness (m)	Lithology	Thickness (m)	Lithology	Thickness (m)	Lithology
A-1332	1701728	395260	Bor	2673	200	1	200	Volcanic	0			
A-1333	1701599	395000	Bor	2675	200	1	200	Volcanic	0			
A-1029	1700866	395022	Bor	2715	340	1	340	Volcanic	0			

4.7.6 Sub-surface geological cross-section M-M' (E-W)

This cross-section has an approximately east-west direction and is constructed based on the lithological data of about 40 wells (Figure 4-18). Data related to these wells (42 wells) are presented in Table 4-18. It extends from Jabal Dhain in the north to Bait Handhal in the south. The cross-section shows the lithostratigraphic sequence of the geological units of the Tertiary volcanic group at its base and the Quaternary alluvial deposits at the top. The salient features from this cross-section are:

1. The Tertiary volcanic aquifer is outcropped on the surface covering most of the cross-section except for a small area which is covered with Quaternary alluvial deposits.
2. Along this cross-section, the Quaternary alluvial deposits form isolated small aquifers overlaying the Tertiary volcanics with a maximum thickness of approximately 100 m in the eastern part.
3. No structural faults were inferred along this cross-section.

The cross-section shows the following aquifer system:

- Aquifer 1: Quaternary alluvial deposits,
- Aquifer 2: Tertiary volcanic.

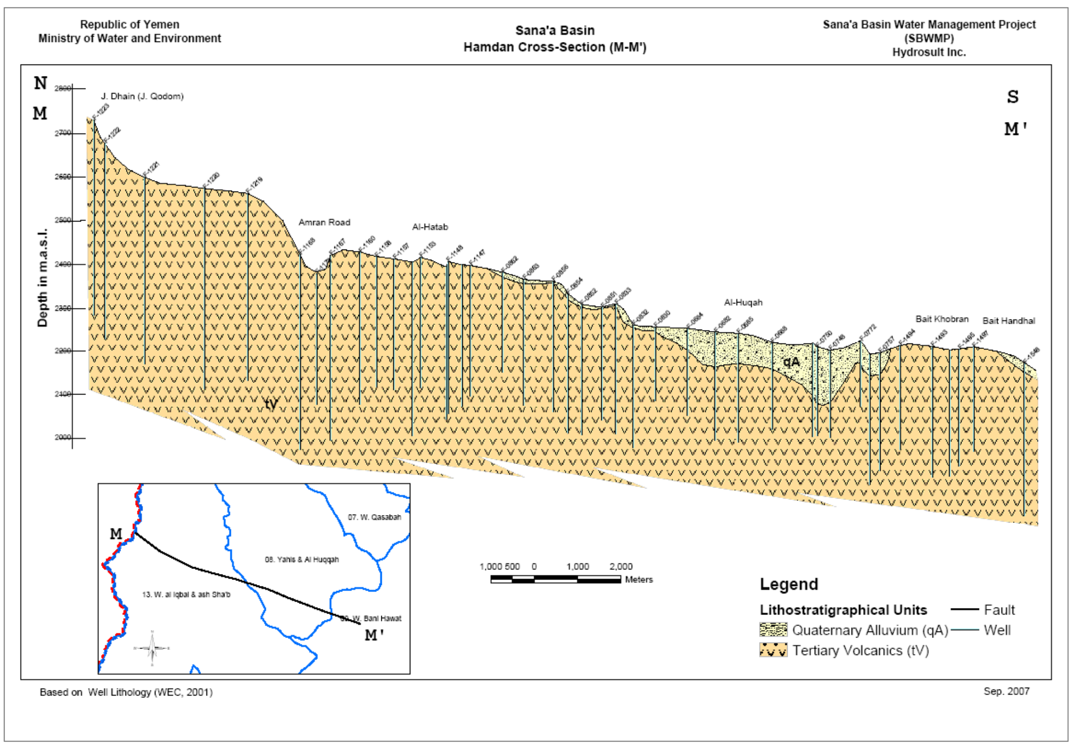

Figure 4-18 Sub-surface geological cross-section (M-M') across the Hamdan area

Table 4-18 Well data of the local geological cross-section (M-M') in the Hamdan area

	X-UTM	Y-UTM	Type	TD (m)	No- Layers	Layer 1		Layer 2	
						Thickness (m)	Lithology	Thickness (m)	Lithology
F-1223	397307	1723596	Bor	450	1	450	Volcanic	0	
F-1222	397534	1723474	Bor	450	1	450	Volcanic	0	
F-1221	398356	1723092	Bor	430	1	430	Volcanic	0	
F-1220	399301	1722093	Bor	460	1	460	Volcanic	0	
F-1219	400092	1721499	Bor	430	1	430	Volcanic	0	
F-1168	401168	1720935	Bor	450	1	450	Volcanic	0	
F-1178	401545	1720968	Bor	300	1	300	Volcanic	0	
F-1167	401842	1720833	Bor	425	1	425	Volcanic	0	
F-1160	402466	1720566	Bor	350	1	350	Volcanic	0	
F-1158	402649	1720248	Bor	300	1	300	Volcanic	0	
F-1157	402981	1720505	Bor	300	1	300	Volcanic	0	
F-1156	403377	1720362	Bor	400	1	400	Volcanic	0	
F-1153	403557	1720391	Bor	300	1	300	Volcanic	0	
F-1145	404110	1720198	Bor	350	1	350	Volcanic	0	
F-1148	404142	1720172	Bor	350	1	350	Volcanic	0	
F-1146	404457	1720106	Bor	325	1	325	Volcanic	0	
F-1147	404507	1719911	Bor	300	1	300	Volcanic	0	
F-0862	405244	1719906	Bor	230	2	10	Alluvial	220	Volcanic
F-0863	405596	1719567	Bor	290	2	10	Alluvial	280	Volcanic
F-0856	406210	1719836	Bor	300	2	3	Alluvial	297	Volcanic
F-0854	406425	1719580	Bor	320	2	10	Alluvial	310	Volcanic
F-0852	406617	1719322	Bor	300	2	5	Alluvial	295	Volcanic
F-0851	407067	1719465	Bor	260	2	3	Alluvial	257	Volcanic
F-0833	407311	1719667	Bor	300	2	3	Alluvial	297	Volcanic

	X-UTM	Y-UTM	Type	TD (m)	No- Layers	Layer 1		Layer 2	
						Thickness (m)	Lithology	Thickness (m)	Lithology
F-0832	407656	1719466	Bor	280	2	5	Alluvial	275	Volcanic
F-0830	407951	1719060	Bor	170	2	10	Alluvial	160	Volcanic
F-0684	408566	1718618	Bor	200	2	50	Alluvial	150	Volcanic
F-0682	409059	1718224	Bor	250	2	80	Alluvial	170	Volcanic
F-0685	409551	1718387	Bor	250	2	70	Alluvial	180	Volcanic
F-0688	410302	1718175	Bor	200	2	60	Alluvial	140	Volcanic
F-0751	411235	1718072	Bor	215	2	120	Alluvial	95	Volcanic
F-0750	411320	1718024	Bor	205	2	130	Alluvial	75	Volcanic
F-0748	411618	1718009	Bor	200	2	120	Alluvial	80	Volcanic
F-0772	412050	1717440	Bor	150	2	50	Alluvial	100	Volcanic
F-0774	412242	1717431	Bor	300	2	50	Alluvial	250	Volcanic
F-0757	412325	1717206	Bor	270	2	50	Alluvial	220	Volcanic
F-1494	412791	1717213	Bor	240	1	240	Volcanic	0	
F-1493	413517	1717074	Bor	300	1	300	Volcanic	0	
F-1499	413837	1716820	Bor	290	1	290	Volcanic	0	
F-1495	413992	1716971	Bor	270	1	270	Volcanic	0	
F-1497	414303	1716867	Bor	240	1	240	Volcanic	0	
F-1548	415329	1716299	Bor	350	2	20	Alluvial	330	Volcanic

4.7.7 Sub-surface geological cross-section N-N' (NW-SE)

This cross-section has a northwest-southeast direction and is constructed based on the lithological data of 41 wells (Figure 4-19). Data related to these wells (41 wells) are presented in Table 4-19. It extends from Bani Muanis in the north to Jadir in the south. The cross-section shows the lithostratigraphic sequence of geological units from the Cretaceous Tawilah sandstone at its base, followed by the Tertiary volcanic group and Quaternary alluvial deposits at the top. The salient features from this cross-section are:

1. The Cretaceous Tawilah sandstone is clearly outcropped at ground surface throughout the central and southeastern parts of the cross-section (Hamdan area). It was uplifted to ground surface through three normal structural faults forming a horst structure.
2. The Tertiary volcanic aquifer is outcropped in the northwestern part of this cross-section.
3. Quaternary alluvial deposits form isolated small aquifers overlaying the Tertiary volcanic group with a maximum thickness of approximately 100 m in the southeastern part of this cross-section (well no. A-1536 and A-1540).
4. Three major faults of approximately northeast-southwest direction were inferred along this cross-section forming a horst structure.

The cross-section shows the following aquifer system:

- Aquifer 1: Quaternary alluvial deposits,
- Aquifer 2: Tertiary volcanic,
- Aquifer 3: Cretaceous Tawilah sandstone.

This sub-surface cross-section confirmed that:

- The Quaternary alluvial aquifer attains its maximum thickness of 100 m in the southeastern part of this cross-section.
- The area was subjected to intense tectonic processes which affected the hydrogeological regime.
- The Tertiary volcanic aquifer is outcropped on ground surface in the northeastern part of this cross-section.
- The Potential Cretaceous Tawilah aquifer is outcropped in the central and southeastern parts of the cross-section (Hamdan Area).

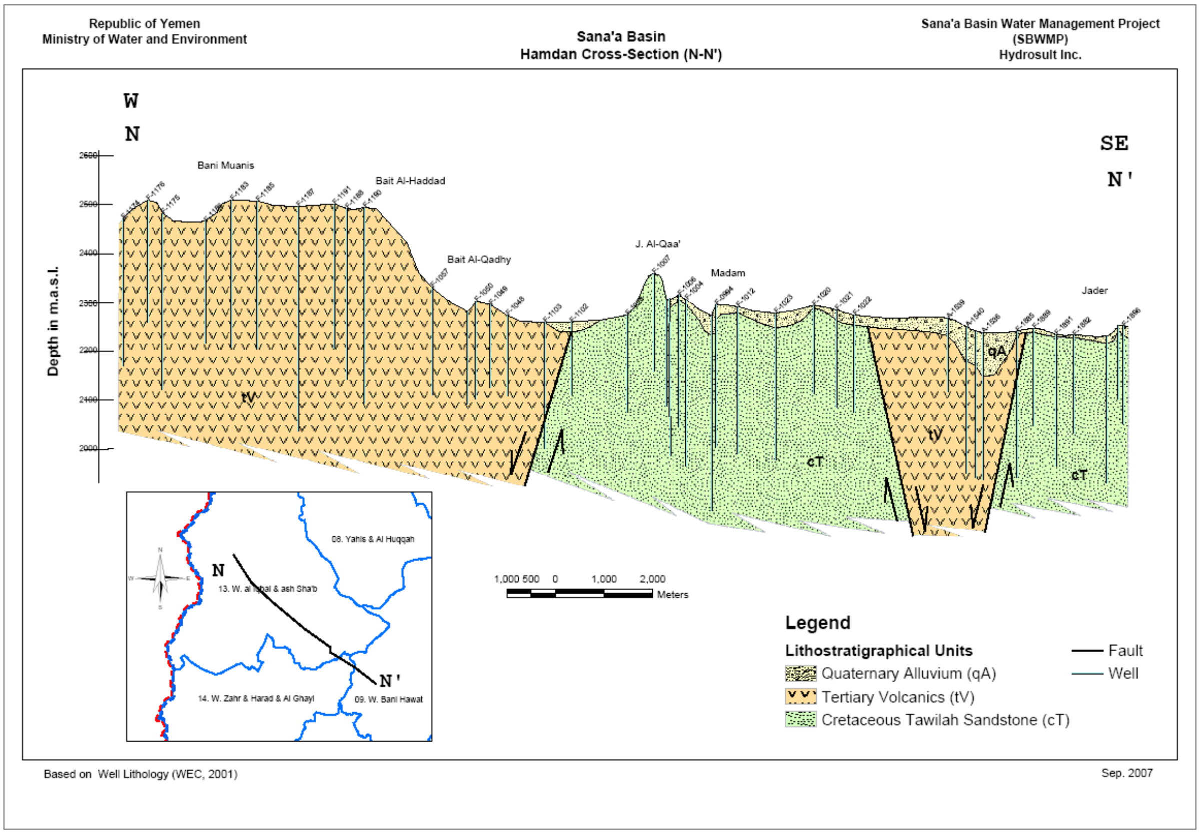

Figure 4-19 Sub-surface geological cross-section (N-N') across the Hamdan area

Table 4-19 Well data of the local geological cross-section N-N' in the Hamdan area

ID	X-UTM	Y-UTM	Type	TD (m)	No. Layers	Layer 1		Layer 2	
						Thickness (m)	Lithology	Thickness (m)	Lithology
F-1174	399182	1719413	Bor	300	1	300	Volcanic	0	-
F-1176	399547	1719053	Bor	250	1	250	Volcanic	0	-
F-1175	399613	1719351	Bor	360	1	360	Volcanic	0	-
F-1186	399692	1718475	Bor	250	1	250	Volcanic	0	-
F-1183	399726	1717940	Bor	300	1	300	Volcanic	0	-
F-1185	400019	1718380	Bor	300	1	300	Volcanic	0	-
F-1187	400398	1717639	Bor	460	1	460	Volcanic	0	-
F-1191	400601	1716924	Bor	295	1	295	Volcanic	0	-
F-1188	400617	1717182	Bor	350	1	350	Volcanic	0	-
F-1190	400731	1716831	Bor	400	1	400	Volcanic	0	-
F-1057	401954	1716194	Bor	220	1	220	Volcanic	0	-
F-1055	402360	1715581	Bor	190	1	190	Volcanic	0	-
F-1050	402415	1715421	Bor	200	1	200	Volcanic	0	-
F-1049	402544	1715151	Bor	170	1	170	Volcanic	0	-
F-1048	402775	1714898	Bor	165	1	165	Volcanic	0	-
F-1103	403544	1714823	Bor	260	2	160	Volcanic	0	-
F-1102	403663	1714293	Bor	150	2	20	Alluvial	130	Sandstone
F-1028	404756	1713974	Bor	200	1	200	Sandstone	0	-
F-1007	404917	1713448	Bor	200	1	200	Sandstone	0	-
F-1001	405035	1713213	Bor	218	2	20	Alluvial	198	Sandstone
F-1002	405113	1713198	Bor	320	2	15	Alluvial	305	Sandstone

ID	X-UTM	Y-UTM	Type	TD (m)	No. Layers	Layer 1		Layer 2	
						Thickness (m)	Lithology	Thickness (m)	Lithology
F-1006	405294	1713193	Bor	270	2	10	Alluvial	260	Sandstone
F-1004	405428	1713134	Bor	340	2	10	Alluvial	330	Sandstone
F-0993	405853	1712840	Bor	400	2	40	Alluvial	360	Sandstone
F-0994	405866	1712738	Bor	290	2	30	Alluvial	260	Sandstone
F-1012	405890	1713174	Bor	300	2	12	Alluvial	288	Sandstone
F-1023	406243	1712480	Bor	300	2	30	Alluvial	270	Sandstone
F-1020	406596	1711782	Bor	180	2	5	Alluvial	175	Sandstone
F-1021	406994	1711550	Bor	200	2	20	Alluvial	180	Sandstone
F-1022	407069	1711914	Bor	200	2	20	Alluvial	180	Sandstone
A-1539	408686	1710886	Bor	150	2	36	Alluvial	114	Volcanic
A-1540	408845	1710526	Bor	300	2	70	Alluvial	230	Volcanic
A-1537	408944	1710364	Bor	300	2	70	Alluvial	230	Volcanic
A-1536	408961	1710225	Bor	300	2	90	Alluvial	210	Volcanic
F-1885	409431	1709702	Bor	300	2	5	Alluvial	295	Sandstone
F-1889	409442	1710042	Bor	200	2	5	Alluvial	195	Sandstone
F-1891	409513	1709589	Bor	270	2	5	Alluvial	265	Sandstone
F-1882	409816	1709381	Bor	200	2	5	Alluvial	195	Sandstone
F-1886	410462	1709164	Bor	300	2	15	Alluvial	285	Sandstone
F-1895	410661	1709039	Bor	150	2	10	Alluvial	140	Sandstone
F-1896	410706	1708948	Bor	200	2	20	Alluvial	180	Sandstone

4.7.8 Sub-surface geological cross-section O-O' (E-W)

This cross-section has an approximately east-west direction and is constructed based on lithological data of 29 wells (Figure 4-20). Data related to these wells (29 wells) are presented in Table 4-20. It extends from Qa'a Al-Manaqab in the west to Wadi Thahban in the east. The cross-section shows the lithostratigraphic sequence of the geological units from Cretaceous Tawilah sandstone at its base, followed by the Tertiary volcanic group and Quaternary alluvial deposits at the top. The salient features from this cross-section are:

1. The Cretaceous Tawilah sandstone is clearly outcropped in the central and eastern parts of the cross-section (Hamdan area). It has been uplifted to the ground surface through three normal structural faults forming a horst structure.
2. The Tertiary volcanic aquifer is outcropped in the western part of this cross-section.
3. Quaternary alluvial deposits form isolated small aquifers overlaying the Tertiary volcanics.
4. Two major faults of approximately north-south direction were inferred along this cross-section forming a horst structure.
5. The cross-section shows the following aquifer system:
   - Aquifer 1: Quaternary Alluvial deposits,
   - Aquifer 2: Tertiary volcanic, and
   - Aquifer 3: Cretaceous Tawilah sandstone.

   This sub-surface cross-section confirmed that:

   - Quaternary alluvial deposits form isolated small aquifers overlaying the Tertiary volcanics.
   - The area has been subjected to intense tectonic processes which have affected the hydrogeological regime.
   - The Tertiary volcanic aquifer is outcropped on the ground surface in the eastern part of this cross-section.
   - The Potential Cretaceous Tawilah aquifer is outcropped in the central and eastern parts (Hamdan Area).

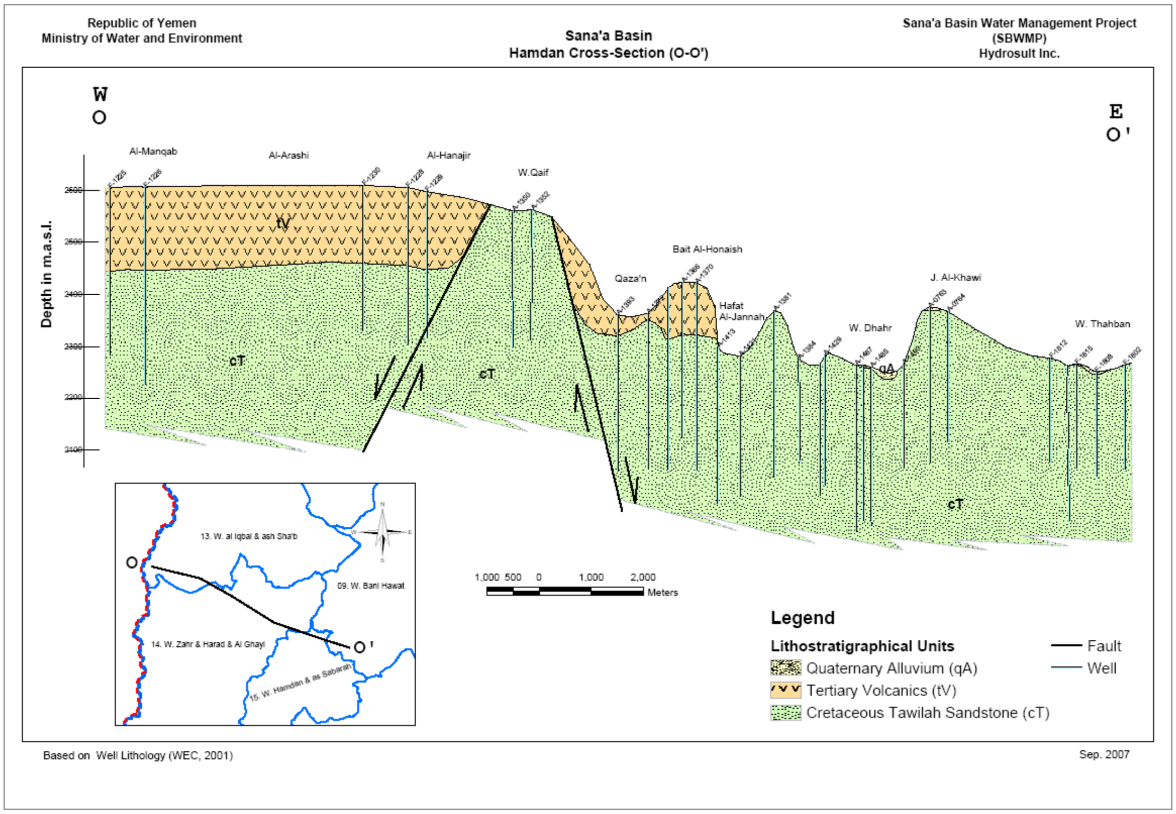

Figure 4-20 Sub-surface geological cross-section (O-O') across the Hamdan area

Table 4-20 Well data of the local geological cross-section O-O' in Hamdan area

ID	X-UTM	Y-UTM	Type	TD (m)	No. Layers	Layer 1		Layer 2	
						Thickness (m)	Lithology	Thickness (m)	Lithology
F-1225	394563	1711933	Bor	320	2	160	Volcanic	160	Sandstone
F-1226	395245	1711923	Bor	380	2	160	Volcanic	220	Sandstone
F-1230	399315	1710886	Bor	280	2	150	Volcanic	130	Sandstone
F-1228	399914	1710298	Bor	300	2	150	Volcanic	150	Sandstone
F-1229	399922	1710666	Bor	280	2	150	Volcanic	130	Sandstone
A-1350	401135	1709521	Bor	250	1	250	Sandstone	0	-
A-1352	401342	1709220	Bor	250	1	250	Sandstone	0	-
A-1393	402801	1708480	Bor	300	2	40	Volcanic	260	Sandstone
A-1372	403120	1707992	Bor	300	2	12	Volcanic	288	Sandstone
A-1368	403442	1707763	Bor	350	2	100	Volcanic	250	Sandstone
A-1366	403627	1707559	Bor	300	2	100	Volcanic	200	Sandstone
A-1370	403873	1707465	Bor	360	2	100	Volcanic	260	Sandstone
A-1413	404281	1707380	Bor	300	1	300	Sandstone	0	-
A-1421	404692	1707295	Bor	270	1	270	Sandstone	0	-
A-1381	405233	1706905	Bor	320	2	1	Alluvial	319	Sandstone
A-1384	405698	1706942	Bor	200	1	200	Sandstone	0	-
A-1428	406076	1706819	Bor	250	1	250	Sandstone	0	-
A-1429	406143	1706751	Bor	250	1	250	Sandstone	0	-
A-1487	406718	1706917	Bor	320	1	320	Sandstone	0	-
A-1486	406789	1706796	Bor	300	2	5	Alluvial	295	Sandstone
A-1485	406923	1706882	Bor	300	2	3	Alluvial	297	Sandstone

ID	X-UTM	Y-UTM	Type	TD (m)	No. Layers	Layer 1		Layer 2	
						Thickness (m)	Lithology	Thickness (m)	Lithology
A-1490	407474	1706985	Bor	200	1	200	Sandstone	0	-
A-0763	407914	1706747	Bor	300	2	6	Alluvial	294	Sandstone
A-0764	408183	1706508	Bor	250	1	250	Sandstone	0	-
F-1812	409756	1705328	Bor	200	1	200	Sandstone	0	-
F-1814	409994	1705599	Bor	300	1	300	Sandstone	0	-
F-1815	410110	1705542	Bor	200	2	3	Alluvial	197	Sandstone
F-1808	410429	1705325	Bor	200	2	6	Alluvial	194	Sandstone
F-1802	410957	1705198	Bor	200	1	200	Sandstone	0	-

4.8 Vertical distribution of the lithostratigraphic units (Fence Diagram)

The fence diagram is a three-dimensional pattern which demonstrates the correlation between lithology and borings, or well logs. They have customized colors for easy identification of layers. It is a drawing in perspective of three or more geologic sections with their relationship to one another (also called a panel diagram).

In order to illustrate the surface as well as the sub-surface distribution of the different lithostratigraphic units in Sana'a Basin, 23 well logs were selected to construct the fence diagram (Figure 4-21). The selected wells were drilled by several foreign and local drilling projects and companies such as Italconsult, 1973; Russian, 1986; Howard Humphrey and Sons, 1981-1982; SAWAS, 1996; NWSA, 2000;NWSA, 04; and other local companies. The deepest wells are DS1 and DS2 with a depth of 1260 m, located to the north of Sana'a Basin i.e. in Arhab and Al-Hataresh areas respectively. In the south, the deepest wells are HZ1, H8, EX-S, C2459, OS, Exp-3, with depths of 960, 900, 884, 780, 766 and 618 m respectively (Table 4-21). The lithological log reports of these wells were collected in an early stage of this project. The lithological data of the three new drilled wells in the western part of the basin (EXP-1, at Al-Subbaha; EXP-2, at Al-Masajid; and EXP-3, at Al-Eshash) were also collected and used during construction of this fence diagram.

It is clear from the fence diagram (Figure 4-21) that:

- The upper surface of the Precambrian basement rocks was only encountered in wells DS-1 and DS-2 at depths of 1325 and 1676 m respectively.
- The Permian-Jurassic Kohlan sandstone was encountered in the northern part of the Sana'a Basin in wells DS-1 and DS-2 at depths of 39 and 37 m below ground level respectively.
- The Jurassic Amran limestone is only outcropped in the northern part of the Sana'a Basin. Towards the east, it is present at the sub-surface underlaying the Cretaceous Tawilah sandstone group whereas, towards the northwest, it is present at the sub-surface underlaying the Tertiary volcanic group as well as the Quaternary volcanics.
- Wells DS-1 and DS-2, drilled in the Arhab and Al-Hataresh areas, have penetrated the entire thickness of the Jurassic Amran limestone group and indicated that the sub-surface thickness of the limestone group in these areas is 1286 and 1444 m respectively.
- Well A-2071 only encountered the top surface of the Jurassic Amran limestone group at a depth of 226 m below ground surface.
- Towards the western, eastern and southern areas of the basin, Jurassic Amran limestone was not encountered in any well. This indicates that this group has been uplifted to the surface in the northern part of the basin (Figure 4-3) and is present at a greater depth under a considerable layer of Cretaceous Tawilah and Tertiary volcanic groups.
- The fence diagram indicates that the Cretaceous Tawilah sandstone group is outcropped towards the northeastern, eastern and western parts of the basin i.e. in Nihm, Bani Hushaish and Hamdan areas. This was confirmed by the wells (E-0118, E-0486 and A-1458). Other than the above-mentioned areas, the Cretaceous Tawilah sandstone group is present at sub-surface, underlaying either Tertiary volcanic group or Quaternary alluvial deposits in the rest of the basin.
- It is clear from the fence diagram that the Cretaceous Tawilah sandstone group was completely eroded in the area between Al-Rawdah and Sana'a airport as confirmed through the data of well log lithology (A-2071) and the geophysical resistivity data (Italconsult 1973).
- Towards the south, the Cretaceous Tawilah sandstone group is present under a substantial layer of the Tertiary volcanic group and Quaternary alluvial deposits.
- The Volcanic group is mainly outcropped at ground surface in the western, eastern and southern parts of the basin. In localized restricted areas (such as Sana'a south, Hadda, Sanhan, Sawan, Bani Matar, etc) this group is overlain by Quaternary alluvial deposits.

- It is clear from the fence diagram that the thickness of the Tertiary volcanics group increases towards the southern part of the basin.
- Quaternary alluvial deposits are mainly present in the Sana'a Plain. They were deposited unconformably overlying the Jurassic Amran limestone in the area between Al-Rawdah and Sana'a airport. In this particular area, it attains its maximum thickness. A significant thickness of alluvial deposits is detected towards the south, as confirmed by the wells R1, OS, EX-S and HZ1.

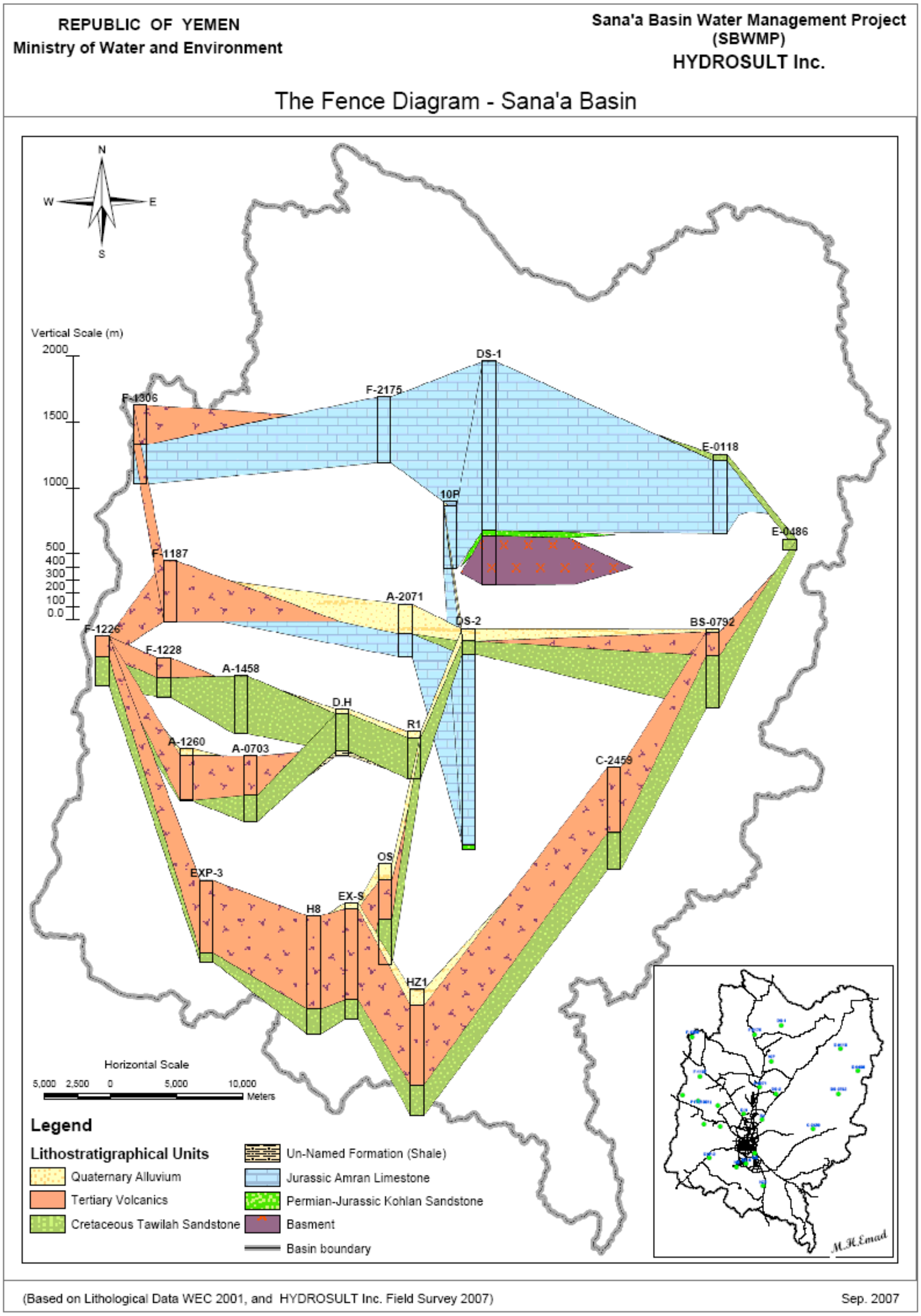

Figure 4-21 Fence diagram of Sana'a Basin

Table 4-21 Well data used in construction of the Fence Diagram

ID	X-UTM	Y-UTM	Type	Total Depth (m)	No. Layers	Alluvial Thickness (m)	Volcanic Thickness (m)	Tawilah Thickness (m)	Amran Thickness (m)	Shale Thickness (m)	Kohlan Thickness (m)	Basement Thickness (m)
T	417885.0	1701005.0	Bor	400	4	90.0	55.0	253.0	0.0	2.0	0.0	0.0
HA	411005.0	1691410.0	Bor	851	4	81.0	415.0	338.0	0.0	17.0	0.0	0.0
DS-2	423039.6	1712498.4	Bor	1676	4	95.0	0.0	100.0	1444.0	0.0	37	0.0
P17(f1881)	409659.0	1708837.0	Bor	210	3	16.0	0.0	173.0	21.0	0.0	0.0	0.0
D.H	413470.0	1706400.0	Bor	357	3	0.0	37.0	282.5	0.0	37.5	0.0	0.0
KA	417245.0	1693470.0	Bor	823	3	155.0	444.0	224.0	0.0	0.0	0.0	0.0
M19-A	417176.0	1689477.0	Bor	1000	3	157.0	598.0	245.0	0.0	0.0	0.0	0.0
OS	416750.0	1694655.0	Bor	766	3	127.0	294.0	345.0	0.0	0.0	0.0	0.0
SP	414245.0	1694334.0	Bor	900	3	79.0	620.0	201.0	0.0	0.0	0.0	0.0
EX-S	414157.0	1691674.0	Bor	884	3	43.0	695.0	146.0	0.0	0.0	0.0	0.0
M24	417695.0	1699194.0	Bor	854	3	140.0	460.0	394.0	0.0	0.0	0.0	0.0
EXP-1	403801.0	1695406.0	Bor	700	2	154.0	546.0	0.0	0.0	0.0	0.0	0.0
EXP-2	409213.0	1692323.0	Bor	520	2	32.0	488.0	0.0	0.0	0.0	0.0	0.0
10P	421642.4	1722182.3	Bor	515	2	40.0	0.0	0.0	475.0	0.0	0.0	0.0
R1	418930.0	1704702.0	Bor	360	2	50.0	0.0	310.0	0.0	0.0	0.0	0.0
EXP-3	403173.0	1693373.0	Bor	618	2	0.0	550.0	68.0	0.0	0.0	0.0	0.0
H8	411300.0	1690690.0	Bor	900	2	0.0	708.0	192.0	0.0	0.0	0.0	0.0
DS-1	424626.2	1732804.0	Bor	1699	3	0.0	0.0	0.0	1286.0	0.0	39	374
E-0118	442184.0	1725737.0	Bor	600	2	0.0	0.0	50.0	550.0	0.0	0.0	0.0
BS-0792	441593.0	1712443.0	Bor	600	3	20.0	180.0	400.0	0.0	0.0	0.0	0.0
C-2459	434123.0	1701995.0	Bor	780	2	0.0	500.0	280.0	0.0	0.0	0.0	0.0
HZ1	419152.0	1685100.0	Bor	960	3	123.0	604.0	233.0	0.0	0.0	0.0	0.0

ID	X-UTM	Y-UTM	Type	Total Depth (m)	No. Layers	Alluvial Thickness (m)	Volcanic Thickness (m)	Tawilah Thickness (m)	Amran Thickness (m)	Shale Thickness (m)	Kohlan Thickness (m)	Basement Thickness (m)
A-1606	415451.0	1684810.0	Bor	600.0	2	36.0	564.0	0.0	0.0	0.0	0.0	0.0
F-1187	400398.0	1717639.0	Bor	460.0	1	0.0	460.0	0.0	0.0	0.0	0.0	0.0
F-1306	398098.0	1729475.0	Bor	600.0	2	0.0	300.0	0.0	300.0	0.0	0.0	0.0
F-0592	410503.0	1727829.0	Bor	500.0	2	50.0	450.0	0.0	0.0	0.0	0.0	0.0
F-2175	416652.0	1730099.0	Bor	500.0	1	0.0	0.0	0.0	500.0	0.0	0.0	0.0
A-2071	418241.0	1714359.0	Bor	400.0	2	226.0	0.0	0.0	174.0	0.0	0.0	0.0

4.9 Reconstruction of the aquifer maps in the Unified Coordinate System

The main purpose of these maps is to show top, bottom, thickness and lateral boundaries of the different lithostratigraphic units in Sana'a Basin.

Available well data were compiled from previous studies (Italconsult 1973; Russian, 1986; SAWAS 1990-1996; NWSA, 2000; NWSA, 2004; WEC, 2001; NWRA, 2004-2006), and from recent field surveys conducted during the course of the present study. These data were reviewed and verified. It was observed that each study had applied its own projection system, mainly for determining the altitude of each water point. Some studies applied projection of the location (X,Y) on topographic maps of different scales; others applied G.P.S. systems of varying accuracy. Therefore, it was essential to transfer all available well data onto a unified geographic coordination system (X,Y,Z). It was recommended that an advanced and dependable digital geographic system be applied. The digital elevation model (DEM) was selected as it represents GIS delineation processes, starting with a grid representation of topography. The project used a DEM map obtained from the Shuttle Radar Topographic Mission (SRTM).

During the first stage of the activity "Inventory, Reviewing and Processing of available collected data", the contour maps for the geometry of the Quaternary alluvial, Quaternary and Tertiary Volcanics and the Cretaceous Tawilah sandstone aquifers were constructed in GIS format and described in detail in a special Technical Note No. 2. These maps were considered as a first trial based on available data. In the second stage, after identification of the main information gaps and after conducting an intense geological field survey to collect new data, these maps were reconstructed and their accuracy was verified with the unified projection system. The following steps were carried out:

- The entire available inventory of data and information on the dug and drilled wells (about 14,000 water points) in the Sana'a Basin which were compiled from previous and present studies was revised. Their coordinates (X,Y) were projected on the unified DEM map where the altitude for each water point was determined. Accordingly, the altitude value was defined for the top and bottom of each aquifer penetrated for each water point.
- The geometric maps, mainly the contour of the top and bottom of each aquifer, were reconstructed.

The following steps were conducted to verify the correlation of these maps with the available geological and hydrological materials:

- The delineation of the different water-bearing formations was verified with the geological map constructed by Russian, 1986, GAF, 2005; and was updated.
- Within the implementation of Activity 1 of the present project, an intense geological survey was carried out mainly in the areas of Nihm (Northeast), Hamdan (West), Beni Hushaish (East). The boundary of each formation was checked with the results of this survey.
- The contouring of the outcrops of the different aquifers was overlapped into one contour map and then was checked with the topographic map of the Basin prepared by DEM map, and with the available geological maps.
- The geometry of the different aquifers was verified with the available geological cross-sections (Regional cross sections updated and modified by Hydrosult, 2007 after Russian, 1986, and the fifteen sections prepared by Hydrosult, 2007).

Therefore, the contour maps representing the geometry of the different water-bearing formations have been verified and modified according to the projection of the unified DEM map and the consultation of all available geological and hydrogeological information. A consistent, complete set of maps representing the delineation of the different water-bearing formations were constructed. These maps are as follows:

1. Top level contour map of the Quaternary Alluvial Aquifer.
2. Bottom level contour map of the Quaternary Alluvial Aquifer.

3. Contour map of the thickness of the Quaternary alluvial aquifer.
4. Top level contour map of the Quaternary and Tertiary volcanic aquifers.
5. Bottom level contour map of the Quaternary and Tertiary volcanic aquifers.
6. Contour map of the thickness of the Quaternary and Tertiary volcanic aquifers.
7. Top level contour map of the Tawilah sandstone aquifer.
8. Bottom level contour map of the Tawilah sandstone aquifer.
9. Contour map of the thickness of the Tawilah sandstone aquifer.
10. Top level contour map of the Amran limestone aquifer.

4.9.1 The Quaternary alluvial aquifer geometry

Extent:

The surface extension of the alluvial aquifer is well known from the recent geological map that was constructed (Figure 4-3). It is mainly located in the central area of the basin and confined to wadi beds and low areas that form the Sana'a Plain. Based on the present geological field survey, the unconsolidated deposits of the Quaternary aquifer cover approximately 15.6% of the Sana'a Basin area (i.e. 505 km^2).

4.9.2 Top Level Map of the Quaternary alluvial aquifer

The top level map of the alluvial aquifer was constructed. The map (Figure 4-2) indicates:

- The elevation of the top surface of the alluvial aquifer ranges from 2150 m to 2375 m amsl in the northern and southern parts of the basin respectively.
- The alluvial aquifer is located along the central part of the basin.

4.9.3 Bottom Level Map of the alluvial aquifer

The bottom level map of the alluvial aquifer was constructed. It is clear from this map (Figure 4-23) that:

- The elevation of the bottom surface of the alluvial aquifer ranges from 1850 m to 2300 m amsl.
- The lowest point above mean sea level is 1850 m, found at two locations in the northwestern part of the map.
- The highest point above mean sea level is 2300 m, located in the southern part of the map.

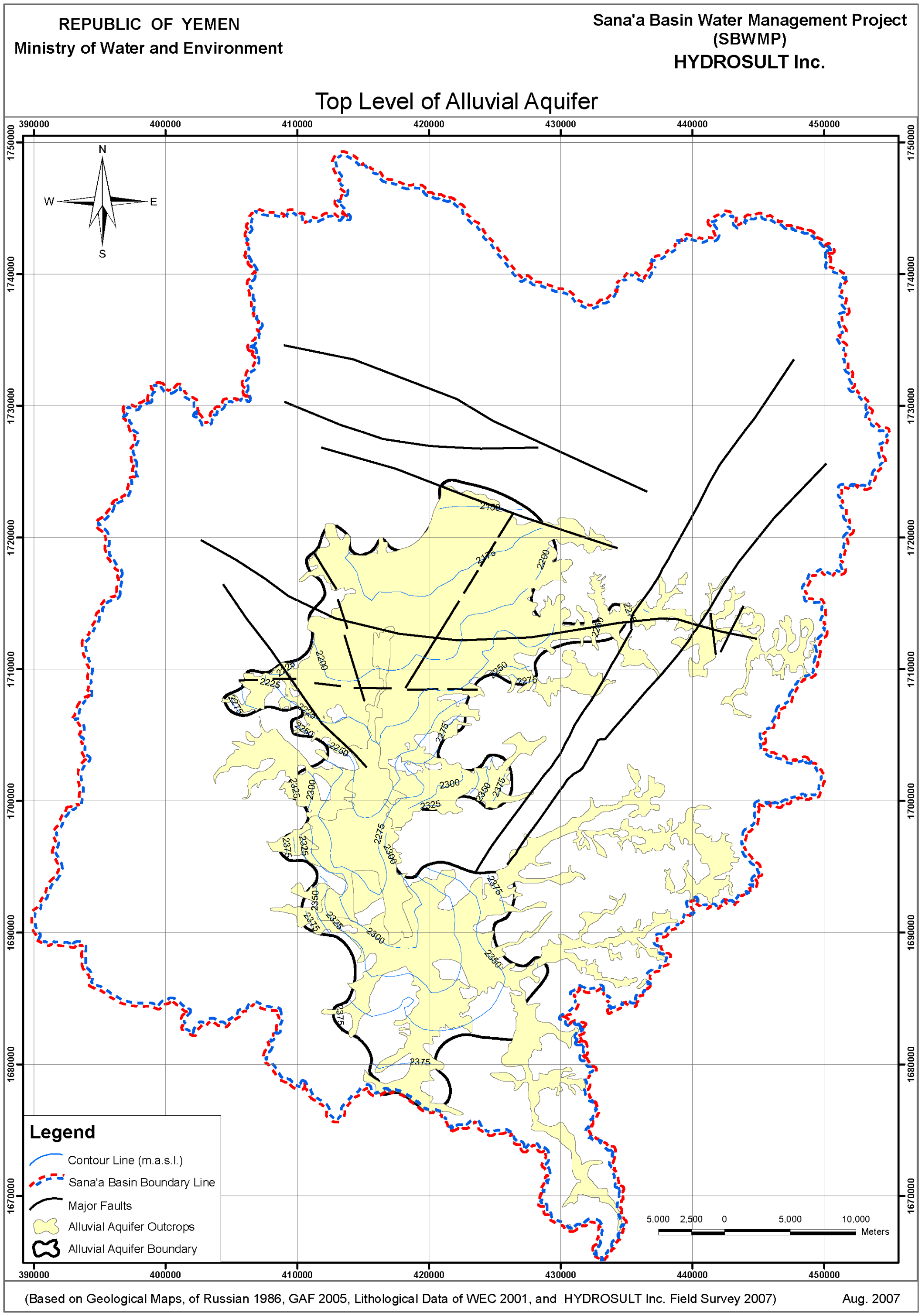

Figure 4-22 Top level map of the Quaternary alluvial aquifer, m amsl

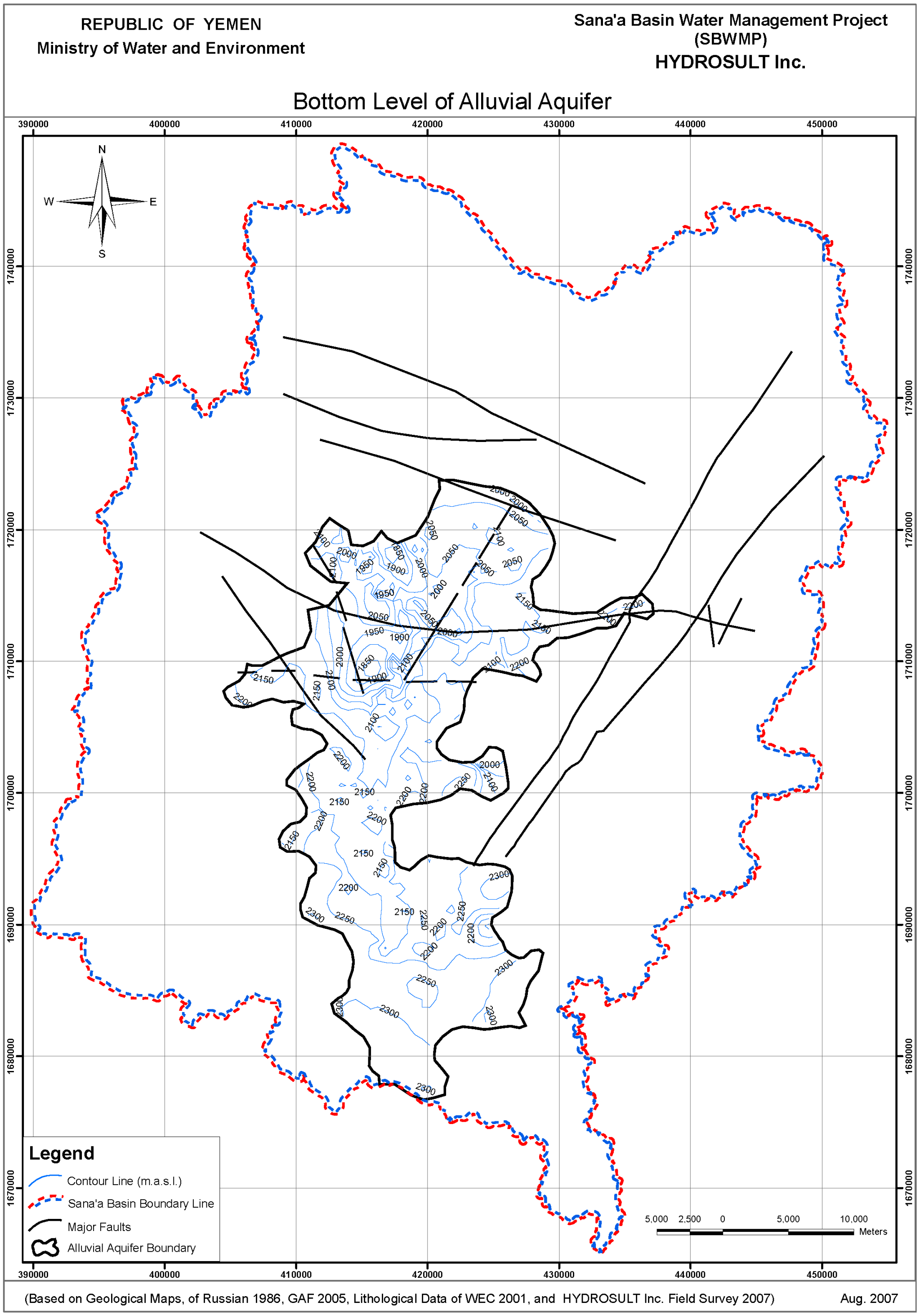

Figure 4-23 Bottom level map of the Quaternary alluvial aquifer, m amsl

4.9.4 Thickness Map of the Quaternary alluvial aquifer

A thickness map of the alluvial aquifer was constructed. The thickness of the alluvial aquifer varies from about 50 meters in the southern part along the boundary of this aquifer to about 350 m in the central and northwestern parts of the Sana'a Plain.

This map (Figure 4-24) indicates:

- The alluvial aquifer thickness reaches a maximum value along the longitudinal axis of the Sana'a Plain, particularly north of Al-Rawdah where the alluvial deposits are approximately 400 m thick.
- The alluvial aquifer thickness map (Figure 4-24) shows that it consists of four small depositional basins. Two sub-basins are situated north of Sana'a City at sub-basin 9 (Bani Huwat). The first is located in the area between the airport and Al-Rawdah, with a thickness of more than 350 m. The second is located north of Sana'a airport with a thickness of more than 250 m. The third sub-basin is located at Wadi Sawan to the east of Sana'a City, with a thickness of approximately 350 m. The fourth sub-basin is located at the confluence of Wadi Shahik (sub-basin 18) and Wadi Ghaiman (sub-basin 19) southwest of Sana'a City, with a thickness of approximately 250 m.
- The alluvial deposits are present mainly in the central part of the basin.
- Maximum thickness of the alluvial deposits is approximately 400 m, as reflected through the wells located in the central plain (particularly at Wadi Bani Huwat, sub-Basin 9 north of Sana'a City, and the area between Al-Rawdah and Sana'a airport).
- It is evident from the thickness map that the alluvial thickness diminishes toward the peripheries of Sana'a Basin.

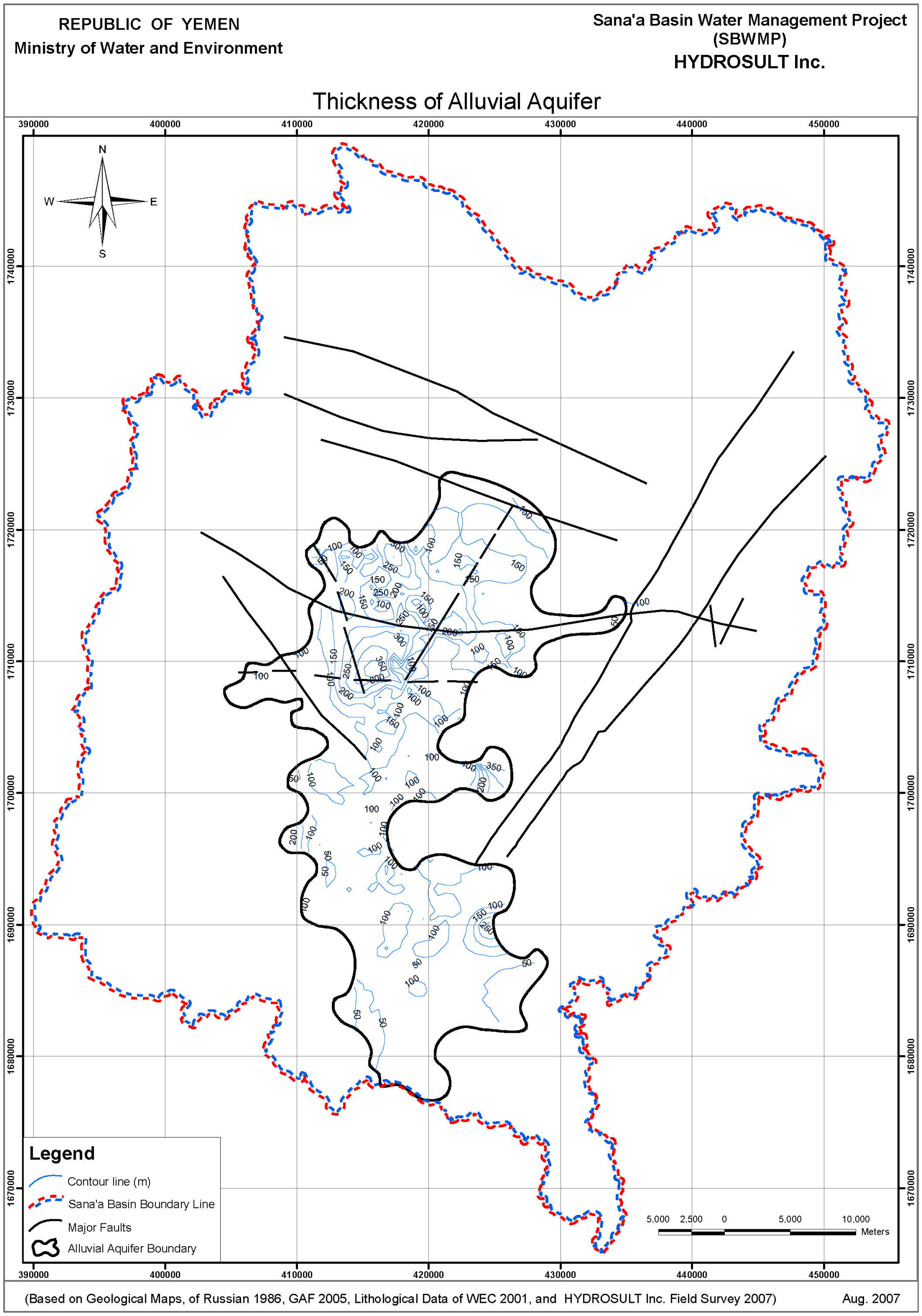

Figure 4-24 Thickness map of the Quaternary alluvial aquifer, m

4.10 Quaternary and Tertiary volcanic aquifer geometry

Extent:

The areal extent of the Tertiary volcanics is well known from the geological map (Figure .4-1). According to the recent geological field survey, the volcanic aquifer outcrops over 59.54% of the area of the Sana’a Basin (i.e. 1925 km^2). The thickness of the aquifer increases rapidly southwards to about 600 m in the southern part of Sana’a City. South of this, 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, 1996).

4.10.1 Top Level Map of the Quaternary and Tertiary volcanic aquifer

This map (Figure 4-25) was constructed using the lithological well data.

The outcropped surface of the volcanic rocks correlates to the topographical elevation of the basin at which the eruptions occurred. This situation is indicated on the map constructed (Figure 4-25). This map indicates the following:

- The volcanic aquifer occupies the eastern, western and southern parts of the basin.
- The maximum depth from ground surface to upper surface of the volcanic aquifer is 2150 m amsl. This point is located in the south-central part of the basin, i.e. at the junction between Wadi Sawan and the alluvial plain.
- The lowest elevation (contour value) of the upper surface of the volcanic aquifer is 3050 m amsl. The highest elevations of the outcropped volcanics are 3050, 3000 and 2700 m amsl in the eastern, southwestern and southern parts of the basin respectively.
- Volcanic rocks are absent from the areas where the older lithostratigraphic units (Cretaceous Tawilah sandstone and Jurassic Amran limestone) are exposed at ground surface.

4.10.2 Bottom Level Map of the Quaternary and Tertiary volcanic aquifers

This map (Figure 4-26) was constructed using lithological well data. This map indicates the following:

- The elevation of the bottom level of the Quaternary and Tertiary volcanic aquifer ranges from 1400 m amsl in the southern and south-central parts of the basin to 2350 m amsl at the northwest of the basin.
- The point of maximum depth from ground surface to the lower surface of the Quaternary and Tertiary volcanic aquifer is in the south-central part of the basin.

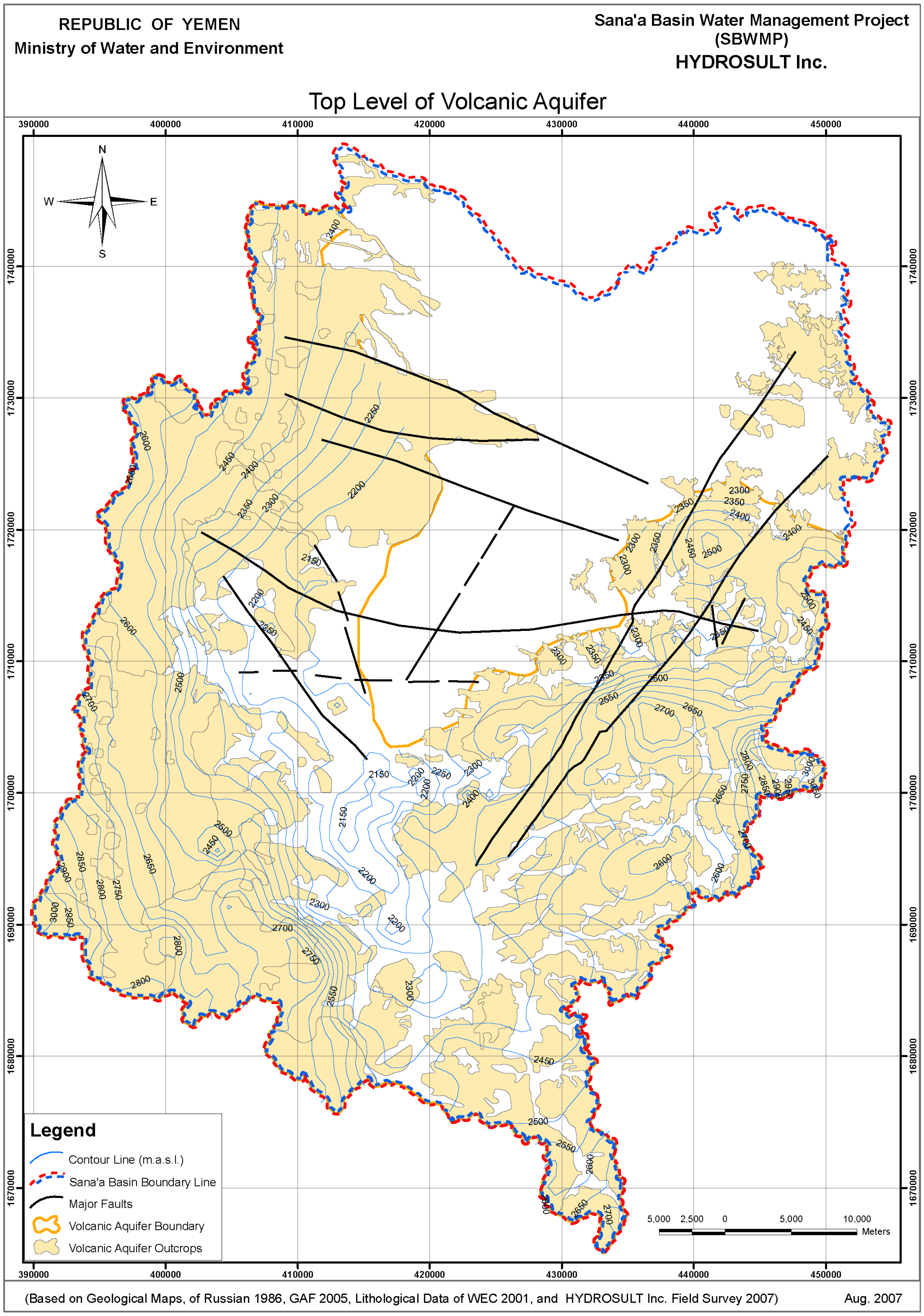

Figure 4-25 Top Level Map of the volcanic aquifer, m amsl

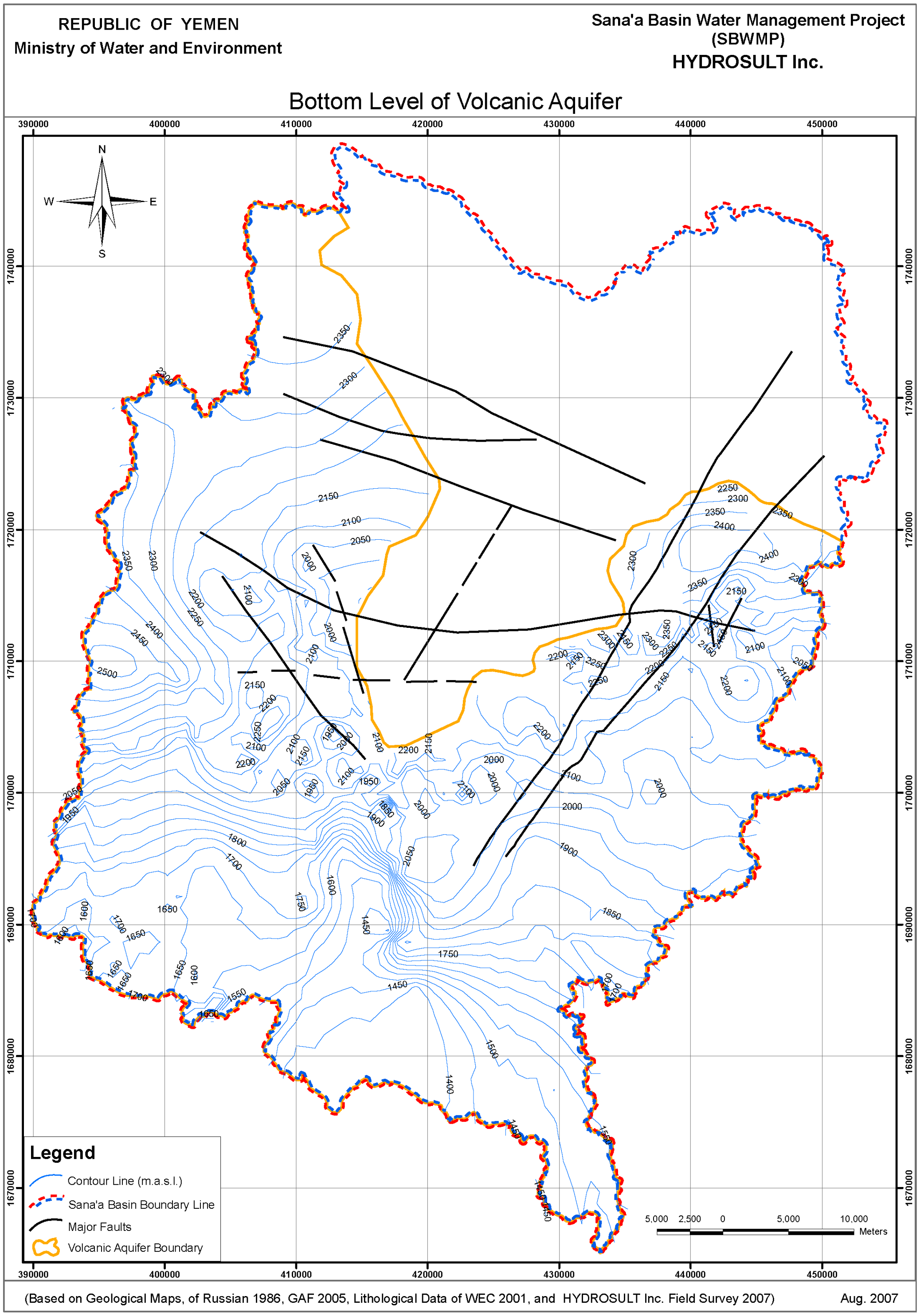

Figure 4-26 Bottom level map of the volcanic aquifer, m amsl

4.10.3 Thickness map of the Quaternary and Tertiary volcanic aquifers

The volcanic aquifer thickness map (Figure 4-27) was constructed using the well lithology data.

The thickness of the volcanic aquifer varies from approximately 50 m in the northeastern and northwestern parts to approximately 850 m in the southern part of the Sana’a Basin. This map indicates the following:

- The thickness of the volcanic aquifer increases towards the southern part of the basin.
- The thickness of the volcanic aquifer decreases towards the central part of the basin (the central plain).
- The volcanic aquifer in the western part of the basin has a thickness greater than in the eastern part.

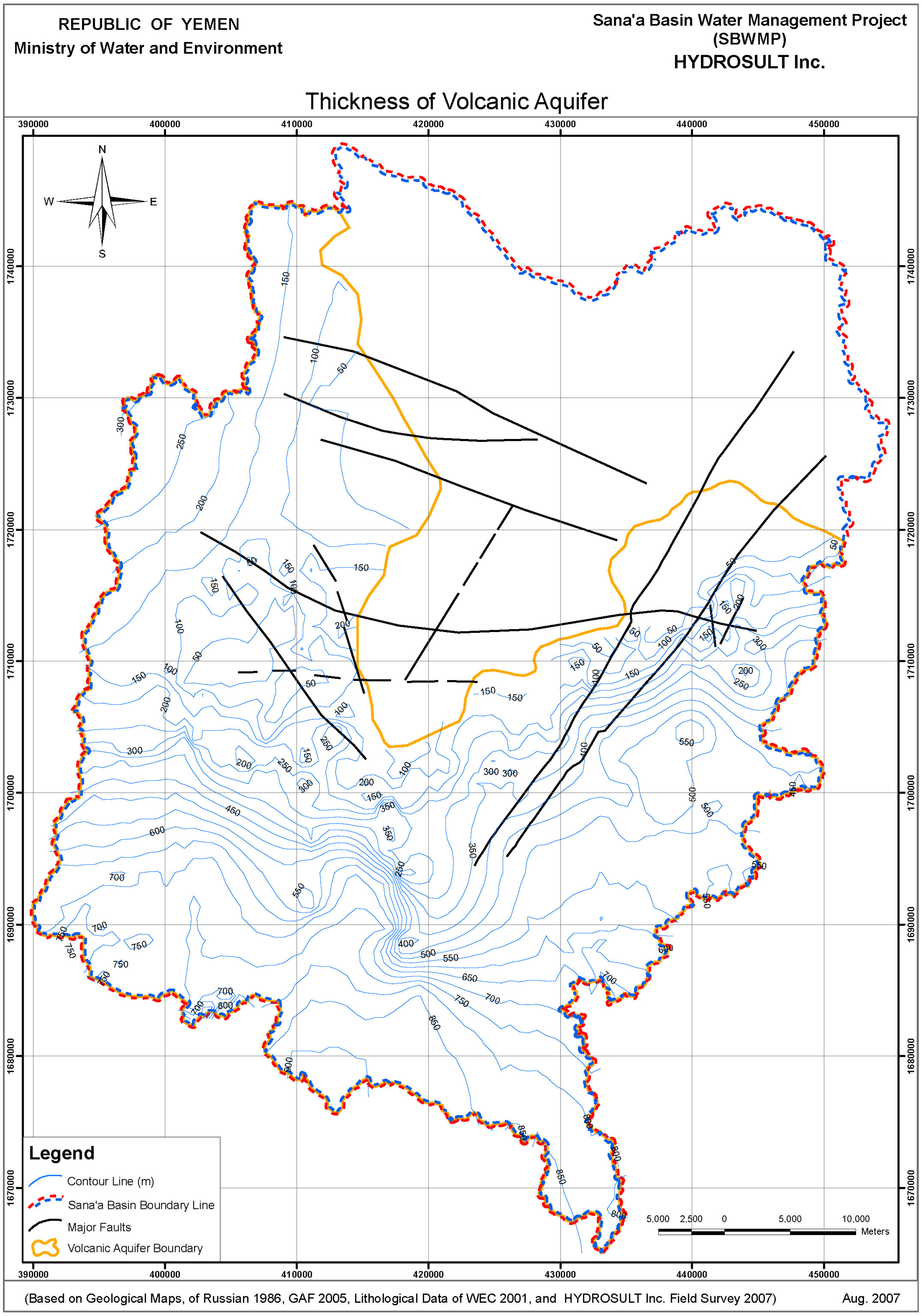

Figure 4-27 Thickness map of the volcanic aquifer, m

4.11 Cretaceous Tawilah sandstone aquifer geometry

Extent:

The Cretaceous Tawilah sandstone outcrops over approximately 8.37% (i.e. approximately 271 km^2) of the basin. It outcrops over a large area around Sana'a City, particularly the north-western, north-eastern area of the Hamdan and Bani Hushaish areas and the northern part of the basin (Al-Hatarish area) (Figure 4-3). It is thought to reach a thickness of 400 to 500 m where it has been protected from erosion by overlying Tertiary volcanics (Naaman, 2004).

The Cretaceous Tawilah sandstone aquifer is bounded by Jurassic Amran limestone at its base, while the top boundary (in leaky artesian conditions) is formed either by the Tertiary/Quaternary Basalts or Quaternary volcanics. In the Sana'a Plain, the Cretaceous Tawilah aquifer either comes into contact with the Quaternary Alluvial or outcrops on the surface representing unconfined conditions.

Towards the south, in the Al-Sabaeen area, abrupt change occurs in the appearance of the Cretaceous Tawilah sandstone which subsides from a depth of 650 m to at least 850 m from ground surface beneath the volcanic rocks. This indicates a great E-W fault in the Al-Sabaeen area (SAWAS project, 1990-1996).

4.11.1 Top Level Map of Cretaceous Tawilah sandstone aquifer

The contour map (Figure 4-28) of the top level of the Cretaceous Tawilah sandstone aquifer was constructed using the well lithology data. This map indicates the following:

It is clear from this map that:

- The Cretaceous Tawilah sandstone outcrops in the Bani Husheish, Nihm and Hamdan areas, as marked in green.
- In the rest of the Sana'a Basin, the top level of the Cretaceous Tawilah sandstone aquifer is hidden under a considerable thickness of alluvial and/or volcanic rocks.
- In the outcropped areas, the elevation of the top level of the Cretaceous Tawilah sandstone aquifer ranges from 2550 m to 2600 m amsl.
- In the sub-crop areas (southern part of the basin), the elevation of the top level of the Cretaceous Tawilah sandstone aquifer ranges from 1700 m to 2450 m amsl.
- In general, the elevation of the Cretaceous Tawilah sandstone aquifer ranges from 1700 to 2600 m amsl.

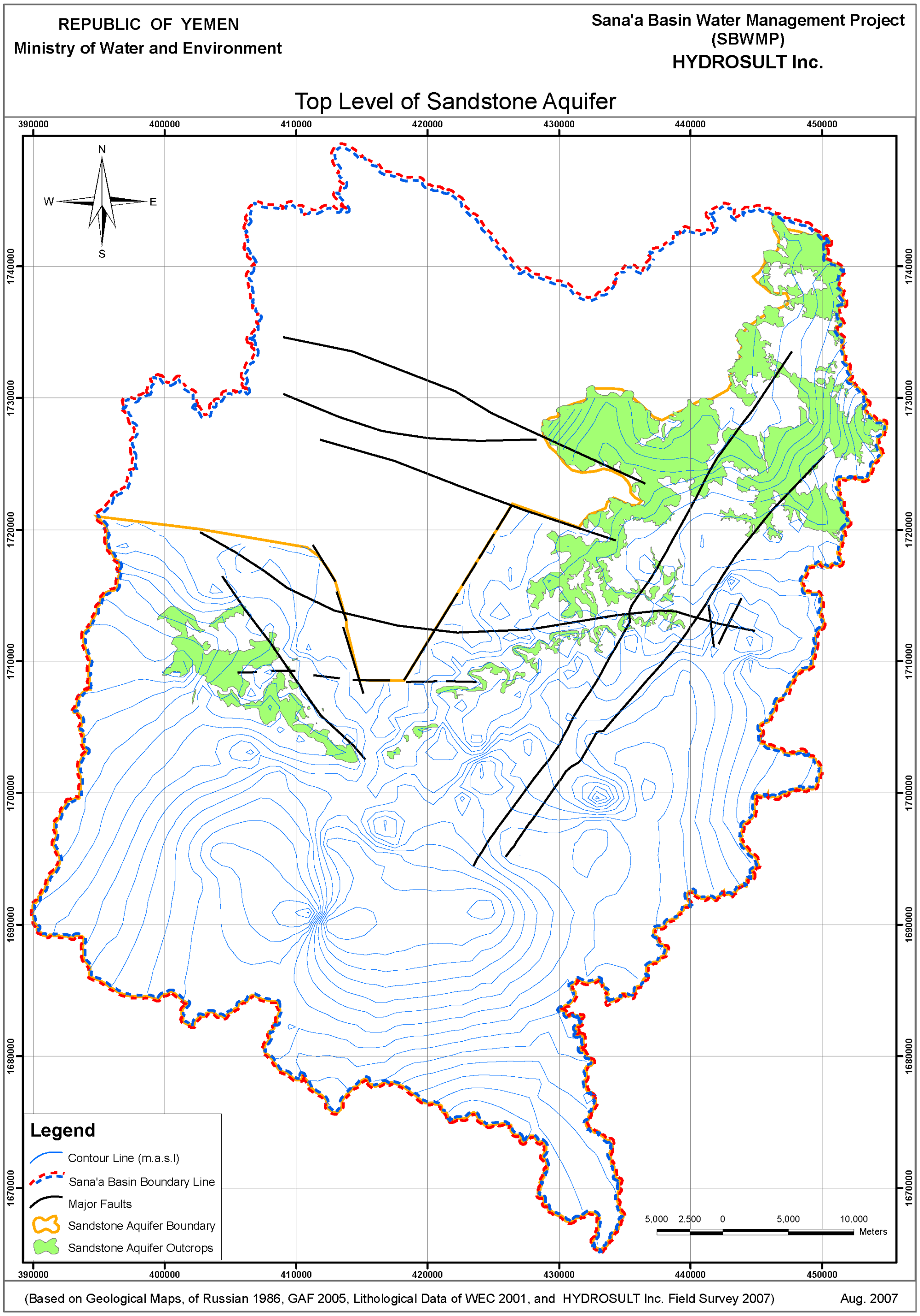

Figure 4-28 Top level map of the Cretaceous Tawilah sandstone aquifer, m amsl

4.11.2 Bottom Level Map of the Tawilah sandstone aquifer

The contour map of the bottom level of the Tawilah sandstone aquifer (Figure 4-29) is constructed using the well lithology data.

Very limited data related to the lower boundary of the Tawilah sandstone aquifer is available over the entire Sana’a Basin. Therefore, it was assumed that the average thickness of Tawilah sandstone is 350 m from the lower surface of any stratigraphic horizon overlying the Tawilah sandstone aquifer. The figure of 350 m was selected based on the review and analysis of previous stratigraphic studies (El-Anbaawy, 1983 and Al-Subbary, 1995) and the deep seismic data of Exxon, 1987, which indicated that the average thickness of this lithostratigraphic unit ranges from 350 m to 400 m.

The map constructed shows that:

- The lowest elevation value of the bottom level of the Cretaceous Tawilah sandstone is 1250 m amsl and is detected in the southern part of Sana’a Basin. The highest elevation values are 2150 m and 2250 m. These points were detected in areas where the Cretaceous Tawilah sandstone aquifer is exposed (western, eastern and north-eastern parts of the basin).
- In general, the elevation of the bottom level of the Tawilah sandstone aquifer ranges from 1250 m to 2250 m amsl.

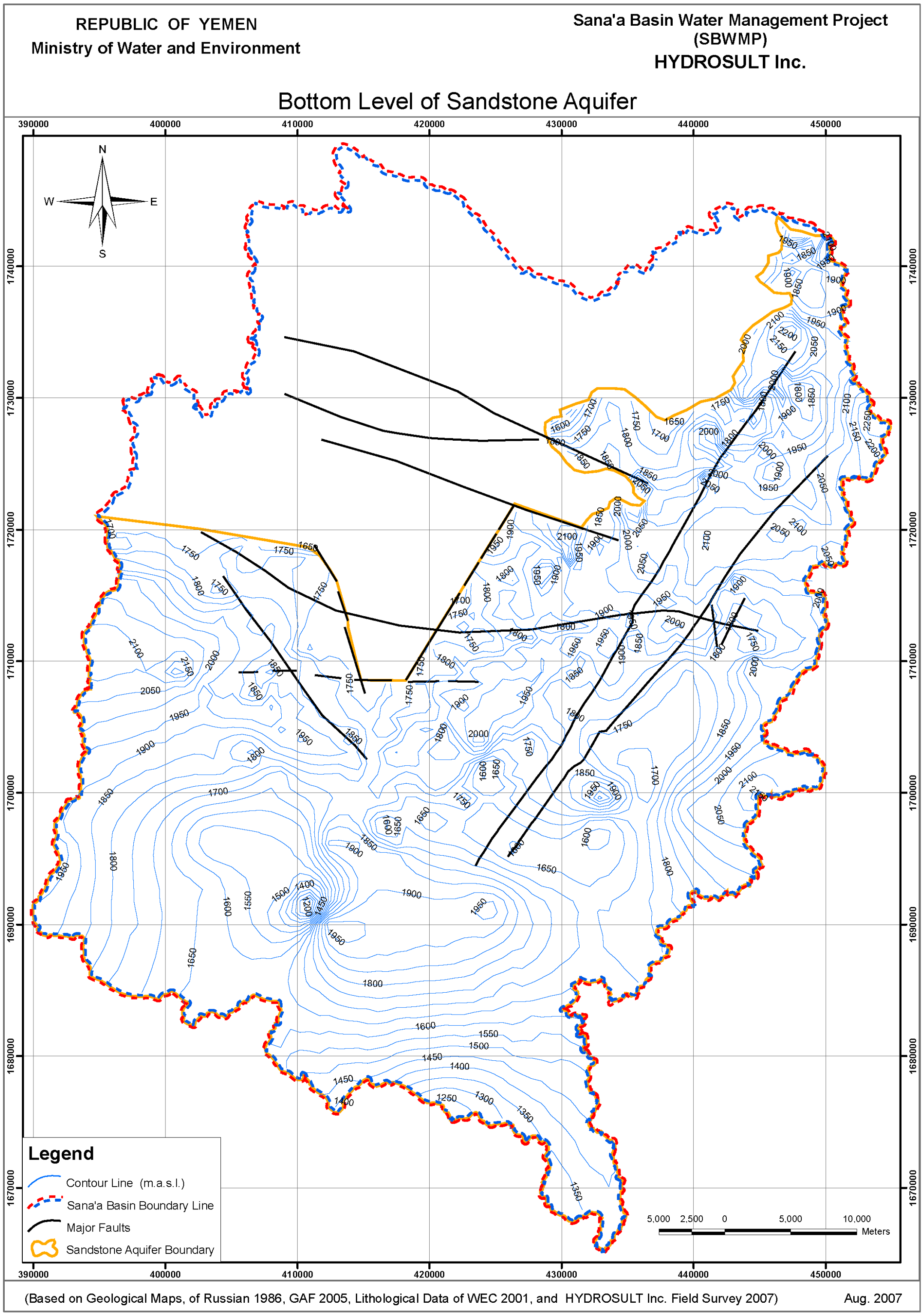

Figure 4-29 Bottom level map of the Cretaceous Tawilah sandstone aquifer, m amsl

4.11.3 Thickness Map of the Tawilah sandstone aquifer

The recent Tawilah sandstone aquifer thickness map (Figure 4-30) was constructed using the well lithology data.

The average thickness of the Tawilah sandstone aquifer varies from approximately 50 m in northeastern parts to more than 700 m in the southwestern part of the Sana'a Basin. This map indicates:

- In the Nihm area, where the Cretaceous Tawilah sandstone outcrops at the surface, the average thickness ranges from 50 m, where the sandstone was subjected to intense weathering, to 350 m in some localities where the sandstone is capped and protected from erosion by the Tertiary volcanic rocks.
- In the Bani Hushaish area, where the Cretaceous Tawilah sandstone outcrops at the surface, the average thickness of the Cretaceous Tawilah sandstone aquifer ranges from 150 m to 350 m.
- In the Hamdan area, where the Cretaceous Tawilah sandstone outcrops at the surface, the average thickness of the sandstone ranges from 350 m to 450 m.
- In the southern part where the Cretaceous Tawilah sandstone is present below the volcanic and alluvial deposits, the average thickness of the Cretaceous Tawilah sandstone ranges from 350 m to 700 m (in the southeastern and southwestern parts respectively).

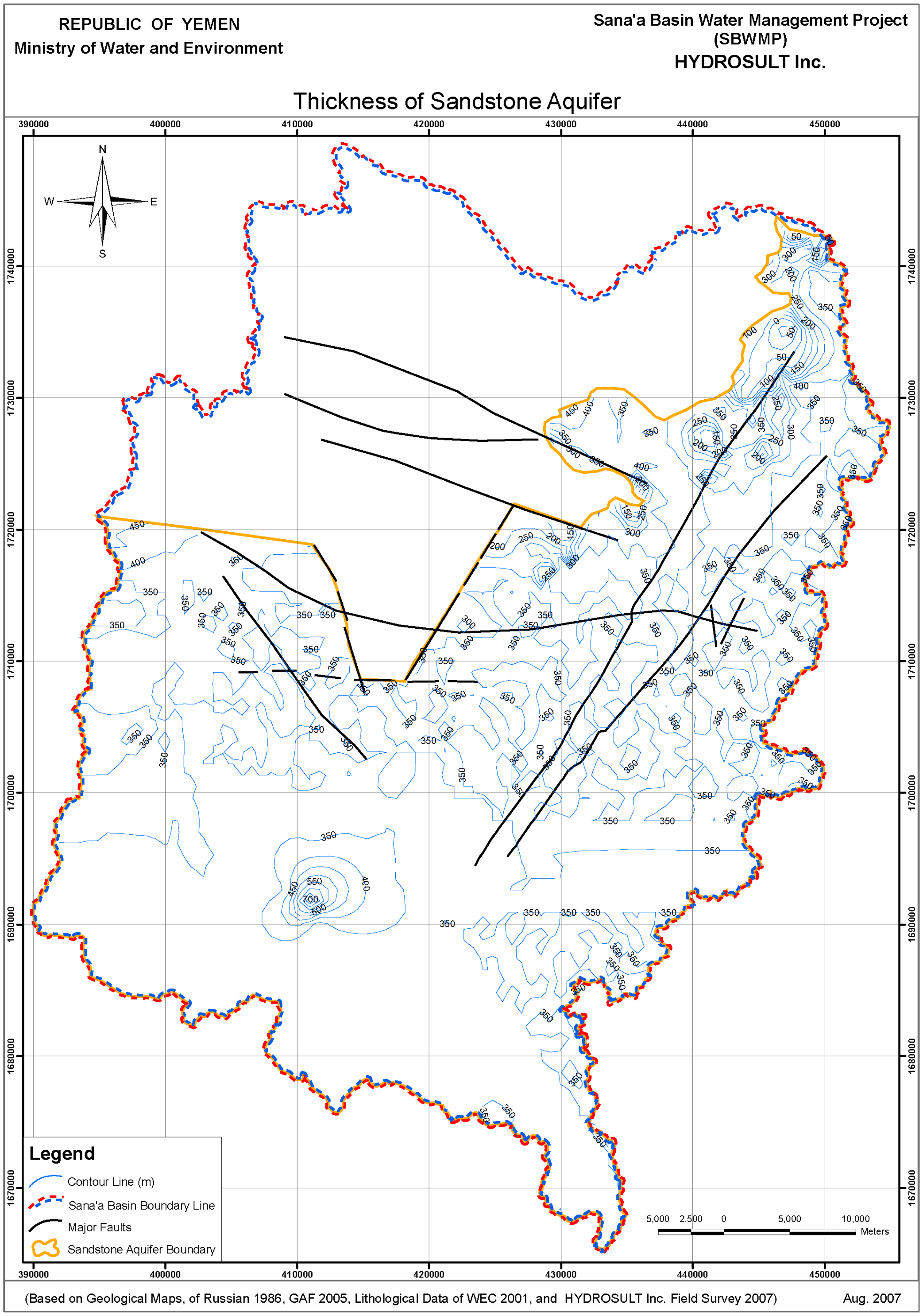

Figure 4-30 Thickness map of the Cretaceous Tawilah sandstone aquifer, m

4.12 The Jurassic Amran limestone geometry

Extent:

The Jurassic Amran limestone outcrops at the surface in the northern part of the basin covering approximately 16.58% (i.e. approximately 536.7 km^2). It outcrops over a large area to the north of Sana'a City, in Arhab, Bani Al-Harith and Nihm areas (Figure 4-3).

It has an outcropped thickness of approximately 320 m (WEC, 2001). The surface contact between the Amran group and outcrops of the other lithostratigraphic units can be easily traced in several areas such as Jabal As-Sama, Bani Jermouz, Bait Dahra, Bait Al-Anz, Shera'a, Arisha, Al-Hayathem, Bani Zeter, Nobat Shekwan, Mahali, Meswarah. The surface contact can also be traced in the northwestern part of the basin (Hamdan area) with the Tertiary and Quaternary volcanics. In the remainder of the basin, the thickness of the Amran group is almost obscured, since the majority of the wells in Sana'a Basin do not penetrate the limestone. The only available information about its thickness was obtained from two boreholes, DS-1 and DS-2, 10 km and 30 km respectively northeast of Sana'a City. The thickness of the limestone in DS-1 is 1280 m and in DS-2 it is 1260 m (Kruseman and Vasak, 1996). It occurs at depth beneath the Sana'a Plain: at the airport, the top of the Amran is approximately 350 m deep; at Al-Rawdah 500 m and further south near Sana'a City it reaches 900 m or more. The Amran is overlain by a sequence of lagoonal shales, marls and fine-grained sandstone inter-bedded with lignite, probably of Upper Jurassic or Lower Cretaceous age, which outcrops in a narrow band in the north-eastern part of the basin (Naaman, 2004). It conformably overlies the Kohlan group.

4.12.1 Top Level Map of the Jurassic Amran limestone aquifer

The contour map (Figure 4-31) of the top level of the Amran limestone aquifer was constructed using well lithology data.

This map indicates:

- The Amran limestone outcrops in the northern part of the basin and is marked in blue.
- In the remaining parts of the Sana'a Basin, the top level of the Amran limestone aquifer is hidden under a thick layer of either Tawilah sandstone, alluvial and/or volcanic rocks.
- In the outcropped areas, the elevation of the top level of the Cretaceous Tawilah sandstone aquifer ranges from 2000 m to 2450 m amsl.
- In the sub-surface, the elevation of the top level of the Amran limestone aquifer ranges from 1250 m to 2350 m amsl in the southern and western parts respectively.
- In general, the elevation of the Amran limestone aquifer ranges from 1250 m to 2450 m amsl.

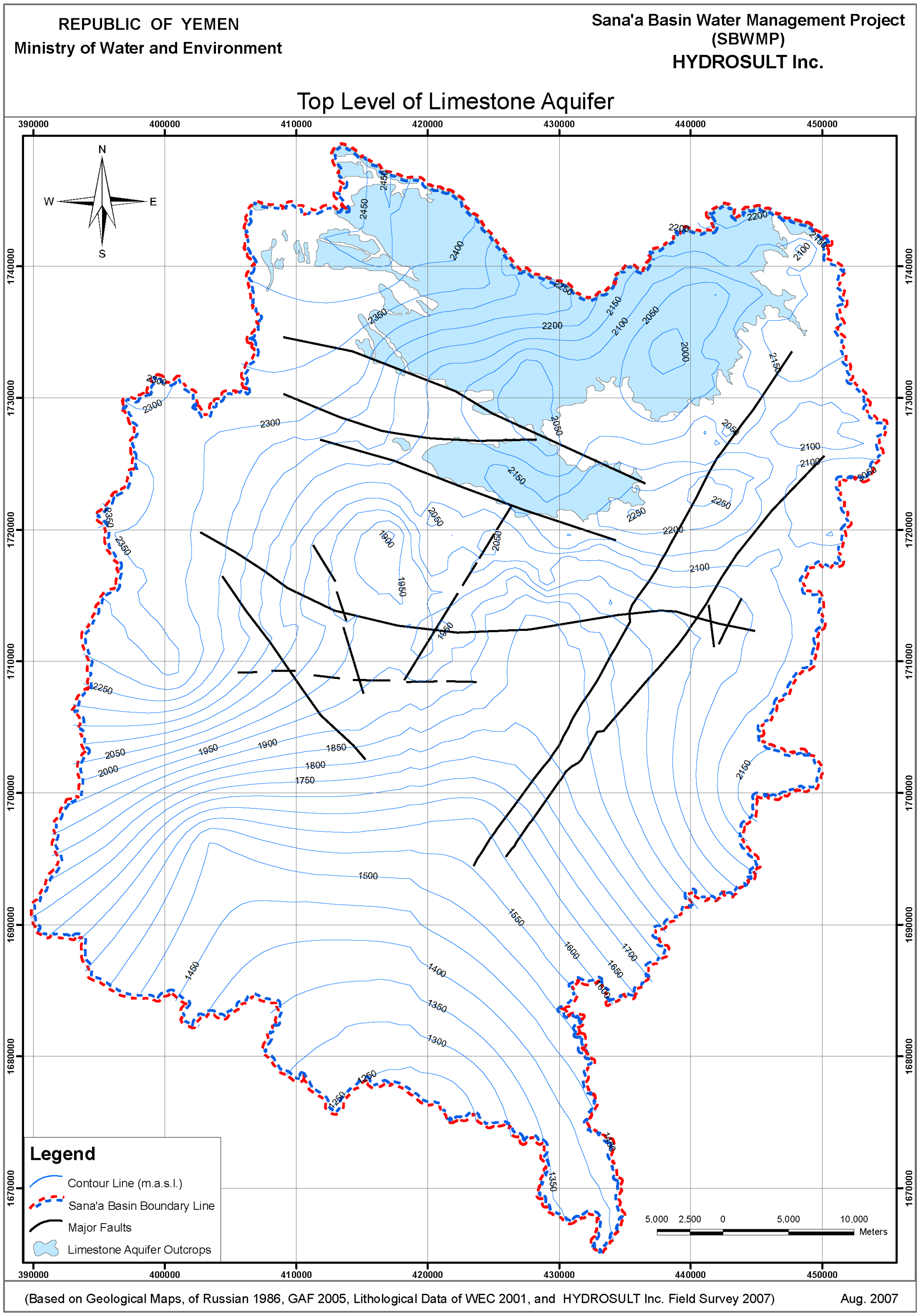

Figure 4-31 Top level map of the Jurassic Amran limestone aquifer, m amsl