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Chapter 10. HYDROGEOLOGIC FINDINGS IN SANA'A BASIN

GENERAL OUTLINE

This chapter covers three important issues of the hydrogeological findings of the activities carried out in Sana'a Basin. These issues are the relationship between the different aquifers in the basin, the impact of the different structural features on the hydrogeologic setting and the effect of impermeable layers on groundwater flow. The following is a brief discussion of these three items.

10.1. Relation between different aquifers in Sana'a Basin

The three main aquifers distinguished in Sana'a Basin – Alluvium, Volcanics and Sandstone – are described in the previous chapters. The properties of each aquifer are presented extensively, but not yet the interaction between the aquifers.

The presence of a hydraulic connection between the aquifers can be derived from the characteristics of the springs at the head of Wadi Al-Kharid. The hydrogeochemical characteristics of the springs are similar to that of the groundwater of the alluvium and Tawilah sandstone. Also, the spring discharge has declined during the period of important groundwater abstraction in the northern Sana'a Basin (WEC-ITC, 2001).

In this chapter, the relationship between the present aquifers in Sana'a Basin is proved based on the following findings:

- Geologic finding,
- Hydrogeologic finding,
- Hydrogeochemical finding,
- Cluster analysis finding.

10.1.1. Geologic finding

The hydrogeologic cross-section B-B' (Figure 10-1 and Table 10-1, see also chapter 4) is constructed near the springs of Wadi Al-Kharid. The cross-section reflects more or less a lateral hydraulic connection between adjacent aquifers through fault planes. The visual inspection of Figure 10-1 supposes a hydraulic connection between the fractured Volcanic aquifer and the Alluvium aquifer in the west through continuum (active fractures). The same case is also present with the Alluvium outcrops and Shallow Tawilah sandstone zone in the east.

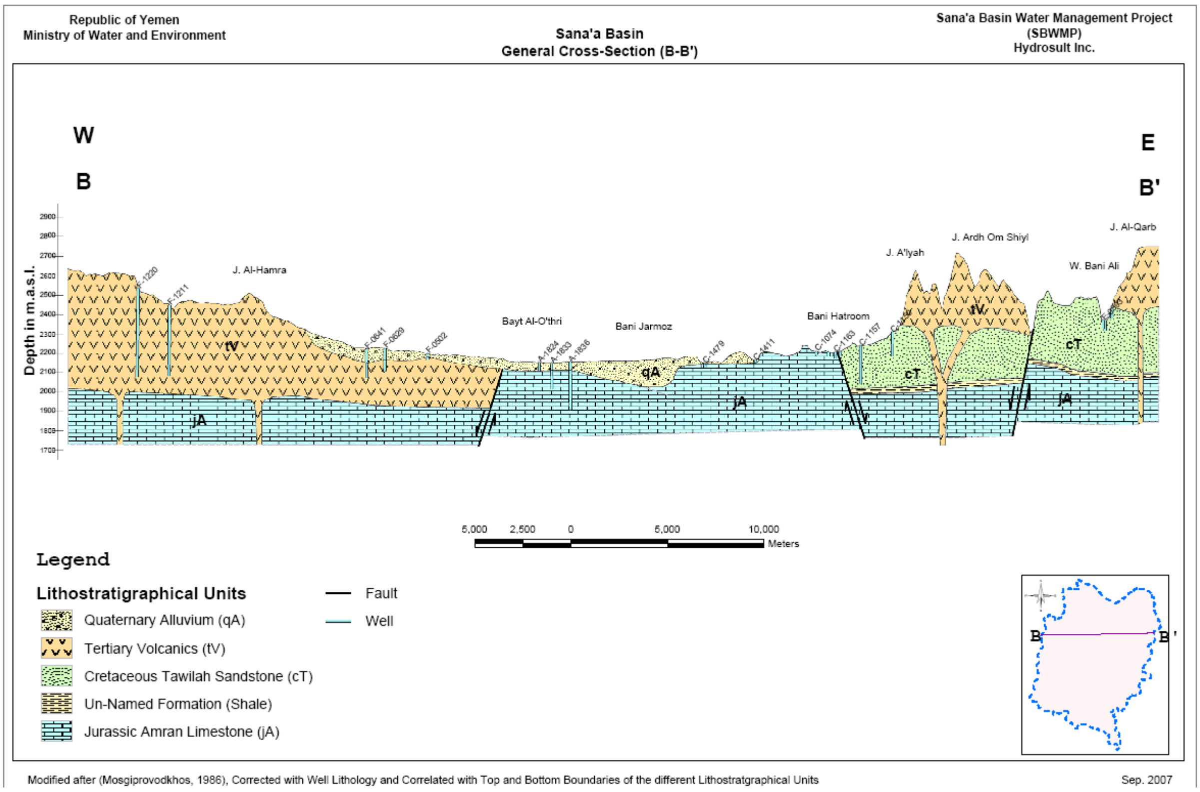

Figure 10-1 Hydrogeological cross-section B-B' in Sana'a Basin in W-E direction

Table 10-1 Description of lithologic units present in B-B' cross-section

Name of the Cross-Section	Location	Direction	No. of wells covered	Aquifers encountered through the cross-section	Geological Structures
B-B'	Sana'a Basin	East-West	20	Quaternary alluvium Tertiary Volcanics Cretaceous Tawilah sandstone Un-named formation (Shale) Jurassic Amran limestone	Three normal faults are encountered forming graben and horst structures

10.1.2. Hydrogeologic finding

To check the hydraulic connection between the different aquifers present, the three water table maps constructed for the Alluvium aquifer (green-colored contour lines), Tawilah sandstone aquifer (blue-colored contour lines) and Volcanic aquifer (red-colored contour lines) were superimposed on the same base map (Figure 10-2). A line coinciding with the latitude of 1,720,000 UTM passes through the outcrops of the aquifers representing cross-section Z-Z' (this corresponds more or less with the position of cross-section B-B' of Figure 10-1). Cross-section line Z-Z' cuts the superimposed contour lines in points of intersection with different longitudes values. The relation between the values of the different longitudes and the different water levels was graphic as scattered points (Figure 10-3).

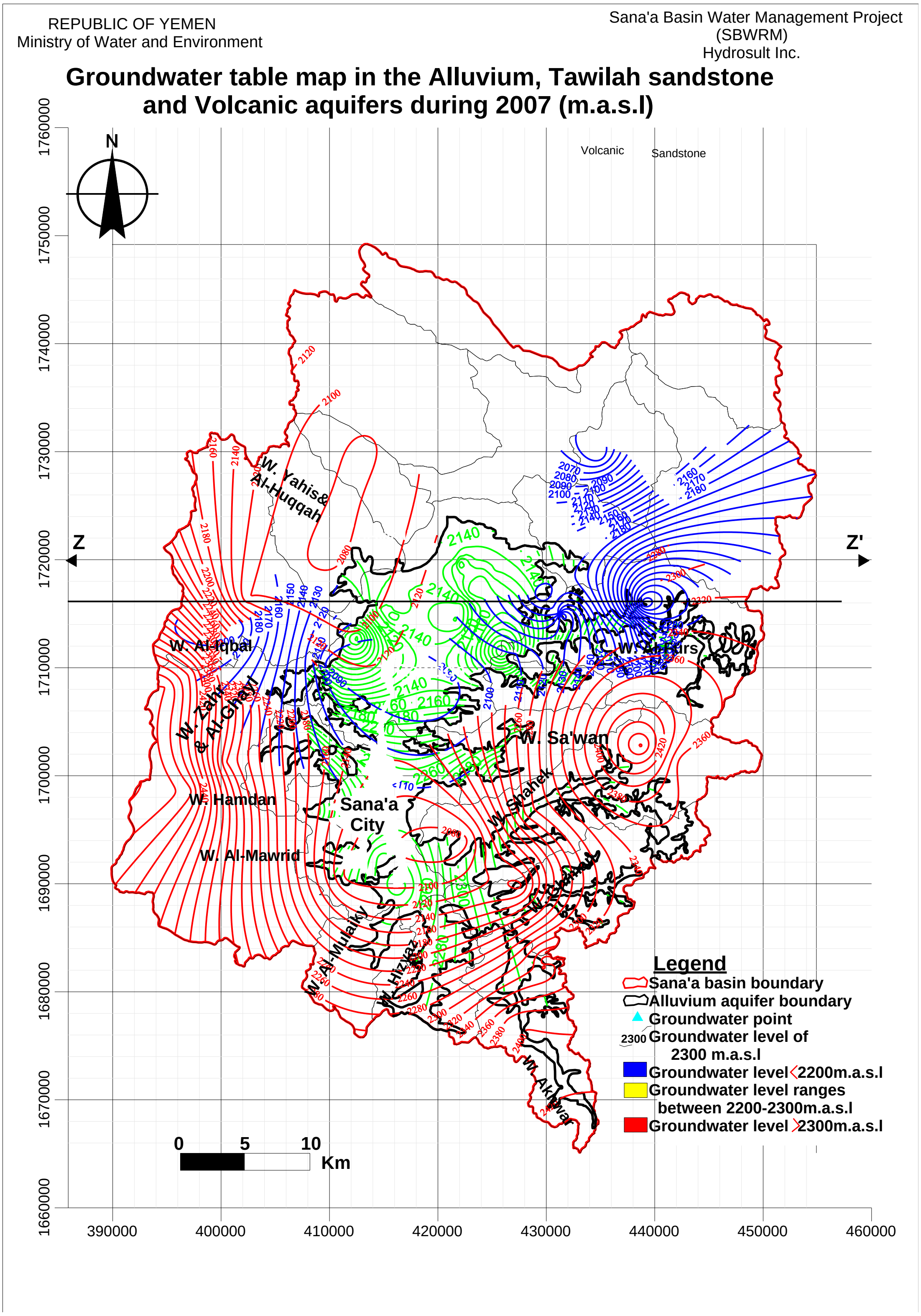

Figure 10-2 Superimposed maps of water table contour lines of different aquifers in Sana'a Basin

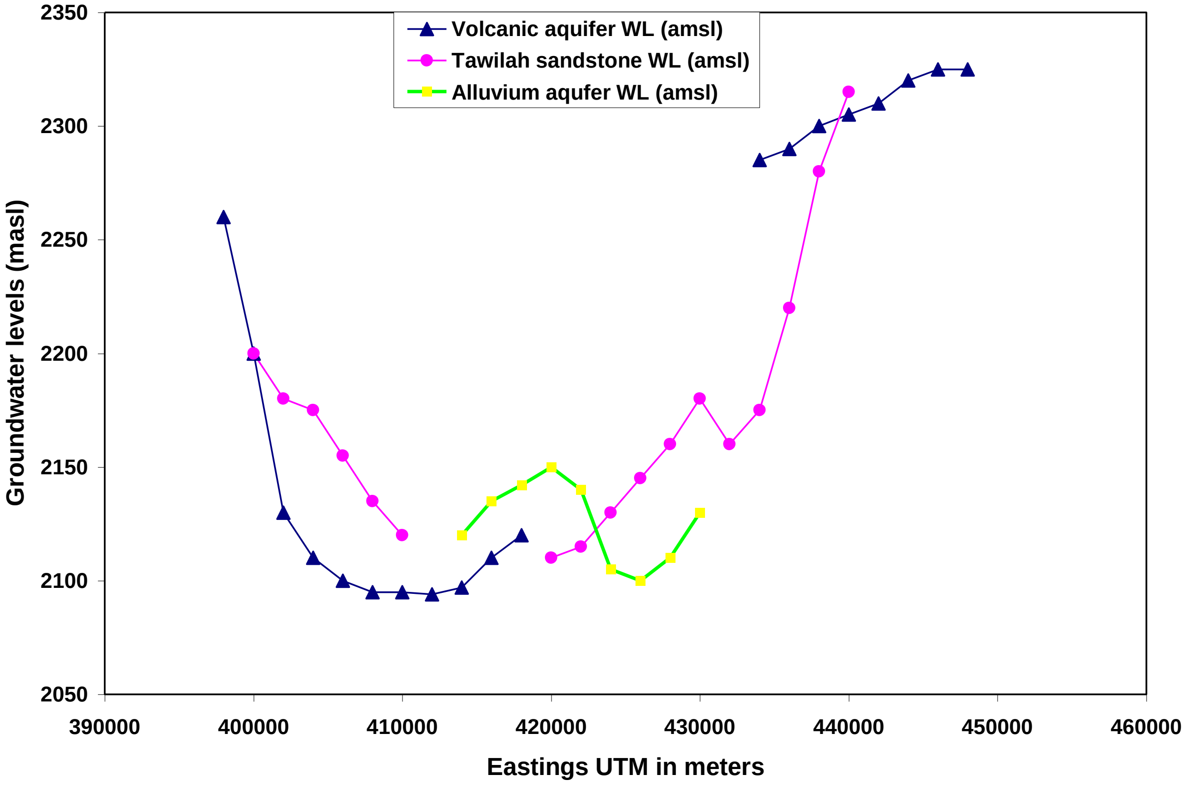

Figure 10-3 Water levels along cross-section Z-Z' in the present aquifers in Sana'a Basin

Figure 10-3 shows two intersection points between groundwater levels in the Volcanic aquifer (dark-blue-colored line) and groundwater level in Tawilah sandstone aquifer (pink-colored line) at groundwater level of 2200 m in the western part of Sana'a Basin and 2300 masl in the eastern part. This means that there is hydraulic connection at these locations between these two aquifers in the western and eastern sides of the basin (at longitudes 400000 UTM and 440000 UTM respectively). With respect to the Alluvium aquifer, it is noticed that the intersection point between groundwater of the Alluvium aquifer and that of the Tawilah sandstone aquifer lies East of latitude 420000 UTM, which means that Tawilah sandstone groundwater feeds the Alluvium aquifer by vertical flow (downstream of Wadi As-Sir).

It is worth mentioning that the groundwater level of Volcanic aquifer (dark-blue-colored line) shows that hydraulic conditions of the eastern part of the aquifer differ from the western part, which leads to the hypothesis of dividing this aquifer into two separate aquifers. More detailed studies are recommended to substantiate this result.

10.1.3. Hydrogeochemical findings

To study the relationship between the present aquifer in Sana'a Basin based on the chemical composition of groundwater samples analyzed, different profiles are drawn traversing the different aquifers in E-W and N-S directions.

Profile A-A' was constructed depending on the available chemical analyses of 5 wells, including three aquifers across Sana'a Basin in an E-W direction (Table 10-3 and Figure 10-4). It shows a general trend of decreasing salinity, sodium, potassium and chloride from east to west. This means a descending order of salinity from Volcanic aquifer in the east, to Tawilah sandstone aquifer, to Alluvium and Volcanic aquifers in the west. Abrupt decrease in salinity of groundwater at water point HS 129, which may be attributed to recharge from Tawilah sandstone outcrops at Wadi As-Sir to the adjacent Volcanic aquifer through faults and fissures characterizing Tawilah sandstone aquifer in this locality. Another abrupt increase of calcium and sulphate at the middle of the profile is noticed at water point HS 55 (El-Gheras locality), which lies at the boundary between Alluvium and Tawilah sandstone aquifers. This may be due to the mixing process between the groundwaters of the two aquifers. To the contrary, magnesium, carbonate and bicarbonate are constant, generally from east to west. The prevailing salts along this profile are the sulphates of Na^{+}, Mg^{++} and Ca^{++} in addition to $Ca(HCO_3)_2$ and NaCl. As the salinity decreases towards the west, the salts $Ca(HCO_3)_2$, $Mg(HCO_3)_2$ and $NaHCO_3$ appear in groundwater in addition to NaCl and Na_2SO_4.

Table 10-2 Ion concentration in epm of groundwater samples from different aquifers in Sana'a Basin

Well ID and aquifer type	Ca	Mg	Na+K	HCO3+CO3	SO4	Cl
HS 131(Volcanic aquifer)	7.89	2.89	21.10	7.88	13.53	9.18
HS 129 (Volcanic aquifer)	4.31	1.02	1.09	3.15	1.52	1.69
HS 55 (Sandstone aquifer)	13.73	2.58	4.99	3.15	15.62	1.89
HAS 94 (Alluvium aquifer)	3.24	1.19	3.21	3.81	1.50	2.36
HAS 93 (Alluvium aquifer)	0.53	0.14	4.37	2.23	1.33	1.55
HSH 8 (Volcanic aquifer)	1.94	1.11	1.32	3.42	0.46	0.68

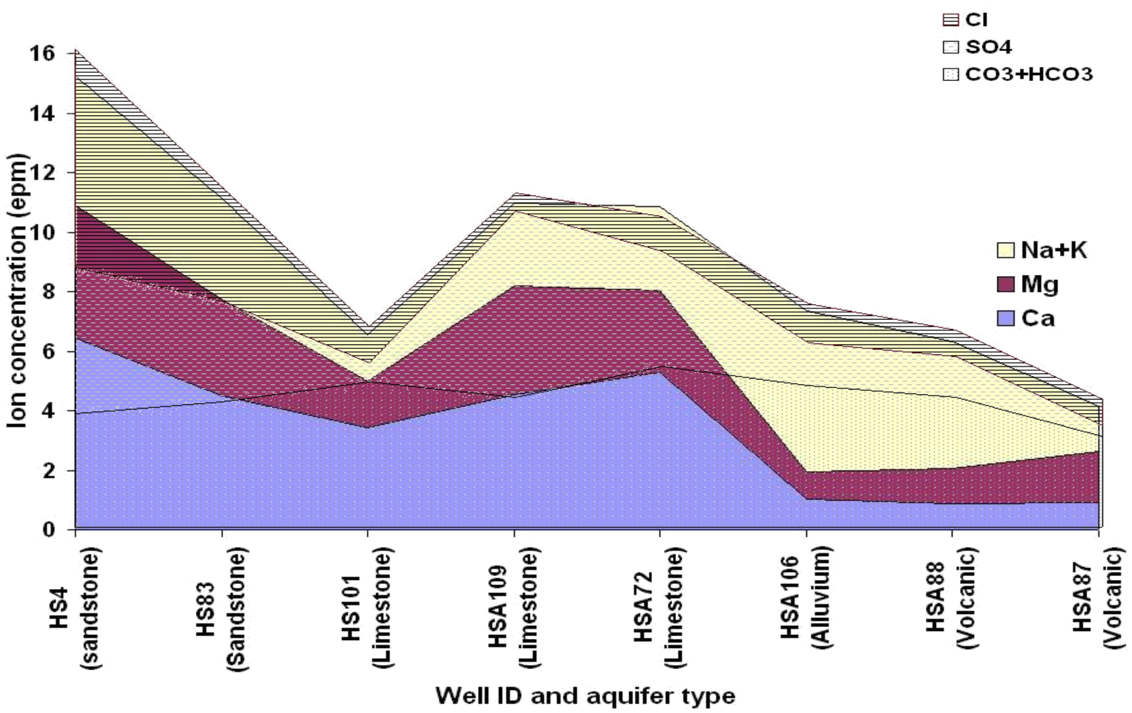

Figure 10-4 Hydrochemical profile A-A' in E-W direction of Sana'a Basin

Profile B-B' was constructed based on available chemical analyses of six wells, including three aquifers across Sana'a Basin in E-W direction (Table 10-4 and Figure 10-5).

This profile passes through Sana'a plain in an E-W direction. It shows a general decrease of salinity from east to west as a result of mixing between groundwater of the Alluvium aquifer with groundwater of the adjacent Quaternary Volcanic aquifer in the western part of the basin. Calcium, magnesium, sulphate and chloride ions follow the same trend of salinity decrease. To the contrary, sodium and potassium increase generally from east to west. But carbonate and bicarbonate are in the same constant trend. The prevailing salts along this profile are $Ca(HCO_3)_2$, $Mg(HCO_3)_2$, $NaHCO_3$, $CaSO_4$, $MgSO_4$, $MgCl_2$ and NaCl in a due east direction. These marine salts $CaSO_4$, $MgSO_4$, Na_2SO_4 and NaCl prevail towards the beginning of the profile due east. The abrupt change in hydrochemical profile at well HS 129 (Volcanic groundwater) reflects recharge process to the groundwater of this locality from adjacent aquifers. In addition, the smooth decrease in salinity of Alluvium groundwater (from well HAS 94 to well HAS 93) reflects recharge from the adjacent Tawilah sandstone aquifer.

Table 10-3 Ion concentration in epm of groundwater samples from different aquifers in Sana'a Basin

Well ID and aquifer type	Ca	Mg	Na+K	HCO3+CO3	SO4	Cl
HS 131(Volcanic)	7.89	2.89	21.10	7.88	13.53	9.18
HS 129 (Volcanic)	4.31	1.02	1.09	3.15	1.52	1.69
HS 55 (Sandstone)	13.73	2.58	4.99	3.15	15.62	1.89
HSA 94 (Alluvium)	3.24	1.19	3.21	3.81	1.50	2.36
HSA 93 (Alluvium)	0.53	0.14	4.37	2.23	1.33	1.55
HSH 8 (Volcanic)	1.94	1.11	1.32	3.42	0.46	0.68

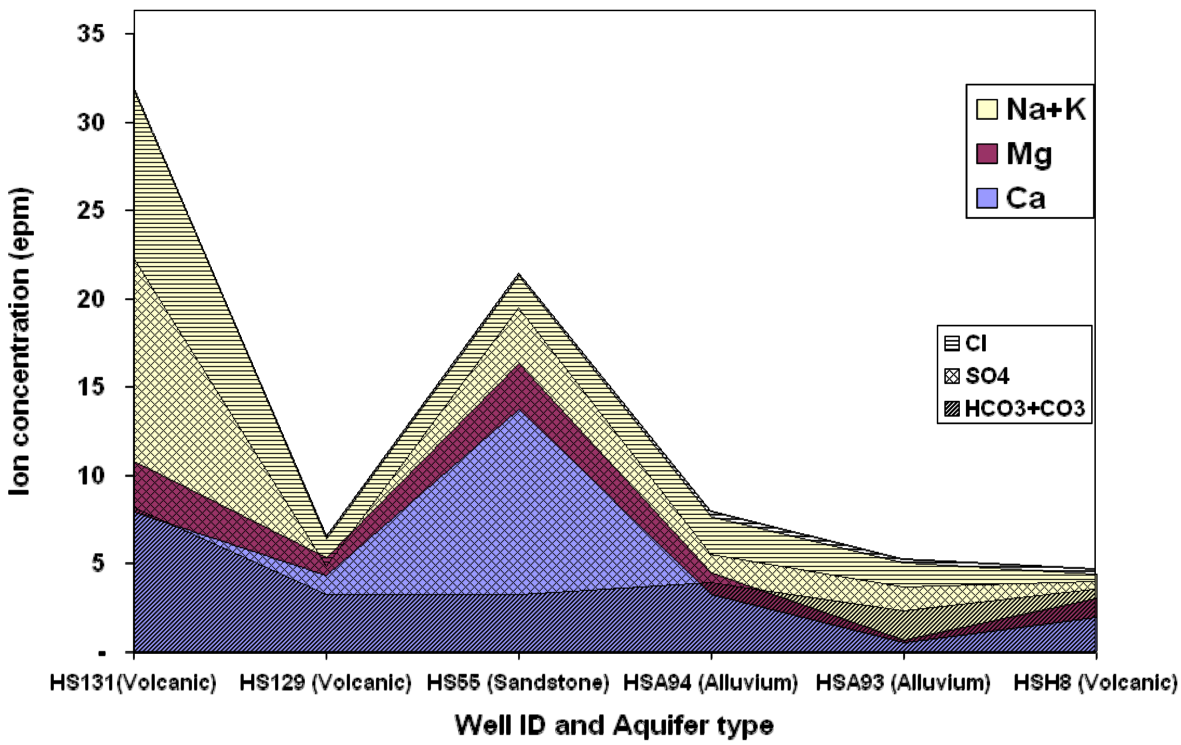

Figure 10-5 Hydrochemical profile B-B' in E-W direction passes through Sana'a plain in Sana'a Basin

10.1.4. Cluster analysis findingS

The analysis of variance (ANOVA) of the hydrochemical analysis of 119 samples cover the four present aquifers in Sana'a Basin with Alpha-level of 0.05 was carried out to study the relation between different aquifers. The multivariate statistics, correlation analysis and cluster analysis were carried out using computer program (STATISTICA, 4.5B, 1993). From these analyses, the general remarks may be obtained (Table 10-5 and Figs.10.6-8):

1- Normal distribution of the hydrochemical variables of the groundwater samples reflects a good correlation between them (Figure 10-6), while the analysis of variance of data sets shows that the linear regression between variables are significant with confidence level 95% and 124 degrees of freedom as shown in Table 10-5.

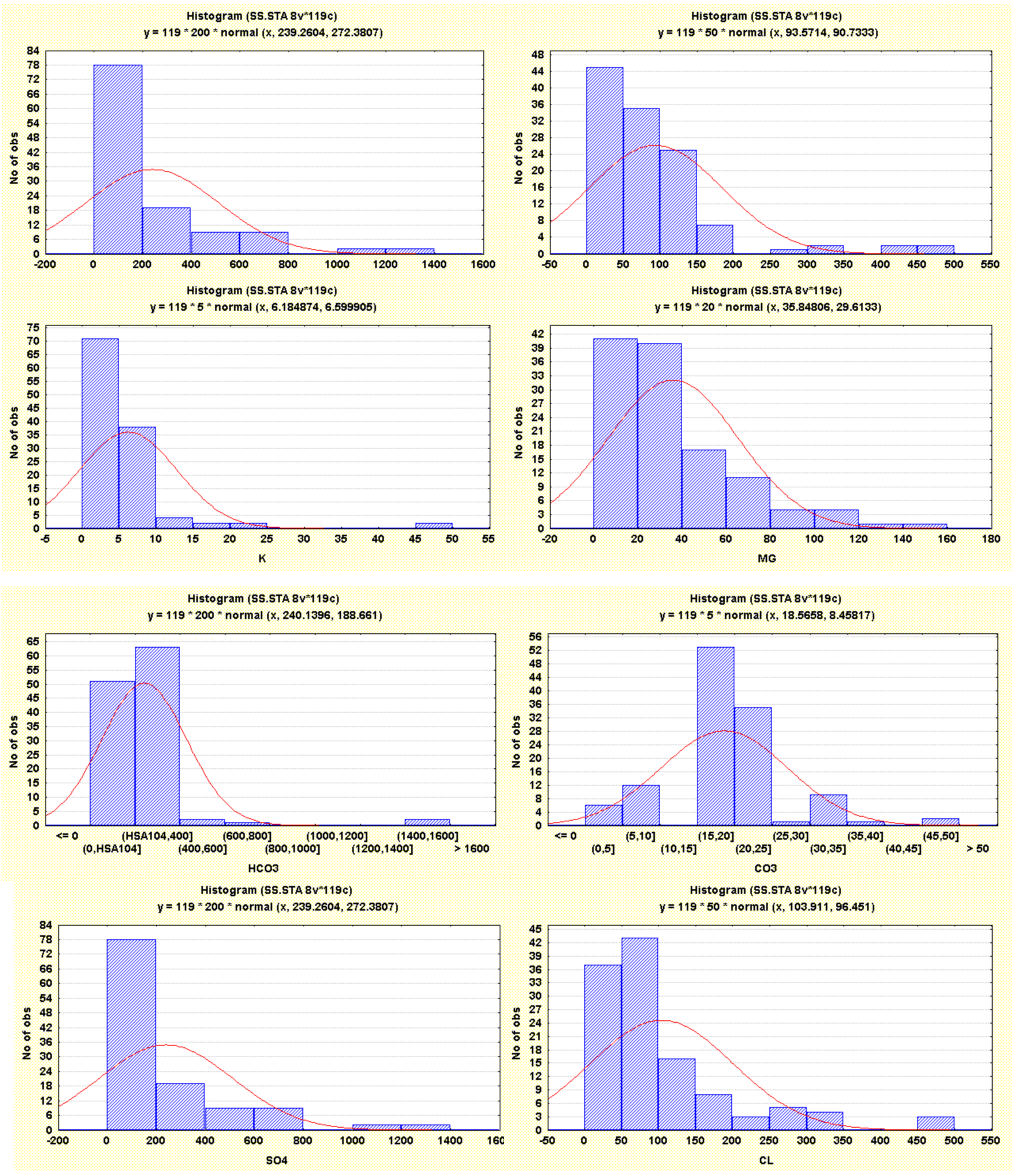

Figure 10-6 Normal distribution of all hydrochemical ions in Sana'a Basin groundwater (124 samples)

Table 10-4 Correlation coefficient of groundwater ions for all aquifers in Sana'a Basin

Correlations (new.sta)

Marked correlations are significant at $p < .05000$

N=54 (Casewise deletion of missing data)

	Ph	TDS	Ca	Mg	Na	K	CO3	HCO3	SO4	Cl
pH	1.00	-0.27	-0.42	-0.34	0.09	-0.34	0.19	-0.27	-0.22	-0.13
TDS	-0.27	1.00	0.85	0.85	0.64	0.67	0.18	0.43	0.92	0.59
Ca	-0.42	0.85	1.00	0.79	0.17	0.47	0.12	0.23	0.90	0.35
Mg	-0.34	0.85	0.79	1.00	0.31	0.54	0.04	0.40	0.77	0.60
Na	0.09	0.64	0.17	0.31	1.00	0.59	0.19	0.53	0.43	0.51
K	-0.34	0.67	0.47	0.54	0.59	1.00	0.03	0.74	0.52	0.23
CO3	0.19	0.18	0.12	0.04	0.19	0.03	1.00	-0.07	0.21	0.10
HCO3	-0.27	0.43	0.23	0.40	0.53	0.74	-0.07	1.00	0.16	0.16
SO4	-0.22	0.92	0.90	0.77	0.43	0.52	0.21	0.16	1.00	0.36
Cl	-0.13	0.59	0.35	0.60	0.51	0.23	0.10	0.16	0.36	1.00

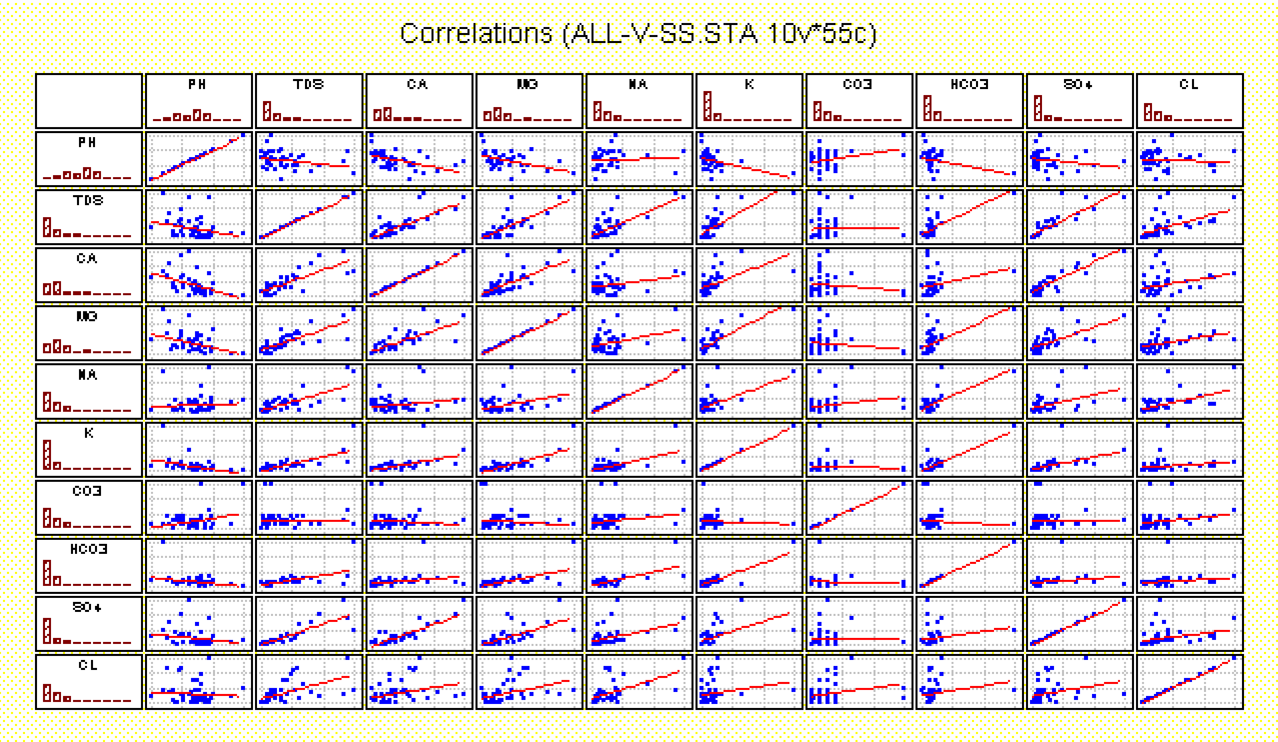

Figure 10-7 Linear regression matrix between different ions in groundwater of Alluvium, Tawilah sandstone and Volcanic aquifers

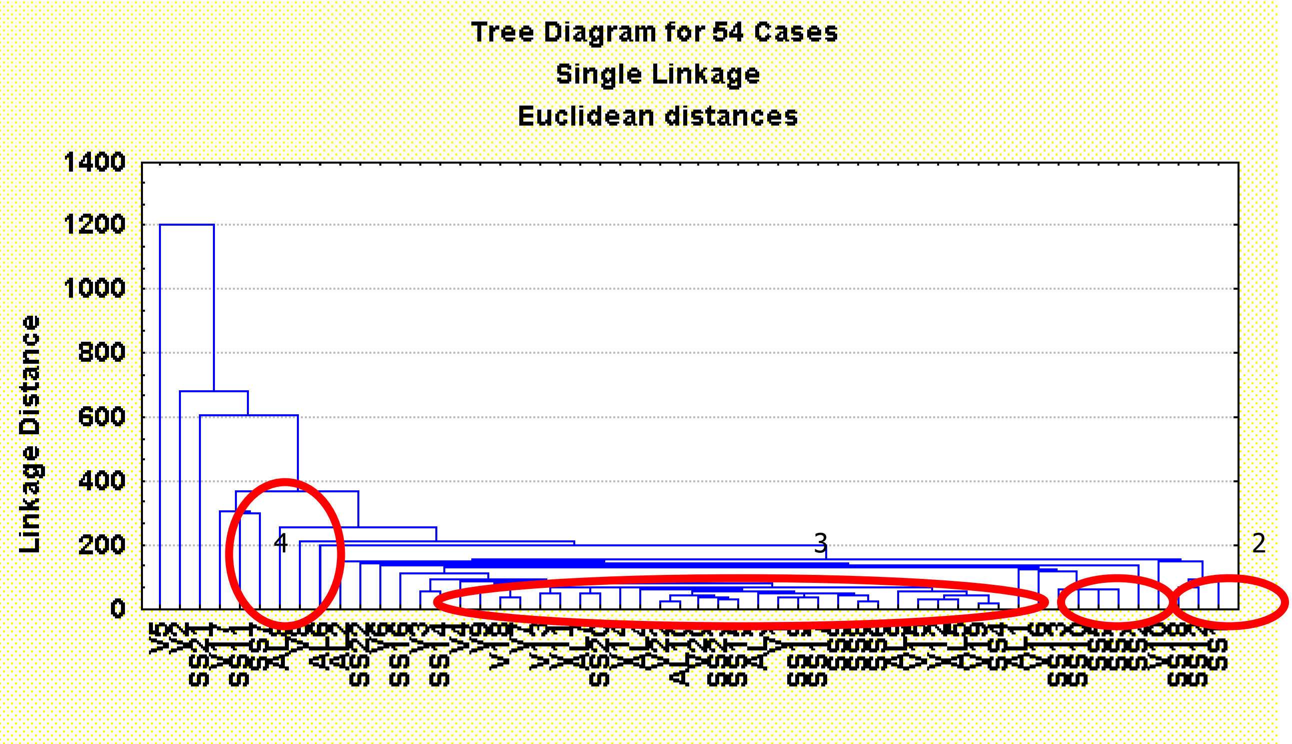

Figure 10-8 Vertical icicle plot of the 54 non-transformed wells studied related to Alluvium, Tawilah sandstone and Volcanic aquifers (Q-mode) applying Euclidean linkage method

- The correlation matrix of the selected groundwater samples shows very strong correlation between Ca with SO_4 and Mg/Na with HCO_3. This reflects a good probability of mixing process between these two different groundwater sources, i.e. presence of hydraulic connection conditions.
- The cluster analysis was carried out on the non-transformed input data matrix of 55 groundwater samples of Alluvium, Tawilah sandstone and Volcanic aquifers only, with 10 hydrogeochemical parameters. The groundwater input data of Amran limestone were excluded, since this aquifer is outside the scope of study, the relation of the other three aquifers. The results are given as a Q-mode dendrogram with an amalgamation rule of single linkage and Euclidean distance method (Figure 7-61). The Q-mode dendrogram of the three aquifers exhibits four clusters when interpreted at similarity level with a distance of 200. The first cluster domains the groundwater samples of 70% of input data and includes well samples related to the three aquifers tested. This confirms the last findings about the hydraulic connection between the three aquifers tested.

The second and third clusters reflect good correlation between wells related to Tawilah sandstone aquifer with high active conduits. This cluster is characterized by low productivity and high tendency to recharge the shallow groundwater aquifers through fault zones. The fourth cluster involves the groundwater from two aquifers, Tawilah sandstone and Volcanic aquifers, which exhibit minimum values of linkage distance of 200. This may be attributed to the effect of aquifer lithology more than aquifer structure.

10.2. Impact of structure features on groundwater flow

The occurrence and movement of groundwater in any terrain is mainly controlled by many factors such as geology, geomorphology, structure, soil, and land use pattern. However, subsurface features, such as shear zones, faults and geologic contacts, greatly influence the groundwater system. These subsurface features usually have surface manifestations that should be determined to study their impact on groundwater flow. The surface expression of these subsurface features usually appears as linear or curvilinear topographic features, either negative or positive. They could be determined by almost tracing the tonal-textural discontinuity.

In Sana'a Basin, several tectonic elements have direct hydrogeologic influences. Among these, the following have remarkable impacts:

- The fracturing system,
- The faulting system,
- The folding system.

10.2.1. Fracturing system

Fracturing is generally favorable for developing aquifers in the Tertiary and Quaternary Volcanic and limestone and compact lithologies. In the Jurassic Amran limestone terrains dominating the northern part of Sana'a Basin, groundwater occurrences reflect characteristics of fracture systems and their relationships. The water is stored and exists in the intricate fracturing system influencing this limestone. According to field investigations, a group of fracture systems affected the carbonates of Jurassic rocks. These fractures represent the essential element of groundwater occurrence in the limestone because of its very low primary porosity. It creates a suitable media for groundwater movement and facilitates initiation of karstic features (cavities and vugs). The irregular tunnels and cavities in the northern boundary of Sana'a Basin (karstic systems) which may have developed along lineaments are associated with fossil groundwater levels and flow systems. Therefore, it cannot be excluded that groundwater leaves the Sana'a Basin through the sandstones and limestone in the north. This is conditional to the piezometric surface being lower towards the north. Also along the north-eastern boundary, groundwater may escape from the basin through sandstone formations and perhaps through underlying limestone.

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 highly fractured and contain perched aquifers which supply dug wells and feed high-level springs. The upper layers of the Volcanic 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 (Water and Environment Center, WEC, 2001, Volume III).

The Quaternary basalts are highly permeable due to fracturing and to the presence of clastic deposits between flows. Where the formation is saturated, it provides an unconfined aquifer. Water levels are deep, ranging from 60 to 130 m depending on the elevation. Wells are generally limited to the southern edge of the outcrop where water levels are less than 100 m deep. In the rest of the area, surface water is stored in cisterns to provide water for domestic purposes (Water and Environment Center, WEC, 2001, Volume III).

In the present study, structural lineaments are very important from the hydrogeological point of view. This is due to the fact that these lineaments often display zones of high porosity and permeability. Intensive work was carried out during this study to delineate the number of lineaments in Sana'a Basin (3645 lineaments, Table 10-10).

In the beginning, the newly-developed geological map which was modified after GAF 2005 for Sana'a Basin was divided into a grid of 500 cells. Every cell has dimensions of 5x5 km. In every cell, the number of the present lineament was traced, applying GIS techniques. The values obtained for structural lineament density were represented on a contour map (Figure 10-9). The distribution of structural lineament density map in Sana'a Basin reveals that the lineament density is greater in the north, where Amran limestone is characterized by high fracture density as mentioned before and as indicated in Figure 10-9. While the mountainous areas of both Tawilah sandstone and Quaternary and Tertiary Volcanic aquifers in the northeast, east and west directions (Nihm, Wadi As-Sir and Hamadan- Wadi Dahr localities respectively) than in lower central areas of the basin (Sana'a plain) which are masked and covered by alluvial deposits. It ranges from zero to 1.5. The mountainous areas (catchment areas) are characterized by high density of lineaments. The increasing density direction is similar to the direction of groundwater flow inside both Tawilah sandstone and Volcanic aquifers.

In addition, the fractures can contribute to the recharge of aquifers as in the Tawilah sandstone and Quaternary and Tertiary Volcanic aquifers (Wadi As-Sir, Wadi Dahr and Wadi Shahek respectively), which consist of fractured sandstone and fractured Volcanic, where it bears water with low salinity (from 200 ppm to 800 ppm).

Table 10-5 Location of lineaments, their density and frequency in Sana'a Basin

X	Y	Density	Frequency
432564.17	1668350.80	0.02	0.033
429370.44	1669182.16	0.05	0.033
431952.70	1672253.42	0.41	0.232
428766.32	1673136.36	0.07	0.066
424616.38	1674892.97	0.01	0.033
431165.15	1677446.58	0.53	0.398
427499.00	1677499.00	1.10	0.930
422630.63	1677745.04	0.89	0.664
417777.69	1678746.02	0.47	0.299
412627.85	1678469.60	0.56	0.631
409250.00	1679364.99	0.12	0.133
430763.03	1682101.50	0.18	0.232
427499.00	1682499.00	0.76	0.398
422499.00	1682499.00	0.41	0.432
417499.00	1682499.00	0.71	0.531
412499.00	1682499.00	1.40	1.494
408462.29	1682760.79	0.67	0.730
402957.14	1684001.44	0.28	0.266
434185.38	1684643.24	0.02	0.033
436182.10	1687832.11	0.31	0.332
432523.02	1687658.71	0.85	0.797
427499.00	1687499.00	0.62	0.664

X	Y	Density	Frequency
422499.00	1687499.00	0.73	0.432
417499.00	1687499.00	0.92	0.531
412499.00	1687499.00	1.39	0.996
407499.00	1687499.00	1.15	0.764
402499.00	1687499.00	1.40	0.764
442208.04	1693707.40	0.62	0.564
437350.86	1692637.10	1.23	1.029
432499.00	1692499.00	1.31	1.162
427499.00	1692499.00	0.82	0.664
422499.00	1692499.00	0.63	0.398
417499.00	1692499.00	0.38	0.199
412499.00	1692499.00	0.14	0.199
407499.00	1692499.00	0.68	0.697
402499.00	1692499.00	1.22	0.863
446082.59	1699883.20	0.01	0.033
442229.65	1697573.80	1.24	0.963
437499.00	1697499.00	1.02	0.896
432499.00	1697499.00	1.26	1.560
427499.00	1697499.00	1.21	1.129
422499.00	1697499.00	0.50	0.332
417499.00	1697499.00	0.17	0.100
412499.00	1697499.00	0.20	0.100
407499.00	1697499.00	0.63	0.830
402499.00	1697499.00	1.49	1.062
447096.48	1701777.65	0.27	0.166
442499.00	1702499.00	1.50	0.996
437499.00	1702499.00	1.31	0.930

X	Y	Density	Frequency
432499.00	1702499.00	2.05	1.826
427499.00	1702499.00	0.80	0.896
422499.00	1702499.00	0.37	0.266
417499.00	1702499.00	0.24	0.133
412499.00	1702499.00	0.79	0.531
407499.00	1702499.00	0.90	0.697
402499.00	1702499.00	2.02	1.992
446365.40	1708222.79	0.28	0.498
442499.00	1707499.00	1.37	1.328
437499.00	1707499.00	2.12	1.693
432499.00	1707499.00	1.67	1.560
427499.00	1707499.00	0.79	0.764
422499.00	1707499.00	0.20	0.232
417499.00	1707499.00	0.04	0.033
412499.00	1707499.00	0.22	0.332
407499.00	1707499.00	1.61	1.560
402499.00	1707499.00	1.75	1.859
447362.07	1712568.55	0.73	0.764
442499.00	1712499.00	0.67	0.598
437499.00	1712499.00	1.79	1.793
432499.00	1712499.00	0.93	0.863
427499.00	1712499.00	0.84	0.598
422499.00	1712499.00	0.15	0.100
417499.00	1712499.00	0.11	0.066
412499.00	1712499.00	0.40	0.232
407499.00	1712499.00	0.71	0.398
402499.00	1712499.00	1.11	0.963

X	Y	Density	Frequency
450723.43	1718698.59	0.17	0.199
447259.88	1717665.59	1.03	0.896
442499.00	1717499.00	1.29	1.195
437499.00	1717499.00	1.79	1.394
432499.00	1717499.00	1.01	1.394
427499.00	1717499.00	0.26	0.398
422499.00	1717499.00	0.67	0.697
417499.00	1717499.00	0.23	0.133
412499.00	1717499.00	0.56	0.332
407499.00	1717499.00	0.43	0.332
402499.00	1717499.00	1.01	0.963
451218.93	1722838.24	0.20	0.266
447499.00	1722499.00	1.46	1.162
442499.00	1722499.00	1.38	1.195
437499.00	1722499.00	1.61	1.295
432499.00	1722499.00	1.37	1.062
427499.00	1722499.00	1.13	1.195
422499.00	1722499.00	0.72	0.564
417499.00	1722499.00	0.25	0.166
412499.00	1722499.00	0.31	0.232
407499.00	1722499.00	0.03	0.033
402499.00	1722499.00	0.53	0.697
452094.35	1727394.27	0.41	0.365
447499.00	1727499.00	0.95	0.697
442499.00	1727499.00	1.18	0.930
437499.00	1727499.00	0.94	0.963
432499.00	1727499.00	0.94	1.029

X	Y	Density	Frequency
427499.00	1727499.00	0.77	0.598
422499.00	1727499.00	0.71	0.564
417499.00	1727499.00	0.53	0.332
412499.00	1727499.00	0.77	0.398
407499.00	1727499.00	0.23	0.266
402461.57	1727370.86	0.66	0.531
451088.05	1732132.90	0.02	0.033
447499.00	1732499.00	0.77	0.631
442499.00	1732499.00	1.16	0.930
437499.00	1732499.00	1.52	1.892
432499.00	1732499.00	1.29	1.793
427499.00	1732499.00	1.50	2.058
422499.00	1732499.00	1.28	1.328
417499.00	1732499.00	0.95	0.896
412499.00	1732499.00	0.31	0.166
408094.43	1732330.20	0.40	0.232
450710.23	1737558.00	0.09	0.100
447499.00	1737499.00	0.58	0.332
442499.00	1737499.00	0.91	0.797
437513.30	1737473.64	1.30	1.295
432613.21	1736718.87	1.01	1.062
427367.98	1737288.04	1.12	1.195
422499.00	1737499.00	1.01	1.195
417499.00	1737499.00	1.00	0.963
412499.00	1737499.00	0.33	0.199
408343.30	1737599.25	0.28	0.166
425537.74	1740677.98	0.08	0.066

X	Y	Density	Frequency
422215.40	1742234.51	0.68	0.631
417499.00	1742499.00	1.09	1.062
412578.01	1742267.94	0.56	0.664
408169.09	1742356.00	0.09	0.066
420992.35	1745405.25	0.01	0.033
417114.45	1746128.55	0.17	0.133
414018.42	1747053.95	0.06	0.100
447263.83	1741836.27	0.06	0.100
442723.85	1741976.65	0.79	0.598
438715.16	1741084.90	0.17	0.232
397542.82	1687545.80	0.25	0.166
393535.71	1688719.36	0.04	0.066
397499.00	1692499.00	0.95	0.797
392823.51	1692270.60	0.79	0.365
397499.00	1697499.00	0.80	0.465
393464.82	1697300.77	0.40	0.100
397499.00	1702499.00	0.75	0.498
397499.00	1707499.00	1.82	1.262
397506.58	1712491.79	0.92	1.062
398001.01	1717578.00	0.63	0.531
398012.15	1722160.41	0.06	0.066
398688.22	1727613.87	0.41	0.564
399308.35	1730690.95	0.07	0.066
394312.69	1702412.60	0.13	0.066
394329.91	1707115.82	0.01	0.033
394527.21	1711736.10	0.16	0.166

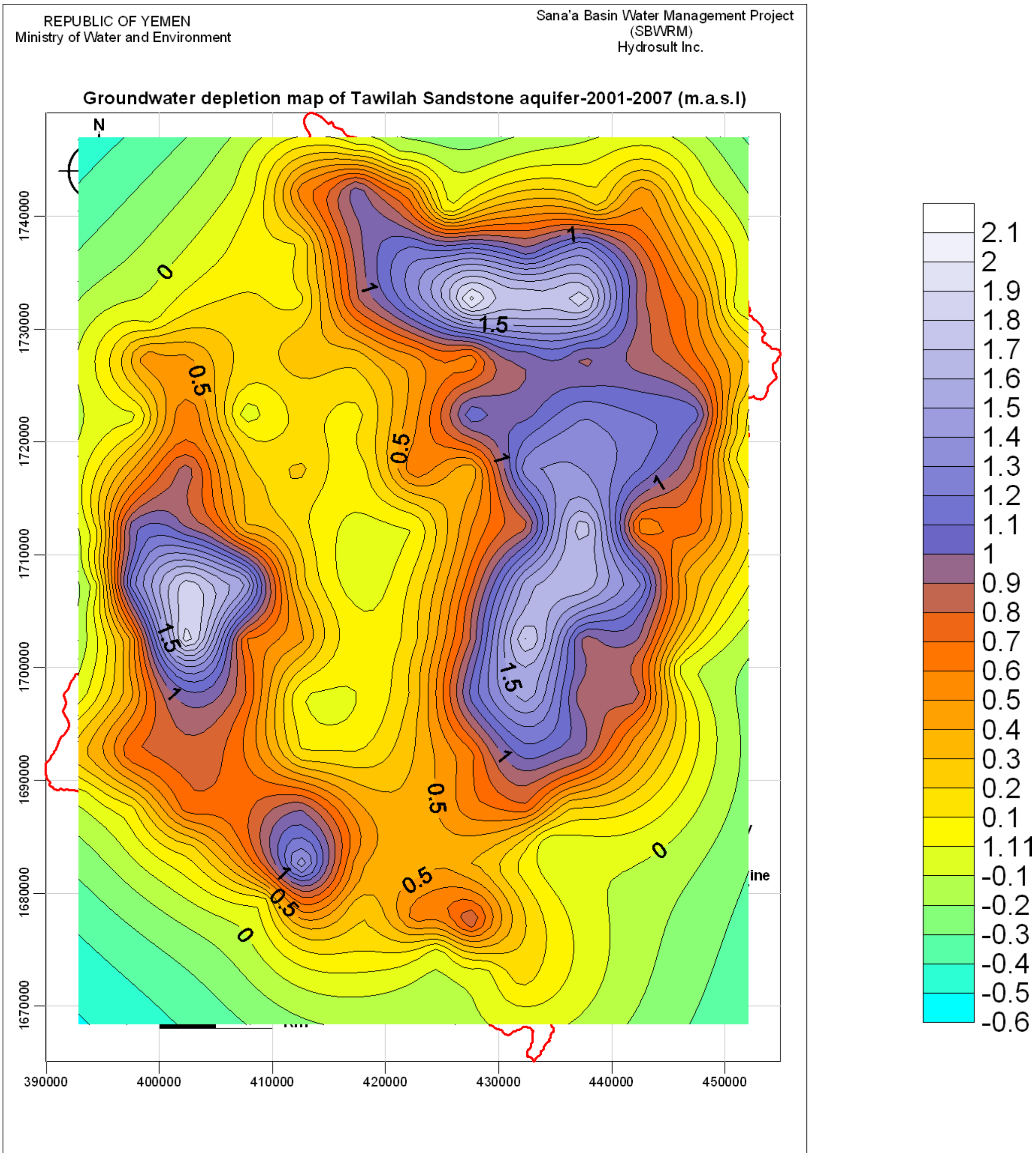

Figure 10-9 Distribution contour map of structural lineament density in Sana'a Basin

10.2.2. Faulting system

The faulting system is one of the main factors which reflect tectonic responsibility on groundwater occurrence, movement and hydraulic condition.

From the field investigation, some faults were noted affecting different formations in Sana'a basin. It was found that the Cretaceous Tawilah sandstone, located along the eastern boundary of the basin (Al-Madarej and Al-Madfon areas), has been subjected to intensive tectonism. This can be attributed the major normal fault located close to the eastern boundary (Water Divide) between Sana'a and Al-Jawf Basins. This fault is northwest-southeast in direction, with approximately vertical displacement of about 300 m. Along this fault, the Jurassic Amran limestone was uplifted to the surface (about 300 m above ground level) forming a huge mountain range extending northwest-southeast for a considerable distance towards the old Jabali mine. The major fault can be traced easily by satellite image (see chapter 3). This fault contributes to a great extent to the hydrogeologic conditions. It has effectively influenced the Cretaceous rocks and caused modifications to their physical conditions, hydraulic parameters and groundwater potentiality. In addition, this fault, in combination with fractures, plays an important role in recharge of the Cretaceous Tawilah sandstone aquifer. The amount of recharge can be increased through the fault planes which facilitate the passing of rainfall to bearing rocks. It has also affected hydraulic parameters in such a manner that the Tawilah sandstone aquifer possesses primary and secondary porosity.

As mentioned before (see chapter 5), the secondary porosity is important in the Tawilah sandstone aquifer since it gives high permeability to the aquifer. The higher permeability values are found in the weathered and fractured zones. It is heavily exploited in the northeast and northwest of Sana'a city, where it either outcrops or occurs beneath an unconsolidated cover of Volcanics and Alluvium of up to 50 m thickness (WEC, 2001, Volume III).

The most important regional faults that affect groundwater flow, as detected from the groundwater piezometric map (Figure 6-16, chapter 6) and aquifer hydraulics in Sana'a basin, are the last mentioned northwest-southeast (see transmissivity distribution map, chapter 5). In addition, at Arisha and Al-Mahajir Bait AL-Anz, several faults have been delineated. They are normal faults with northwest-southeast direction. They act as potential area for groundwater occurrence. Along these faults, the Tawilah sandstone has been moved down and the Amran limestone uplifted.

Upon checking the relation between the Tawilah sandstone aquifer transmissivity values and the total depth of the wells tested (Figure 10-10), it is noticed that the wells with high transmissivity values are beside the last mentioned northeast-southwest oriented structure of faulting system that affects the Cretaceous Tawilah sandstone aquifer.

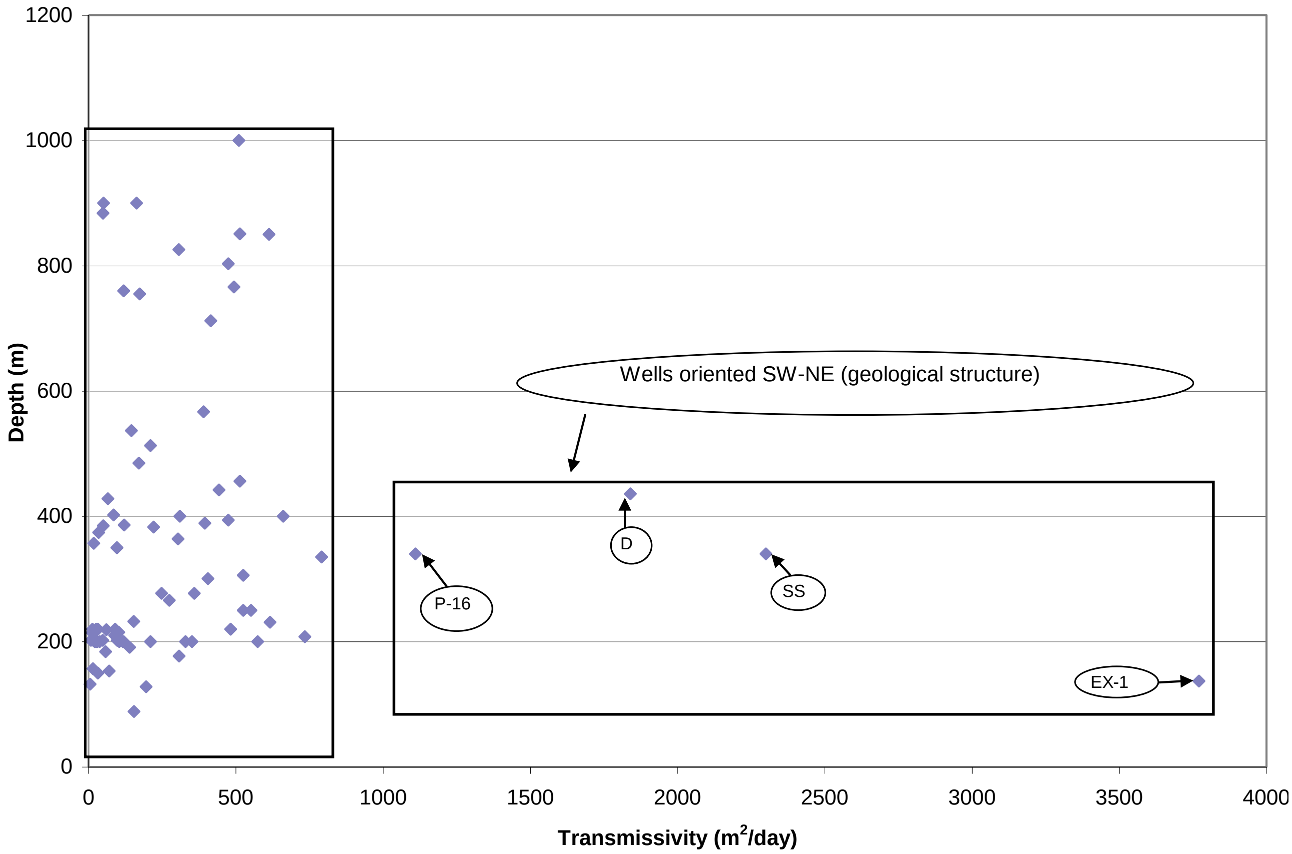

Figure 10-10 Graph showing effect of fracture system in Sana'a basin on Tawilah sandstone aquifer transmissivity

10.2.3. Folding system

The Sana’a Basin forms a distinct geomorphological and structural unit characterized by a large number of northeast trending elliptical anticlines and synclines.

These folds (Nihm locality) are symmetrical anticlines oriented in a northeast-southwest direction with steep southeastern limbs and much greater amplitude.

The folding in Sana'a basin, with associated features such as faulting, fracturing and jointing, plays a vital role in the hydrogeologic situation. These northeast-southwest anticlinal structures constitute local barriers to the groundwater flow, particularly in the contact between Tawilah sandstone aquifer and Amran limestone aquifer in the Nihm area. They expose partially or entirely the major aquifers in these strata, interrupting their continuities, and developing new hydrogeologic conditions. Therefore, the hydraulic parameters and the groundwater contour lines of the Tawilah sandstone aquifer in the Nihm area show variable changes in their values while they are more or less homogeneous in Hamadan area (see chapters 5 and 6).

The folding has an effective influence on the physical characteristics of the Tawilah sandstone aquifer, due to compaction of the rock strata as a result of pressure and forces originating from and associated with the folding. This is due to the thrusting of the aquifer mentioned against the Amran limestone aquifer where the two formations are in juxtaposition to each other and contamination of the Tawilah sandstone groundwater with the relatively higher salinity of the Amran limestone groundwater. This case is encountered at Hamadan and Bani Husheish localities, where repetitions of the rock strata have occurred, reflecting reverse faulting (Italconsult, 1973). The groundwater of the lower Cretaceous sandstone at this locality is slightly brackish (2990 ppm).

In addition, the folds play an important role in the aquifer recharge through the dips of its beds. The dip of exposure beds of the anticlines concerned in Sana’a Basin (Nihm locality anticlines) is in a northeast-southwest. The dip of water-bearing formations has an essential implication on groundwater occurrence, movement, recharge and characteristics. For existing aquifers nearby, their exposures are generally partially saturated e.g. shallow zone of Cretaceous sandstone aquifer at Nihm, which represents the main replenishment area. Most of the existing aquifers extend over a wide area beside the anticline mentioned, where their recharging areas are located at their surrounding exposures. These exposures dip regionally towards the aquifers. Rainwater flows in the direction of the dip, with consequent increase in its potentiometric surface.xxx

10.3. Impact of impermeable layers on groundwater flow

The impact of the impermeable layers on groundwater flow in Sana’a Basin is detected by comparison between groundwater table maps and corresponding aquifer lithology. The impermeable layers in Sana’a Basin include the Jurassic Unnamed Formation and Amran Limestone group, the Volcanic plugs, the green shale layer and the clay layers. In the following, a brief discussion of the impact of these impermeable layers on groundwater flow is given.

The Jurassic Unnamed Formation and Amran Limestone Group are assumed to be impermeable, since data show that both units have a very low production of water. This means that there is no flow across the boundary of the Cretaceous Sandstone and the Unnamed Formation. The model developed by Foppen, 1996, only takes into consideration flow in the Cretaceous, Tertiary and Quaternary lithostratigraphical units. On the contrary, if the Amran is assumed to be impermeable, then all groundwater would be collected in the Tawilah and flow either north, south or even west. This is not very likely, according to the Tawilah sandstone groundwater piezometric map (see chapter 6, Figure 6-16). So, Amran Limestone does not appear to be a no-flow boundary (Foppen, 1996).

Series of volcanic plugs have intruded the Cretaceous Tawilah Sandstone Group at several locations along the northeast boundary of the basin. The most important volcanic plugs recorded in this area are Jabal Al-Salda plug, Jabal Al-Harim and Jabal Al-Qatab (see chapter 3). These volcanic plugs are aligned along a straight line located in proximity to the major fault. As mentioned in chapter 6, the potentiometric groundwater maps of Tawilah sandstone aquifer, which distinguish by unconfined to confined conditions, show two anomalies of closed contour lines near these plugs. The hydrogeological cross-section through the northwest NWSA well field shows that these plugs act as barriers/water divides for the flow of groundwater within the aquifer (Figure 10-11). Also, Figure 10-1 shows that these plugs divided Tawilah sandstone into three separate isolated local water-bearing formations in Jebel Alyah and Jebel Om Shiyl locality in the east of Sana'a Basin, although this aquifer is extended in east-west direction and connected through fault zones.

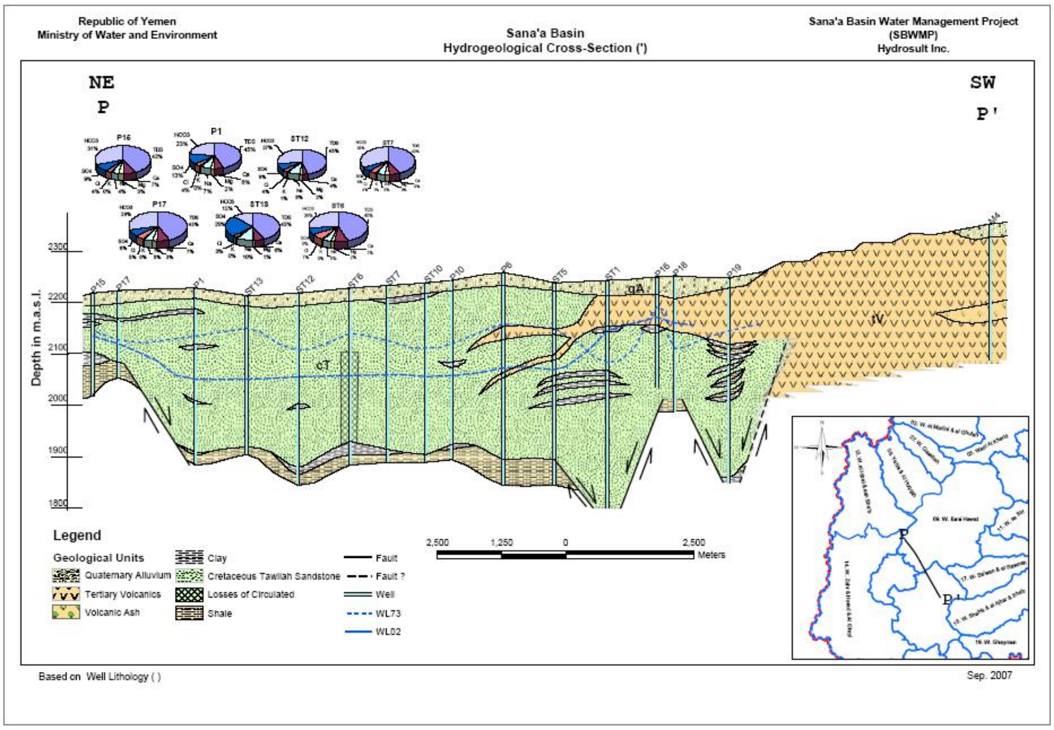

Figure 10-11 Hydrogeological cross-section in northwest NWSA well fields in Sana'a Basin showing the Volcanic plugs

This may lead to later silicification (ferruginous sandstone) of fault planes as a result of invasion by hydrothermal solutions.

The basal portion of the Tawilah sandstone aquifer in northeast and northwest NWSA well fields as detected from the hydrogeological map (Figure 10-12) is the green shale layer and the clay layers. The Tawilah Sandstone aquifer comprises a series of continental cross-bedded sandstones (Figure 10-13), generally medium to coarse-grained with inter-bedded mudstones, siltstones and occasional silty sandstone in the northeast NWSA well field. The cross-bedded sandstones and inter-bedded mudstones decrease the groundwater velocity and decrease the recharge rate to the aquifer, while the green shale in the base of the aquifer prevents upward leakage to this aquifer.

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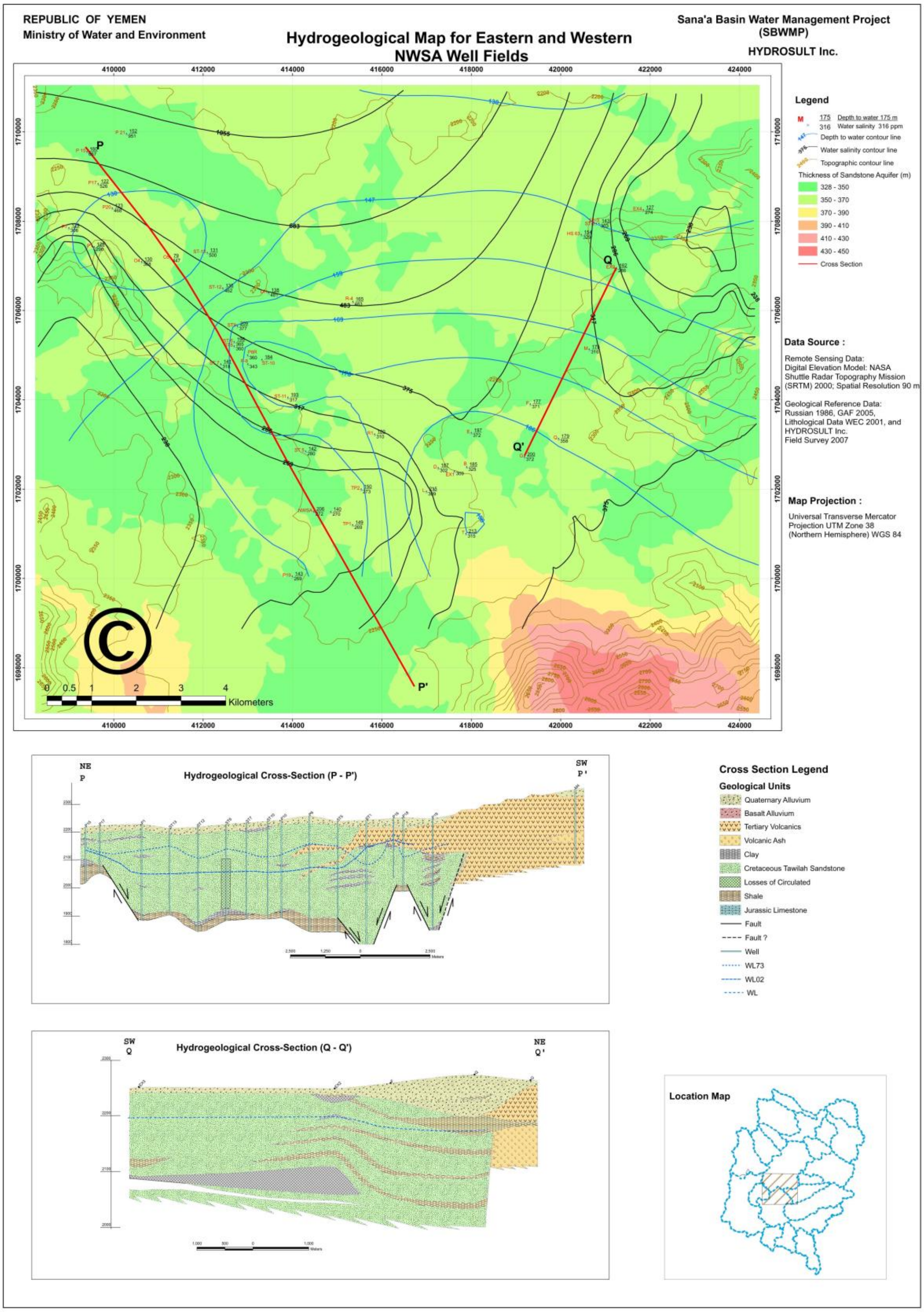

Figure 10-12 Hydrogeological map across Tawilah sandstone aquifer in NE and SW NWSA well field in Sana'a Basin (for details see the attached A0 size map)

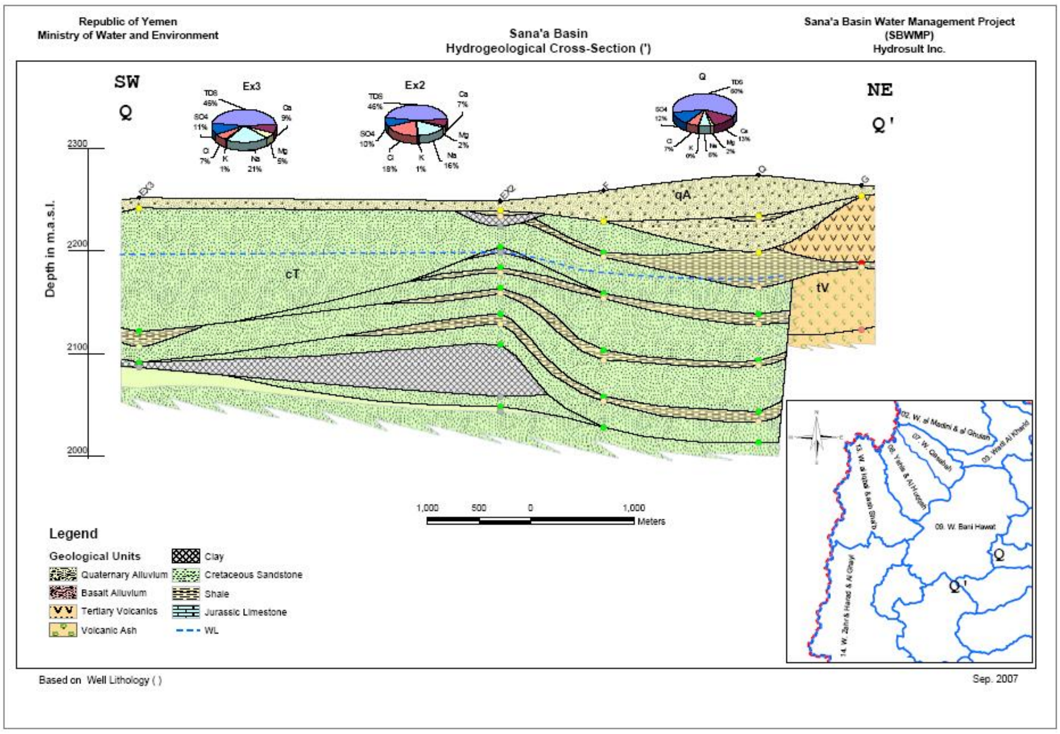

Figure 10-13 Hydrogeological cross-section across Tawilah sandstone aquifer in NE NWSA well field in Sana'a Basin