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Chapter 7. HYDROGEOCHEMICAL SETTING IN SANA'A BASIN

EXECUTIVE SUMMARY

The results of the groundwater quality sampling in Sana'a Basin are presented in the form of tables, maps, diagrams and statistics.

In the alluvium aquifer, the groundwater is of mixed origins of mineralization, where rainwater and sub-surface flow from neighboring aquifers are the main sources of salt contribution. The groundwater salinity of the alluvium aquifer ranges between fresh and slightly brackish. The TDS (Total Dissolved Solids) ranges between 85 and 2,950 ppm. Close to 66% of the water points have TDS less than 1,000 ppm, 26% range between 1,000-2,000 ppm, and only 8% are reported to have TDS in excess of 2,000 ppm.

Groundwater salinity increases towards the north, reflecting the increase in aquifer thickness and groundwater use in this direction. It is observed that the higher salinities are mainly recorded in dug wells of the Wadi El Ghayl downstream area. The possible source of contamination of the alluvium aquifer in the Arhab area is the marine salts from the underlying fractured limestone aquifer.

In the volcanic aquifer, the groundwater is of mixed origins of mineralization, where rainwater and fossil water are the main sources of salt contribution. The groundwater salinity of the volcanic aquifer ranges between fresh and brackish. The TDS varies from 217 ppm to 2,010 ppm with a mean value of 670 ppm. Groundwater salinity increases towards the north. A large part of the aquifer area has a TDS value below 400 mg/l, and, in the western part of the basin, the TDS value is much lower: 100-200 mg/l. The high TDS values in the north-east may be attributed to groundwater originating from Tawilah sandstone aquifer.

In Tawilah sandstone aquifer, the groundwater of both shallow and deep zones is of mixed origins of mineralization. The feeding recharge source is rainwater for the shallow zone and, during pluvial times, for the deep zone. Subsurface flow is the source of possible contamination from adjacent aquifers.

Groundwater salinity of the sandstone aquifer is generally fresh with brackish water only in a few samples from the unconfined zone. The TDS varies from 193 ppm to 1,872 ppm, with a mean value of about 600 ppm. About 70% of the aquifer area has a TDS value between 200 and 400 mg/l. Relatively high values of TDS exist in the east, in the range of 500 mg/l and 1,200 mg/l. Groundwater salinity is highest in the northeast where the aquifer is in contact with Amran limestone.

Groundwater in the limestone aquifer was sampled from 29 wells, even though this aquifer is beyond the scope of the study. Groundwater salinity is close to 400 mg/l in about 75% of the aquifer area. The TDS dramatically increases in the southwest and reaches a value of about 1,800 mg/l, with a maximum of 2,200 mg/l.

The desirable level of TDS in Yemen is 650 mg/l, while the maximum permissible value is 1,500 mg/l. The permissible value is exceeded in about 10% of wells in the alluvium and sandstone aquifers, and is exceeded in about 20% of wells in the volcanic aquifers.

The groundwater in Sana'a Basin is generally hard to very hard water, causing problems when used for domestic purposes. The water is suitable for livestock purposes, in view of the TDS levels. The suitability for irrigation was verified using the SAR-ratio. The groundwater in the Sana'a Basin is generally suitable for all soils.

7.1 General Outline

Nearly all groundwater originates as rainwater that infiltrates through the soil into flow systems in the underlying geologic materials. The soil zone has unique and powerful capabilities to alter the water

chemistry, as infiltration occurs through this thin, biologically active zone. In recharge areas, the soil zone undergoes a net loss of mineral matter to the flowing water. As groundwater moves along flow lines from recharge to discharge areas, its chemistry is altered by the effects of a variety of geochemical processes. In the natural system, groundwater has a geochemical variability caused by natural processes, such as the geological formations through which its flow occurs, chemical changes resulting from annual flow fluctuations, recharge sources and mixing with other groundwater of different chemistry. All groundwater types contain a certain amount of dissolved solids and never occur in a pure state. More than 90% of the dissolved solids in the groundwater can be attributed to seven ions which are: Na^+ , Ca^{2+} , Mg^{2+} , K^+ , SO_4^{2-} , Cl^- , and HCO_3^- ions.

The hydrogeochemical investigation in the present project is mainly concerned with the major ions in the groundwater and their concentrations, distributions, relative abundances, and their variability patterns. On the basis of the groundwater chemistry, an evaluation of groundwater for domestic and irrigation uses was undertaken. To accomplish this, the following stages were established:

- Field measurements of the unstable parameters such as pH, EC, TDS and collection of some representative samples from various groundwater aquifers in the area;
- Laboratory analysis of these water samples collected;
- Representation of the field and the analyzed data in tables, figures and diagrams;
- Interpretation and discussion of the resulting data;
- Identification of groundwater types and characteristics based on the dominant ions.

Field and laboratory stages and procedures include collection of water samples and field measurements. A total of 135 representative groundwater samples were collected. The samples were stored in clean, dried plastic bottles which were completely filled with water, leaving no air inside, to avoid change in chemical characteristics. The bottles were labeled with waterproof markers and were exported directly to the Desert Research Center laboratory in Egypt for analysis.

During field trips, unstable parameters were measured, including hydrogen ion concentration (pH), electrical conductivity (EC) and total dissolved solids (TDS). These parameters were measured by the use of the Oyster pH / conductivity + TDS meter. The hydrogen ion concentration (pH) in solution is the negative logarithm of the hydrogen ion concentration in moles per liter. In pure water, the dissociated molar concentrations H (Hydrogen) and OH (Hydroxyl) ions are equal, each being 10 moles per liter, equivalent to a pH of 7. In acidic solution, pH is less than 7, while it is more than 7 in basic solutions.

The electrical conductivity (EC) is the ability of water to conduct an electrical current; it is expressed in **micromhos/cm**. The total dissolved solids (TDS) are the total amount of solids, in milligrams per liter or parts per million (ppm), that remain when a water sample is evaporated until dryness. As all natural water contains mineral salts in solution, the presence of dissociated ions render the solutions conductive, so there is a relation between EC and TDS. Hem, (1970) recognized the relationship between the two parameters as in the following equation:

$$\text{TDS (ppm)} = 0.64 \text{ EC } (\mu\text{mhos/cm})$$

The chemical analyses of the samples were carried out in the Desert Research Center in Egypt, according to Rainwater and Thatcher (1960). The sodium (Na^+) and potassium (K^+) contents were determined by means of the flame photometer technique. The concentrations of the other main cations (Ca^{2+} and Mg^{2+}) were measured by means of a spectrophotometer. Chloride, sulfate and bicarbonate (Cl^- , SO_4^{2-} and HCO_3^-) were determined by a titration method (calorimetrically). The AQWACHEM and SPSS computer programs were used for plotting the data and performing the cluster analyses. The ion concentration values were expressed in milli-equivalent and converted to ppm and percentage.

Sodium adsorption ratio (SAR) for each water sample was determined by using the following equation (Richard, 1954):

$$\text{SAR} = \frac{\text{Na}^{+1}}{1/2 \sqrt{\text{Ca}^{+2} + \text{Mg}^{+2}}} \quad (\text{units in epm})$$

Total groundwater hardness (TH) can be represented as calcium and magnesium concentrations relative to calcium carbonate. Hardness is generally expressed by the following equation:

$$\text{TH} = \text{Ca} (\text{CaCO}_3 / \text{Ca}) + \text{Mg} (\text{CaCO}_3 / \text{Mg}) \quad (\text{units in ppm})$$

where this equation reduces to:

$$\text{TH} = 2.497 \text{ Ca} + 4.115 \text{ Mg} \quad (\text{units in ppm})$$

while Carbonate hardness, or temporary hardness, (CH% of TDS) and Non-carbonate hardness, or permanent hardness, (NCH% of TDS) can be estimated by the following relationship:

- Temporary hardness (CH% of TDS) = [Mg (HCO₃)₂ + Ca(HCO₃)₂] salts as percent;
- Permanent hardness (NCH% of TDS) = [MgSO₄ + CaSO₄ + MgCl₂ + CaCl₂] salts as percent.

The hydrogeochemical characteristics (groundwater pH values, spatial and temporal variation of groundwater salinity and major ions, groundwater classification and cluster analyses) of the alluvium aquifer, Tawilah sandstone aquifer and volcanic aquifer are given below in details, while the Amran limestone aquifer is beyond the scope of this study and will only be touched on in brief.

7.2 Hydrogeochemical characteristics of alluvium aquifer

7.2.1 Groundwater pH values

Approximately 91% of the total measured wells have pH of less than 8. The normal pH range for groundwater in general (i.e. from 7 to 8) is represented by about 79% of the measured wells. The remaining 9% have a pH in excess of 8 (Table 7-1). Interestingly, there is no significant difference between the pH of water in the different types of water points. This may signify that the water abstracted from most wells is mixed groundwater rather than originating from a single aquifer layer. The majority of wells are production wells in which owners try to maximize the yield rather than select a particular aquifer zone.

Table 7-1 pH value of water in the various types of well points

pH of groundwater in the various types of well points in the study area				
well type	< 7	(7-8)	>8	Total
Dug	5	34	4	43
Dug/Bore	0	3	0	3
Bore	1	4	2	7
Total	6	41	6	53

In general, the pH value of groundwater in the alluvium aquifer ranges between 6.79 and 8.17, in well no. HSA 19 and well no. HAS 30 respectively (Table 7-2). The high value of groundwater pH observed (well no. HAS 30) may be attributed to the effect of sewage contamination in Bani El Hareth (Beat El Barati). Figure 7-1 shows the contour lines of the pH value distribution. From the contour map, it is obvious that the effect of sewage water pollution on groundwater is pronounced in the high pH value

zone in the Tawilah sandstone aquifer in the northeastern area, and the alluvium aquifer in the central part.

Table 7-2 Measured pH values of the water samples of the alluvium aquifer

Well ID	Easting (m)	Northing (m)	Well type	Aquifer type	pH
HS51	440585	1711095	Dug	Alluvium Aquifer	7.01
HSA 2	422002	1719988	Dug	Alluvium Aquifer	7.4
HSA 4	417905	1716847	Dug	Alluvium Aquifer	7.27
HSA 5	416155	1715019	Dug	Alluvium Aquifer	6.83
HSA 6	416241	1715122	Dug	Alluvium Aquifer	6.83
HSA 15	417243	1717735	Dug	Alluvium Aquifer	6.96
HSA 19	416322	1715307	Dug	Alluvium Aquifer	6.79
HSA 27	422267	1715645	Dug	Alluvium Aquifer	8
HSA 28	422695	1716025	Dug	Alluvium Aquifer	7.66
HSA 30	422810	1716400	Dug	Alluvium Aquifer	8.17
HSZ1	418990	1686713	Dug	Alluvium Aquifer	7.55
HSZ3	429988	1675461	Dug	Alluvium Aquifer	7.45
HSZ5	439684	1701903	Dug	Alluvium Aquifer	7.63
HSZ6	430466	1697997	Dug	Alluvium Aquifer	7.8
HSZ7	422211	1690122	Dug	Alluvium Aquifer	7.74
HSS2	425190	1700940	Dug	Alluvium Aquifer	7.72
HSS3	425231	1701003	Dug	Alluvium Aquifer	7.48
HSS4	426652	1699852	Dug	Alluvium Aquifer	7.33
HSS5	428053	1700726	Dug	Alluvium Aquifer	7.5
HSB1	408880	1696762	Dug	Alluvium Aquifer	7.47
HSB2	408943	1696768	Dug	Alluvium Aquifer	7.74
HSB5	402470	1695440	Dug	Alluvium Aquifer	7.76
HSB6	401303	1692293	Dug	Alluvium Aquifer	7.4
HSH 2	407985	1703832	Dug	Alluvium Aquifer	7.07

Well ID	Easting (m)	Northing (m)	Well type	Aquifer type	pH
HSA 53	416336	1717861	Dug	Alluvium Aquifer	7.51
HSZ12	416473	1689675	Dug	Alluvium Aquifer	7.67
HSA 55	416631	1717743	Dug	Alluvium Aquifer	7.27
HSA 56	416582	1717597	Dug	Alluvium Aquifer	8.08
HSA 57	416964	1717773	Dug	Alluvium Aquifer	7.03
HSA 58	414746	1715368	Dug	Alluvium Aquifer	7.6
HSA 60	415955	1714858	Dug	Alluvium Aquifer	6.93
HSA 61	416062	1714747	Dug	Alluvium Aquifer	7.18
HSA 62	414799	1715584	Dug	Alluvium Aquifer	7.1

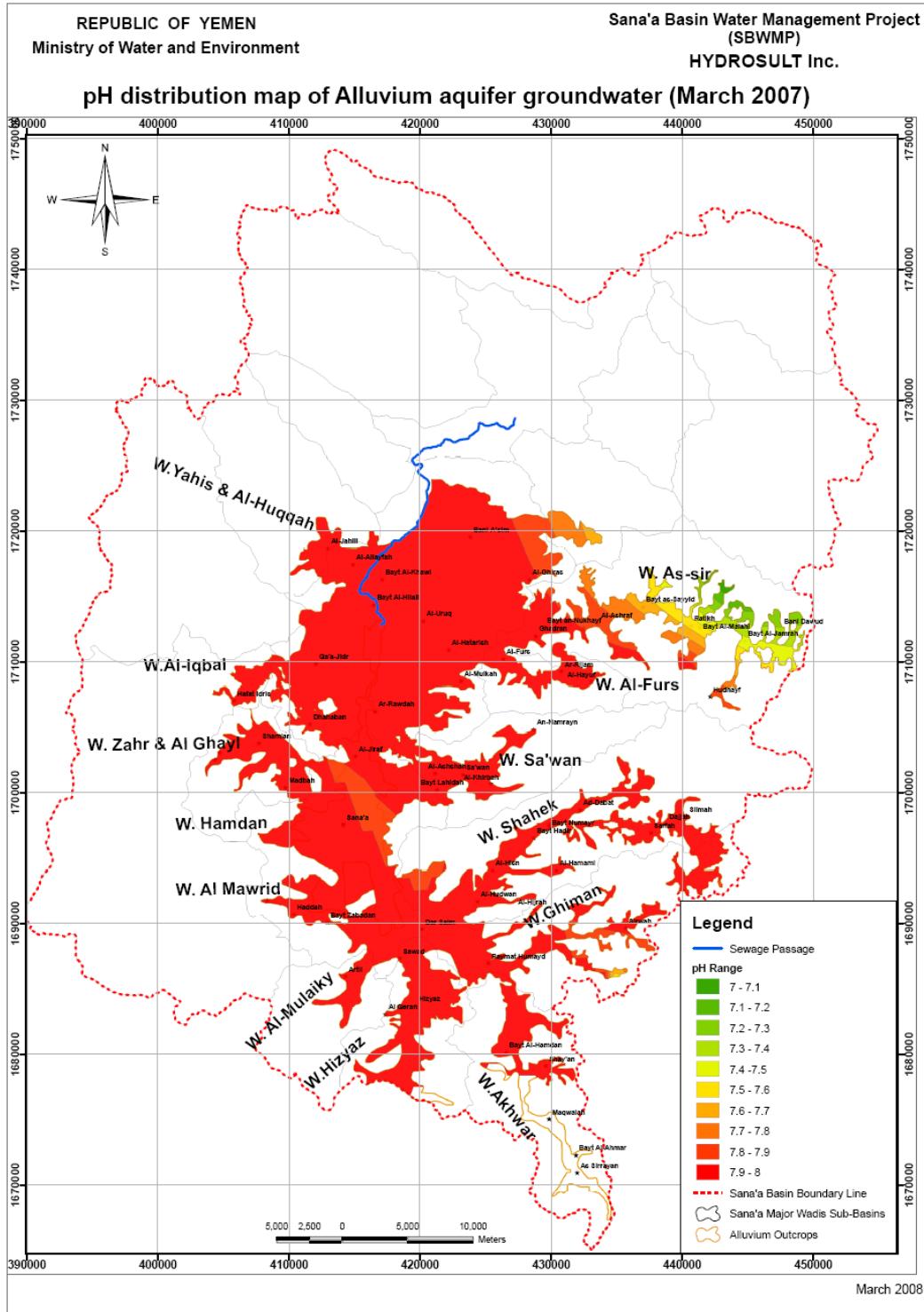


Figure 7-1 Contour map of pH distribution in alluvium aquifer

7.2.2 Groundwater temperature

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

Table 7-3 shows that almost 6% of the wells surveyed, all dug wells, have temperatures of less than 20 °C while 92% have temperatures ranging from 20 to 30°C. Only one well (about 2%) recorded temperatures more than 30°C. Although a good number of these wells are in Bani al Harith (sub-basin 9), such wells with higher temperatures are found across the Basin, indicating most likely the significance of a geothermal effect throughout the entire area.

Table 7-3 Temperature of surveyed groundwater wells in Sana'a Basin

Temperature of water				
Well Type	<20	20-30	>30	Total
Dug	3	38	1	42
Dug/Bore	0	3	0	3
Bore	0	8	0	8
Total	3	49	1	53

7.2.3 Groundwater salinity

Total dissolved solids (TDS) is a measure of the amount of material dissolved in water, which means that it is a measure of the "freshness" of water. Increasing TDS levels in an aquifer indicate that the aquifer is being contaminated. Based on the electrical conductivity measurements for 38 water samples from inventoried wells in the alluvium aquifer during Jan.-Feb. 2007, the TDS values were estimated according to Hem 1989 (Tables 7-4 and 7-5). The salinity distribution map for the alluvium aquifer in Sana'a Basin was constructed based on available TDS values of 38 water samples (Figure 7-2). A discussion of this map is given below.

The TDS in the alluvium aquifer ranges between 85 and 2,950 ppm in well no. HSH 3 and well no. HSH 2 respectively. Close to 25 water points (66%) have TDS less than 1,000 ppm, 26% range from 1,000 to 2,000 ppm (10 water samples), and only 8% are reported to have TDS in excess of 2,000 ppm (Table 7-4). It is observed, however, that the higher salinities are mainly recorded in dug wells of the Wadi El Ghayl downstream area. Groundwater salinity of the alluvium aquifer ranges between fresh and slightly brackish based on the classification of the following Chebotarev classification (1955):

- Fresh water category, where TDS value is less than 1,500 mg/l.
- Brackish water category, where TDS value lies between 1,500 and 5,000 mg/l.

The general features of the alluvium aquifer salinity map can be explained rather easily. Groundwater steadily dissolves minerals from the sediment matrix. As a result, it can acquire a higher salinity after a longer residence time underground (downstream areas). The TDS map (Figure 7-2) correlates with the water table map in the study area, where salinity increases gradually with the hydraulic gradient and vice versa. This explains the increasing TDS values towards the central part of Sana'a Basin where the alluvium aquifer exhibits the greatest thickness. Otherwise, hydrodynamic

stagnation zones west of Jabal Zi Marmar are characterized by salinity anomalies. E-W running finger-like protrusions of relatively fresh groundwater in the area between Bani Husheish in the east, and Wadi Dahr in the west, (Bani El Hareth area) are possibly associated with preferential zones for groundwater flow (buried channel beds).

The iso-salinity distribution map shows a general increase towards the north and from Wadi Sa'wan downstream to Wadi Zahr downstream in E-W direction, while the reverse direction is observed in the Wadi Dhaban downstream area. This may be attributed to the difference in alluvium aquifer thickness in this area and lithofacies impact. The iso-salinity contour lines are distributed in a clear area from eastern downstream of Wadi As-sir and Wadi Sa'wan with lower values to western Wadi Zahr downstream, which may reflect a leaching process of the subsurface flow. This is consistent with the general flow direction of the adjacent sandstone aquifer. Also, the general continuous recharge from rainfall of the western catchment dissolves the salts from the soil zone of these western wadis' downstream and increases the salinity. Local conditions of intensive agriculture and seepage of wastewater also increase the salinity. The discharge may be local from the central plain to the west, as reflected by the condensed contour lines in the Wadi Al-Iqbal area. The harmony between the water table map and the iso-salinity map confirm the relationship between the different factors affecting the groundwater flow in this aquifer.

Table 7-4 TDS range in ppm for different well types

TDS in ppm				
Well type	<1,000	1,000-2,000	>2,000	Total
Dug	22	9	3	34
Dug/Bore	2	--	--	2
Bore	1	1	--	2
Total	25	10	3	38

Table 7-5 TDS for water samples from the alluvium aquifer (Jan.-Feb. 2007)

Well ID	Easting (m)	Northing (m)	Well type	Aquifer type	TDS (mg/l)
HS51	440585	1711095	Dug	Alluvial deposits	202
HS76	433877	1724495	Dug	Alluvial deposits	2,131
HSA 1	425298	1718800	Bore	Alluvial deposits	1,178
HSA 2	422002	1719988	Dug	Alluvial deposits	499
HSA 4	417905	1716847	Dug	Alluvial deposits	1,178
HSA 5	416155	1715019	Dug	Alluvial deposits	1,901

Well ID	Easting (m)	Northing (m)	Well type	Aquifer type	TDS (mg/l)
HSA 6	416241	1715122	Dug	Alluvial deposits	1,434
HSA 15	417243	1717735	Dug	Alluvial deposits	2,240
HSA 19	416322	1715307	Dug	Alluvial deposits	1,491
HSA 27	422267	1715645	Dug	Alluvial deposits	359
HSA 28	422695	1716025	Dug	Alluvial deposits	604
HSA 30	422810	1716400	Dug	Alluvial deposits	367
HSZ1	418990	1686713	Dug	Alluvial deposits	454
HSZ3	429988	1675461	Dug	Alluvial deposits	667
HSZ5	439684	1701903	Dug	Alluvial deposits	252
HSZ6	430466	1697997	Dug	Alluvial deposits	294
HSZ7	422211	1690122	Dug	Alluvial deposits	465
HSS2	425190	1700940	Dug	Alluvial deposits	457
HSS3	425231	1701003	Dug	Alluvial deposits	483
HSS4	426652	1699852	Dug	Alluvial deposits	280
HSS5	428053	1700726	Dug	Alluvial deposits	234
HSB1	408880	1696762	Dug	Alluvial deposits	321
HSB2	408943	1696768	Dug	Alluvial deposits	404
HSB5	402470	1695440	Dug	Alluvial deposits	426
HSB6	401303	1692293	Dug	Alluvial deposits	287
HSZ9	414631	1692575	Dug/Bore	Alluvial deposits	413
HSB 2	407985	1703832	Dug	Alluvial deposits	2,950
HSB 3	409225	1715501	Bore	Alluvial deposits	85
HSA 53	416336	1717861	Dug	Alluvial deposits	545
HSZ12	416473	1689675	Dug	Alluvial deposits	292

Well ID	Easting (m)	Northing (m)	Well type	Aquifer type	TDS (mg/l)
HSA 55	416631	1717743	Dug	Alluvial deposits	1,262
HSA 56	416582	1717597	Dug	Alluvial deposits	1,274
HSH 6	412518	1713248	Dug/Bore	Alluvial deposits	385
HSA 57	416964	1717773	Dug	Alluvial deposits	1217
HSA 58	414746	1715368	Dug	Alluvial deposits	928
HSA 60	415955	1714858	Dug	Alluvial deposits	1,216
HSA 61	416062	1714747	Dug	Alluvial deposits	1,009
HSA 62	414799	1715584	Dug	Alluvial deposits	858

Table 7-6 Results of chemical routine analyses of groundwater samples of the alluvium aquifer (March 2007)

S.No	Well ID	EC µmhos / cm	pH	TDS (mg/l)	Units	Ca ⁺⁺	Mg ⁺⁺	Na ⁺	K ⁺	Sum	CO ₃ ⁼⁼	HCO ₃ ⁻	SO ₄ ⁼⁼	Cl ⁻	Sum	Hydro-chemical coefficients			SAR (epm)	Na% (epm)	Hardness (epm)	CEI
																rNa / rCl	rCa / rMg	rClrNa / rCl				
					mg/l	42.3	14.47	152	3		31.56	232.62	124	78.99								
1	HSA 95	920	8.3	563	meq/l	2.11	1.19	6.61	0.08	9.99	1.05	3.81	2.58	2.23	9.67	2.97	1.77	-1.97	5.1	66.9	165.2	
					e%	21.14	11.92	66.18	0.77		10.87	43.29	26.69	23.03								-1.91
					mg/l	64.35	36.79	118	7		15.78	288.77	71	179.52								
2	HSA 96	1157	7.8	637	meq/l	3.21	3.03	5.13	0.18	11.55	0.53	4.73	1.48	5.06	11.80	1.01	1.06	-0.01	2.9	46.0	312.1	
					e%	27.81	26.20	44.43	1.55		4.46	40.10	12.53	42.91								-0.07
					mg/l	43.25	16.35	66	3		31.56	168.45	64	38.3								
3	HSA 97	576	8.2	347	meq/l	2.16	1.34	2.87	0.08	6.45	1.05	2.76	1.33	1.08	6.22	2.66	1.61	-1.66	2.2	45.7	175.3	
					e%	33.46	20.85	44.50	1.19		16.90	44.34	21.41	17.36								-1.63
					mg/l	10.48	1.79	88	2		7.89	160.43	32	43.09								
4	HSA 99	462	8.1	265	meq/l	0.52	0.15	3.83	0.05	4.55	0.26	2.63	0.67	1.22	4.77	3.15	3.55	-2.15	6.6	85.3	33.5	
					e%	11.50	3.24	84.14	1.13		5.51	55.07	13.96	25.46								-2.35
					mg/l	32.32	15.39	22	3		15.78	120.32	34	26.33								
5	HSB 10	380	8.1	209	meq/l	1.61	1.27	0.96	0.08	3.91	0.53	1.97	0.71	0.74	3.95	1.29	1.27	-0.29	0.8	26.4	144.0	
					e%	41.23	32.36	24.45	1.96		13.32	49.93	17.93	18.81								-0.40
					mg/l	65.38	43.93	168	6		31.56	377.01	86	210.64								
6	HSA 105	1232	7.9	800	meq/l	3.26	3.61	7.30	0.15	14.33	1.05	6.18	1.79	5.94	14.96	1.23	0.90	-0.23	3.9	52.0	344.0	
					e%	22.76	25.21	50.96	1.07		7.03	41.29	11.97	39.71								-0.31
					mg/l	20.77	11.21	122	3		31.56	224.6	70	45.48								
7	HSA 106	666	8.3	416	meq/l	1.04	0.92	5.30	0.08	7.34	1.05	3.68	1.46	1.28	7.47	4.14	1.12	-3.14	5.4	73.3	98.0	
					e%	14.12	12.56	72.27	1.05		14.08	49.25	19.51	17.17								-3.27
					mg/l	30.77	26.17	290	4		31.56	320.86	320	148.4								
8	HSA 108	1429	7.9	1011	meq/l	1.54	2.15	12.61	0.10	16.40	1.05	5.26	6.66	4.18	17.15	3.01	0.71	-2.01	9.3	77.5	184.5	
					e%	9.36	13.12	76.89	0.62		6.13	30.64	38.84	24.40								-2.18
					mg/l	52.52	20.36	6	1		16.47	194.24	17	21.7								

S.No	Well ID	EC µmhos / cm	pH	TDS (mg/l)	Units	Ca ⁺⁺	Mg ⁺⁺	Na ⁺	K ⁺	Sum	CO ₃ ⁻⁻	HCO ₃ ⁻	SO ₄ ⁻⁻	Cl ⁻	Sum	Hydro-chemical coefficients			SAR (epm)	Na% (epm)	Hardness (epm)	CEI	
																rNa / rCl	rCa / rMg	rClrNa / rCl					
9	HSA 109	440	7.8	232	meq/l	2.62	1.67	0.26	0.03	4.58	0.55	3.18	0.35	0.61	4.70	0.43	1.57	0.57	0.2	6.3	214.9		
					e%	57.20	36.55	5.69	0.56		11.69	67.75	7.54	13.03								0.52	
					mg/l	47.6	8.47	46	1		15.78	176.47	32	43.09									
10	HSA 69	500	7.7	282	meq/l	2.38	0.70	2.00	0.03	5.10	0.53	2.89	0.67	1.22	5.30	1.65	3.41	-0.65	1.6	39.7	153.7		
					e%	46.60	13.67	39.24	0.50		9.92	54.56	12.58	22.94									-0.73
Mean value			8.0 1	476		28.52	19.57	50.88	1.04		9.99	43.29	18.30	24.48		2.15	1.70	-1.15			182.5	-1.20	

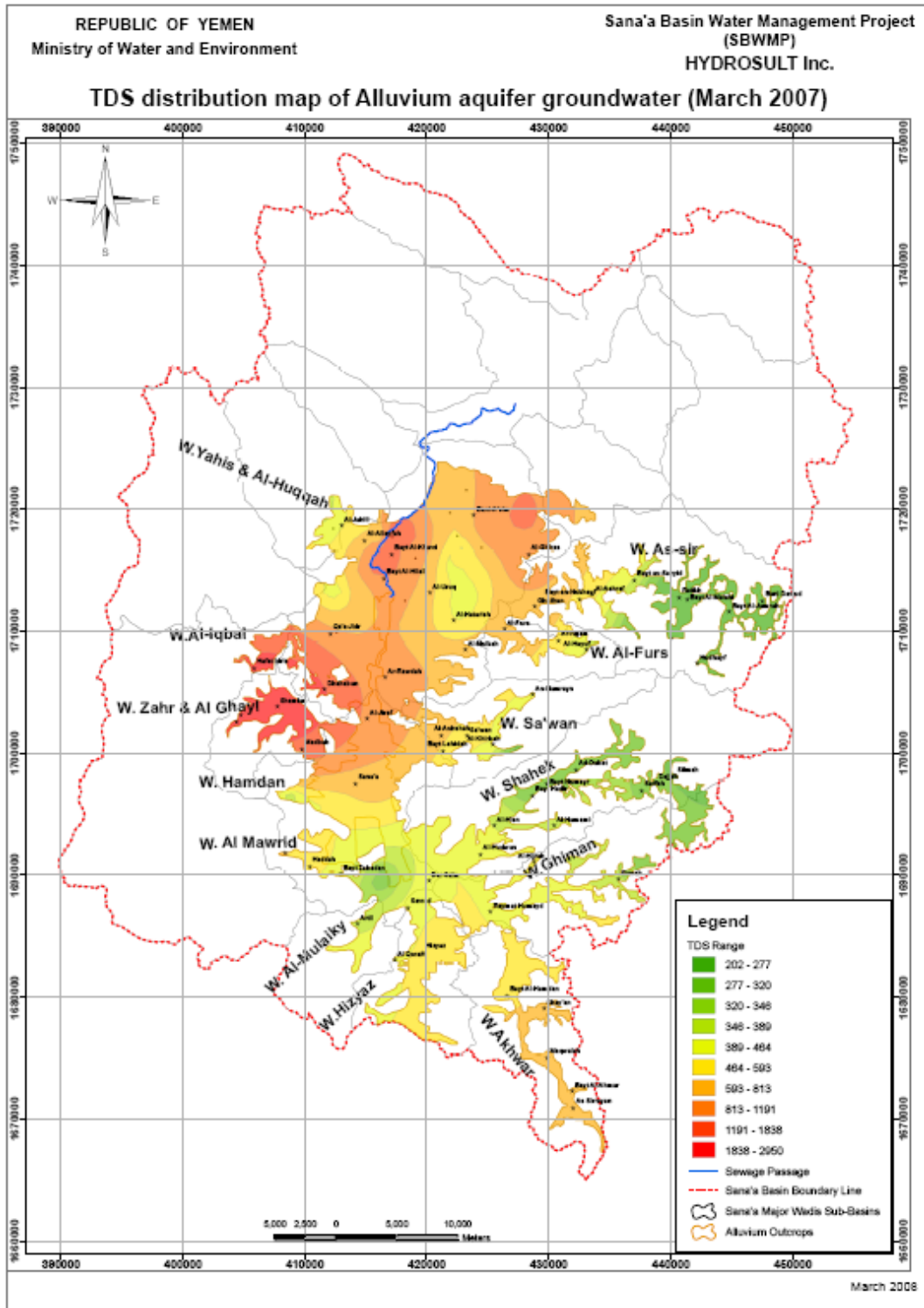


Figure 7-2 Iso-salinity contour map of groundwater of alluvium aquifer in study area

7.2.4 Distribution of major ions

The distribution of ions in groundwater of the alluvium aquifer in Sana'a Basin (Table 7-6 and Figures 7-3 to 7-8), are discussed herein as follows:

- 1) The Ca^{2+} concentration ranges from 9 to 57%, with a mean value of 28.5% of the total dissolved cations in groundwater of the alluvium aquifer. Since the concentrations in percentages of Ca^{2+} are 3% and 70% for both rain and sea (marine) waters respectively, the source of calcium mineralization is thus pure infiltrated rainwater affected by leaching and dissolution of terrestrial salts from aquifer matrices and marine salts from the adjacent catchment areas. It can be concluded that the concentration is less than the maximum permissible limit over the entire aquifer, except at contact with the limestone aquifer. However, the western part of the aquifer has a relatively low concentration. The spatial distribution of the calcium ion concentration exhibits an increase in the general flow direction of the alluvium aquifer. Also, a local direction of increase is present from east to west (downstream of Wadi Sa'wan in the east to downstream of Wadi Iqbal in the west). The effect of the sewage passage is more pronounced in the north of the alluvium aquifer since a considerable increase in calcium ion concentration is present.
- 2) The Mg^{2+} concentration ranges from 3 to 37%, with a mean value of 20% of total dissolved cations in the alluvium aquifer. As the concentration percentages of Mg^{2+} are 10% and 20% for both rain and sea (marine) waters respectively, this indicates that the Mg^{2+} content is attributed to the dolomitization processes that have occurred in the aquifer, as well as Mg^{2+} content, which is nearly identical to sea water.

Figure 7-4 presents the distribution of magnesium ion concentration within the alluvium aquifer. It was noted that there is a great similarity between the distribution of calcium ion concentration and magnesium ion concentration in the alluvium aquifer. This may be attributed to dolomitization processes in the aquifer, as well as leaching and dissolution processes of terrestrial salts during groundwater flow in this aquifer.

- 3) The Na^+ concentration ranges from 6 to 84%, with a mean value of 51% of total dissolved cations in the alluvium aquifer. The Cl^- concentration ranges from 13 to 43%, with a mean value of 28% of the total dissolved anions of this aquifer. Concentration percentages of both Na^+ and Cl^- are 77% & 90% and 20% & 29% for both sea (marine) and rainwaters respectively. Thus, it is believed that both Na^+ and Cl^- have the same sources of mineralization (mixed mineralization) in the groundwater of those aquifers.

The sodium ion concentration distribution map of the alluvium aquifer (Figure 7-5) shows a general increase towards the north, while a decrease is observed in the E-W direction (from Wadi As-Sir in the east to downstream of Wadi Yahis and Al-Huqqah in the west) as a result of continuous recharge from the infiltrated rainwater characteristic of this location. The discharge direction may be due north and west. The harmony between the water table map and the iso-sodium concentration map confirms the relationship between the different factors affecting groundwater flow in this aquifer.

Notably, the effect of sewage passage is pronounced in a manner such that the area of highest sodium ion concentration is present downstream of this passage.

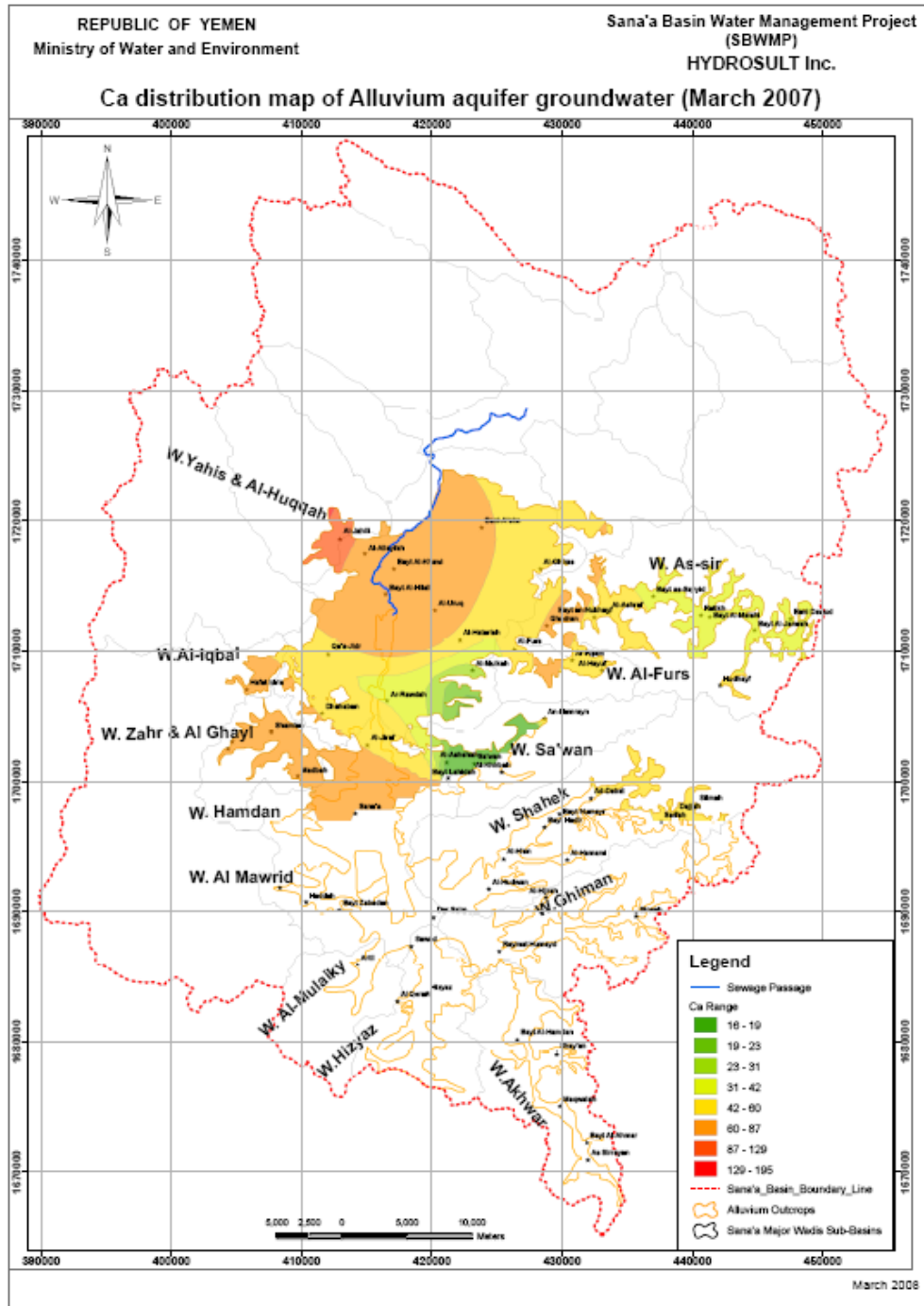


Figure 7-3 Calcium distribution map of groundwater of the alluvium aquifer in Sana'a Basin

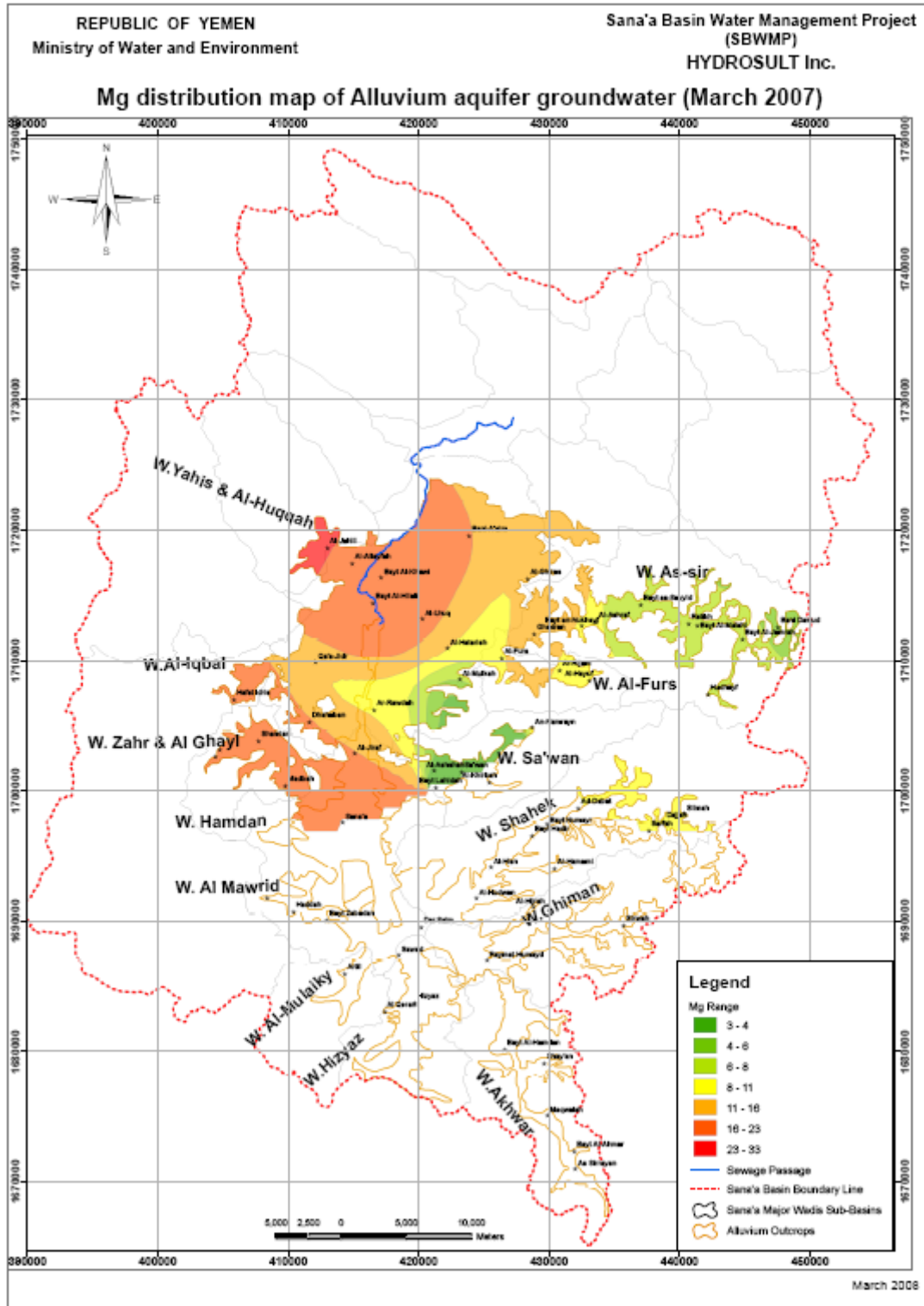


Figure 7-4 Magnesium distribution map of groundwater of the alluvium aquifer in Sana'a Basin

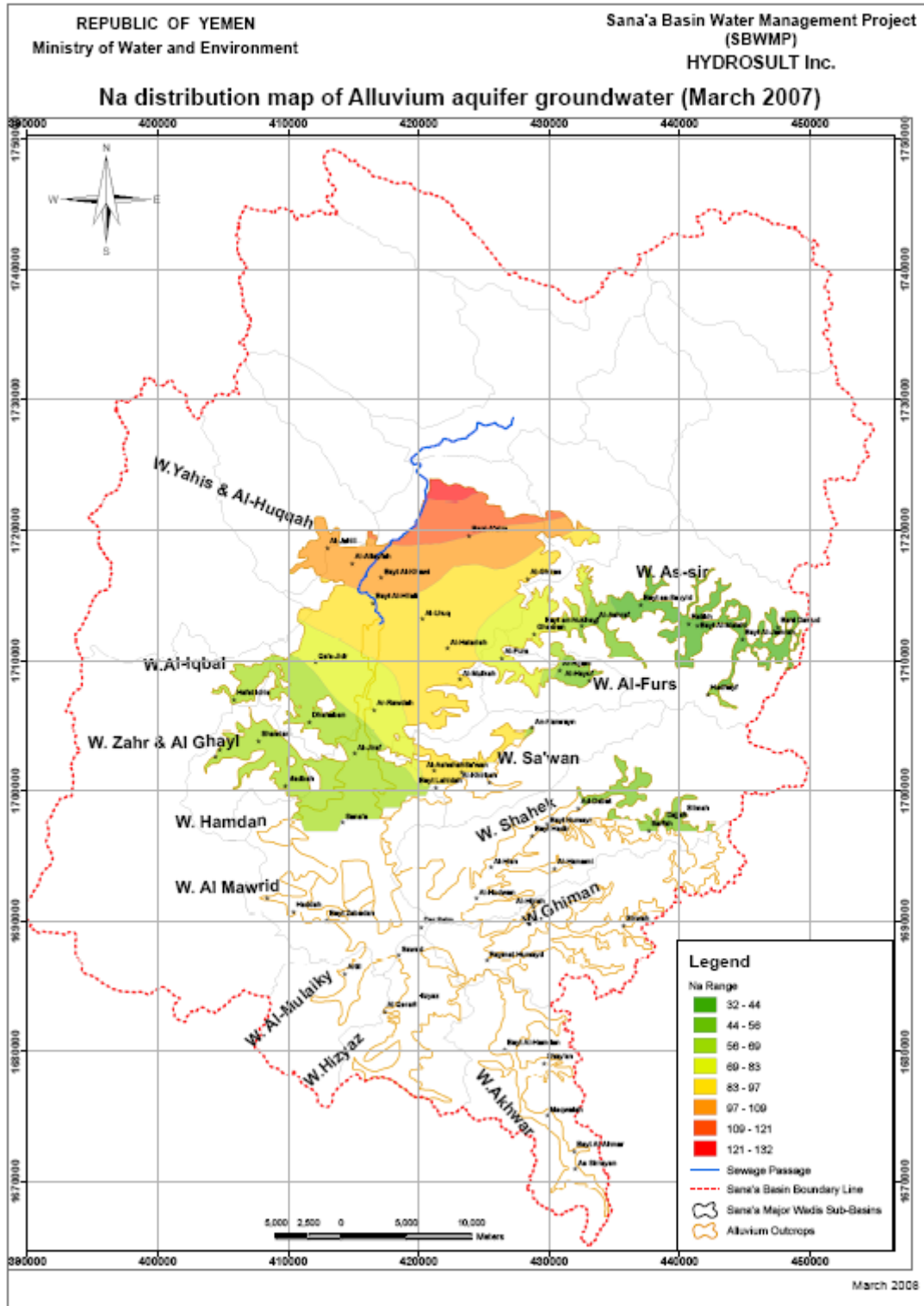


Figure 7-5 Sodium distribution map of groundwater of the alluvium aquifer in Sana'a Basin

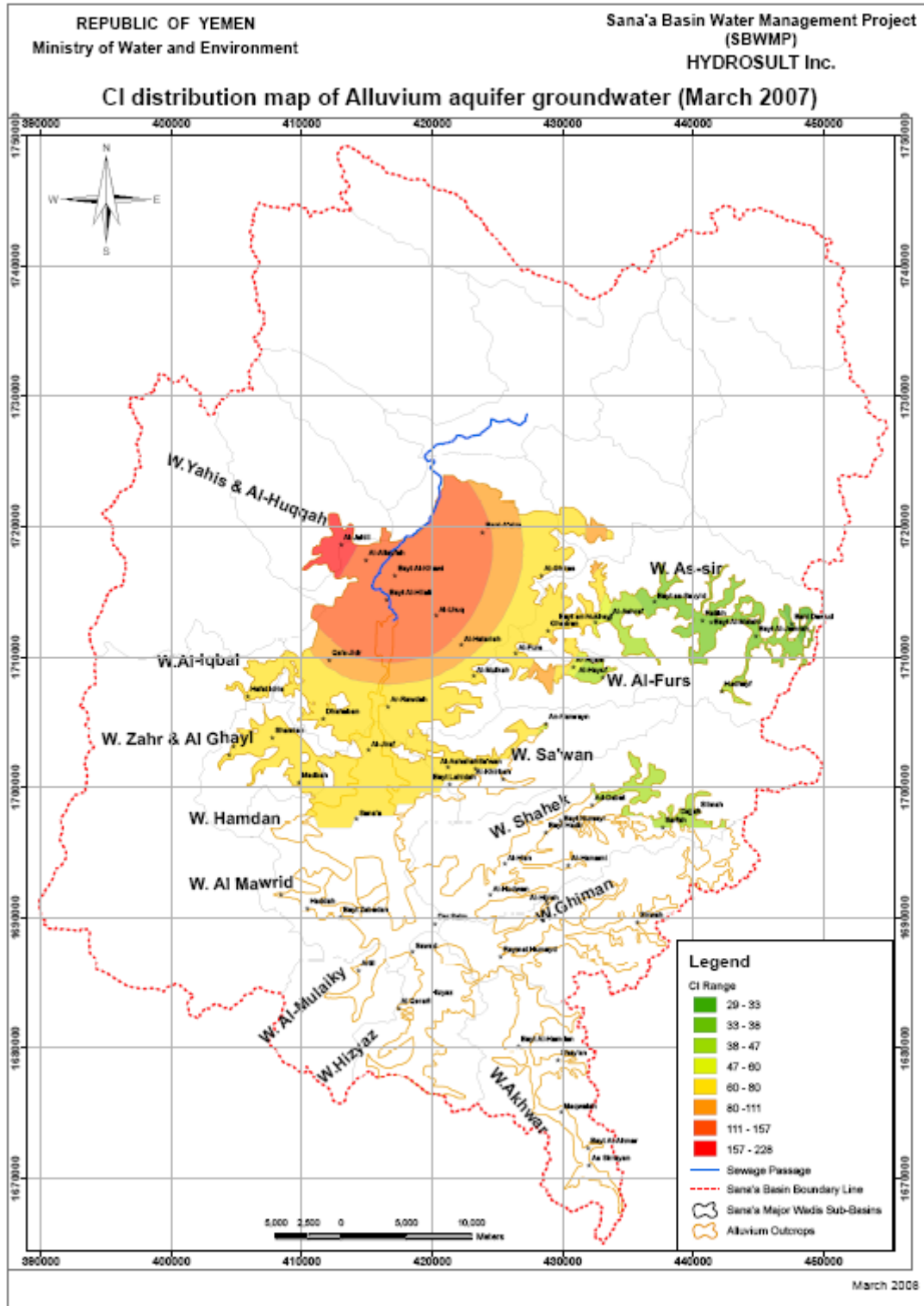


Figure 7-6 Chloride distribution map of groundwater of the alluvium aquifer in Sana'a Basin

The chloride ion concentration distribution map of the alluvium aquifer (Figure 7-6) shows a general increase towards the north, while a decrease is observed in the E-W direction (from Wadi As-Sir in

the east to downstream of Wadi Yahis and Al-Huqqah in the west), similar to the sodium distribution map. The map confirms that the discharge direction is due north and west. The harmony between the water table map and the iso-chloride concentration map, as with the iso-sodium concentration map, correlates with the water table map of the alluvium aquifer. Also, the effect of sewage passage is pronounced in that the area of highest chloride ion concentration is present downstream of this passage.

- 4) The SO_4^{2-} concentration ranges from 8 to 39%, with a mean value of 18% of the total dissolved anions in this aquifer. The concentration percentages of SO_4^{2-} are 9.5% and 25% for both sea (marine) and rainwaters respectively. The sulfate mineralization is of meteoric origin. This could indicate that sulfate content is governed by a biogenic system that significantly distorts the other mechanisms (wet deposition, evaporation, dissolution of sulfate solid-phases and mixing).

Figure 7-7 presents the sulfate distribution over the entire alluvium aquifer. It was noted that almost all of the aquifer has a relatively low concentration of sulfate within the range of 14 mg/l and 258 mg/l. The highest concentration is found at well HAS 108 at Arhab, where the effect of sewage water is the most pronounced. The distribution of the sulfate ion concentration as revealed in Figure 7-7 shows a general increase towards the west (from Wadi As-sir in the east to downstream of Wadi Yahis in the west) while a decrease is noted in the area between Bayt El-Hilali and Uruq. The map confirms that the discharge direction is due north and west. Also, the effect of sewage passage is pronounced in that the area of highest sulfate ion concentration is present around the course of this sewage.

- 5) The HCO_3^- concentration ranges from 31 to 68%, with a mean value of 43% of the total dissolved anions in the studied aquifer. The concentration percentages of HCO_3^- are 0.5% and 46% for both sea (marine) and rainwaters, respectively. The source of HCO_3^- mineralization is mixed between rain and sea (marine) waters. The bicarbonate ion concentration ranges from 112 to 233 mg/l. The bicarbonate ion concentration distribution map (Figure 7-8) shows a general increase towards the north and west, as mentioned before. The discharge direction may be due north and west. The harmony between the water table map and the iso-bicarbonate concentration map confirms the true flow direction. The effect of sewage passage is absent in that the distribution is perpendicular to the sewage passage.

Notably, the anomalies of the concentration of both cations and anions of wells HAS 101 and HAS 103 may be attributed to mixing between groundwater of two different aquifers (Figure 7-9). This is confirmed in the discussion on cluster analyses of alluvium groundwater.

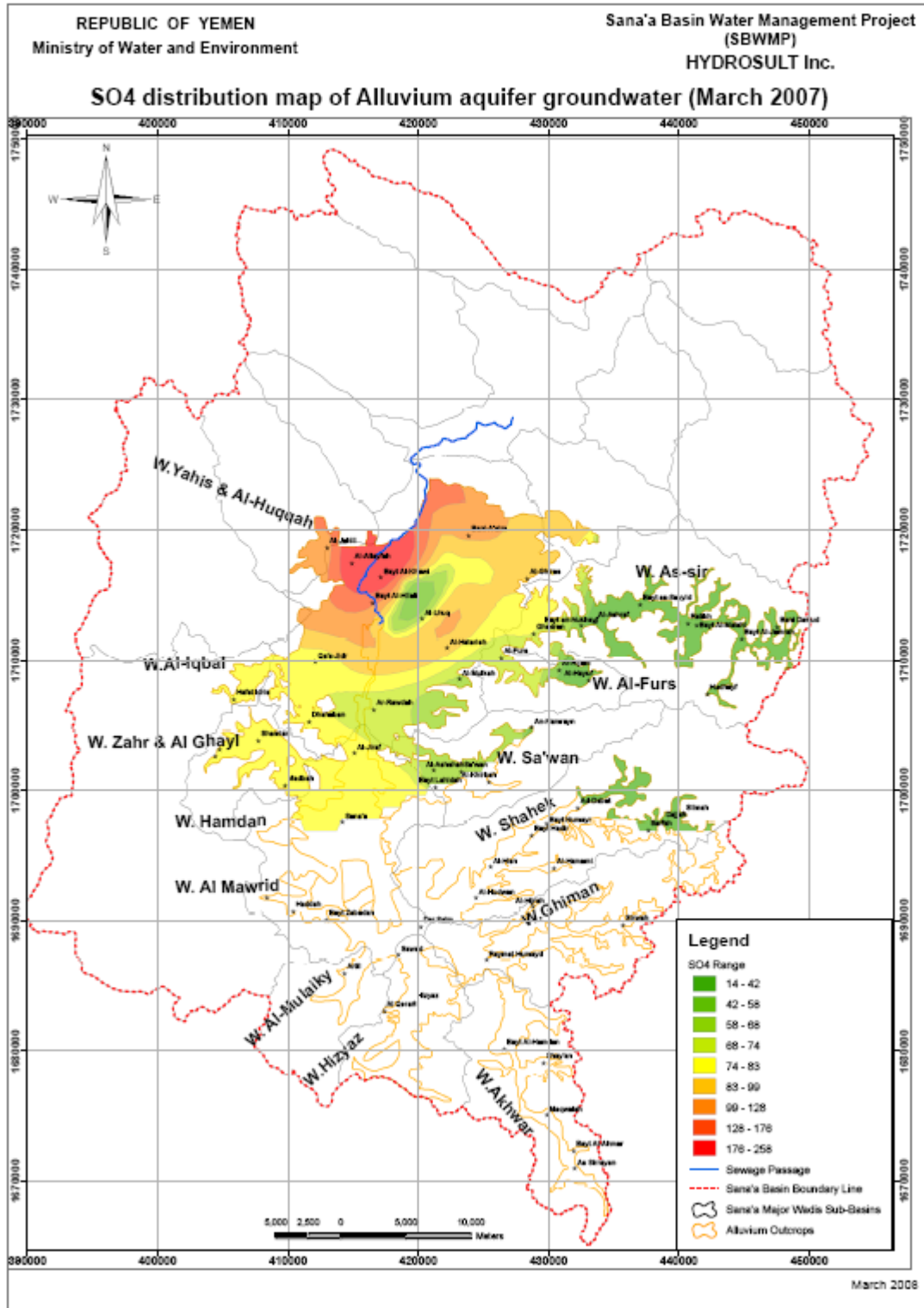


Figure 7-7 Sulfate distribution map of groundwater of the alluvium aquifer in Sana'a Basin

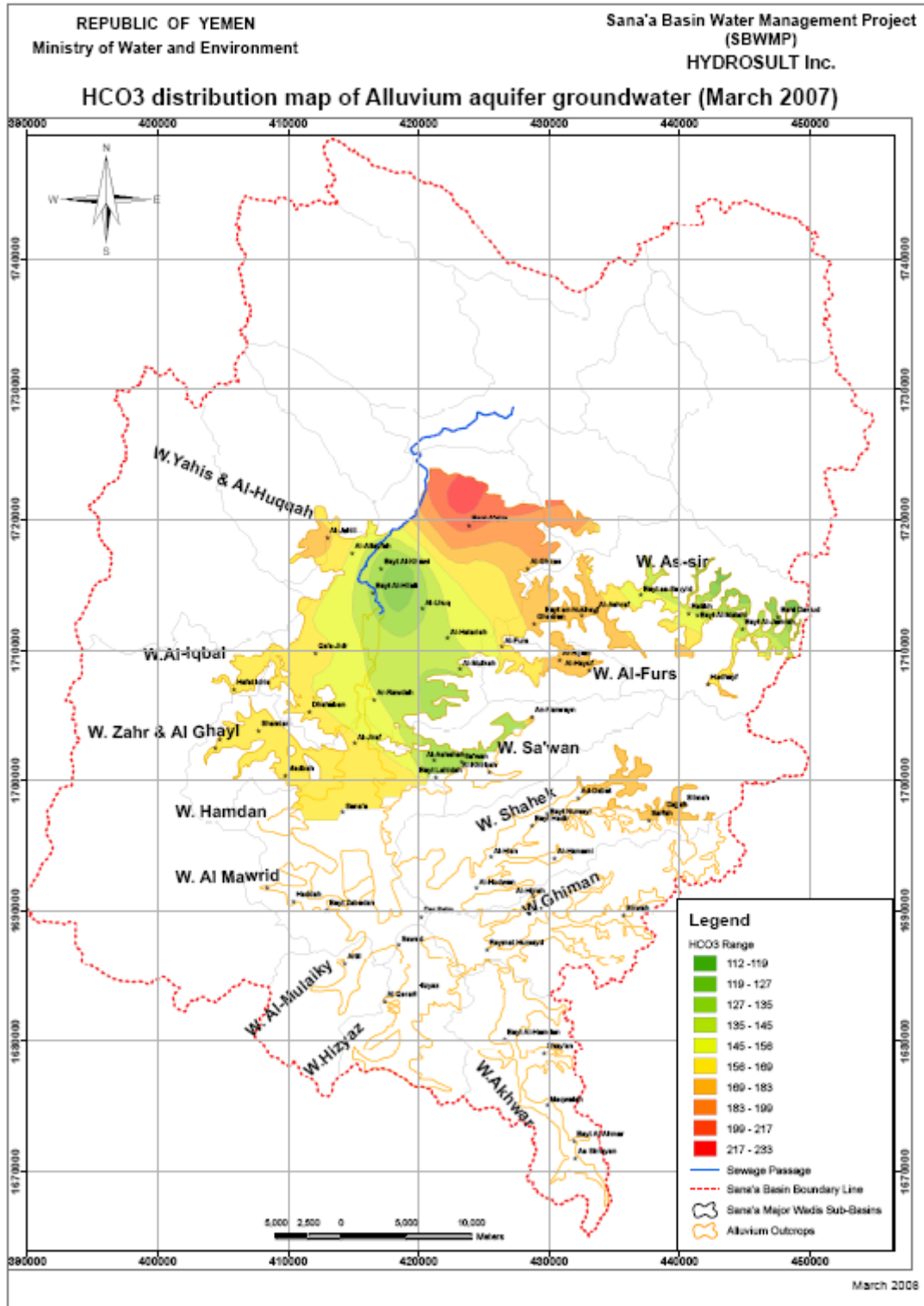


Figure 7-8 Bicarbonate distribution map of groundwater of the alluvium aquifer in Sana'a Basin

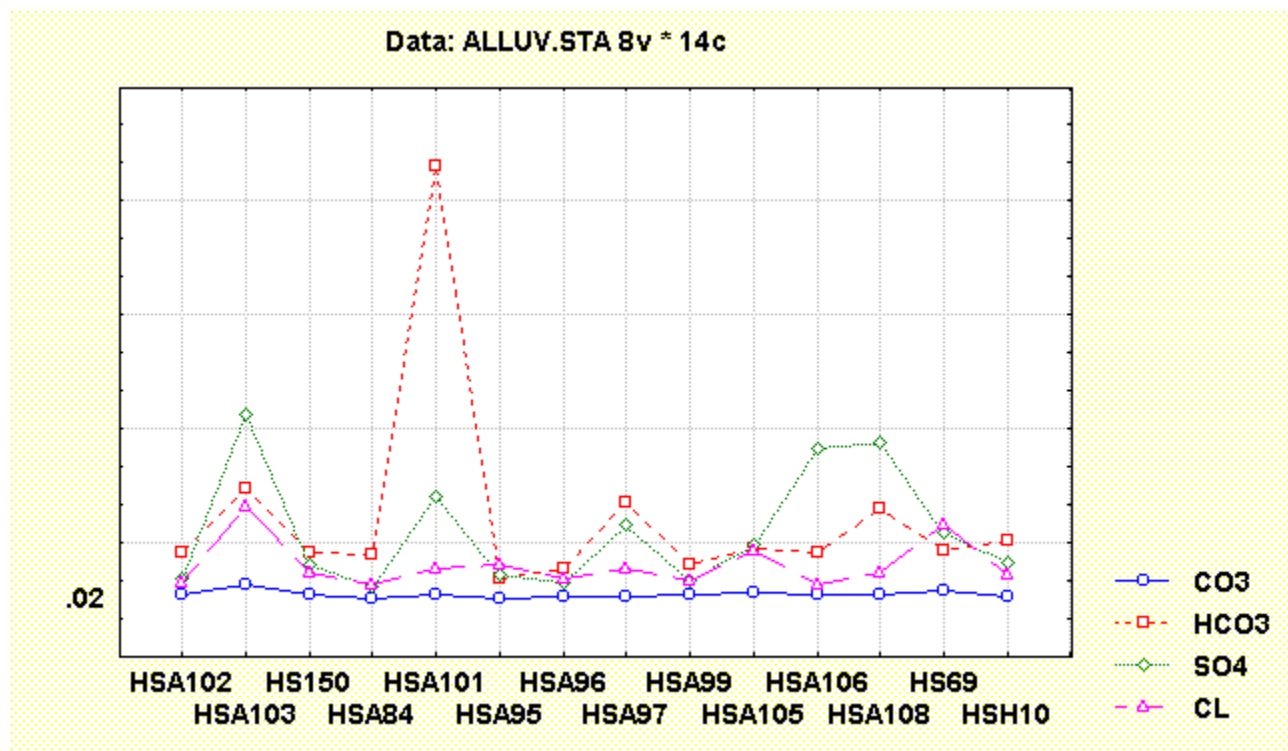
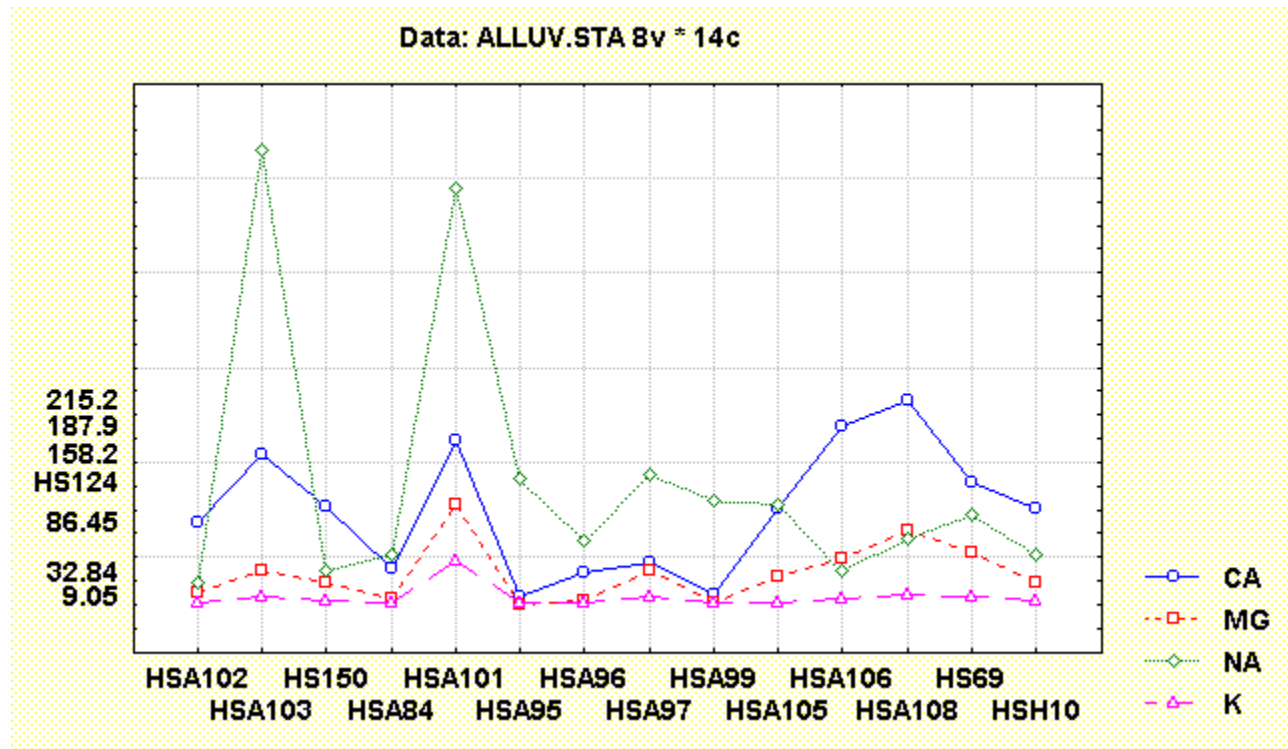


Figure 7-9 Graph showing the general trend of distribution of groundwater ions of the alluvium aquifer in Sana'a Basin

7.2.5 Ion relationships and hydro-chemical coefficients

The alluvium aquifer groundwater in Sana'a Basin constitutes three main groups of ion relationships.

Group 1: Having $\text{Na} > \text{Ca} > \text{Mg}$ and $\text{Cl} > \text{SO}_4 > \text{HCO}_3$ (60%) where $r\text{Na}/r\text{Cl}$ is more than unity. This group (60%) characterizes groundwater samples no. HSA 69, HSA 95, HSA 96, HSA 97, HSA 99 and HSA 106 which were collected from Arhab area.

According to salinity levels, the water type is mainly fresh water. Conversely, the hydro-chemical features of this group of the alluvium aquifer indicate marine salt contamination from the marine deposits of the neighboring catchment area and aquifer matrices. There is also a possible contamination of the alluvium aquifer with marine salts from the adjacent fractured limestone aquifer.

Group 2: Having $\text{Na} > \text{Mg} > \text{Ca}$ and $\text{Cl} > \text{SO}_4 > \text{HCO}_3$ (20%) where $r\text{Na}/r\text{Cl}$ is more than unity. This group characterizes the groundwater samples no. HSA 105 and HSA 108, which were collected from the Arhab area.

According to the total salinity, the groundwater samples lie within the brackish water type. The hydro-chemical features and assemblages of hypothetical salt combinations indicate marine salt contamination in this area.

Group 3: Having $\text{Ca} > \text{Mg} > \text{Na}$ and $\text{HCO}_3 > \text{Cl} > \text{SO}_4$ (20%), where $r\text{Ca}/r\text{Mg}$ is more than unity. This group characterizes the groundwater samples no. HSA 10 and HSA which were collected from the Arhab area.

The assemblages of hypothetical salts combinations include the following:

- $\text{NaCl}, \text{Na}_2\text{SO}_4, \text{NaHCO}_3, \text{MgCO}_3, \text{Ca}(\text{HCO}_3)_2$
- $\text{NaCl}, \text{Na}_2\text{SO}_4, \text{Ca}/\text{MgSO}_4, \text{MgCO}_3, \text{Ca}(\text{HCO}_3)_2$
- $\text{NaCl}, \text{MgCl}_2, \text{Mg}/\text{Ca SO}_4, \text{Ca}(\text{HCO}_3)_2$
- $\text{NaCl}, \text{MgCl}_2, \text{CaCl}_2, \text{Mg}/\text{Ca SO}_4, \text{Ca}(\text{HCO}_3)_2$

Regarding the assemblages of hypothetical salt combinations of the alluvium aquifer, most groundwater samples exhibit a continental origin with leaching and dissolution processes (Table 7-7), while those mixed between continental and marine origin, or flushing with other groundwater sources, is limited to the well HAS.

In brief, Group 1 characterizes most groundwater samples (60%), while Group 2 characterizes the rest of groundwater samples. Most of the groundwater samples of the alluvium aquifer investigated reveal that calcium exceeds magnesium. This is due to the leaching of the catchment area and carbonate materials in the aquifer matrix of the alluvium aquifer. Groups 1 and 2 reflect an advanced stage of hydro-chemical evolution, where the metasomatic sequence is: $\text{Cl} > \text{SO}_4 > \text{HCO}_3$. This is due to the leaching and dissolution of marine sediments (clay layer in stratigraphic sequence in the alluvium aquifer). The general shape of such groundwater belonging to Groups 1 and 2 show complete similarity to that of sea water, indicating that this groundwater is of meteoric origin and affected by leaching and dissolution of marine salts (marine sediments). Consequently, groundwater of the alluvium aquifer represents one main class of geochemical character that is the groundwater of marine affinity.

From the data collected (Table 7-6), it is clear that the total hardness ranges from 33.5 to 344 **epm** with a mean value of 182.5 **epm**, in the fresh groundwater samples of the alluvium aquifer. These data indicate an increase in total hardness with increasing water salinity (Figure 7-10). This is mainly attributed to the effect of leaching and dissolution of terrestrial and marine salts, leading to an increase of hardness with particular importance on the effect of NaCl concentration (effect of ionic strength) on increasing solubility of Ca^{2+} and Mg^{2+} in water (Freeze and Cherry, 1979 and Hem, 1989). This does not exclude the contribution of CO_2 , longer residence time, influence of salty water and cation exchange processes.

Table 7-7 Assemblages of hypothetical salt combinations of the selected groundwater samples from the alluvium aquifer

Well ID	Assemblages of hypothetical salt combinations (%)							Groundwater origin
	NaCl	Na ₂ SO ₄	NaHCO ₃	MgCl ₂	MgSO ₄	Mg(HCO ₃) ₂	Ca(HCO ₃) ₂	
HSA 95	23	27	16	--	--	12	12	Continental
HSA 96	43	2	---	---	11	15	27	Continental
HSA 97	17	21	7	--	---	21	33	Continental
HSA 99	25	14	44	--	--	3	13	Continental
HAH 10	19	8	--	--	10	22	41	Continental
HSA 105	40	12	--	--	--	25	23	Continental
HSA 106	17	20	36	--	--	13	14	Continental
HSA 108	24	39	14	--	--	13	9	Continental
HAS	6	--	--	7	8	22	57	Mixed
HSA 69	23	13	4	--	--	14	46	Continental

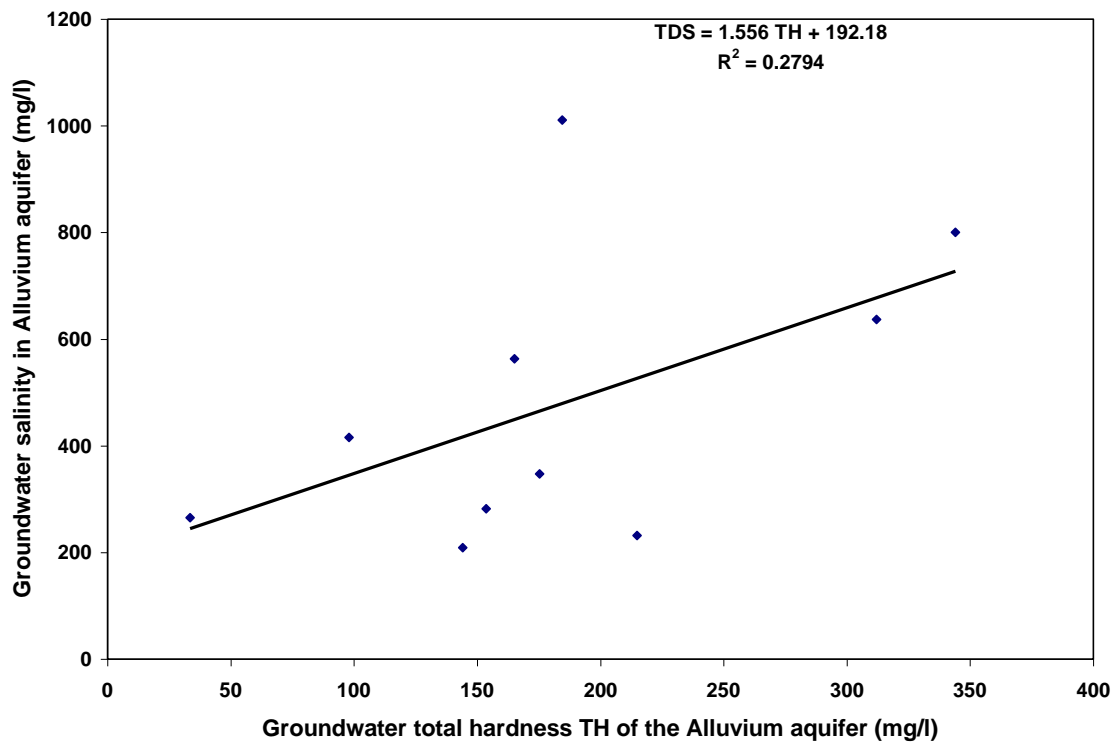


Figure 7-10 Graph showing relationship between TDS and total hardness in mg/l of groundwater of alluvium aquifer in Sana'a Basin

7.2.6 Groundwater classification

Natural waters can be genetically classified into two major types:

- Indogenetic water, which is originally formed due to magmatic activities (juvenile water) or mineral dehydration processes (metamorphic water).
- Exogenetic water, which is formed either from infiltration of surface water into already existing rock formations (meteoric water) or formed during sedimentation times (marine water).

Several authors have proposed methods for geochemical classification of groundwater on genetic bases. Some of these methods are based mainly on the use of anions, while others are based on anions and cations (Piper 1953 and Schoeller 1962). The trilinear diagram proposed by Piper 1953 usually gives a more coherent picture of the cation distribution applied in the present work. The trilinear diagram (Figures 7-11 and 7-12) permits the cation and anion compositions of many samples to be represented on a single graph in which major groupings or trends in the data can be discerned visually.

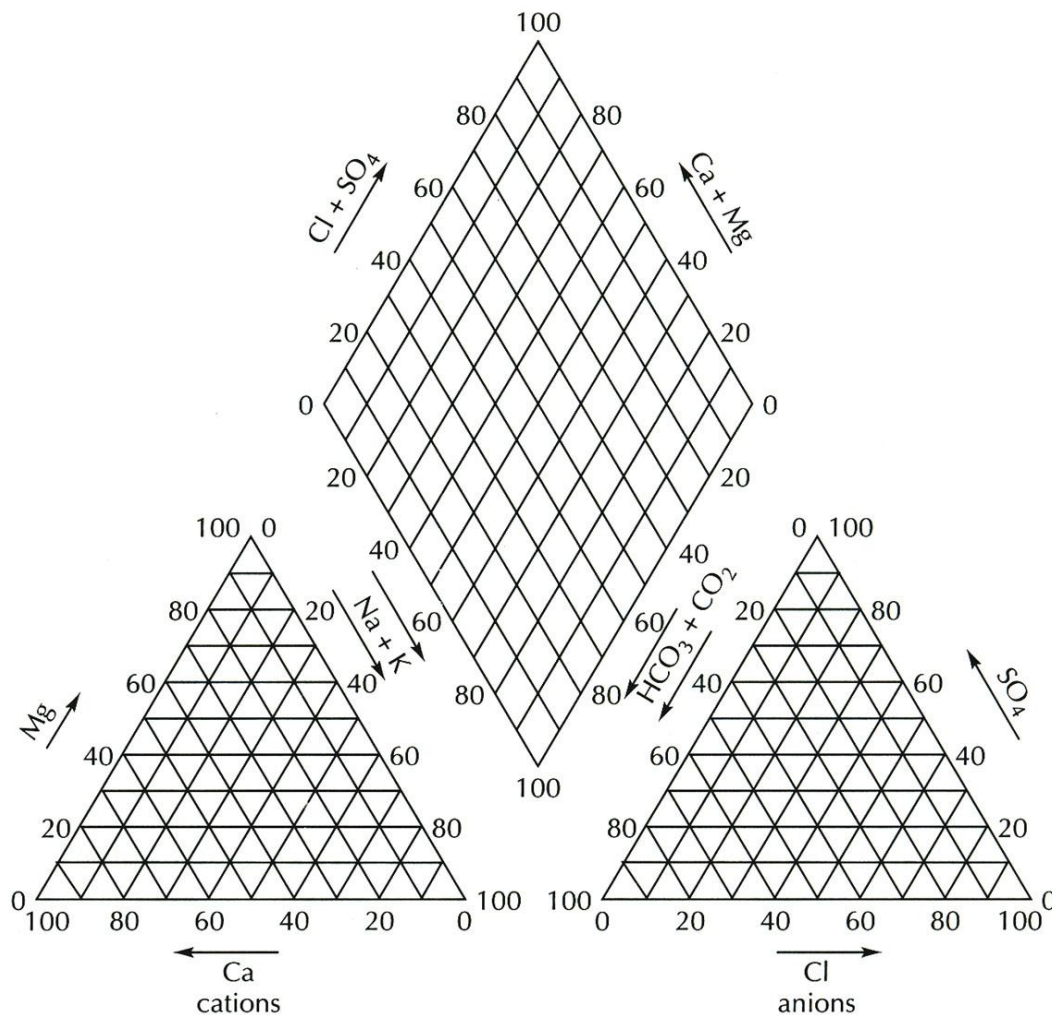


Figure 7-11 Trilinear diagram for groundwater classification proposed by Piper 1953

The Piper trilinear diagram combines three distinct fields for plotting, two triangular fields at the lower left and lower right respectively, and an intervening diamond-shaped field. All three fields have scales reading in 100 parts. In the triangular field on the lower left, the percentage reacting values of

the three cation groups (Ca, Mg and Na) are plotted as a single point according to conventional trilinear coordinates. The three-anion groups (HCO_3 , SO_4 , Cl) are plotted likewise in the triangular field on the lower right. Thus, two points on the diagram, one in each of the two triangular fields, indicate the relative concentrations of the dissolved constituents of a groundwater.

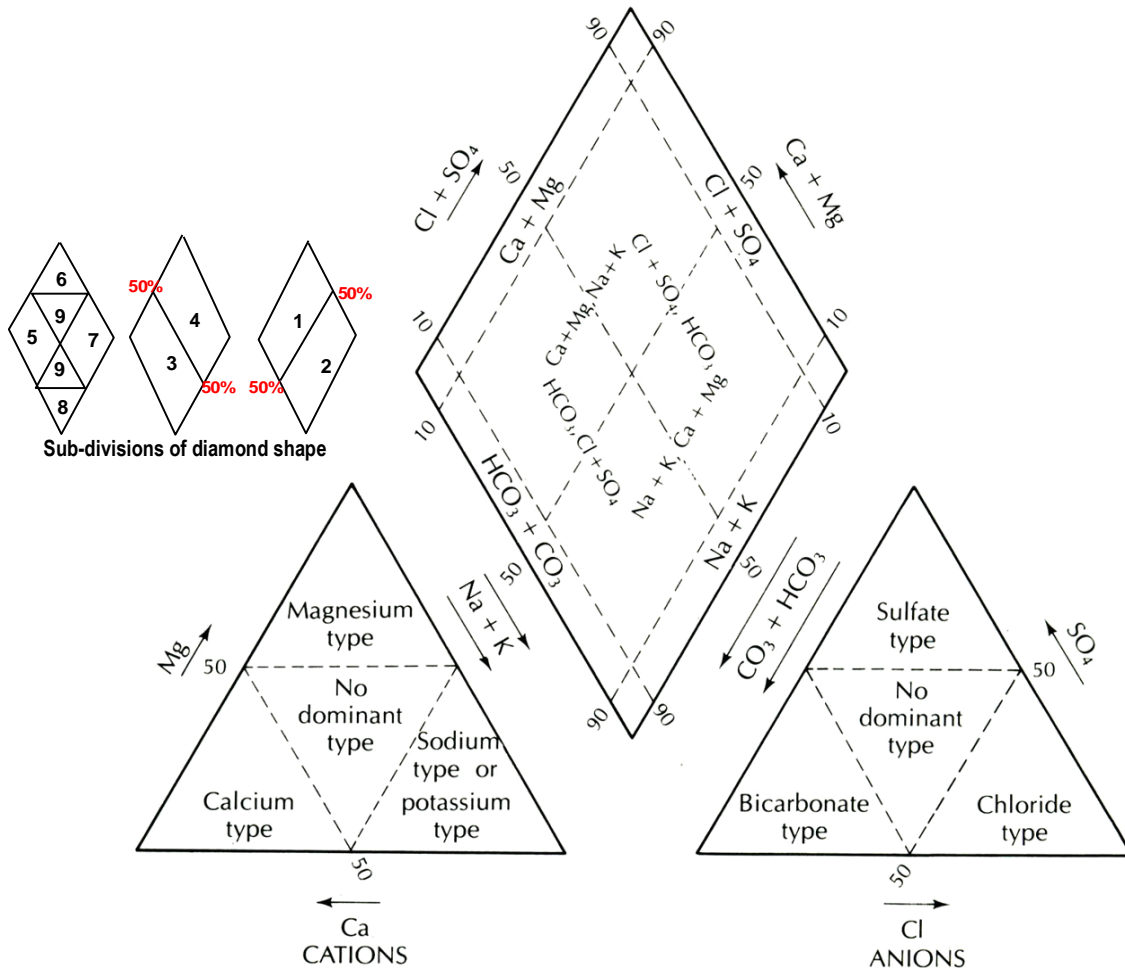


Figure 7-12 Different water types of the trilinear diagram proposed by Piper 1953

The central, diamond-shaped field is used to show the overall chemical character of the groundwater by a third single-point plotting, which is at the intersection of rays projected from the plotting of cations and anions. Distinct groundwater quality types can be quickly discriminated by their plotting in certain subareas of the diamond-shaped field as follows:

1. Sub-area 1 - alkaline earths (Ca+Mg) exceed alkalies (Na+K).
2. Sub-area 2 - alkalies exceed alkaline earths.
3. Sub-area 3 - weak acids (CO_3+HCO_3) exceed strong acids (SO_4+Cl).
4. Sub-area 4 - strong acids exceed weak acids.
5. Sub-area 5 - carbonate hardness (secondary alkalinity) exceeds 50 percent, that is, chemical properties of the groundwater are dominated by alkaline earths and weak acids.
6. Sub-area 6 - noncarbonate hardness (secondary salinity SO_4+Cl) exceeds 50 percent.

7. Sub-area 7 - noncarbonate alkali (primary salinity) exceeds 50 percent, that is, chemical properties of the groundwater are dominated by alkalis and strong acids.
8. Sub-area 8 - carbonate alkali (primary alkalinity $\text{CO}_3 + \text{HCO}_3$) exceeds 50 percent.
9. Sub-area 9 - no one cation-anion pair exceeds 50 percent.

The results of the analysis of the water quality samples from the alluvium aquifer were used as input data for determination of groundwater types by using AQUACHEM Software. The output of the Piper diagram presentation applying this program was given in Figure 7-13 and the water type was tabulated in Table 7-8.

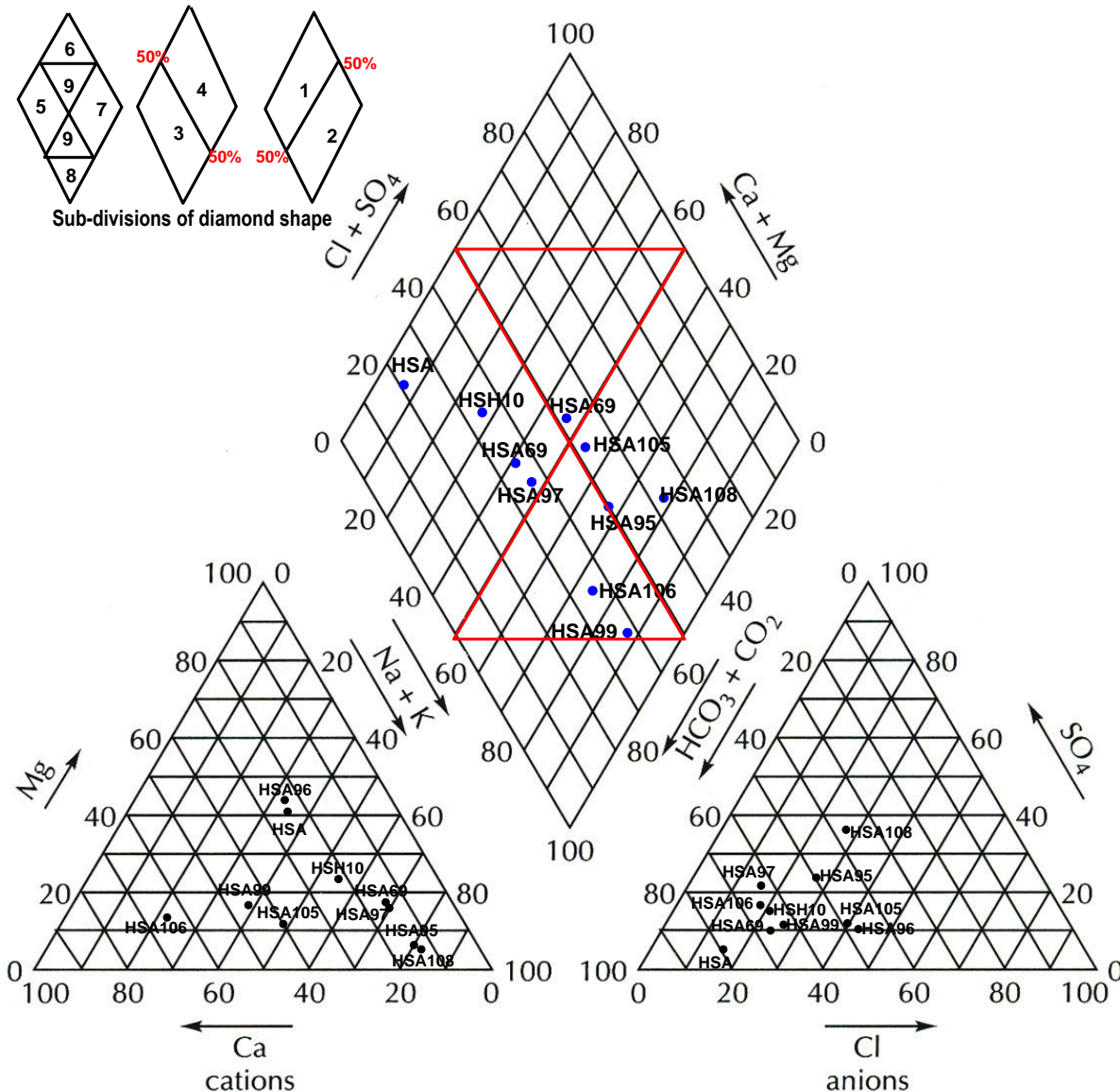


Figure 7-13 Classification of groundwater of the alluvium aquifer according to Piper 1953

Table 7-8 Water type for the alluvium aquifer water samples

Well ID	Water Type	Water Type
HSA 16	Ca-Mg-Cl-SO ₄	2
HS161	Ca-Mg-HCO ₃ -SO ₄	1
HS150	Ca-Na-HCO ₃ -Cl	3
HS69	Ca-Na-HCO ₃ -Cl	3
HSA 94	Ca-Na-HCO ₃ -Cl	1
HSA 104	Ca-Na-HCO ₃ -Cl-SO ₄	1
HSA 90	Ca-Na-HCO ₃ -Cl-SO ₄	1
HSA 74	Mg-Na-Ca-Cl-SO ₄ -HCO ₃	2
HSA 100	Na-Ca-Cl-HCO ₃ -SO ₄	2
HSA 101	Na-Ca-Cl-HCO ₃ -SO ₄	2
HSA 95	Na-Ca-HCO ₃ -SO ₄ -Cl	4
HSA 110	Na-HCO ₃ -Cl-SO ₄	2
HSA 7	Na-HCO ₃ -Cl-SO ₄	4
HSA 93	Na-HCO ₃ -Cl-SO ₄	4
HSA 98	Na-HCO ₃ -SO ₄	4

Figure 7-13 shows that the majority 40% of the alluvium aquifer samples are located in sub-area 9, where no one cation-anion pair exceeds 50 percent. However, 40% of the groundwater lies in sub-area 5, which is dominated by alkaline earths and weak acids (carbonate hardness and secondary alkalinity). The rest of the groundwater samples lie in sub-area 7. The majority of the groundwater samples (60%) are influenced by direct rainwater recharge and 20% are affected by continental conditions. Few groundwater samples (20%) located in sub-areas 7 and 9 have marine facies type due to contamination as a result of over-pumping.

In conclusion, Piper's trilinear diagram suggests that the groundwater of the alluvium aquifer in Sana'a basin is of mixed origins of mineralization, where rainwater and salt water are the main sources of salt contribution. The feeding recharge sources are rainwater and subsurface flow of water which dissolve the marine salts of the aquifer matrix and catchment area, as well as a possible contamination of the alluvium aquifer in the Arhab area, with marine salts from the underlying fractured limestone aquifer. This correlates with the hydro-chemical coefficients and hypothetical salts combinations.

7.2.7 Cluster analysis of alluvium aquifer groundwater

Cluster analysis is an exploratory data analysis tool for solving classification problems. Its objective is to sort cases into groups, or clusters, so that the degree of association is strong between members of the same cluster and weak between members of different clusters. Each cluster thus describes, in terms of the data collected, the class to which its members belong; and this description may be abstracted through use from the particular to the general class or type.

Cluster analysis is thus a tool of discovery. It may reveal associations and structure in data which, though not previously evident, nevertheless are sensible and useful once found. The results of a cluster analysis may contribute to the definition of a formal classification scheme, such as a taxonomy for related animals, insects or plants; or suggest statistical models with which to describe populations; or indicate rules for assigning new cases to classes for identification and diagnostic purposes; or provide measures of definition, size and change in what previously were only broad concepts; or find exemplars to represent classes. Cluster analysis might provide the methodology to help solve a classification problem. In this study, either a grouping of the major ions into a relatively small number of clusters was obtained, or the similarity relationships between the different water points (cases) were analyzed and described (Davis 1975).

7.2.8 Statistical analysis of alluvium aquifer groundwater

7.2.8.1 Descriptive statistical analysis

The statistical analysis of data sets shows that linear regressions between variables are significant since the critical value of F, with confidence level 95% and 9 degrees of freedom, is less than the estimated value. Table 7-9 shows the data of descriptive analyses. The most striking results are the maximum values of TDS, Na⁺, SO₄⁻ and Cl⁻ where they exceed the WHO standard (World Health Organization 1984) for most domestic use.

Table 7-9 Descriptive statistics of the groundwater chemical components analyzed for the alluvium aquifer

	N	Minimum	Maximum	Mean	Standard deviation	WHO Standard (1984) (acceptable)
pH	10	7.7	8.3	8.01	0.218326972	7 - 8.5
EC	10	380	1429	776.2	379.5941693	-
TDS	10	209	1011	476.2	270.3729112	500
Ca	10	10.48	65.38	40.974	17.77433118	75
Mg	10	1.79	43.93	19.493	12.89763807	50
Na	10	6	290	107.8	83.50888176	200
K	10	1	7	3.3	1.946506843	-
CO ₃	10	7.89	31.56	22.95	9.390782715	-
HCO ₃	10	120.32	377.01	226.377	80.29700701	-
SO ₄	10	17	320	85	88.47598544	200
Cl	10	21.7	210.64	83.554	69.48931688	200

The correlation analysis between the different hydrogeochemical parameters shows that TDS is highly positively correlated with Na, Cl, HCO₃ and SO₄ (0.91, 0.91, 0.9 and 0.88 respectively) and moderately positively correlated with Mg (0.55) and CO₃ (0.59), indicating that the recharge to the alluvium aquifer is from rainfall more than the subsurface flow (Table 7-10 and Figure 7-14). However, the inverse correlation between Ca, Mg, HCO₃ and Cl (-0.58, -0.31, -0.31 and -0.02 respectively) and pH

reflects the flushing and dissolution processes due to long residence time of groundwater flow (effect of clay layers in alluvial sediments, Gad 2001).

Table 7-10 Correlation coefficient matrix between different ion concentrations from alluvium aquifer groundwater

		PH	EC	TDS	Ca ⁺²	Mg ⁺²	Na ⁺¹	K ⁺¹	CO3 ⁻²	HCO3 ⁻¹	SO4 ⁻²	Cl ⁻¹
PH	Correlation Coefficient	1	0.018406	0.018406	-0.58287	-0.31904	0.288365	0.101612	0.457959	-0.16566	0.316937	-0.02769349
	Sig. (2-tailed)	.	0.95975	0.95975	0.076992	0.3689	0.419089	0.780004	0.183198	0.647408	0.372245	0.93946695
	N	10	10	10	10	10	10	10	10	10	10	10
EC	Correlation Coefficient	0.018406	1	1	0.212121	0.551515	0.915152	0.765345	0.596609	0.90303	0.887542	0.91185832
	Sig. (2-tailed)	0.95975	.	.	0.556306	0.098401	0.000204	0.009882	0.068651	0.000344	0.00061	0.00023714
	N	10	10	10	10	10	10	10	10	10	10	10
TDS	Correlation Coefficient	0.018406	1	1	0.212121	0.551515	0.915152	0.765345	0.596609	0.90303	0.887542	0.91185832
	Sig. (2-tailed)	0.95975	.	.	0.556306	0.098401	0.000204	0.009882	0.068651	0.000344	0.00061	0.00023714
	N	10	10	10	10	10	10	10	10	10	10	10
Ca ⁺²	Correlation Coefficient	-0.58287	0.212121	0.212121	1	0.672727	-0.10303	0.257206	0.08523	0.430303	0.018237	0.23708317
	Sig. (2-tailed)	0.076992	0.556306	0.556306	.	0.033041	0.776998	0.473129	0.814908	0.214492	0.960119	0.50956136
	N	10	10	10	10	10	10	10	10	10	10	10
Mg ⁺²	Correlation Coefficient	-0.31904	0.551515	0.551515	0.672727	1	0.321212	0.715159	0.386812	0.672727	0.474166	0.44985011
	Sig. (2-tailed)	0.3689	0.098401	0.098401	0.033041	.	0.365468	0.020077	0.269491	0.033041	0.166192	0.1920757
	N	10	10	10	10	10	10	10	10	10	10	10
Na ⁺¹	Correlation Coefficient	0.288365	0.915152	0.915152	-0.10303	0.321212	1	0.690066	0.583497	0.781818	0.905779	0.88146305
	Sig. (2-tailed)	0.419089	0.000204	0.000204	0.776998	0.365468	.	0.027209	0.076596	0.007547	0.000307	0.00074686
	N	10	10	10	10	10	10	10	10	10	10	10
K ⁺¹	Correlation Coefficient	0.101612	0.765345	0.765345	0.257206	0.715159	0.690066	1	0.366458	0.658699	0.808576	0.78340632
	Sig. (2-tailed)	0.780004	0.009882	0.009882	0.473129	0.020077	0.027209	.	0.297629	0.03834	0.00463	0.00734484
	N	10	10	10	10	10	10	10	10	10	10	10
CO3 ⁻²	Correlation Coefficient	0.457959	0.596609	0.596609	0.08523	0.386812	0.583497	0.366458	1	0.570385	0.651034	0.33538118
	Sig. (2-tailed)	0.183198	0.068651	0.068651	0.814908	0.269491	0.076596	0.297629	.	0.085113	0.041464	0.34345454
	N	10	10	10	10	10	10	10	10	10	10	10
HCO3 ⁻¹	Correlation Coefficient	-0.16566	0.90303	0.90303	0.430303	0.672727	0.781818	0.658699	0.570385	1	0.747724	0.8449887
	Sig. (2-tailed)	0.647408	0.000344	0.000344	0.214492	0.033041	0.007547	0.03834	0.085113	.	0.0129	0.0020858
	N	10	10	10	10	10	10	10	10	10	10	10
SO4 ⁻²	Correlation Coefficient	0.316937	0.887542	0.887542	0.018237	0.474166	0.905779	0.808576	0.651034	0.747724	1	0.80487806
	Sig. (2-tailed)	0.372245	0.00061	0.00061	0.960119	0.166192	0.000307	0.00463	0.041464	0.0129	.	0.00497413
	N	10	10	10	10	10	10	10	10	10	10	10
Cl ⁻¹	Correlation Coefficient	-0.02769	0.911858	0.911858	0.237083	0.44985	0.881463	0.783406	0.335381	0.844989	0.804878	1
	Sig. (2-tailed)	0.939467	0.000237	0.000237	0.509561	0.192076	0.000747	0.007345	0.343455	0.002086	0.004974	.
	N	10	10	10	10	10	10	10	10	10	10	10
Correlation is significant at the .01 level (2-tailed).												
Correlation is significant at the .05 level (2-tailed).												

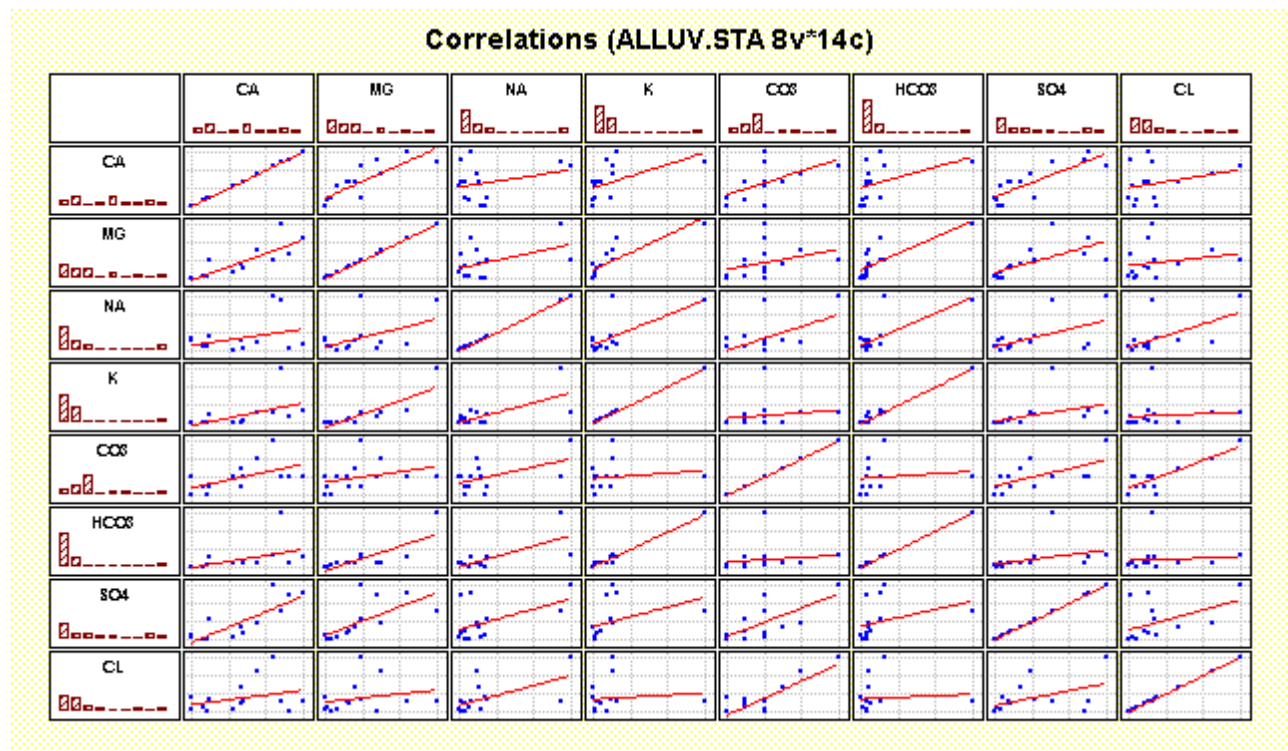


Figure 7-14 Linear regression between different ions in groundwater of alluvium aquifer

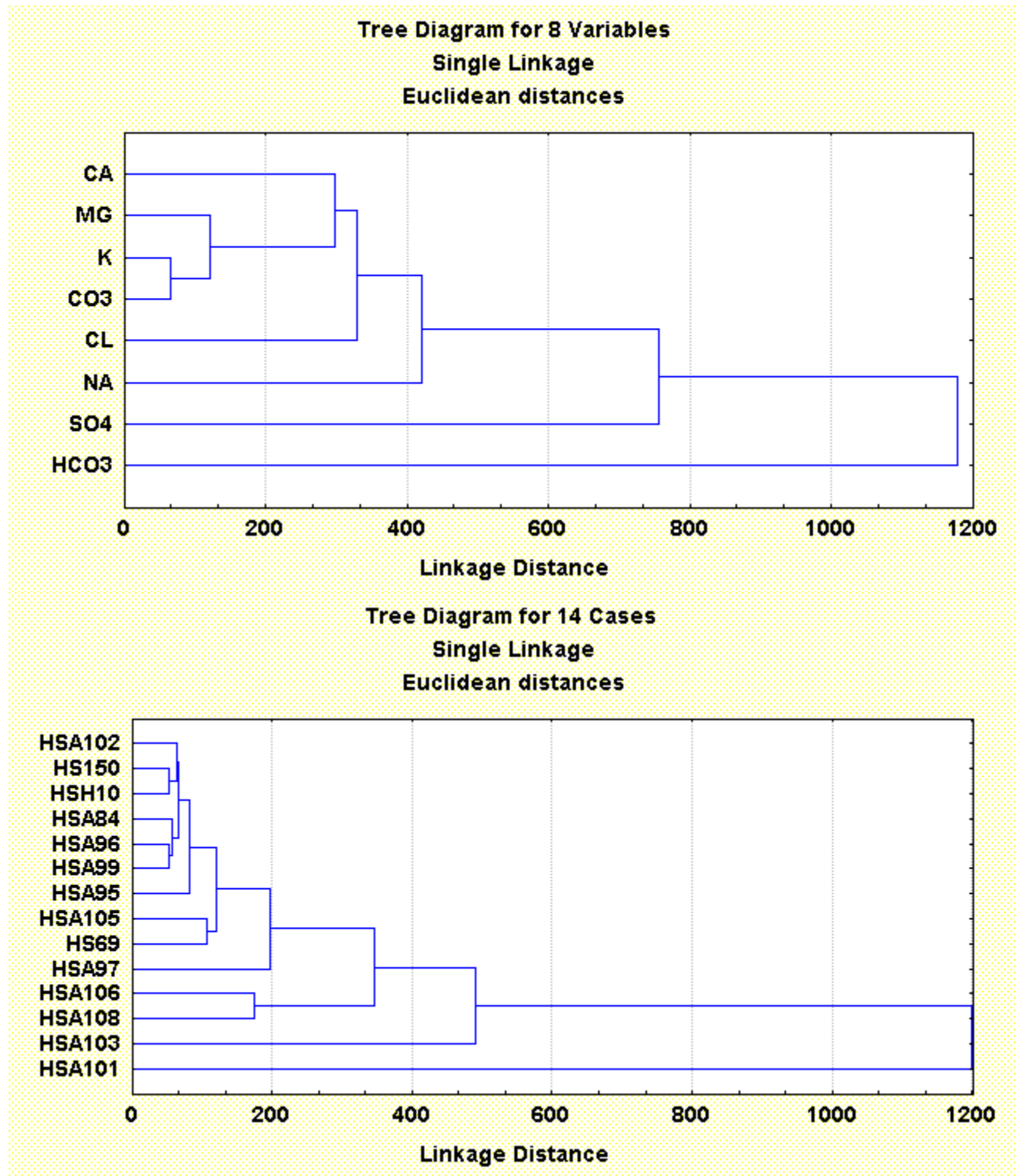


Figure 7-15 Horizontal icicle plot of 8 non-transformed hydrogeochemical variables (R-mode-upper figure) studied and 14 wells (Q-mode-lower Figure) applying Euclidean distance method

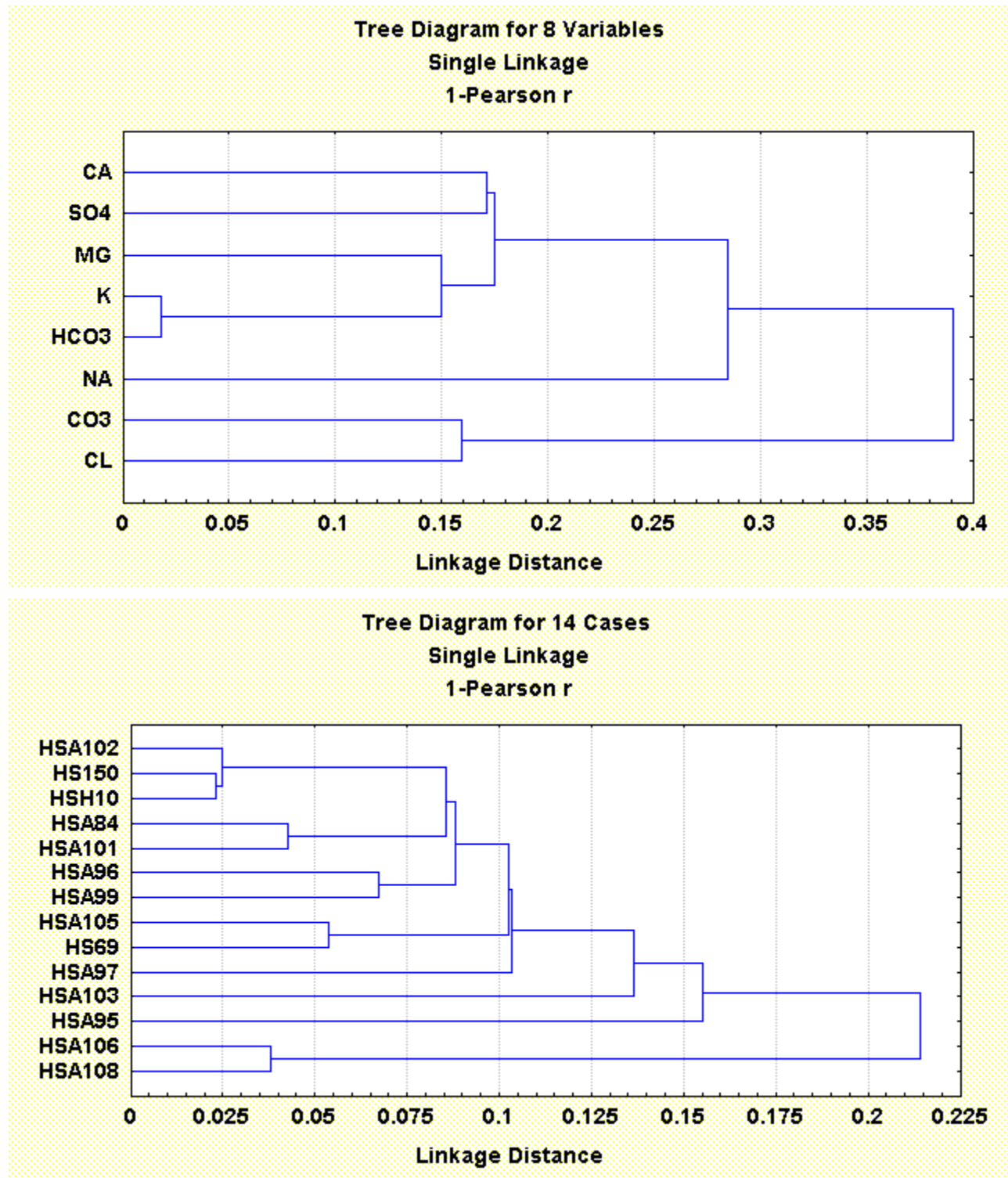


Figure 7-16 Horizontal icicle plot of non-transformed 8 hydrogeochemical variables studied (R-mode-upper figure) and 14 wells (Q-mode-lower Figure) applying 1-Pearson r method

7.2.8.2 Cluster analyses (Q-mode dendrogram)

The non-transformed data and the transformed data of the hydrogeochemical analysis of the alluvium aquifer are used in constructing the tree diagrams (Figures 7-15 to 7-17), which are classified into two clusters and four independent samples as follows:

Cluster A: represents the main cluster and includes four samples (HSA, HSA 99, HSH 10 and HAS 108). These are located in the contact between alluvium and limestone and inside the Quaternary volcanic in the west of Sana'a Basin, reflecting local recharge from the Quaternary volcanic to the adjacent alluvium aquifer. This cluster is characterized by a lower salinity range (209-282 mg/l), lower sodium and sulfate content, yet low to moderate calcium, magnesium, bicarbonate and chloride content.

Cluster B: includes two samples, 26 and 30 (wells no. HSA 97 and HSA 106), located in the contact between Tawilah sandstone outcrops and the alluvium aquifer. This may indicate lateral subsurface flow to the alluvium aquifer in this location. This cluster is characterized by a moderate salinity range compared to Cluster A (347-416 mg/l), and higher cation and anion concentrations than Cluster A. The increase in salinity is due to high evaporation with precipitation and saline water intrusion from saline soils.

Sample no. 24 (HSA 95) is an independent sample, characterized by higher salinity content than Clusters A and B. It is located in the northern part of the study aquifer.

Sample no. 25 (HSA 96) is an independent sample, also characterized by higher salinity, calcium, magnesium, sodium, bicarbonate and chloride contents than previous samples.

Sample no. 29 (HSA 105) is an independent sample located in the Arhab area, characterized by higher salinity and sodium contents than previous samples. Also, it has the highest values of calcium, magnesium, bicarbonate and chloride contents of all samples. The chloride content exceeds WHO standards. This is likely due to over-pumping, seepage from sewage and municipal wastes.

Sample no. 31 (well HSA 69) is an independent sample located in the El-Barati village, characterized by the highest values of salinity, sodium and sulfate contents, which reflects contamination from the landfill and sewage channel present in this area.

Sample	Well ID	Location	Sample_Date	UTM E (m)	UTM N (m)	Rim Elv (m)
64	HS129	Bite Al abid /nihm	17/03/2007	436267	1718700	2626
65	HS131	Bani Rasam /nihm	17/03/2007	440083	1720084	2570
68	HS134	Sara'a- Khawlan	22/03/2007	449088	1713454	2477
69	HS136	Al mahajirah-Khawlan	22/03/2007	446320	1719200	2406
70	HS139	Alsrar -Khawlan	22/03/2007	447450	1711272	2414
71	HS140	Bani Zamwmah -Bani Husheish	22/03/2007	444695	1712454	2380
73	HS142	Hozayfah -Khawlan	24/03/2007	443756	1708408	2464
74	HS143	Hozayfah -Khawlan	24/03/2007	443420	1708089	2481
75	HS144	Hozayfah -Khawlan	24/03/2007	443669	1706585	2568
77	HS145	aradah -Bani Husheish	24/03/2007	437115	1710061	2343
127	HS164	Al Rowna /Bani Husheish	14/05/2007	427530	1703755	2394
129	HSH12	Garban -Qwla'a / Hamdan	17/05/2007	401253	1722329	2468
130	HSH14	Qwla'a / Hamdan	17/05/2007	400459	1719547	2481
135	HSS10	Al Hadowr/ SANHAN	24/05/2007	424849	1691790	2372
136	HSS11	Al Hijrah/Sanhan	24/05/2007	427537	1689763	2426
137	HSS19	Shahik Khawlan	31/05/2007	438762	1702751	2574
140	HSH30	Hamdan Qa'a Al Munakab	06/06/2007	397248	1709399	2646
141	HSS31	Sna'a /Sanhan	06/06/2007	411771	1690739	2346
142	HSS40	Ruhm / Sanhan	07/06/2007	418400	1677271	2416
143	HSS44	Al Sirin / Sanhan	07/06/2007	429126	1669927	2605
84	HSA84	Al-jahman/baraman / ARHAB	07/04/2007	413496	1723877	2239
85	HSA85	Al-Asmad/Hzam / ARHAB	07/04/2007	413350	1727319	2281
86	HSA86	Al-Asmad/ ARHAB	07/04/2007	413814	1726919	2268
87	HSA87	Hotban/ ARHAB	07/04/2007	408295	1728198	2506
88	HSA88	Bait Dafa'a/ ARHAB	07/04/2007	414334	1729656	2303
90	HSH8	Al Hawry / Hamdan	09/04/2007	407277	1714451	2248
91	HSH10	Bait Al Rafik /Hamdan	09/04/2007	405457	1721136	2248
104	HSH11	Al Hokah /Hamdan	12/04/2007	409246	1720948	2253
105	HSA99	Bit Al Thib Al A'alah /Bani Al harith	12/04/2007	416163	1720363	2182

* * * * * H I E R A R C H I C A L C L U S T E R A N A L Y S I S *
* * * * *

Dendrogram using Average Linkage (Between Groups)

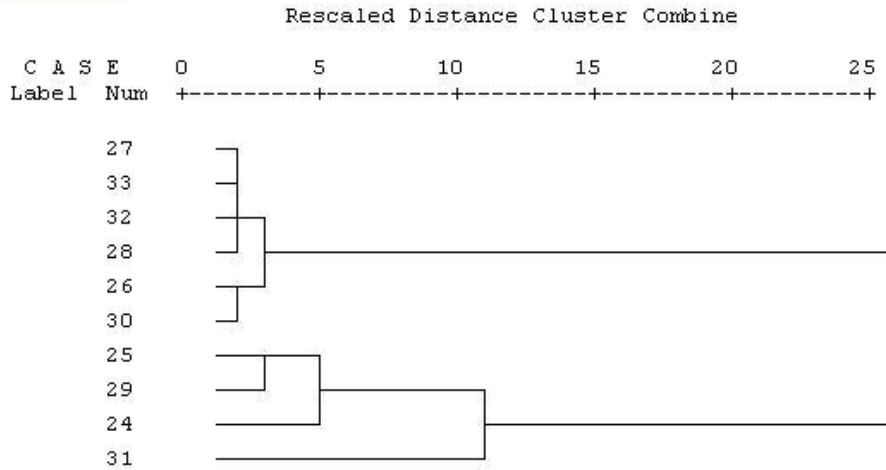


Figure 7-17 Dendrogram of selected transformed alluvium aquifer groundwater data using average linkage

7.3 Hydrogeochemistry of the volcanic aquifer

During the field campaign, 29 samples were selected from different wells over the entire volcanic aquifer. Figure 7-18 shows the locations of the water quality samples collected within the outcrop of the volcanic aquifer. Table 7-11 presents the list of selected wells, their locations and UTM coordinates, while Table 7-12 contains the results of the chemical analysis of these selected wells. A brief description of the different water quality parameters that characterize the volcanic aquifer follows.

Table 7-11 List of wells sampled for water quality and their locations in the volcanic aquifer

WHERE IS TABLE 7-11?

Table 7-12 Results of chemical analyses of groundwater samples of the volcanic aquifer (March 2007)

Well ID	pH	EC umhos/cm	TDS (mg/l)	Units	Ca++	Mg++	Na+	K+	Sum	CO3--	HCO3-	SO4--	Cl-	Sum	Hydrochemical coefficients			SAR (epm)	Na%(epm)	Hardness (mg/l)
															rNa/rCl	rCa/rMg	rCl-rNa/rCl			
HSA86	8.1	630	325	mg/l	12.33	6.22	104	3		15.78	200.54	52	31.12	5.77	5.15	1.20	-4.15	6.0	80.3	56.4
				meq/l	0.62	0.51	4.52	0.08	5.73	0.53	3.28	1.08	0.88							
				e %	10.75	8.93	78.98	1.34		9.11	56.92	18.76	15.21							
HSA87	8.1	408	217	mg/l	18.15	20.97	32	5		23.67	136.37	18	31.12	4.27	1.59	0.53	-0.59	1.2	36.6	131.6
				meq/l	0.91	1.72	1.39	0.13	4.15	0.79	2.23	0.37	0.88							
				e %	21.83	41.56	33.53	3.08		18.45	52.25	8.77	20.53							
HSA88	8.3	636	361	mg/l	17.36	14.52	96	4		23.67	216.58	66	31.12	6.59	4.76	0.73	-3.76	4.1	67.5	103.1
				meq/l	0.87	1.19	4.17	0.10	6.34	0.79	3.55	1.37	0.88							
				e %	13.67	18.84	65.87	1.62		11.97	53.85	20.86	13.32							
HSA90	8	711	398	mg/l	60.54	16.8	60	4		23.67	160.43	76	76.6	7.16	1.21	2.19	-0.21	1.8	38.1	220.3
				meq/l	3.02	1.38	2.61	0.10	7.11	0.79	2.63	1.58	2.16							
				e %	42.47	19.42	36.67	1.44		11.02	36.71	22.10	30.17							
HSH8	8.1	409	234	mg/l	38.89	13.46	28	4		31.56	144.39	22	23.94	4.55	1.80	1.75	-0.80	1.0	30.2	152.5
				meq/l	1.94	1.11	1.22	0.10	4.37	1.05	2.37	0.46	0.68							
				e %	44.43	25.35	27.88	2.34		23.11	51.98	10.07	14.84							
HS152	7.9	1001	571	mg/l	73.14	14.99	95	9		15.78	168.45	205	74.2	9.65	1.97	2.96	-0.97	2.6	47.2	244.3
				meq/l	3.65	1.23	4.13	0.23	9.24	0.53	2.76	4.27	2.09							
				e %	39.48	13.34	44.69	2.49		5.45	28.61	44.25	21.69							
HS55	7.9	2160	1338	mg/l	275.2	31.36	110	8		15.78	160.43	750	67.02	20.66	2.53	5.32	-1.53	1.7	23.4	816.2
				meq/l	13.73	2.58	4.78	0.20	21.30	0.53	2.63	15.62	1.89							
				e %	64.47	12.11	22.46	0.96		2.55	12.72	75.59	9.15							
HSA16	7.7	2680	1460	mg/l	296.91	67.29	110	4		15.78	136.37	400	497.87	25.13	0.34	2.68	0.66	1.5	19.4	1018.3
				meq/l	14.82	5.53	4.78	0.10	25.23	0.53	2.23	8.33	14.04							
				e %	58.71	21.93	18.95	0.41		2.09	8.89	33.14	55.87							
HSA100	8	512	290	mg/l	22.31	3.74	80	2		15.78	72.19	56	74.2	4.97	1.66	3.62	-0.66	4.1	71.3	71.1
				meq/l	1.11	0.31	3.48	0.05	4.95	0.53	1.18	1.17	2.09							
				e %	22.49	6.21	70.26	1.03		10.59	23.81	23.48	42.13							
HS129	7.6	593	353	mg/l	86.45	12.38	24	2		15.78	160.43	73	59.84	6.36	0.62	4.24	0.38	0.6	17.0	266.8
				meq/l	4.31	1.02	1.04	0.05	6.43	0.53	2.63	1.52	1.69							
				e %	67.12	15.84	16.24	0.80		8.27	41.31	23.89	26.53							
HS131	8	3040	1898	mg/l	158.2	35.14	480	9		47.34	385.03	650	325.53	30.60	2.27	2.73	-1.27	9.0	66.2	539.6
				meq/l	7.89	2.89	20.87	0.23	31.88	1.58	6.31	13.53	9.18							
				e %	24.76	9.06	65.46	0.72		5.16	20.61	44.23	30.00							
HS134	7.6	866	476	mg/l	103.2	22.04	36	3		15.78	160.43	120	95.74	8.35	0.58	2.84	0.42	0.8	19.1	348.4
				meq/l	5.15	1.81	1.57	0.08	8.60	0.53	2.63	2.50	2.70							
				e %	59.85	21.07	18.19	0.89		6.30	31.46	29.91	32.33							
HS136	7.5	461	264	mg/l	37.99	5.29	52	2		0	152.41	43	47.87	4.74	1.67	4.36	-0.67	2.1	49.8	116.6
				meq/l	1.90	0.44	2.26	0.05	4.64	0.00	2.50	0.90	1.35							
				e %	40.83	9.37	48.70	1.10		0.00	52.65	18.88	28.47							
HS139	7	3280	2010	mg/l	173.3	106.4	440	47		15.78	1524.1	360	105.32	35.96	6.44	0.99	-5.44	6.5	53.9	870.6
				meq/l	8.65	8.75	19.13	1.20	37.73	0.53	24.96	7.50	2.97							
				e %	22.92	23.19	50.70	3.19		1.46	69.43	20.85	8.26							
HS140	7.9	689	385	mg/l	9.05	0.47	132	1		0	72.19	89	117.29	6.34	1.74	11.68	-0.74	11.6	92.2	24.5
				meq/l	0.45	0.04	5.74	0.03	6.26	0.00	1.18	1.85	3.31							
				e %	7.22	0.62	91.75	0.41		0.00	18.64	29.21	52.15							
HS142	7.6	523	288	mg/l	32.84	2.97	68	1		7.89	104.28	54	69.41	5.05	1.51	6.71	-0.51	3.0	61.3	94.2
				meq/l	1.64	0.24	2.96	0.03	4.87	0.26	1.71	1.12	1.96							
				e %	33.68	5.02	60.77	0.53		5.20	33.81	22.25	38.74							
HS143	7.2	1442	843	mg/l	118	34.78	136	8		7.89	336.9	260	110.11	14.30	1.90	2.06	-0.90	2.8	41.2	437.8
				meq/l	5.89	2.86	5.91	0.20	14.87	0.26	5.52	5.41	3.11							
				e %	39.61	19.24	39.78	1.38		1.84	38.59	37.86	21.71							
HS144	8.2	575	322	mg/l	9.66	1.26	110	1		15.78	120.32	62	62.23	5.54	2.73	4.65	-1.73	8.8	89.1	29.3
				meq/l	0.48	0.10	4.78	0.03	5.39	0.53	1.97	1.29	1.75							
				e %	8.94	1.92	88.67	0.47		9.49	35.56	23.29	31.66							
HS145	7.6	1255	707	mg/l	100.8	29.37	105	1		23.67	176.47	189	169.95	12.41	0.95	2.08	0.05	2.4	38.1	372.6
				meq/l	5.03	2.42	4.57	0.03	12.04	0.79	2.89	3.93	4.79							
				e %	41.79	20.07	37.93	0.21		6.36	23.30	31.72	38.63							
Mean	7.78		670.52632		35	15.43	48.29	1.28		7.28	36.37	28.37	27.97		2.18	3.33	-1.18			311.3

7.3.1 Groundwater pH values

The pH distribution map of the volcanic aquifer was built based on available data (Table 7-12). From the map (Figure7-19), it is evident that the green color (zone of pH range of 7 to 7.6) covers about 65% of the volcanic aquifer. This indicates that most of the aquifer has a pH value between 7 and 8 which is considered ideal. There are some locations where pH is relatively high, but it doesn't exceed the

critical value of 8.55. The highest pH value within the aquifer is located at Wadi Iqbal on the western side of the Basin. Also, pH values within the boundary of Wadi Shahik and Wadi Al-Qasaba are relatively high.

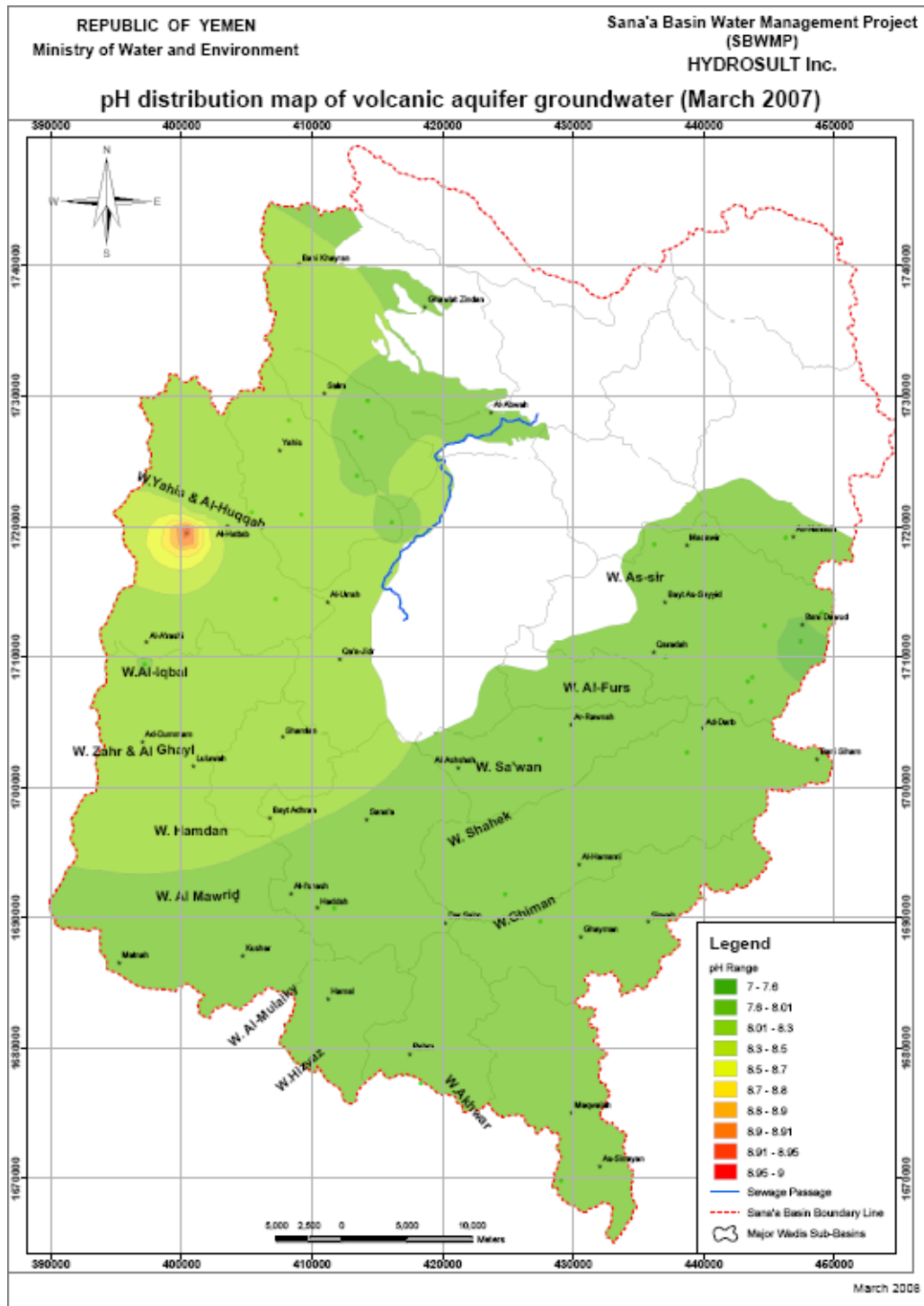


Figure 7-19 pH distribution map of the volcanic aquifer groundwater

7.3.2 Groundwater salinity

Total Dissolved Solids (TDS) consist mainly of carbonates, bicarbonates, chlorides, sulfates, phosphates, nitrates, calcium, magnesium, sodium, potassium, iron, manganese, and a few others. They do not include gases, colloids, or sediment. Dissolved solid concentration in natural water can range from less than 10 mg/l for rain to more than 100,000 mg/l for brines. Since TDS is the sum of all materials dissolved in the water, it has many different mineral sources. High levels of total dissolved solids can adversely affect industrial applications requiring the use of water such as cooling tower operations, boiler feed water, food and beverage industries, and electronics manufacturers. High levels of chloride and sulfate will accelerate corrosion of metals. The desirable level of Total Dissolved Solids in Yemen is 650 mg/l while the maximum permissible value is 1,500 mg/l.

It is evident that 95% of the aquifer area has a TDS value below 400 mg/l. Even in the western part of the basin, the TDS value is much lower and reaches 100 to 200 mg/l. The groundwater salinity in the volcanic aquifer varies from 217 ppm (well ID HSA 87) and 2,010 ppm (well ID HS 139), with a mean value of 670.5 (Table 7-12). It ranges between fresh and brackish water based on the classification of Chebotarev (1955).

Figure 7-20 presents distribution of TDS over the entire volcanic aquifer. The iso-salinity map shows a general increase towards the northeast and from west to south, which reflects the harmony between groundwater flow direction of this aquifer and direction of increasing salinity.

7.3.3 Distribution of major ions

Distribution of ions in groundwater of the volcanic aquifer in Sana'a Basin, Table 7-12 and Figures 7-21 to 7-26, are discussed herein as follows:

- The Ca^{2+} concentration ranges from 7 to 67%, with a mean value of 35% of the total dissolved cations in groundwater of the volcanic aquifer. Since the concentrations in percentages of Ca^{2+} are 3% and 70% for both rain and sea (marine) waters respectively, the source of calcium mineralization is thus pure infiltrated rainwater affected by leaching and dissolution of terrestrial salts from aquifer matrices. Figure 7-21 presents the distribution of calcium concentration within the boundary of the volcanic aquifer. It was concluded that the concentration is less than the maximum permissible limit over the entire aquifer, except upon contact with the limestone aquifer. However, the west part of the aquifer has a relatively low concentration.
- Hard water is high in dissolved minerals, both calcium and magnesium. As water moves through soil and rock, it dissolves small amounts of these naturally-occurring minerals and carries them into the ground water supply. Water is a great solvent for calcium and magnesium, so, if the minerals are present in the soil around a groundwater well and its water supply, it can end up with hard water.

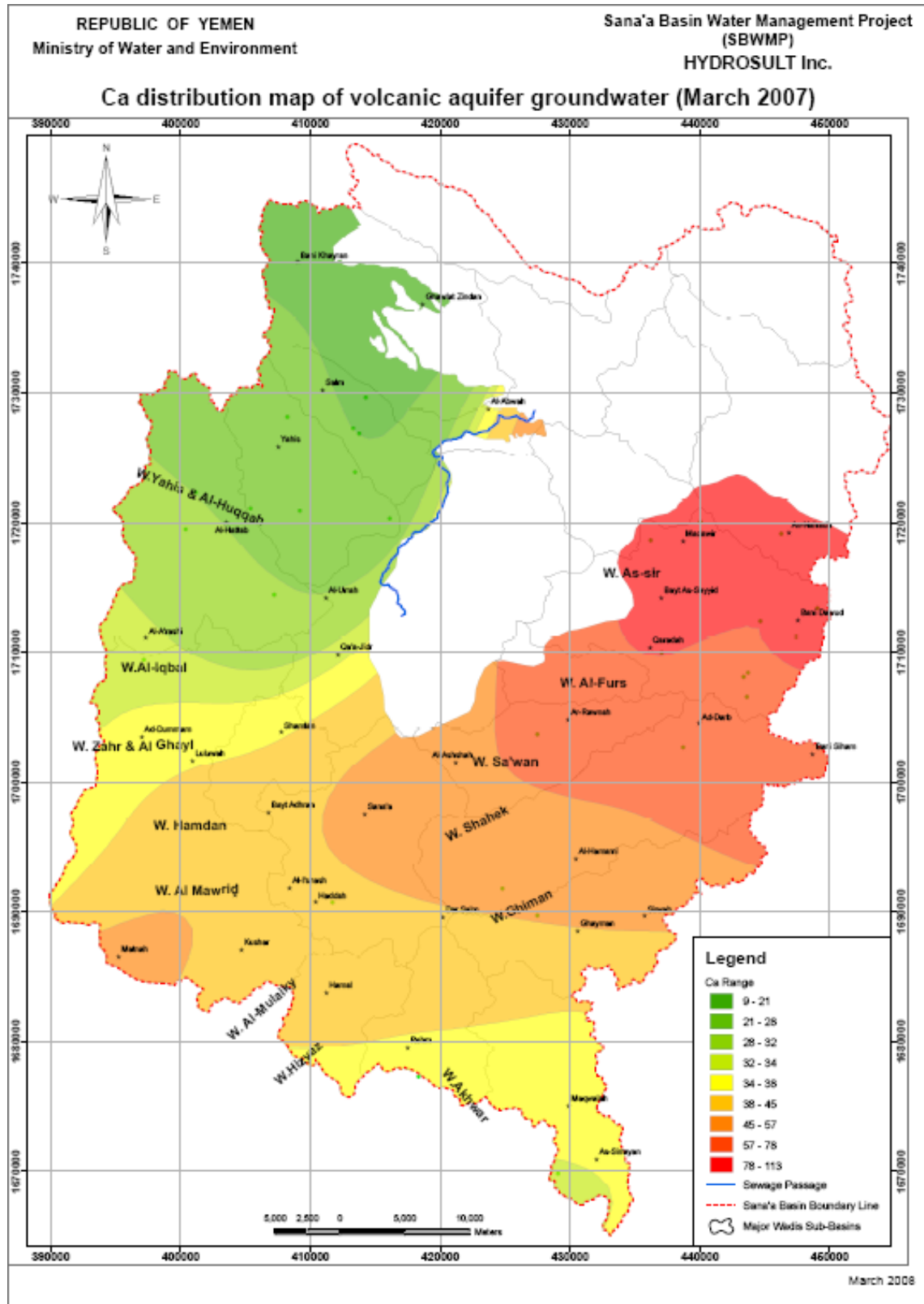


Figure 7-21 Ca distribution map of groundwater of the volcanic aquifer in Sana'a Basin

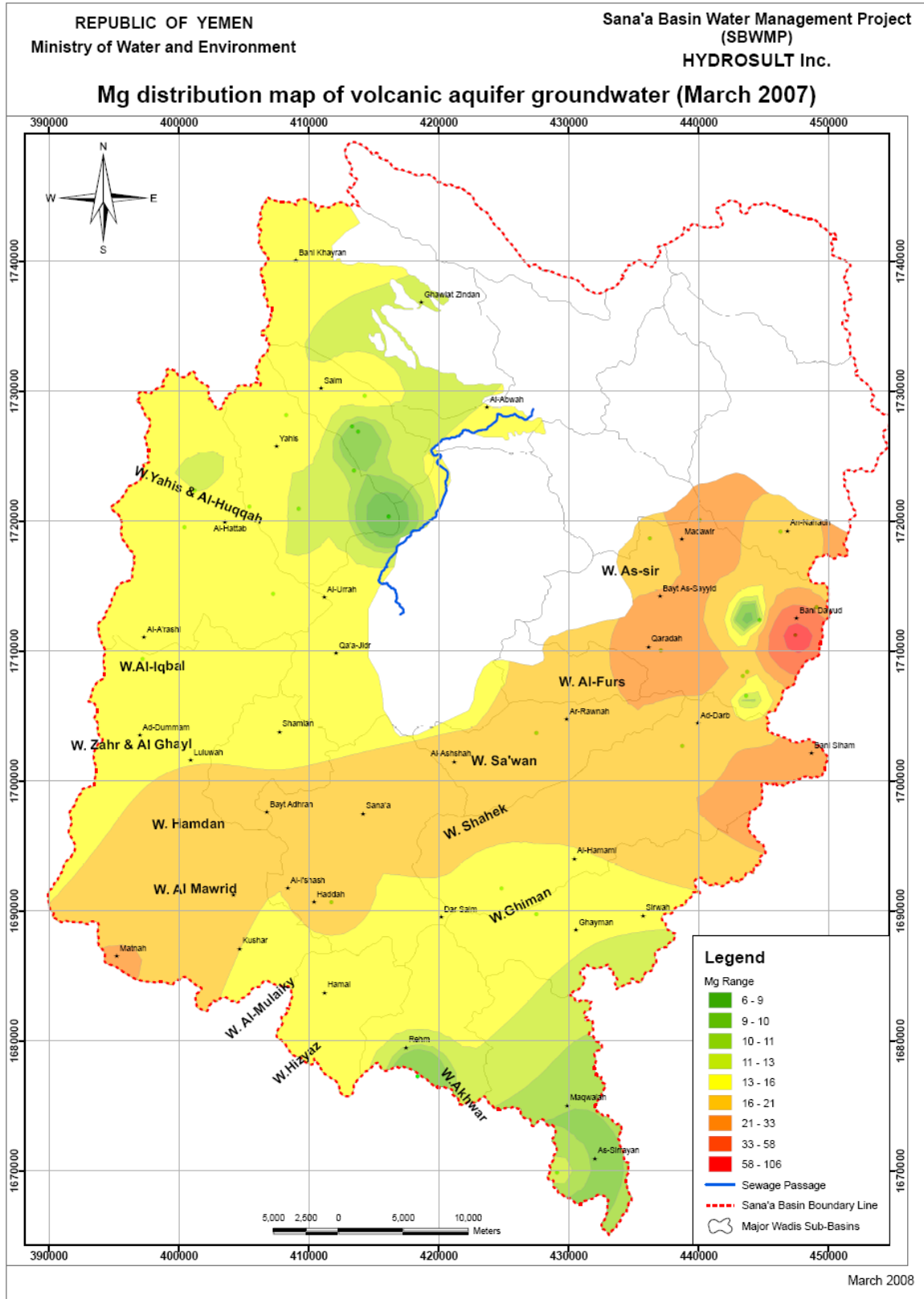


Figure 7-22 Mg distribution map of groundwater of the volcanic in Sana'a Basin

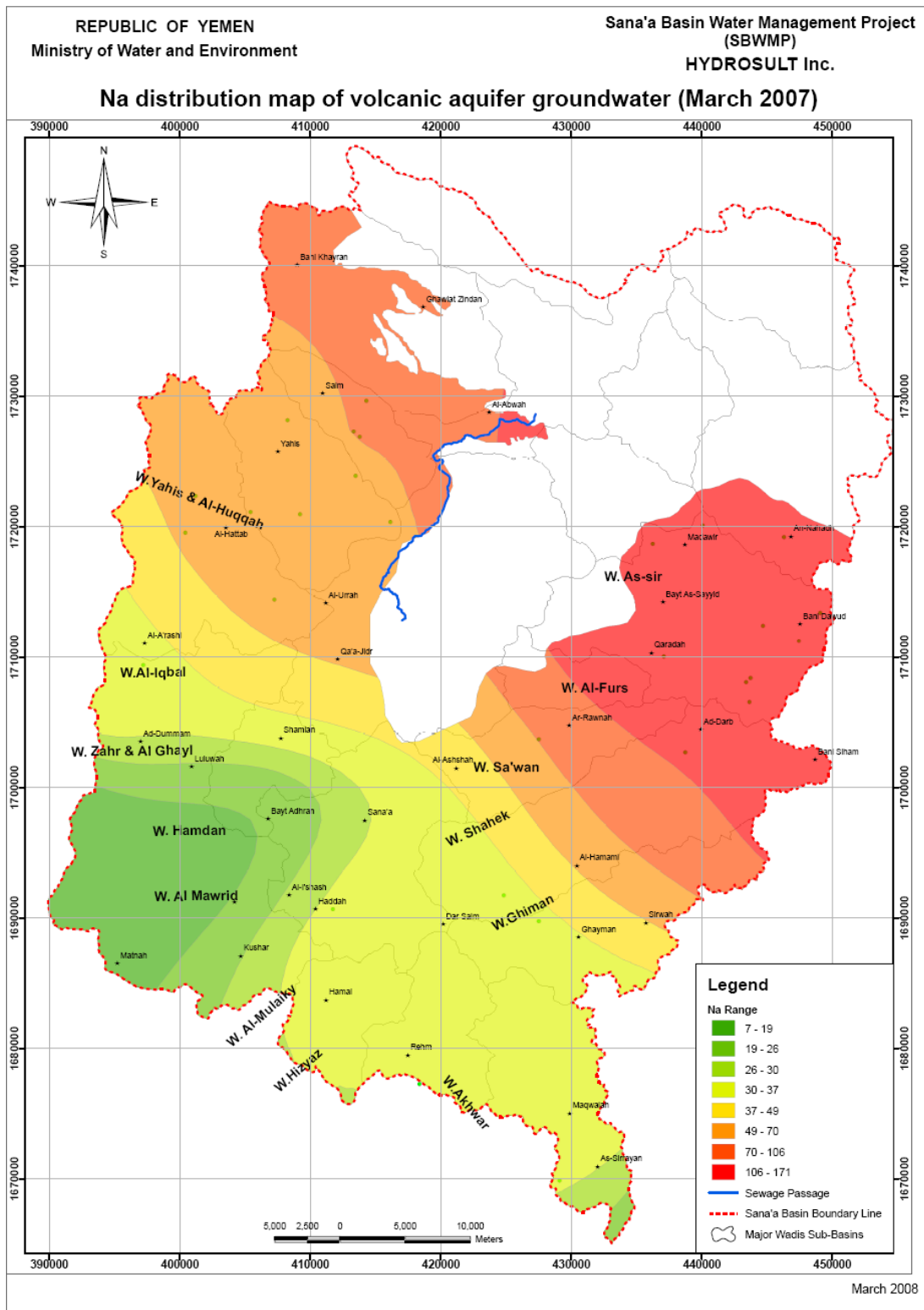


Figure 7-23 Na distribution map of groundwater of the volcanic aquifer in Sana'a Basin

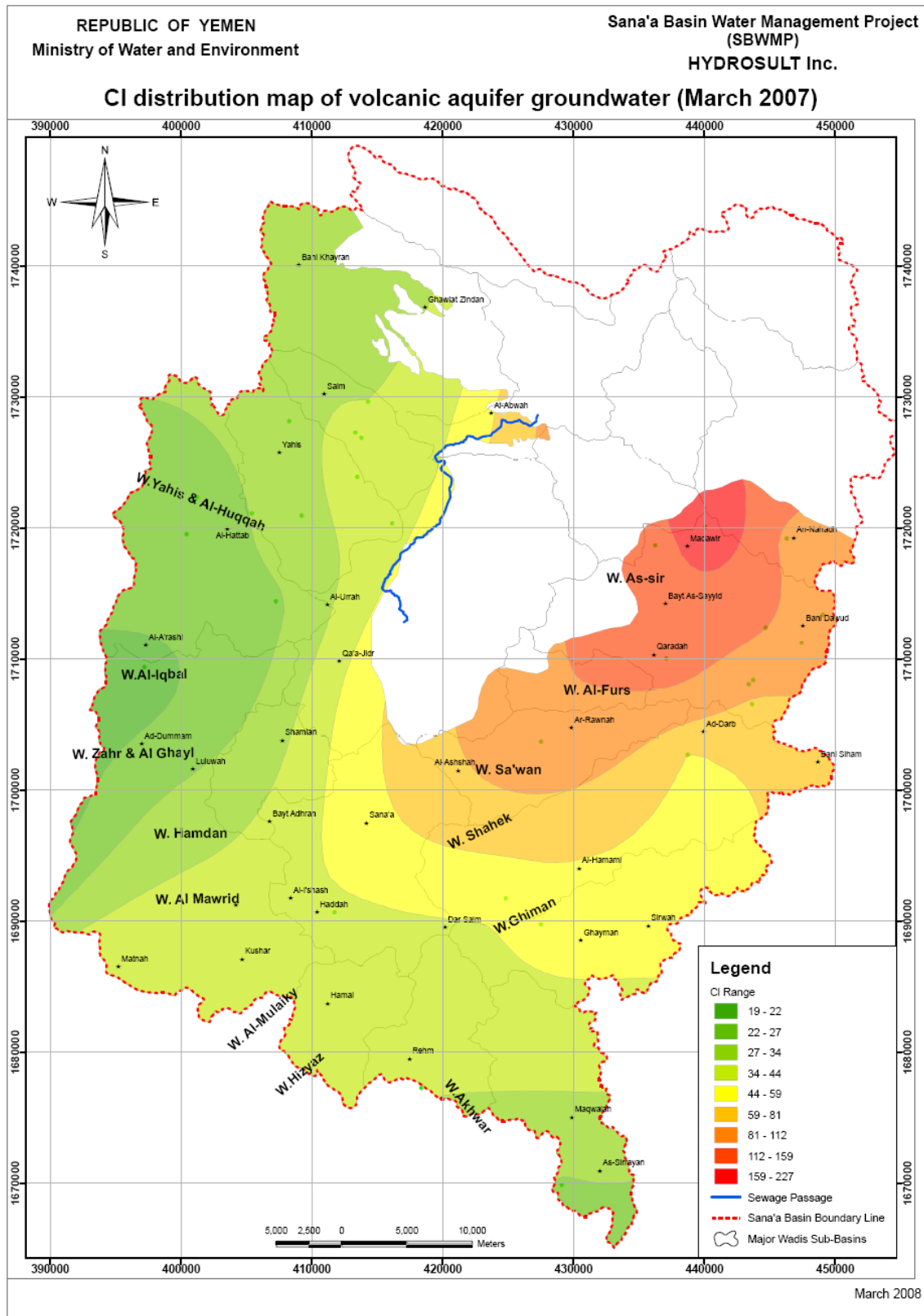


Figure 7-24 Cl distribution map of groundwater of the volcanic aquifer in Sana'a Basin

The Mg^{2+} concentration ranges from 1 to 42%, with a mean value of 15% of the total dissolved cations in the volcanic aquifer. As concentrations in percentages of Mg^{2+} are 10% and 20% for both rain and sea (marine) waters respectively, this means that the Mg^{2+} content is attributed to the dolomitization processes that has occurred in the aquifer, as well as Mg^{2+} content which is nearly identical to sea water.

- The Na^+ concentration ranges from 16 to 92%, with a mean value of 48% of total dissolved cations in the volcanic aquifer. The Cl^- concentration ranges from 8 to 56%, with a mean value of 28% of total dissolved anions of this aquifer. The concentration percentages of both Na^+ and Cl^- are 77% & 90% and 20% & 29% for both sea (marine) and rainwaters respectively. Thus, it is believed that both Na^+ and Cl^- have the same sources of mineralization (mixed mineralization) in the groundwater of this aquifer. Figure 7-23 presents the spatial distribution of sodium within the volcanic aquifer. The desirable limit for sodium concentration is 200 mg/l while the maximum permissible limit is 400 mg/l. It can thus be concluded that the value of sodium concentration is below the desirable limit for the entire aquifer.

Almost all natural waters contain chloride ions. Their concentrations vary considerably according to the mineral content of the earth in any given area. In small amounts, they are not significant. In large concentrations, they present problems. Usually, chloride concentrations are low. Low to moderate concentrations of chloride ions add palatability to water. In fact, they are desirable for this reason. Excessive concentrations can make water unpleasant to drink. The EPA Secondary Drinking Water Regulations recommend a maximum concentration of 250 mg/l for chloride ions (expressed as Cl^- not as $CaCO_3$). Chlorides give water a salty taste. The concentrations at which this becomes noticeable again depends upon the individual. In large concentrations, chlorides cause a brackish, briny taste that definitely is undesirable. Although chlorides are extremely soluble, they possess marked stability. This enables them to resist change and to remain fairly constant in any given water unless the supply is altered by dilution or by industrial or human wastes. Chlorides contribute to the total mineral content of water. As indicated above, the total concentration of minerals may have a variety of effects in the home. High concentrations of chloride ions add to the electrical conductivity of water. Chlorides can be substantially removed from water by reverse osmosis. Deionization (demineralization) or distillation will also remove chlorides and sulfates from water, but these methods are less suitable for household use than reverse osmosis. Referring to Figure 7-24, the chloride concentration in the volcanic aquifer is presented. It is noted that 22% of the aquifer water is suspected to have a chloride concentration greater than 100 mg/l. The most common value of chloride concentration is found to be in the range of 20 mg/l and 100 mg/l. The highest chloride concentration occurs in well HSA 131 at El-Gheras, where the value reaches 325.5 mg/l. The direction of chloride concentration increase is from southwest to northeast direction, which agrees with the general flow direction of both surface and subsurface water flow.

- The SO_4^{2-} concentration ranges from 9 to 76%, with a mean value of 28% of total dissolved anions in this aquifer. The concentrations in percentages of SO_4^{2-} are 9.5% and 25% for both sea (marine) and rain waters respectively. The sulfate mineralization is of meteoric origin. This could indicate that sulfate content is governed by a biogenic system that significantly distorts the other mechanisms (wet deposition, evaporation, dissolution of sulfate solid-phases and mixing). Figure 7-25 presents the sulfate distribution over the entire volcanic aquifer. It is noted that 68% of the aquifer has a concentration of sulfate less than 100 mg/l. However, this value is slightly increased at Wadi Al-Qasaba. The concentration of sulfate lies within the range of 8 mg/l and 750 mg/l over the entire aquifer. The highest concentration is found at well HS 55.
- The HCO_3^- concentration ranges from 9 to 69%, with a mean value of 36% of total dissolved anions in the aquifer studied. The concentrations in percentages of HCO_3^- are 0.5% and 46% for both sea (marine) and rain waters respectively. The source of HCO_3^- mineralization is mixed between rain and sea (marine) waters.

Figure 7-26 presents the distribution of HCO_3^- concentration within the volcanic aquifer. The map shows that the western catchments exhibit low concentrations of bicarbonate ions. The general increase in concentration is from west to east and to northeast. The highest concentration values characterize the eastern boundary of the aquifer. The desirable limit for HCO_3^- concentration is 377 mg/l (well no. HSA 105), while the maximum permissible limit is 500 mg/l. Within the volcanic aquifer, it was found that the concentration of HCO_3^- ranges from 72 to 1,524 mg/l, which reflects fresh water of meteoric origin.

Notably, the normal distribution of groundwater cations and anions of the Tawilah sandstone aquifer (Figure 7-27) confirms the chemical findings resulting from the ion distribution maps.

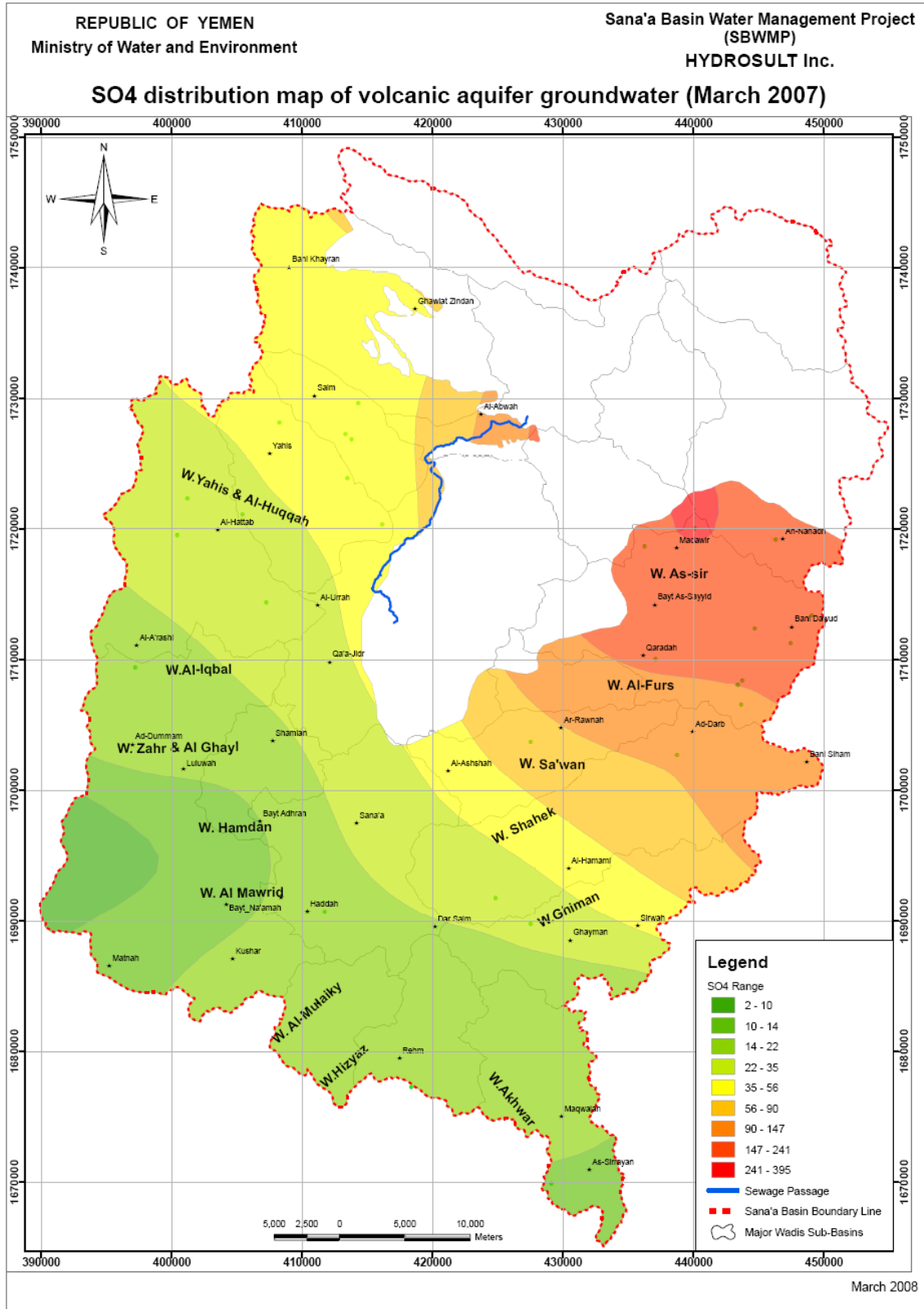


Figure 7-25 Sulfate distribution map in the volcanic aquifer in Sana'a Basin

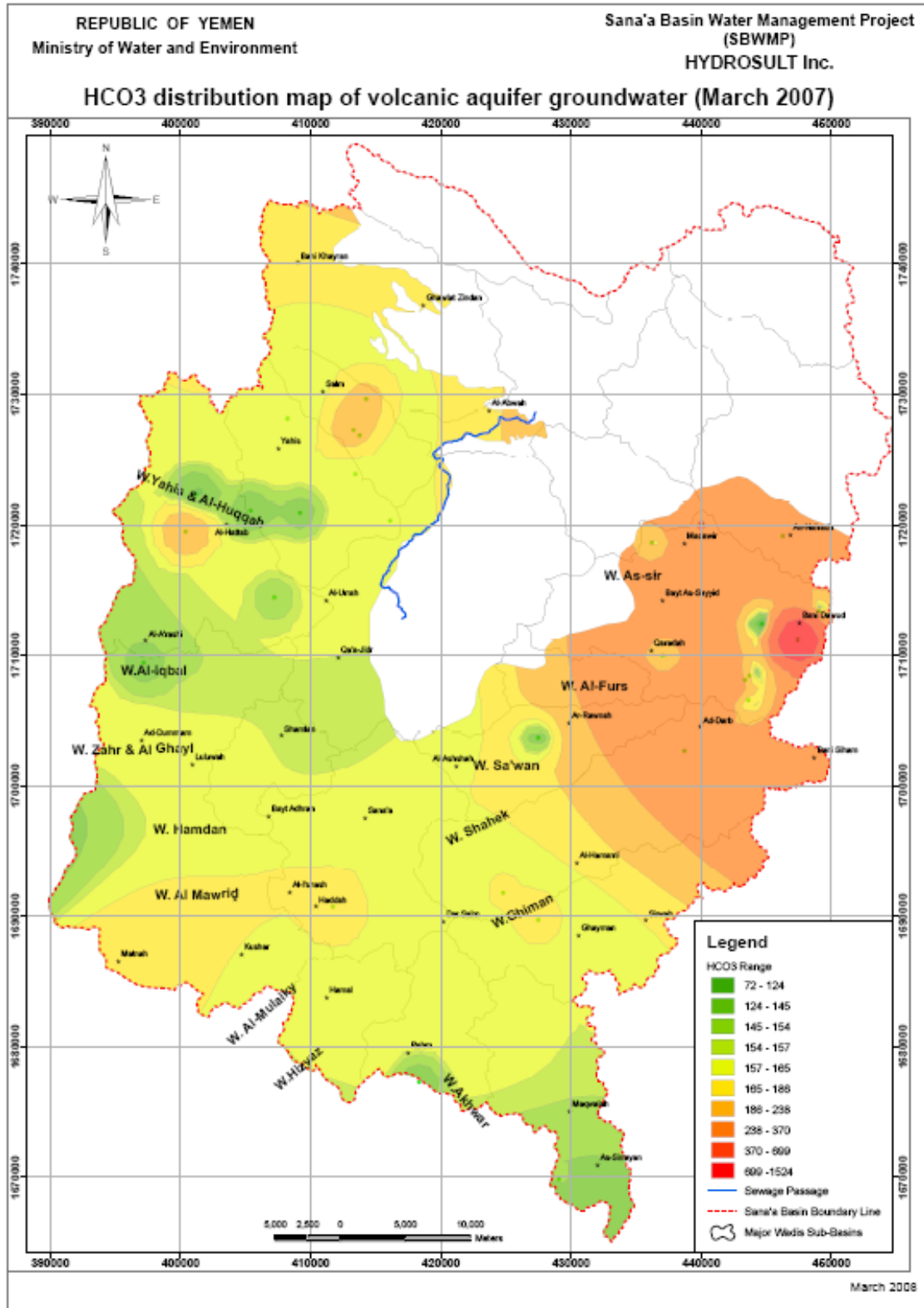


Figure 7-26 Bicarbonate distribution map in the volcanic aquifer in Sana'a Basin

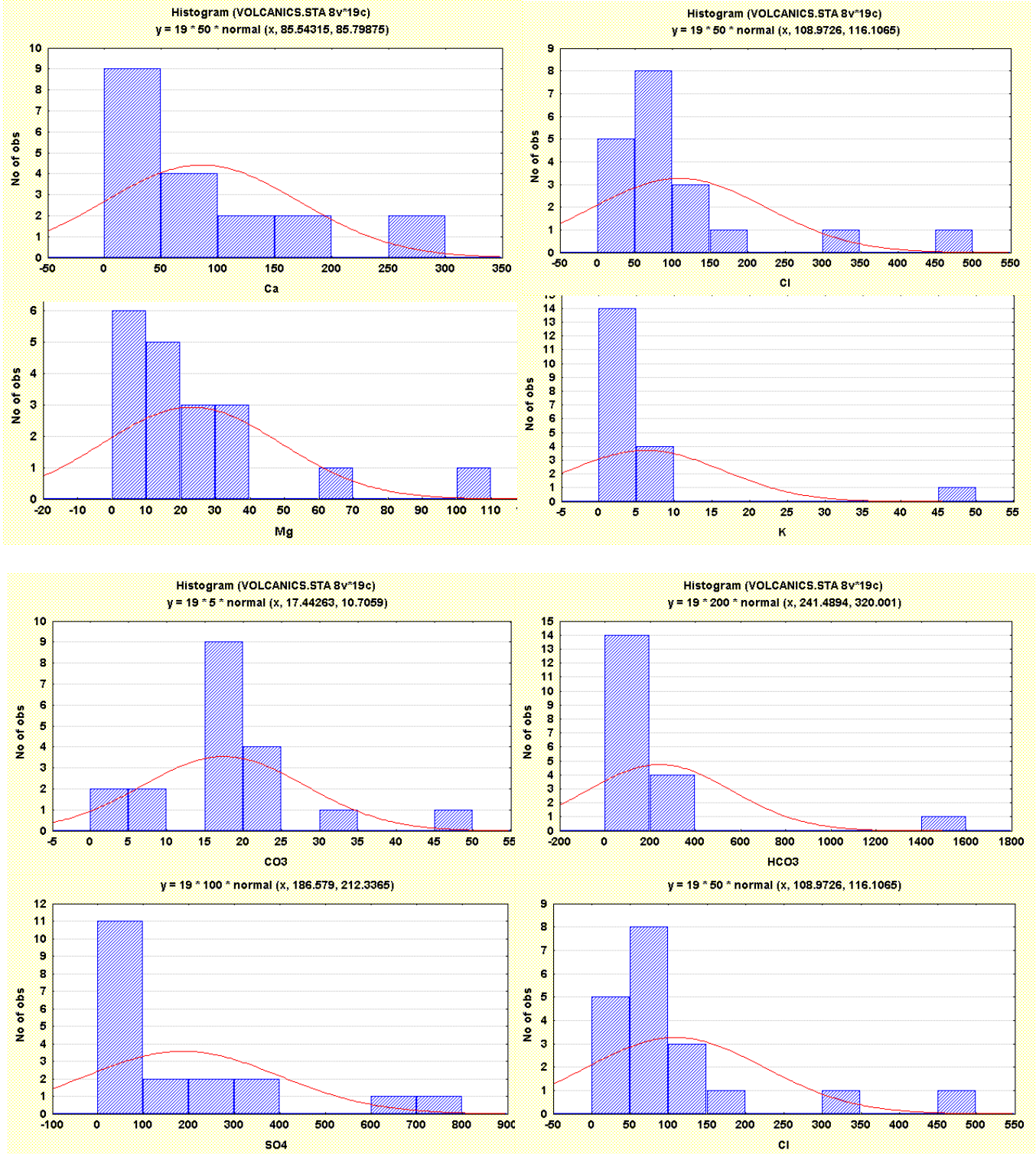


Figure 7-27 Graph showing normal distribution of groundwater ions in the volcanic aquifer of Sana'a Basin

7.3.4 Ion relationships and hydro-chemical coefficients

The volcanic aquifer groundwater in Sana'a Basin constitutes three main groups of ion relationships (Table 7-12).

Group 1: having $\text{Na} > \text{Ca} > \text{Mg}$ and $\text{HCO}_3 > \text{SO}_4 > \text{Cl}$ (66%), where $r\text{Na}/r\text{Cl}$ is more than unity. According to salinity levels, the water type is mainly fresh water type. Conversely, the hydro-chemical features of this group of the volcanic aquifer indicate continental salt contamination from the rainfall of the neighboring catchment area.

Group 2: having $\text{Na} > \text{Mg} > \text{Ca}$ and $\text{HCO}_3 > \text{Cl} > \text{SO}_4$ (20%), where $r\text{Na}/r\text{Cl}$ is more than unity. This group characterizes the groundwater samples of meteoric origin.

According to total salinity, the groundwater samples lie within the fresh water type. The hydro-chemical features and assemblages of hypothetical salts combinations indicate dissolution of terrestrial salts in this group.

Group 3: having $\text{Ca} > \text{Mg} > \text{Na}$ and $\text{HCO}_3 > \text{Cl} > \text{SO}_4$ (20%), where $r\text{Ca}/r\text{Mg}$ is more than unity. This group characterizes the groundwater samples of the eastern part of the aquifer.

In brief, most of the investigated groundwater samples of the volcanic aquifer reveal that sodium exceeds calcium or magnesium. This is due to the leaching of the catchment area. Groups 1 and 2 reflect an early stage of hydro-chemical evolution, where the metasomatic sequence is $\text{HCO}_3 > \text{SO}_4 > \text{Cl}$ due to the leaching and dissolution of terrestrial sediments. The general condition of such groundwater belonging to Groups 1 and 2 shows complete similarity to that of fresh water, indicating that this groundwater is of meteoric origin and affected by leaching and dissolution of terrestrial salts. Consequently, groundwater of the volcanic aquifer represents one main class of geochemical character that is the groundwater of continental affinity.

Hardness does not pose a health risk and is not regulated by state or federal agencies in the United States. In fact, calcium and magnesium in drinking water can help ensure the average daily requirements for these minerals in human diet. But hard water can be a nuisance due to mineral build-up on plumbing fixtures and poor soap and detergent performance. It often causes aesthetic problems, such as an alkaline flavor to the water that makes coffee taste bitter, build-up of scale on pipes and fixtures than can lead to lower water pressure, build-up of deposits on dishes, utensils and laundry basins; difficulty in getting soap and detergent to foam, and lowered efficiency of electric water heaters. The human body needs calcium to develop strong teeth and bones. With that, calcium can combat osteoporosis and other bone disorders. It also helps in regulating nerve transmission, blood coagulation, and muscle contraction. Calcium intake through water sources is shown to protect against death from acute myocardial infarction (heart disease), especially in women. It also protects against rectal and gastric cancers. Water that contains a lot of calcium and magnesium is said to be hard. The hardness of water is expressed in terms of the amount of calcium carbonate – the principal constituent of limestone – or equivalent minerals that would be formed if the water were evaporated. Water is considered soft if it contains 0 to 60 mg/l of hardness, moderately hard from 61 to 120 mg/l, hard between 121 and 180 mg/l, and very hard if more than 180 mg/l. In general, based on water quality standards, the desirable limit in Yemen for calcium concentration in water is 75 mg/l while the permissible value is 200 mg/l.

From the data collected (Table 7-12), it is clear that the total hardness ranges from 25 to 1,018 epm with a mean value of 311 epm in the groundwater samples from the volcanic aquifer. These data indicate an increase in total hardness with increasing water salinity (Figure 7-28). This is mainly attributed to the effect of leaching and dissolution of terrestrial salts, leading to an increase of total hardness.

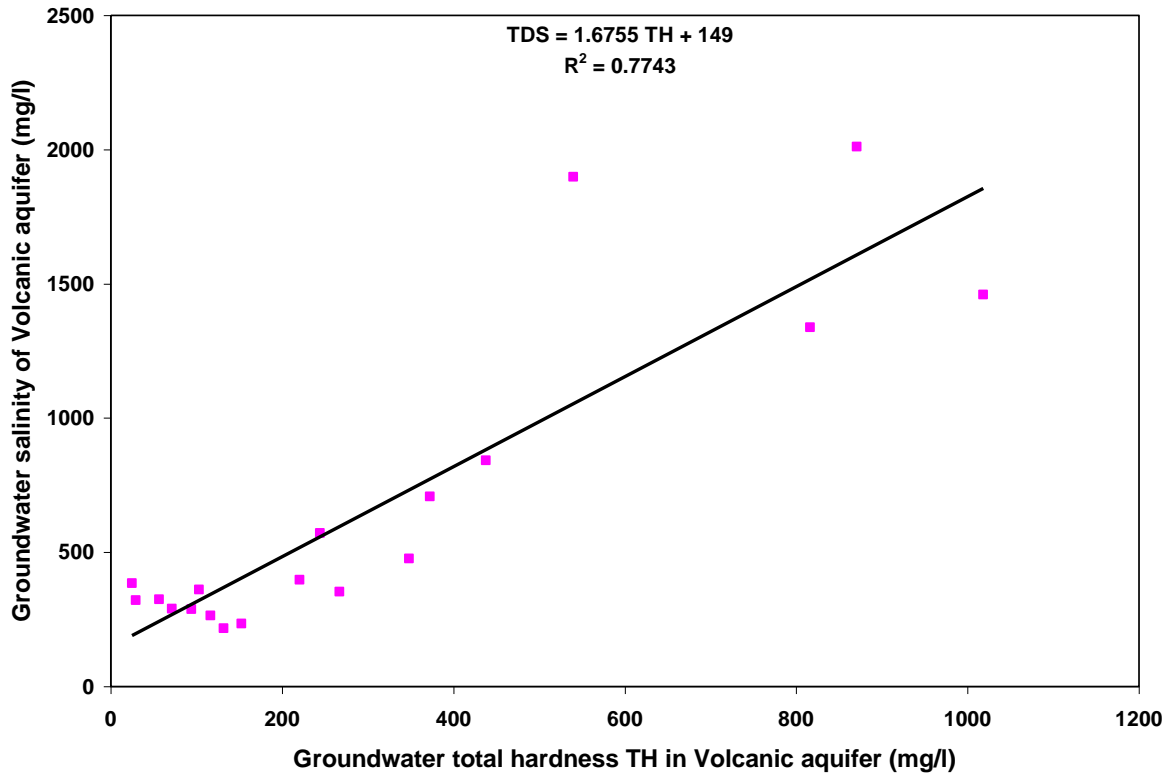


Figure 7-28 Graph showing the relationship between TDS and total hardness in mg/l of groundwater of the volcanic aquifer in Sana'a Basin

7.3.5 Groundwater classification

The results from analysis of water quality samples from the volcanic aquifer were used as input data for the determination of groundwater types using AQUACHEM Software. The output of the Piper diagram presentation from this program is given in Figure 7-29 and the water type is presented in Table 7-13.

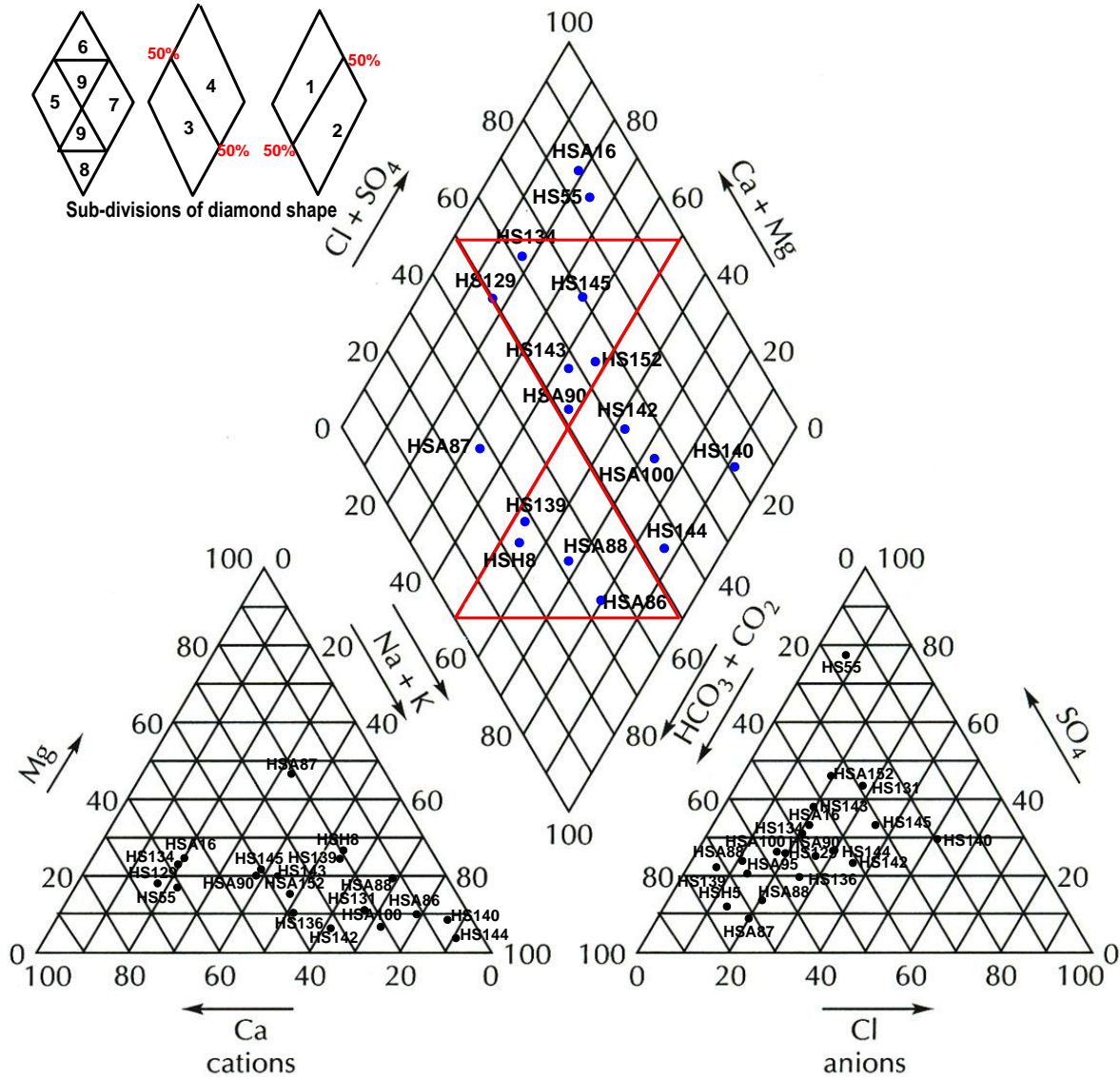


Figure 7-29 Classification of groundwater from the volcanic aquifer according to Piper 1953

Table 7-13 Water type for volcanic aquifer water samples

Well ID	Water Type	Water Type area
HS129	Ca-HCO ₃ -Cl-SO ₄	1
HS164	Ca-Mg-Cl-HCO ₃	1
HS134	Ca-Mg-Cl-HCO ₃ -SO ₄	1
HSH 12	Ca-Mg-HCO ₃	1

Well ID	Water Type	Water Type area
HSB 30	Ca-Mg-HCO ₃	1
HSS31	Ca-Mg-HCO ₃ -Cl	1
HSB 10	Ca-Mg-Na-HCO ₃	4
HSS44	Ca-Mg-Na-HCO ₃	1
HS145	Ca-Na-Cl-SO ₄ -HCO ₃	2
HSS19	Ca-Na-HCO ₃ -Cl	3
HSB 11	Ca-Na-Mg-HCO ₃ -Cl	3
HSS10	Ca-Na-Mg-HCO ₃ -Cl	3
HSS11	Ca-Na-Mg-HCO ₃ -Cl	1
HSB 8	Ca-Na-Mg-HCO ₃ -CO ₃	1
HSA 87	Mg-Na-Ca-HCO ₃ -Cl	1
HS142	Na-Ca-Cl-HCO ₃ -SO ₄	2
HS136	Na-Ca-HCO ₃ -Cl	3
HSS40	Na-Ca-HCO ₃ -Cl	3
HS143	Na-Ca-HCO ₃ -SO ₄ -Cl	2
HSB 14	Na-Ca-Mg-HCO ₃	3
HS131	Na-Ca-SO ₄ -Cl-HCO ₃	2
HS140	Na-Cl-SO ₄	4
HSA 84	Na-HCO ₃	4
HSA 86	Na-HCO ₃	4
HSA 99	Na-HCO ₃ -Cl	4
HS144	Na-HCO ₃ -Cl-SO ₄	4
HSA 85	Na-HCO ₃ -SO ₄	1
HSA 88	Na-HCO ₃ -SO ₄	4
HS139	Na-Mg-Ca-HCO ₃ -SO ₄	3

Figure 7-29 shows that the majority of groundwater samples (59%) from the volcanic aquifer are located in sub-area 9, where no one cation-anion pair exceeds 50 percent. However, the rest of the groundwater samples (24%) lie in sub-area 7, which is dominated by alkalis and strong acids (primary salinity). The majority of groundwater samples (55% of sub-area 7) are affected by continental conditions (35% of sub-area 9) and are more influenced by direct rainwater recharge. Few groundwater samples (11%) located in sub-areas 7 and 9 have marine facies type.

In conclusion, Piper's trilinear diagram suggests that the groundwater of the volcanic aquifer in Sana'a Basin is of mixed origins of mineralization, where rainwater and fossil water are the main sources of salt contribution.

7.3.6 Cluster analysis of volcanic aquifer groundwater

The statistical analysis was performed for the 22 available groundwater samples related to the volcanic aquifer. Although this aquifer has the largest outcropping area (57%), available data is minimal and cover less than half this aquifer.

7.3.6.1 Descriptive statistics

The statistical analysis of data sets shows that the linear regression between variables is significant since the critical value of F, with confidence level 95% and 9 degrees of freedom, is less than the estimated value. Table 7-14 shows the results of descriptive analyses. The most striking results are the maximum of SO_4^- , where it exceeds the WHO standard (World Health Organization 1984) for domestic use.

Table 7-14 Descriptive statistics of groundwater chemical components analyzed for the volcanic aquifer

	N	Minimum	Maximum	Mean	Standard Deviation	WHO Standard (1984) (Acceptable)
pH	22	6.54	9.47	7.81045455	0.666751023	7 - 8.5
EC	22	338	3,550	954.636364	826.7975249	-
TDS	22	197	2,010	558.045455	521.5739437	500
Ca	22	9.05	275.2	68.5604545	65.7112363	75
Mg	22	0.47	106.4	19.9727273	22.39948026	50
Na	22	20	480	104.772727	120.9978086	200
K	22	1	47	5.45454545	9.664501922	-
HCO ₃	22	72.19	1,524.09	235.392727	296.8075575	-
SO ₄	22	8	750	146.409091	200.3719539	200
Cl	21	23.94	325.53	81.0866667	66.49561544	200

The correlation analysis between the different hydrogeochemical parameters shows that TDS is highly positively correlated with Ca, Mg, Na and HCO₃ (0.64, 0.61, 0.72 and 0.96 respectively) and moderately positively correlated with Cl (0.6), which indicates the possibility of recharge from rainfall (Table 7-15 and Figure 7-46).

Table 7-15 Correlation coefficient matrix between the different ion concentrations in the volcanic aquifer

		Well no.	PH	EC	TDS	Ca ⁺²	Mg ⁺²	Na ⁺¹	K ⁺¹	CO3 ⁻²	HCO3 ⁻¹	SO4 ⁻²	Cl ⁻¹
	Correlation Coefficient	1	0.0039559	-0.5247105	-0.4274421	-0.1823828	-0.0468662	-0.3868964	-0.146575	-0.0804309	-0.4918125	-0.442277	1
	Sig. (2-tailed)	.	0.9860602	0.0121703	0.0472279	0.4165826	0.8359289	0.0752733	0.515113	0.7219826	0.0200819	0.0446892	.
	H	22	22	22	22	22	22	22	22	22	22	21	22
PH	Correlation Coefficient	0.0039559	1	-0.3781798	-0.356598	-0.5854763	-0.5532638	0.071792	-0.6184382	-0.388323	-0.2938684	-0.0201823	0.0039559
	Sig. (2-tailed)	0.9860602	.	0.0826695	0.1033061	0.0042007	0.0075647	0.7508731	0.0021555	0.0741119	0.1843625	0.930805	0.9860602
	H	22	22	22	22	22	22	22	22	22	22	21	22
EC	Correlation Coefficient	-0.5247105	-0.3781798	1	0.8980514	0.6201638	0.5704603	0.7050847	0.518907	0.6186994	0.8731997	0.6460643	-0.5247105
	Sig. (2-tailed)	0.0121703	0.0826695	.	1E-06	0.0020774	0.0055664	0.0002477	0.013341	0.0021436	1E-06	0.0015566	0.0121703
	H	22	22	22	22	22	22	22	22	22	22	21	22
TDS	Correlation Coefficient	-0.4274421	-0.356598	0.8980514	1	0.6442688	0.6126482	0.7269133	0.5265204	0.6134269	0.9638622	0.7661799	-0.4274421
	Sig. (2-tailed)	0.0472279	0.1033061	1E-06	.	0.0012114	0.0024363	0.0001271	0.0118229	0.0023969	1E-06	5.13E-05	0.0472279
	H	22	22	22	22	22	22	22	22	22	22	21	22
Ca⁺²	Correlation Coefficient	-0.1823828	-0.5854763	0.6201638	0.6442688	1	0.7662337	0.1790455	0.4920321	0.5902039	0.6182948	0.4760982	-0.1823828
	Sig. (2-tailed)	0.4165826	0.0042007	0.0020774	0.0012114	.	3.213E-05	0.4253054	0.0200179	0.0038338	0.0021622	0.0291306	0.4165826
	H	22	22	22	22	22	22	22	22	22	22	21	22
Mg⁺²	Correlation Coefficient	-0.0468662	-0.5532638	0.5704603	0.6126482	0.7662337	1	0.1733973	0.6742449	0.7833513	0.4884246	0.3213013	-0.0468662
	Sig. (2-tailed)	0.8359289	0.0075647	0.0055664	0.0024363	3.213E-05	.	0.4402892	0.0005794	1.623E-05	0.0210892	0.1555457	0.8359289
	H	22	22	22	22	22	22	22	22	22	22	21	22
Na⁺¹	Correlation Coefficient	-0.3868964	0.071792	0.7050847	0.7269133	0.1790455	0.1733973	1	0.3254309	0.2796045	0.748941	0.6493174	-0.3868964
	Sig. (2-tailed)	0.0752733	0.7508731	0.0002477	0.0001271	0.4253054	0.4402892	.	0.1394392	0.2075874	6.063E-05	0.0014469	0.0752733
	H	22	22	22	22	22	22	22	22	22	22	21	22
K⁺¹	Correlation Coefficient	-0.146575	-0.6184382	0.518907	0.5265204	0.4920321	0.6742449	0.3254309	1	0.5215323	0.4995046	0.1594635	-0.146575
	Sig. (2-tailed)	0.515113	0.0021555	0.013341	0.0118229	0.0200179	0.0005794	0.1394392	.	0.0128006	0.017938	0.4899139	0.515113
	H	22	22	22	22	22	22	22	22	22	22	21	22
CO3⁻²	Correlation Coefficient	-0.0804309	-0.388323	0.6186994	0.6134269	0.5902039	0.7833513	0.2796045	0.5215323	1	0.4310414	0.2085513	-0.0804309
	Sig. (2-tailed)	0.7219826	0.0741119	0.0021436	0.0023969	0.0038338	1.623E-05	0.2075874	0.0128006	.	0.0451989	0.3642935	0.7219826
	H	22	22	22	22	22	22	22	22	22	22	21	22
HCO3⁻¹	Correlation Coefficient	-0.4918125	-0.2938684	0.8731997	0.9638622	0.6182948	0.4884246	0.748941	0.4995046	0.4310414	1	0.807806	-0.4918125
	Sig. (2-tailed)	0.0200819	0.1843625	1E-06	1E-06	0.0021622	0.0210892	6.063E-05	0.017938	0.0451989	.	9.497E-06	0.0200819
	H	22	22	22	22	22	22	22	22	22	22	21	22
SO4⁻²	Correlation Coefficient	-0.442277	-0.0201823	0.6460643	0.7661799	0.4760982	0.3213013	0.6493174	0.1594635	0.2085513	0.807806	1	-0.442277
	Sig. (2-tailed)	0.0446892	0.930805	0.0015566	5.13E-05	0.0291306	0.1555457	0.0014469	0.4899139	0.3642935	9.497E-06	.	0.0446892
	H	21	21	21	21	21	21	21	21	21	21	21	21
Cl⁻¹	Correlation Coefficient	1	0.0039559	-0.5247105	-0.4274421	-0.1823828	-0.0468662	-0.3868964	-0.146575	-0.0804309	-0.4918125	-0.442277	1
	Sig. (2-tailed)	.	0.9860602	0.0121703	0.0472279	0.4165826	0.8359289	0.0752733	0.515113	0.7219826	0.0200819	0.0446892	.

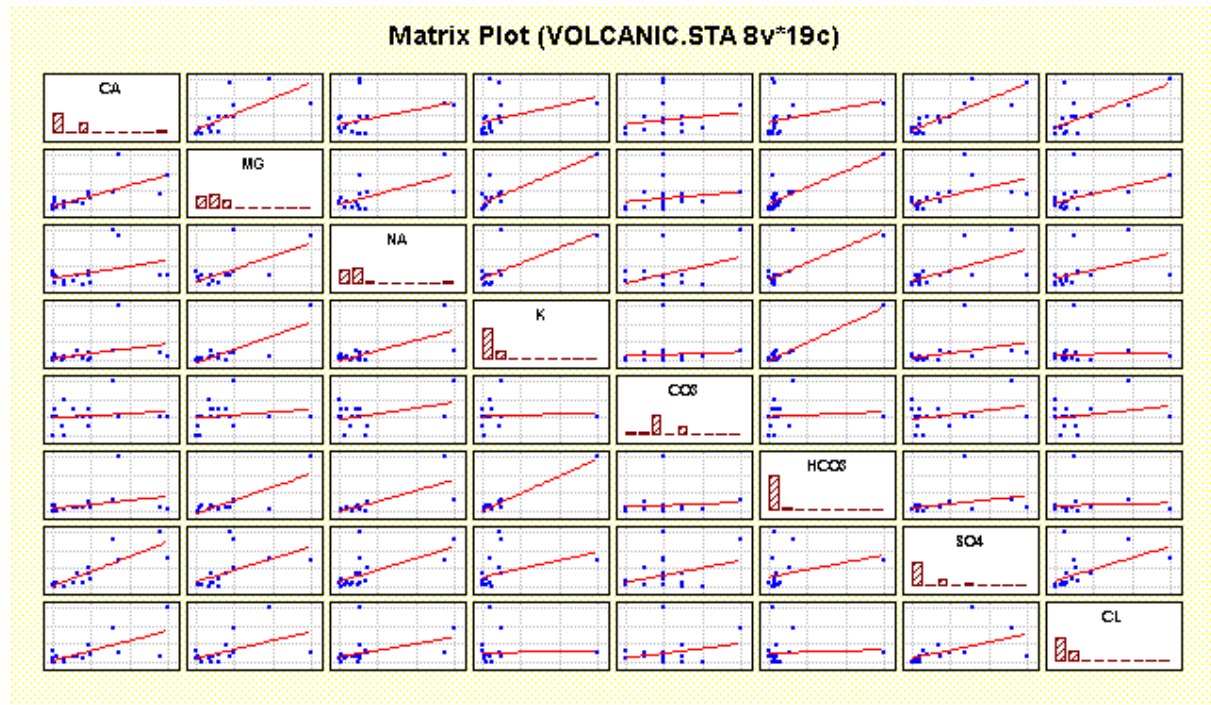


Figure 7-30 Linear regression between different ions in groundwater of the alluvium aquifer

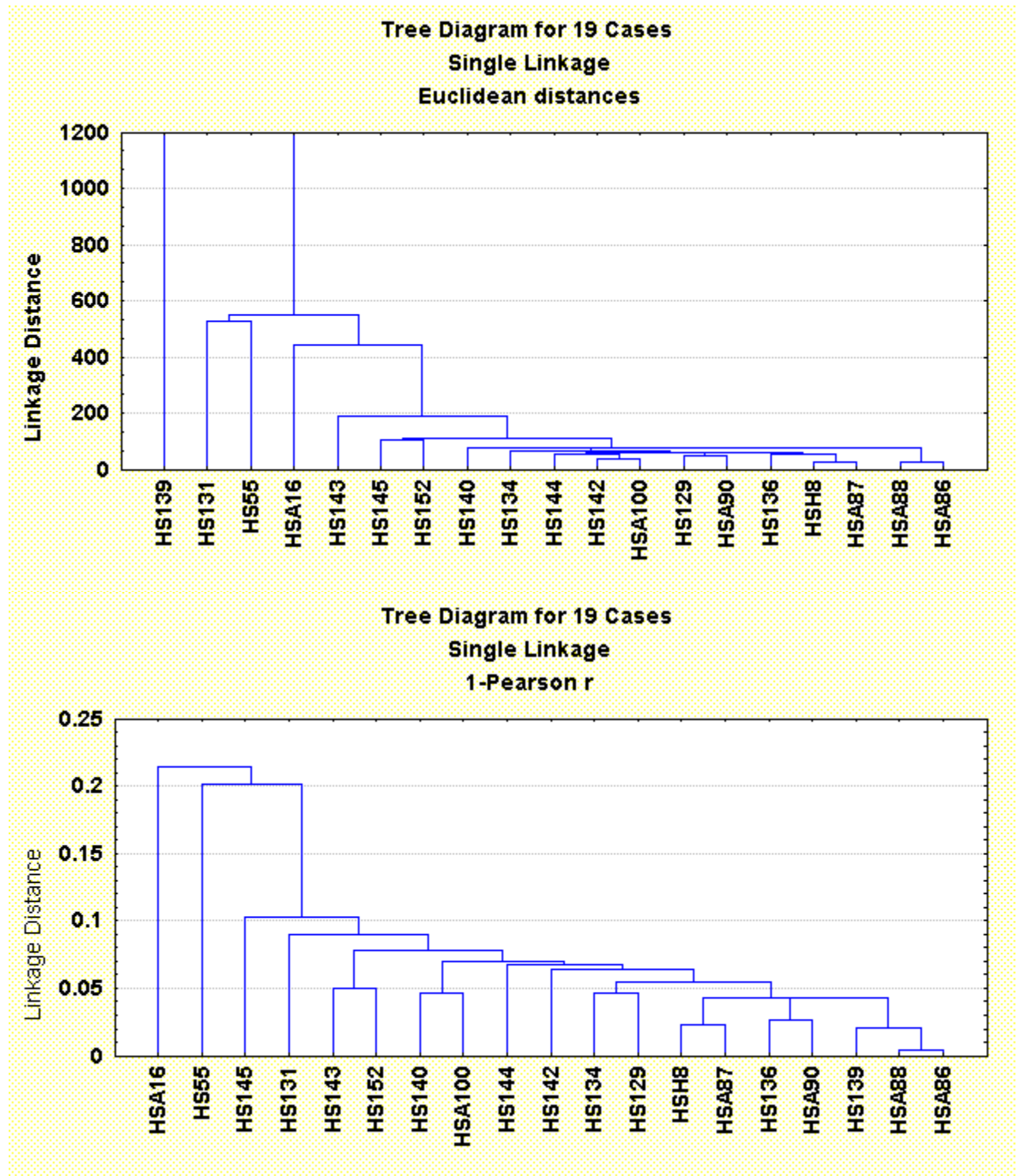


Figure 7-31 Horizontal icicle plot of the 8 non-transformed hydrogeochemical variables studied (R-mode-upper figure) and 22 wells (Q-mode-lower Figure) applying Euclidean distance method

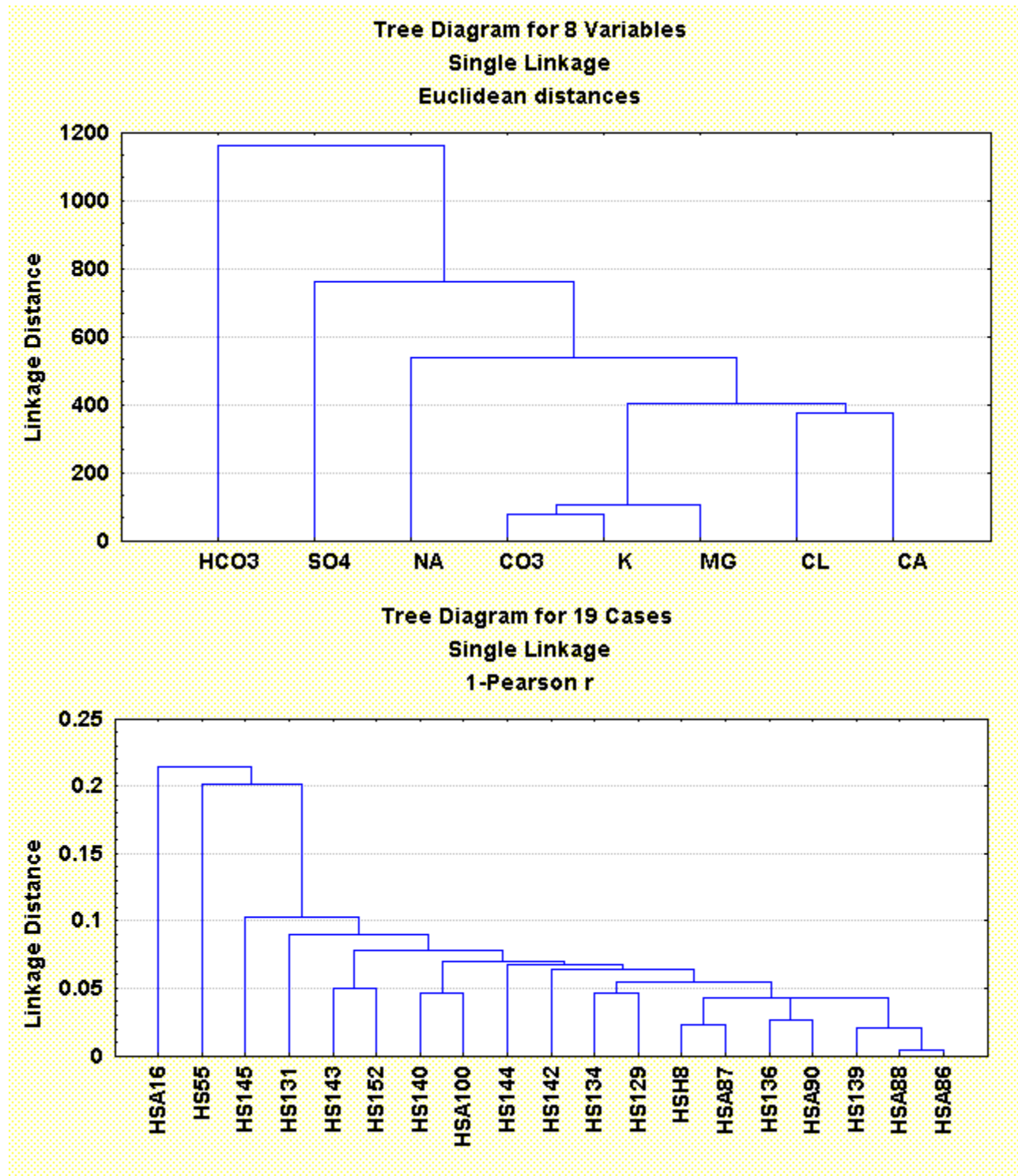


Figure 7-32 Vertical icicle plot of the 8 non-transformed hydrogeochemical variables studied (R-mode-upper figure) and 22 wells (Q-mode-lower Figure) applying 1-Pearson r method

7.3.6.2 Cluster analyses (Q- mode dendrogram)

The non-transformed data and the transformed data of hydrogeochemical analyses of the volcanic aquifer are used in constructing the tree diagrams (Figures 7-30 to 7-32), which are classified into two clusters and three independent samples as follows:

Cluster A: represents the main cluster and includes 16 samples located in the western part of the aquifer investigated. This cluster is characterized by lower salinity (197-476 mg/l). This reflects the effect of high recharge from rainfall characteristic of this area (500 mm/y).

Cluster B: includes two samples (41 & 43) located in the northeastern part of the aquifer, which are characterized by a higher salinity range than Cluster A (707-843 mg/l), as well as higher cation and anion concentrations. This may be attributed to mixing between volcanic groundwater (meteoric origin) and paleowater of the Tawilah sandstone groundwater. This confirms the hydraulic connection between these two aquifers.

Sample no. 35 is an independent sample characterized by higher salinity (1,898 mg/l). It is located on the eastern boundary of Sana'a Basin. Also, it has the highest values of sodium and chloride content which exceed the WHO standard, due to marine origin. **The water type is sodium chloride salts.**

Sample no. 38 is an independent sample characterized by the highest values of salinity (2,010 mg/l) and magnesium content (106.4 mg/l), which exceed WHO standards. This may be due to local over-pumping of the adjacent northeast NWSA well field and subsequent mixing with salt water of the Amran limestone from the north.

Sample no. 50 is an independent sample from the same location as sample no. 38. It has the highest value of calcium and sulfate content of all samples. These concentrations exceed the WHO standards due to agricultural activity, over-pumping, salt water intrusion and municipal wastes.

***** H I E R A R C H I C A L C L U S T E R A N A L Y S I S *

Dendrogram using Average Linkage (Between Groups)

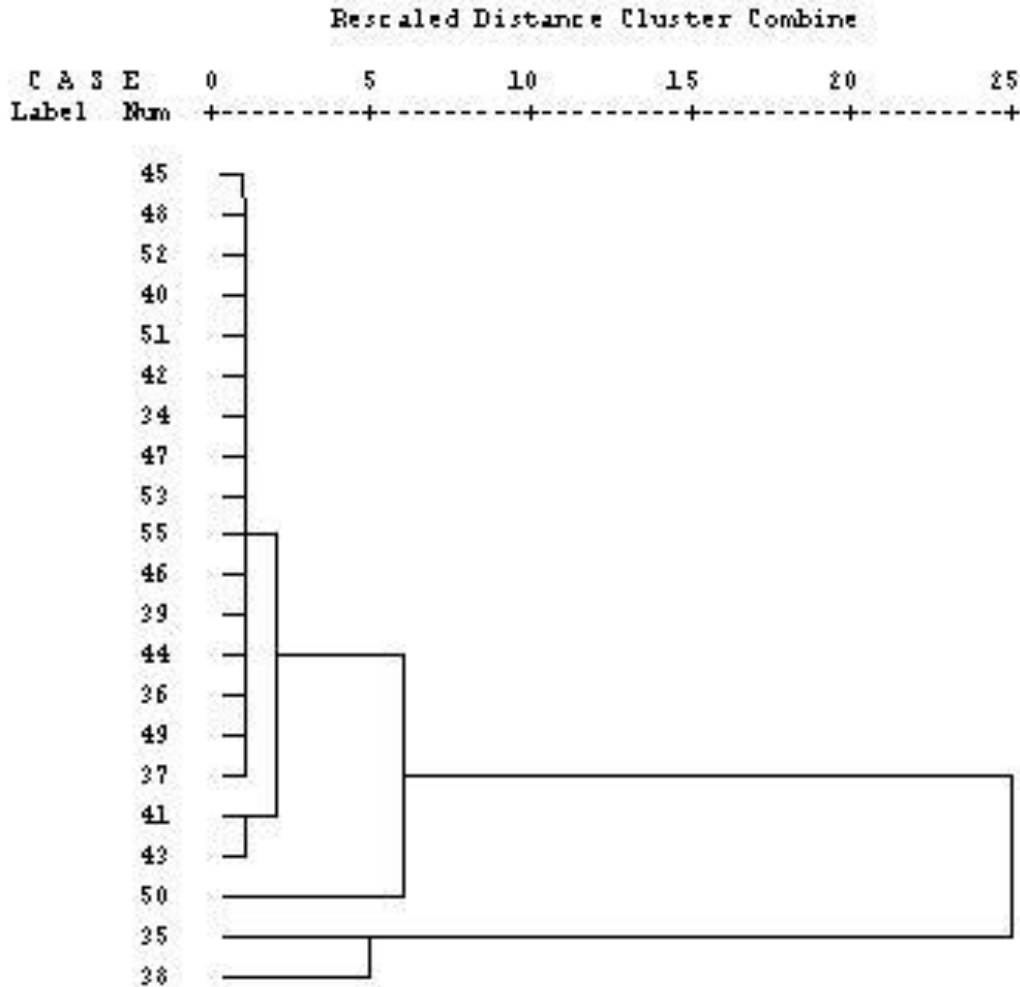


Figure 7-33 Dendrogram of selected transformed volcanic aquifer groundwater data using average linkage

7.4 Hydrogeochemistry of the Tawilah sandstone aquifer

Tawilah sandstone aquifer outcrops are encountered in the western, northeastern and eastern parts of Sana'a Basin (Hamadan, Nihm and Bani Hushaish respectively). The groundwater of this aquifer exists in confined and unconfined conditions. The confined condition is represented by 13 deep wells. The unconfined condition is encountered in outcrops and is represented by 9 shallow wells. The depth-to-water in shallow wells (unconfined conditions) varies between 9.5 and 13.4 m from ground surface and the rate of water extraction is very low (ranges from 2 to 10 m³/d). However, the depth-to-water in deep wells (confined conditions) ranges from 122.3 to 220 m in northwest and northeast well fields and have moderate potentiality.

During the field campaign, 23 groundwater samples were collected from 23 wells over the entire Tawilah sandstone aquifer in Sana'a Basin. Figure 7-34 shows the locations of the collected water quality samples within the sandstone aquifer. Table 7-16 presents the list of selected wells, their locations and UTM coordinates and the results of groundwater analyses.

Table 7-16 List of wells sampled for water quality and their locations

No.	Well ID	Location	Date	UTM E	UTM N
1	HS90	Qariah Aljarf /Nihm	3/15/2007	440981	1725057
2	HS91	Hija'ah al makanah/nihm	3/17/2007	435733	1724826
3	HS96	Maswarah /Nihm	3/11/2007	450033	1741936
4	HS99	Al-mahajer /Nihm	3/13/2007	432883	1724121
5	HS34	KOULAQAH /NIHM	3/13/2007	436297	1726629
6	HS100	Ghoulah Aseam/ NIHM	3/13/2007	448929	1725596
7	HS101	Almoa'ainah / NIHM	3/13/2007	451212	1723827
8	HS102	KOULAQAH /NIHM	3/14/2007	438693	1727668
9	HS104	Qariah Aljarf /Nihm	3/15/2007	440946	1725071
10	HS25	Al ghidah /Nihm	3/15/2007	440794	1723402
11	HS105	Al ghidah /Nihm	3/15/2007	440909	1723588
12	HS107	Bani hoshish	3/17/2007	438891	1716072
13	HS108	Alharf -Bani Husheish	3/22/2007	440459	1713806
14	HS110	aradah -Bani Husheish	3/24/2007	434905	1711413
15	HS24	Rama'a /Bani Husheish	3/25/2007	431026	1714902
16	HS113	Alsatrah /NIHM	3/27/2007	433332	1730112
17	HS119	Hamdan Wadi Zahr	6/5/2007	407966	1706823
18	HS120	Al Ghorzah -Hamdan	6/21/2007	400176	1709097
19	HS95	Maswarah /Nihm	3/11/2007	448870	1739967
20	HS106	Bit Abdalah /Nihm	3/17/2007	439478	1716748
21	HS31	Qadran -Bani Husheish	3/24/2007	430155	1712477

No.	Well ID	Location	Date	UTM E	UTM N
22	HS112	Bit Al saieed /Bani Husheish	3/25/2007	436845	1713808
23	HS18	Shibam //Bani Husheish	4/10/2007	426243	1714598
24	HS115	Zijan //Bani Husheish	4/10/2007	429466	1716736
25	HS121	Thomah /Nihm	3/17/2007	436064	1722730

Figure 7-34 Location map of selected groundwater wells of the Tawilah sandstone aquifer

Table 7-17 Results of chemical analyses of the groundwater samples of the Tawilah sandstone aquifer (March 2007)

S. No	Well ID	EC	pH	TDS	Units	Ca ⁺⁺	Mg ⁺⁺	Na ⁺	K ⁺	Sum	CO ₃ ⁻	HCO ₃ ⁻	SO ₄ ⁻	Cl ⁻	Sum	Hydro-chemical coefficients			SAR (epm)	Na% (epm)	Hardness (epm)	Aquifer Zone
		µmhos / cm		(mg/l)												rNa/rCl	rCa/rMg	rCl/rNa/rCl				
					mg/l	123.3	45.49	40	11		15.78	224.6	272	76.6								
1	HS 25	1,215	7.2	696	meq/l	6.15	3.74	1.74	0.28	11.91	0.53	3.68	5.66	2.16	12.03	0.81	1.64	0.19	0.8	17.0	495.1	Shallow
					e%	51.64	31.40	14.60	2.36		4.37	30.59	47.08	17.96								
					mg/l	44.25	30.62	20	1		13.18	200.93	42	45.82								
2	HSc	565	7.6	297	meq/l	2.21	2.52	0.87	0.03	5.62	0.44	3.29	0.87	1.29	5.90	0.67	0.88	0.33	0.57	15.92	236.49	Shallow
					e%	39.28	44.80	15.47	0.46		7.45	55.81	14.83	21.91								
					mg/l	39.83	10.35	18	1		7.89	160.43	14	21.54								
3	HS 110	387	7.8	193	meq/l	1.99	0.85	0.78	0.03	3.65	0.26	2.63	0.29	0.61	3.79	1.29	2.34	-0.29	0.7	22.2	142.0	Shallow
					e%	54.50	23.34	21.46	0.70		6.94	69.34	7.69	16.03								
					mg/l	86.41	58.24	45	4		15.78	256.69	190	74.2								
4	HS31	1,126	8.4	602	meq/l	4.31	4.79	1.96	0.10	11.16	0.53	4.20	3.96	2.09	10.78	0.94	0.90	0.06	0.9	18.4	455.4	Shallow
					e%	38.64	42.92	17.53	0.92		4.88	39.01	36.70	19.41								
					mg/l	67.26	19.65	14	7		23.67	160.43	67	23.94								
5	HS124	526	7.6	303	meq/l	3.36	1.62	0.61	0.18	5.76	0.79	2.63	1.39	0.68	5.49	0.90	2.08	0.10	0.4	13.7	248.8	Shallow
					e%	58.27	28.06	10.57	3.11		14.37	47.90	25.42	12.30								
					mg/l	85.04	12.02	12	2		15.78	160.43	93	23.94								
6	HS125	594	7.7	324	meq/l	4.24	0.99	0.52	0.05	5.80	0.53	2.63	1.94	0.68	5.77	0.77	4.29	0.23	0.3	9.9	261.8	Shallow
					e%	73.10	17.03	8.99	0.88		9.12	45.58	33.59	11.71								
					mg/l	143.5	23.58	24	2		15.78	224.6	230	28.72								

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S. No	Well ID	EC	pH	TDS	Units	Ca ⁺⁺	Mg ⁺⁺	Na ⁺	K ⁺	Sum	CO ₃ ⁻	HCO ₃ ⁻	SO ₄ ⁻	Cl ⁻	Sum	Hydro-chemical coefficients			SAR (epm)	Na% (epm)	Hardness (epm)	Aquifer Zone
		µmhos / cm		(mg/l)												rNa/rCl	rCa/rMg	rCl ⁻ rNa/rCl				
7	HS126	994	7.3	580	meq/l	7.16	1.94	1.04	0.05	10.19	0.53	3.68	4.79	0.81	9.80	1.29	3.69	-0.29	0.5	10.7	455.4	Shallow
					e%	70.24	19.02	10.24	0.50		5.36	37.53	48.85	8.26								
					mg/l	20.01	10.63	132	3		23.67	232.62	97	45.48								
8	HS85	782	7.7	448	meq/l	1.00	0.87	5.74	0.08	7.69	0.79	3.81	2.02	1.28	7.90	4.48	1.14	-3.48	5.93	75.64	93.71	Shallow
					e%	12.99	11.37	74.65	1.00		9.98	48.23	25.56	16.23								
					mg/l	297.6	91.47	140	21		23.67	144.39	1100	81.38								
9	HS27	2,770	7.5	1827	meq/l	14.85	7.52	6.09	0.54	29.00	0.79	2.37	22.90	2.29	28.35	2.65	1.97	-1.65	1.82	22.85	1,119.51	Shallow
					e%	51.21	25.94	20.99	1.85		2.78	8.34	80.78	8.09								
					mg/l	54.7	19.94	140	8		23.67	152.41	300	26.33								
10	HS28	1,086	6.96	649	meq/l	2.73	1.64	6.09	0.20	10.66	0.79	2.50	6.25	0.74	10.27	8.20	1.66	-7.20	4.12	59.02	218.64	Shallow
					e%	25.60	15.38	57.10	1.92		7.68	24.30	60.80	7.23								
					mg/l	131	34.73	26	6		15.78	240.65	189	64.63								
11	HS105	1,066	6.1	587	meq/l	6.54	2.86	1.13	0.15	10.68	0.53	3.94	3.93	1.82	10.23	0.62	2.29	0.38	0.5	12.0	470.0	Deep
					e%	61.22	26.75	10.59	1.44		5.14	38.55	38.48	17.82								
					mg/l	129	53.99	95	9		31.56	168.45	235	258.5								
12	HS4	1,603	7.2	896	meq/l	6.44	4.44	4.13	0.23	15.24	1.05	2.76	4.89	7.29	15.99	0.57	1.45	0.43	1.8	28.6	544.3	Deep
					e%	42.24	29.14	27.11	1.51		6.58	17.25	30.59	45.58								
					mg/l	62.17	20.43	16	2		7.89	168.45	73	33.51								
13	HS113	547	6.9	300	meq/l	3.10	1.68	0.70	0.05	5.53	0.26	2.76	1.52	0.94	5.49	0.74	1.85	0.26	0.4	13.5	239.3	Deep
					e%	56.11	30.39	12.58	0.93		4.79	50.29	27.70	17.22								

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S. No	Well ID	EC	pH	TDS	Units	Ca ⁺⁺	Mg ⁺⁺	Na ⁺	K ⁺	Sum	CO ₃ ⁻	HCO ₃ ⁻	SO ₄ ⁻	Cl ⁻	Sum	Hydro-chemical coefficients			SAR (epm)	Na% (epm)	Hardness (epm)	Aquifer Zone
		µmhos / cm		(mg/l)												rNa/rCl	rCa/rMg	rCl/rNa/rCl				
					mg/l	187.9	48.86	35	7		15.78	160.43	530	52.66								
14	Has	1,557	7.8	957	meq/l	9.38	4.02	1.52	0.18	15.10	0.53	2.63	11.03	1.49	15.67	1.02	2.33	-0.02	0.6	11.3	670.2	Deep
					e%	62.11	26.62	10.08	1.19		3.35	16.77	70.40	9.47								
					mg/l	144.9	47.76	80	6		31.56	224.6	170	258.5								
15	HS132	1,460	6.7	851	meq/l	7.23	3.93	3.48	0.15	14.79	1.05	3.68	3.54	7.29	15.56	0.48	1.84	0.52	1.5	24.6	558.3	Deep
					e%	48.89	26.56	23.52	1.04		6.76	23.64	22.75	46.85								
					mg/l	215.2	77.67	70	11		15.78	320.86	550	95.74								
16	HSb	1,980	6.7	1196	meq/l	10.74	6.39	3.04	0.28	20.45	0.53	5.26	11.45	2.70	19.93	1.13	1.68	-0.13	1.0	16.3	857.0	Deep
					e%	52.51	31.23	14.88	1.38		2.64	26.37	57.45	13.55								
					mg/l	106.6	34.32	50	5		23.67	248.67	146	100.5								
17	HS133	1,095	7.7	590	meq/l	5.32	2.82	2.17	0.13	10.44	0.79	4.07	3.04	2.83	10.74	0.77	1.88	0.23	1.08	22.04	407.41	Deep
					e%	50.93	27.03	20.82	1.23		7.35	37.94	28.31	26.40								
					mg/l	86.31	18.29	56	4		23.67	184.49	84	110.1								
18	HS141	872	6.9	475	meq/l	4.31	1.50	2.43	0.10	8.35	0.79	3.02	1.75	3.11	8.66	0.78	2.86	0.22	1.43	30.39	290.78	Deep
					e%	51.59	18.02	29.17	1.23		9.10	34.88	20.18	35.84								
					mg/l	60.93	19.06	26	3		23.67	208.56	27	43.09								
19	HS146	590	7.3	307	meq/l	3.04	1.57	1.13	0.08	5.82	0.79	3.42	0.56	1.22	5.98	0.93	1.94	0.07	0.74	20.76	230.57	Deep
					e%	52.28	26.96	19.44	1.32		13.18	57.11	9.40	20.31								
					mg/l	69.08	16.14	44	4		23.67	56.15	96	98.14								
20	HS147	782	7.9	379	meq/l	3.45	1.33	1.91	0.10	6.79	0.79	0.92	2.00	2.77	6.47	0.69	2.60	0.31	1.24	29.68	238.91	Deep

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S. No	Well ID	EC	pH	TDS	Units	Ca ⁺⁺	Mg ⁺⁺	Na ⁺	K ⁺	Sum	CO ₃ ⁻	HCO ₃ ⁻	SO ₄ ⁻	Cl ⁻	Sum	Hydro-chemical coefficients			SAR (epm)	Na% (epm)	Hardness (epm)	Aquifer Zone
		µmhos / cm		(mg/l)												rNa/rCl	rCa/rMg	rCl rNa/rCl				
					e%	50.77	19.55	28.18	1.51		12.18	14.21	30.87	42.74								
					mg/l	63.49	11.44	38	2		23.67	160.43	55	50.27								
21	HS57	565	6.8	324	meq/l	3.17	0.94	1.65	0.05	5.81	0.79	2.63	1.15	1.42	5.98	1.17	3.37	-0.17	1.15	29.31	205.61	Deep
					e%	54.51	16.19	28.43	0.88		13.19	43.95	19.15	23.71								
					mg/l	139.6	32.99	100	5		23.67	176.47	184	248.9								
22	HS148	1,588	7.1	823	meq/l	6.97	2.71	4.35	0.13	14.16	0.79	2.89	3.83	7.02	14.53	0.62	2.57	0.38	1.98	31.62	484.34	Deep
					e%	49.21	19.17	30.72	0.90		5.43	19.89	26.36	48.31								
					mg/l	65.76	20.42	30	6		31.56	176.47	62	50.27								
23	HS21	694	7.3	354	meq/l	3.28	1.68	1.30	0.15	6.42	1.05	2.89	1.29	1.42	6.65	0.92	1.95	0.08	0.83	22.71	248.23	Deep
					e%	51.12	26.16	20.32	2.39		15.81	43.46	19.41	21.32								

7.4.1 Groundwater pH values

The pH of groundwater samples in the shallow Tawilah sandstone aquifer are between 6.96 and 8.4, with a mean value of 7.6, while the pH values in the groundwater samples of the deep Tawilah sandstone aquifer range from 6.1 to 7.9, with a mean value of 7.1 (Table 7-17), indicating that the dissolved inorganic carbon exists almost entirely as HCO_3^- , Freeze and cherry (1979). The spatial distribution of pH within the Tawilah sandstone aquifer, as shown in Figure 7-35, shows that the pH value ranges from 7.2 to 8.2. The eastern part of the aquifer ranges between 7.9 and 8.2, while the western part of the aquifer ranges between 7.2 and 7.9.

The mean pH values (7.55 and 7.07 for shallow and deep wells respectively) greatly differ from that expected for rainwater (pH 5.65). This shift is due to several chemical reactions within the unsaturated zone, as well as the long residence times known for the shallow and deep Tawilah sandstone. The surface and subsurface water flow, as well as local precipitation, are believed to be dominant sources of recharge of the Tawilah sandstone in the shallow unconfined zone under favorable climatic conditions during recent times. The Tawilah sandstone in the shallow confined zone is mainly recharged from deep horizons through upward leakage as a result of cracks and faults, in addition to surface and subsurface flow. In addition to recharge from local rainfall in the past, there is dissolution of biogenic CO_2 gas from non-barren paleosols that have strongly diffused biogenic CO_2 gas into infiltrating water (Himida, 1966). This biogenic gas is expected to decrease the pH value to below that of rainwater in equilibrium with the atmosphere (due to much higher CO_2 in the vegetated soil than in the atmosphere). This decrease should soon be balanced by other reactions causing an increase of pH in the percolating water. Regarding the mineralogical composition of the unsaturated and saturated zones of the aquifer in the studied area, being mostly made up of 90% sandstone and 10% shale as indicated from well logs (Italconsult, 1973), siltstone and sandy limestone, silica dissolution could be responsible for the shift to neutral or basic pH values. Also, further reactions with traces of solid-phase carbonates and hydroxides (Ca, Mg, Fe, Ni, P, etc.) and total dissolved inorganic carbon (TDIC) concentrations could account for increasing groundwater pH, significantly above the contents brought by wet deposition. Sulfate reduction by biogenic reactions produces H_2S in groundwater samples and increases HCO_3^- content, which should thus have a certain effect on pH change (Hem 1989).

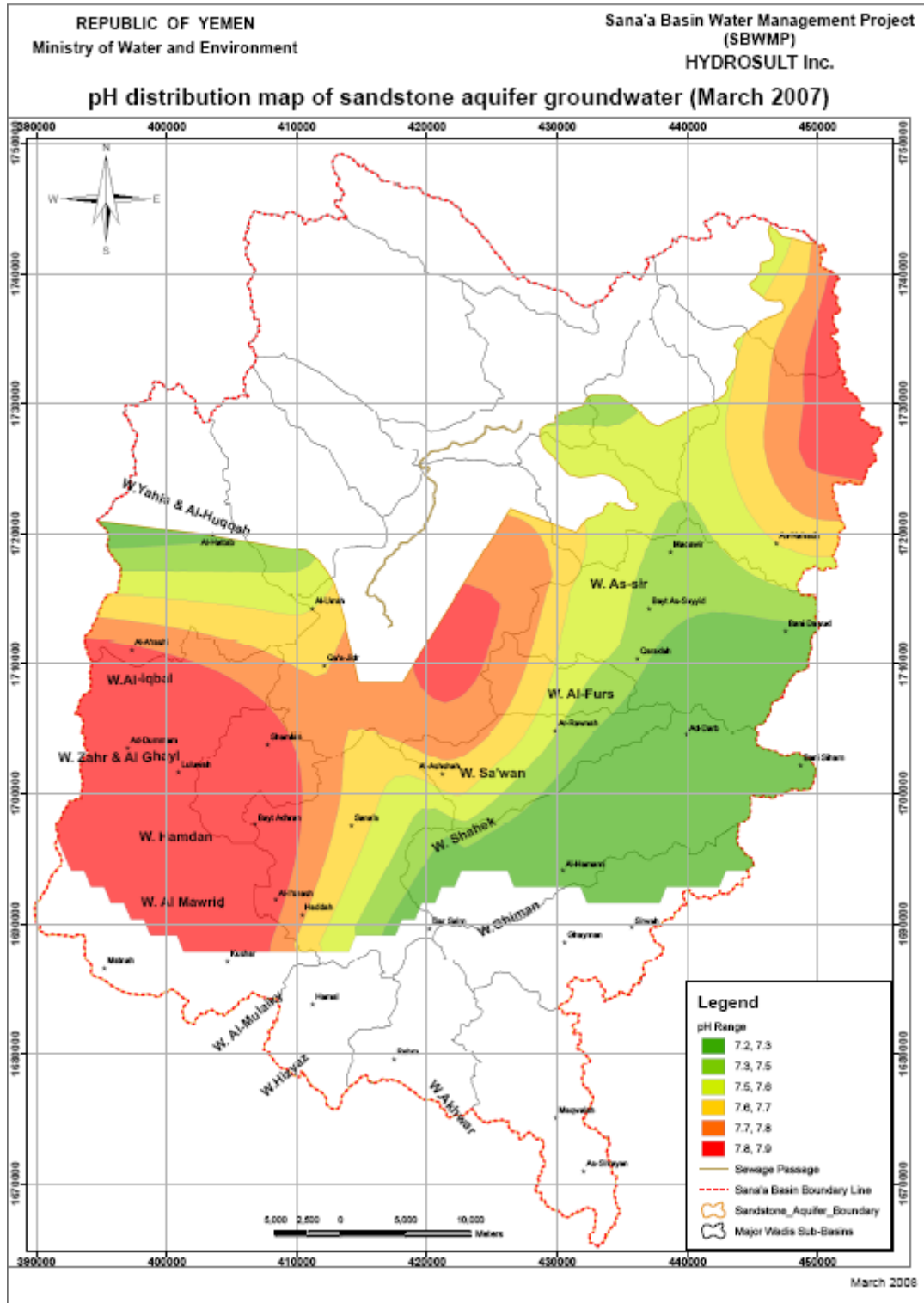


Figure 7-35 pH distribution map of the Tawilah sandstone aquifer groundwater

7.4.2 Groundwater salinity

According to available chemical data, groundwater of the Tawilah sandstone aquifer in the shallow wells has salinity ranging from 193 mg/l to 1,827 mg/l, with a mean value of 592 mg/l (Table 7-17), i.e. groundwater of the aquifer concerned is considered fresh water. The groundwater of the Tawilah sandstone aquifer in the deep wells has salinity ranging from 300 mg/l to 1,196 mg/l, with a mean value of 618 mg/l (fresh water). From the frequency distribution of salinity (Table 7-18), it is clear that most of the groundwater samples (90%) of the shallow, unconfined zone are related to fresh water, while few groundwater samples (10%) are related to brackish water. The groundwater samples of the deep Tawilah sandstone aquifer are related to the fresh water category.

Table 7-18 Frequency distribution of salinity values in mg/l of groundwater in the Tawilah sandstone aquifer

Aquifers types	No. of samples	Frequency distribution	
		Fresh water	Brackish water
		<1,500mg/l	1,500-5,000mg/l
Tawilah sandstone (shallow wells)	10	9	1
Tawilah sandstone (deep wells)	13	13	--

Generally, the relatively low salinity of groundwater of the shallow Tawilah sandstone aquifer may be attributed to the proximity of the recharge area (aquifer outcrops). The wide range of water salinity is attributed to the lateral changes from sandy to clayey facies and the change of saturated thickness. With regard to the relatively low salinity of the shallow confined zone, it reflects that this aquifer was formed under continental conditions, in spite of the presence of relatively high saline shale in aquifer matrices.

Figure 7-36 presents the distribution of TDS over the entire sandstone aquifer. It is obvious that 70% of the aquifer area has a TDS value between 200 and 400 mg/l. However, relatively high TDS values in Wadis Thoma, As-Sirr, Khulaga and Lafaf were found to be in the range of 500 mg/l and 1,200 mg/l. The highest concentration is found at the boundary between the Tawilah sandstone aquifer and the Amran limestone aquifer with (more than 2,000 mg/l). The iso-salinity distribution map of the Tawilah sandstone aquifer (Figure 7-36) shows a general increase towards east and northeast while the reverse is observed in the southwest direction at Nihm as a result of over-pumping of the eastern NWSA well fields, rather than litho-facies impact. The regular distribution of groundwater salinity from west to east with lower values in the west may reflect a continuous recharge from rainfall to the aquifer outcrops in Hamadan in the west. The harmony between the water table map and the iso-salinity map is confirmed, since the salinity increases in the direction of flow (from west to east direction).

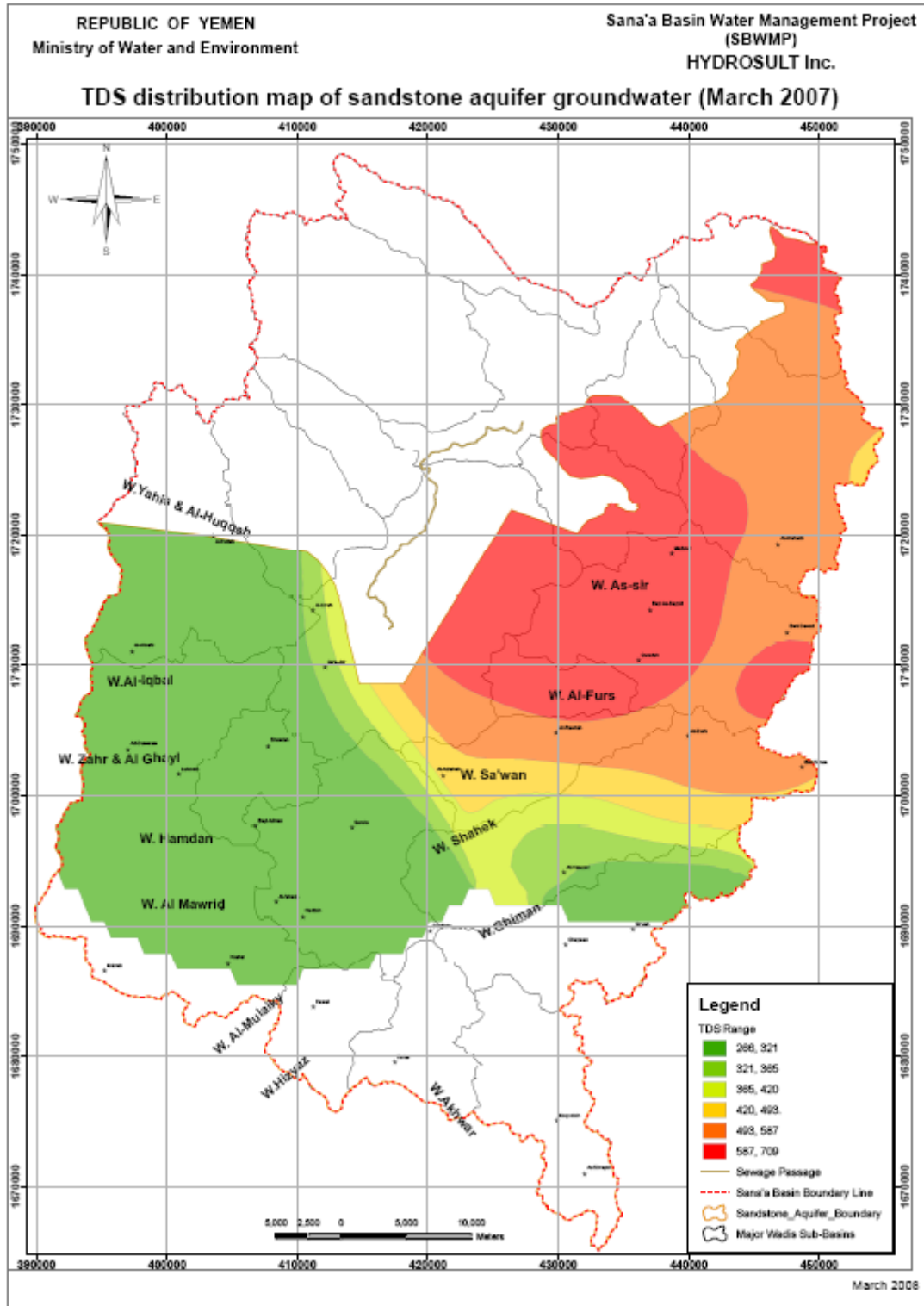


Figure 7-36 Iso-salinity map of groundwater of the Tawilah sandstone aquifer in Sana'a Basin

7.4.3 Distribution of major ions

The distribution maps of ions in groundwater of the shallow and deep Tawilah sandstone wells in Sana'a Basin (Figures 7-37 to 7-42) are constructed based on the results of chemical analyses (Table 7-17). These maps are discussed herein as follows:

- 1) **Ca²⁺** concentration ranges from 13 to 73% with a mean value of 33% and from 42 to 62% with a mean value of 53% of total dissolved cations in groundwater of the shallow and deep Tawilah sandstone zones respectively. Since the concentration percentages of Ca²⁺ are 3% and 70% for both sea (marine) and rain waters respectively, the source of calcium mineralization is thus a pure infiltrated rainwater affected by leaching and dissolution of terrestrial salts from aquifer matrices and marine salts from the catchment area. Figure 7-37 presents the distribution of calcium concentration within the boundary of the Tawilah sandstone aquifer. It is observed that the concentration is less than the maximum permissible limit over the entire aquifer, except at the boundary with the limestone aquifer. However, the west part of the aquifer has a relatively low value of 10 to 30 mg/l. The high value of calcium is located at Wadi Thoma (290 mg/l). This value decreases gradually towards the western areas.
- 2) **Mg²⁺** concentration ranges from 11 to 45% with a mean value of 26% and from 16 to 31% with a mean value of 25% of total dissolved cations in the shallow and deep Tawilah sandstone zones respectively. As the concentration percentages of Mg²⁺ are 20% and 10% for both sea (marine) and rain waters respectively, this means that the Mg²⁺ content is attributed to the dolomitization processes that have occurred in the aquifer, as well as Mg²⁺ content, which is nearly identical to sea water. Figure 7-38 presents the distribution of magnesium within the Tawilah sandstone aquifer. The maximum permissible limit is 30 mg/l. Most of the aquifer area has a value below 7 mg/l. The highest concentration is found at the point where the sandstone aquifer intersects with the limestone aquifer.
- 3) **Na⁺** concentrations range from 9 to 75% with a mean value of 10% and from 10 to 71% with a mean value of 21% of total dissolved cations in the shallow and deep Tawilah sandstone zones respectively. The Cl⁻ concentration ranges from 7 to 22% with a mean value of 14% and from 10 to 48% with a mean value of 28% of total dissolved anions of those aquifer zones respectively. The concentration percentages of both Na⁺ and Cl⁻ are 77% & 90% and 20% & 29% for both sea (marine) and rain waters respectively. Thus, it is believed that both Na⁺ and Cl⁻ have the same sources of mineralization (mixed mineralization) in the groundwater of those aquifer zones. The excess of Na⁺ over Cl⁻ concentration in most groundwater samples of both aquifer zones is possibly due to leaching and dissolution of the terrestrial salts of the aquifer matrices (continental facies groundwater type). However, some groundwater samples of the shallow Tawilah sandstone aquifer are characterized by Cl⁻ over Na⁺ concentration due to leaching and dissolution processes of marine salts by surface and subsurface water from the catchment area dominated by limestone rocks (marine condition).

Figure 7-39 presents the spatial distribution of sodium within the Tawilah sandstone aquifer. The desirable limit for sodium concentration is 200 mg/l while the maximum permissible limit is 400 mg/l. Thus, it is observed that the value of sodium concentration is within desirable standards for the entire aquifer.

Referring to Figure 7-40, chloride concentration in the sandstone aquifer is presented. It is noted that 90% of aquifer water is suspected to have low chloride concentration. The most common value of chloride concentration is found to be in the range of 20 mg/l and 90 mg/l. The highest chloride concentration occurs in Wadi Al-Sirr, where the value exceeds 280 mg/l. The maximum value occurred at the intersection with the limestone outcrop.

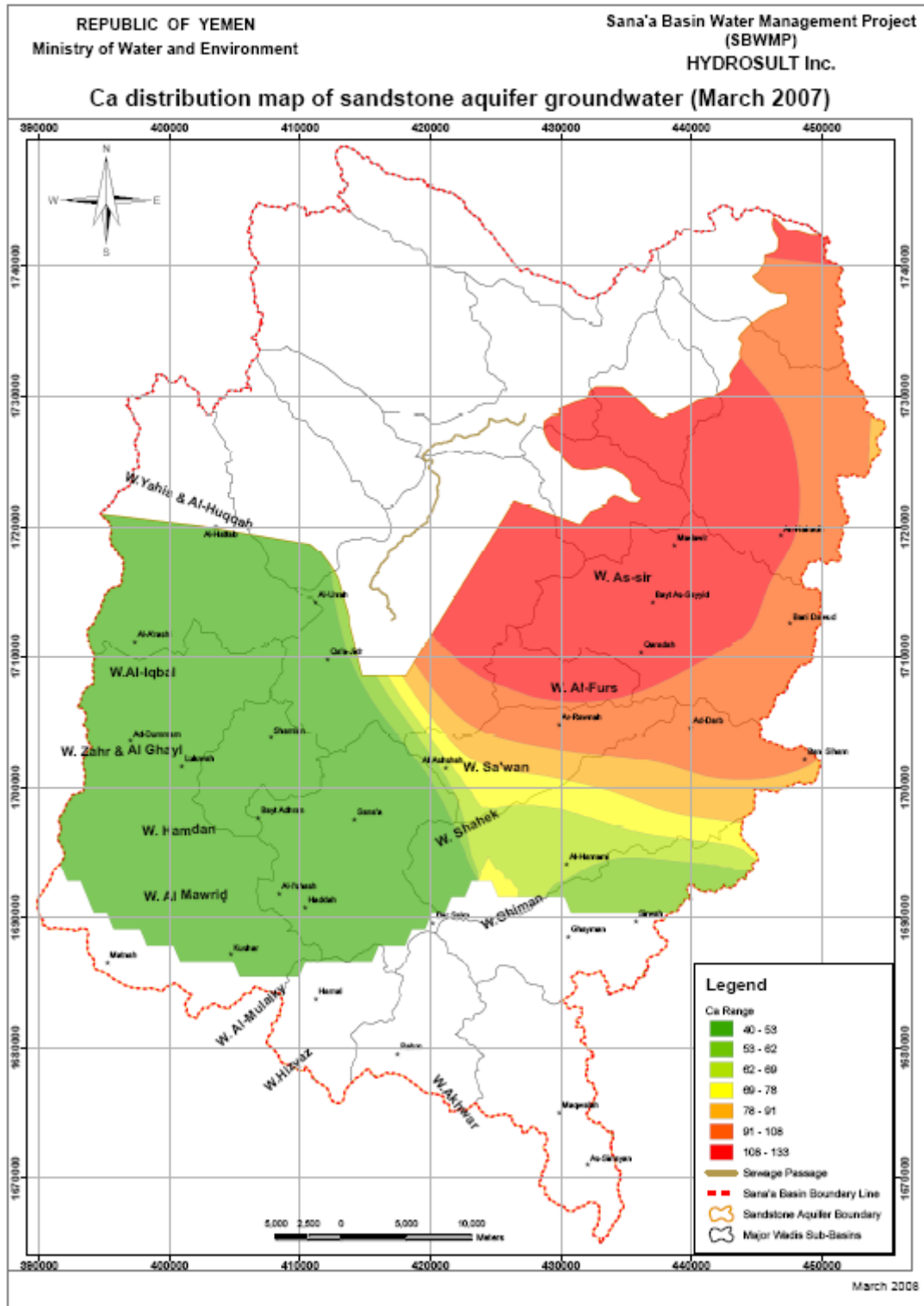


Figure 7-37 Ca distribution map of groundwater of the Tawilah sandstone aquifer in Sana'a Basin

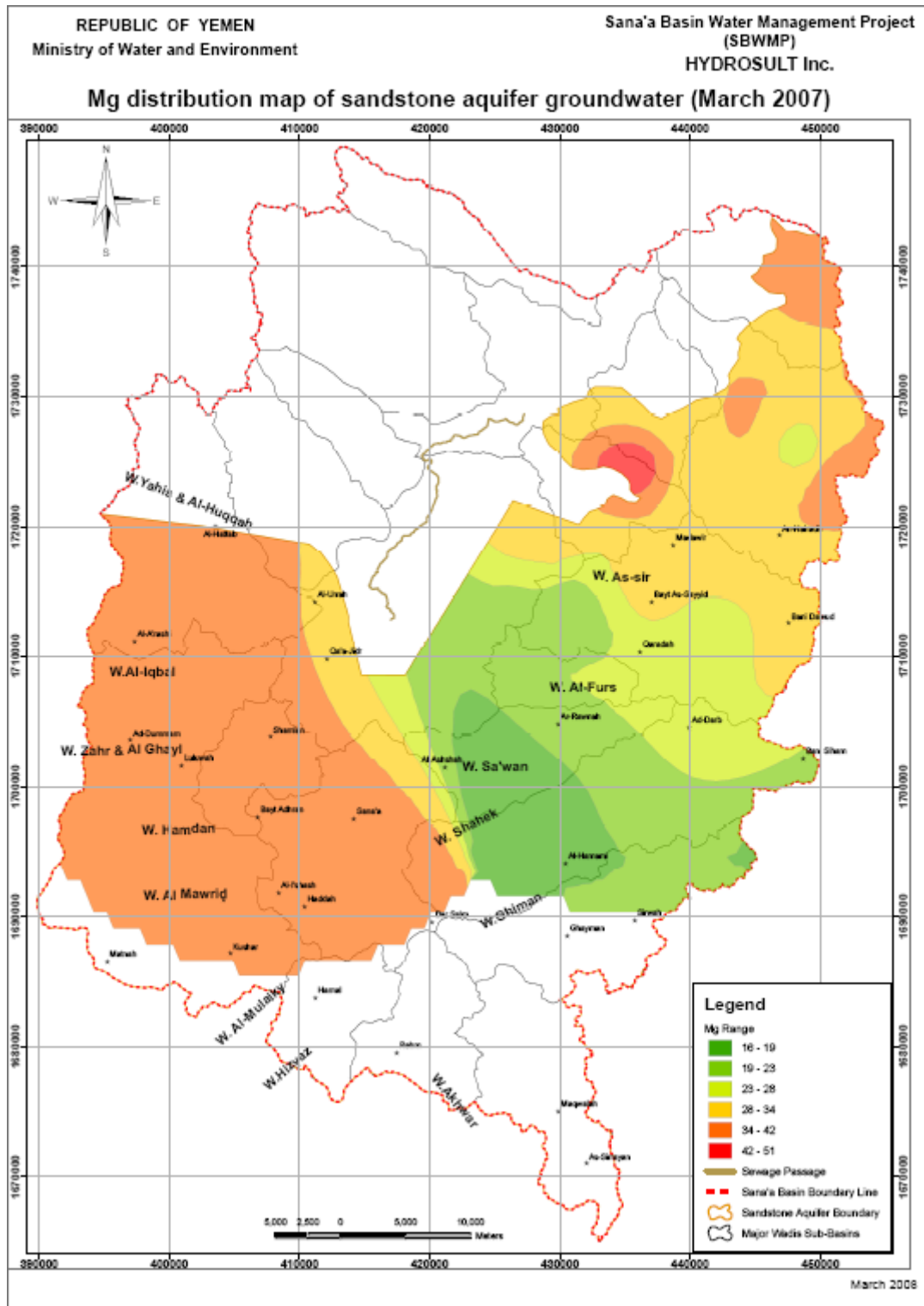


Figure 7-38 Mg distribution map of groundwater of the Tawilah sandstone in Sana'a Basin

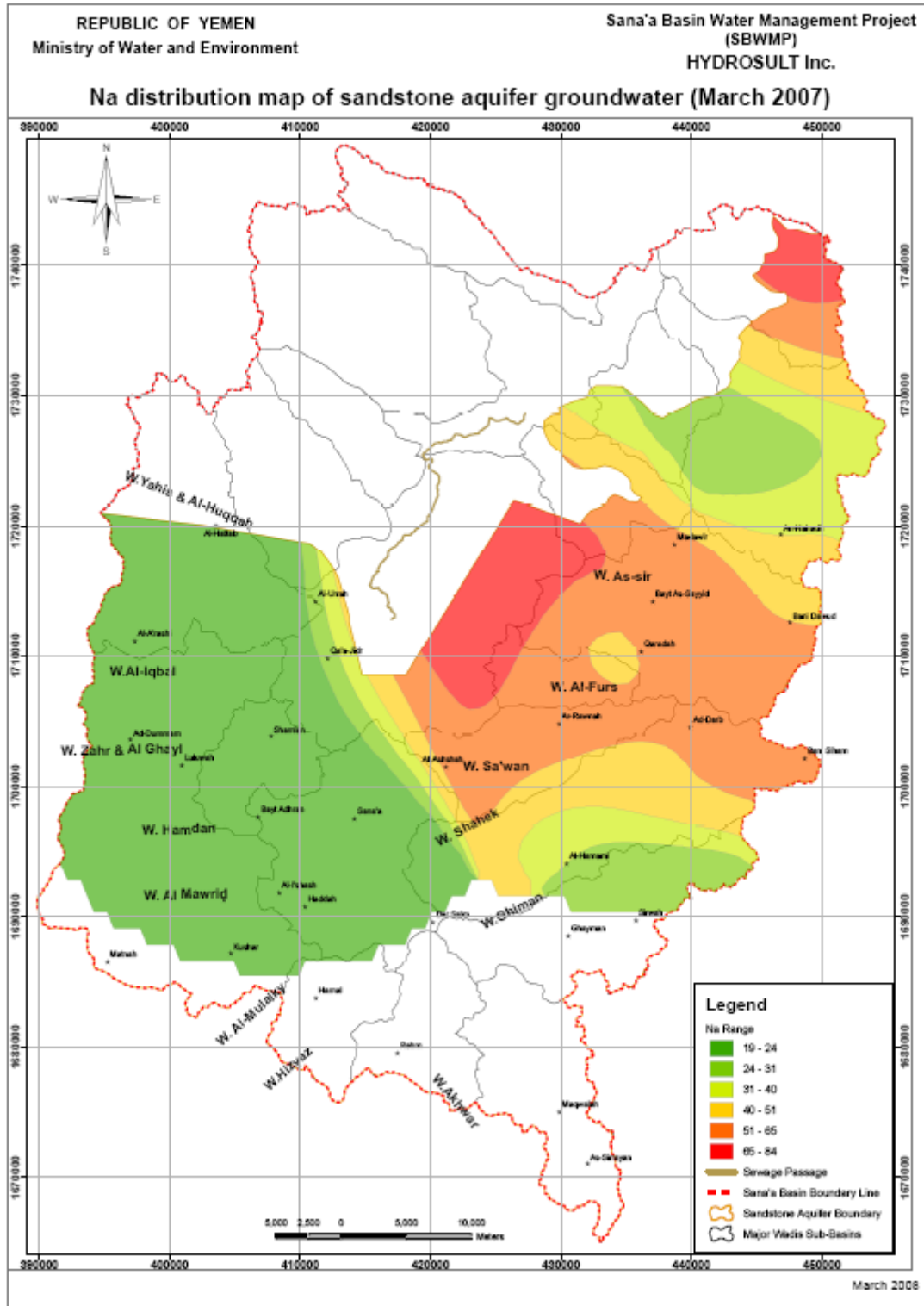


Figure 7-39 Na distribution map of groundwater of the Tawilah sandstone aquifer in Sana'a Basin

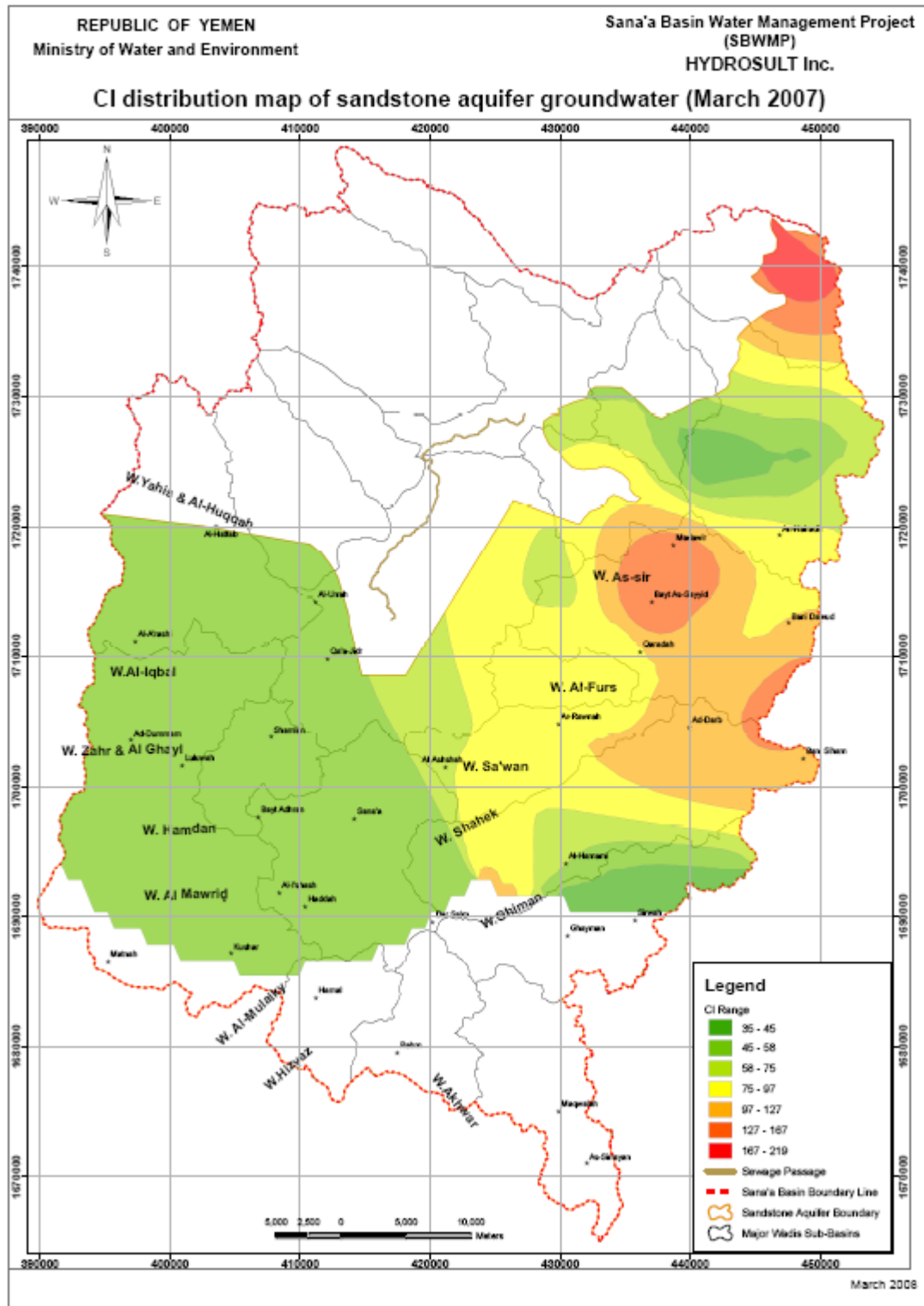


Figure 7-40 Cl distribution map of groundwater of the Tawilah sandstone aquifer in Sana'a Basin

- 4) SO_4^{2-} concentration ranges from 8 to 81% with a mean value of 38% and from 9 to 70% with a mean value of 31% of total dissolved anions in the shallow and deep Tawilah sandstone zones respectively. The concentration percentages of SO_4^{2-} are 9.5% and 25% for both sea (marine) and rain waters respectively. The sulfate mineralization is of meteoric origin. This could indicate that sulfate content is governed by a biogenic system that significantly distorts the other mechanisms (wet deposition, evaporation, dissolution of sulfate solid-phases and mixing). Figure 7-41 presents the sulfate distribution over the entire sandstone aquifer. It is noted that most of the aquifer has a relatively low concentration of sulfate, within the range of 50 mg/l and 300 mg/l. The highest concentration is found at the point where the sandstone aquifer intersects the limestone aquifer.
- 5) HCO_3^- concentration ranges from 8 to 69% with a mean value of 41% and from 14 to 57% with a mean value of 33% of total dissolved anions in the shallow and deep Tawilah sandstone zones respectively. The concentration percentages of HCO_3^- are 0.5% and 46% for both sea (marine) and rain waters respectively. The source of HCO_3^- mineralization is mixed between rain and sea (marine) waters (Godam, 2005).

Figure 7-42 presents the distribution of HCO_3^- concentration within Tawilah sandstone aquifer. The desirable limit for HCO_3^- concentration is 150 mg/l, while the maximum permissible limit is 500 mg/l. Within the Tawilah sandstone aquifer, it has been found that the value of HCO_3^- is relatively low, since it was in the range of 50 to 330 mg/l. Concentrations of HCO_3^- in the Tawilah sandstone aquifer range from 144 to 257 mg/l, with a mean value of 200 mg/l for shallow unconfined zones, while they range from 56 to 321 mg/l, with a mean value of 175 mg/l for the shallow confined zone. This indicates that carbonate minerals have, more or less, been dissolved in this aquifer. These differences in concentration can be attributed to three factors (El-Sayed, M.H. 2001):

- The first is water temperatures of the shallow and deep Tawilah sandstone zones. As would be expected from the solubility consideration, the coldest water has the highest content of carbonate mineral dissolution products and, vice versa, the hot water has the highest content of non-carbonate mineral dissolution products, Freeze and Cherry (1979).
- The second is the differences in partial pressure of CO_2 for the shallow and deep Tawilah sandstone zones.
- The third is the degree of saturation with respect to carbonate minerals for the shallow and deep Tawilah sandstone zones.

In general, for the deep Tawilah sandstone zone, all groundwater samples are supersaturated with respect to aragonite (CaCO_3), calcite (CaCO_3), dolomite $\text{Ca Mg}(\text{CO}_3)_2$ and magnesite (MgCO_3). This indicates that shallow and deep Tawilah sandstone zones contain carbonate materials as a result of chemical weathering of the adjacent rock units (limestone rocks).

It is evident that groundwater types are affected by leaching and dissolution of terrestrial salts (assemblages of hypothetical salt combinations II and III), and possibly accompanied by a cation-exchange process. This process is related to clay/mineral assemblages that are dominated by vermiculite-mica and montmorillonite with minor amounts of kaolinite, palygorskite and saponite, where the shallow Tawilah sandstone zone is made up of about 75% sandstone and 10% shale, siltstone and sandy limestone (15%), while the deep Tawilah sandstone zone is composed of 80% sandstone and 10% shale, siltstone and sandy limestone (10%).

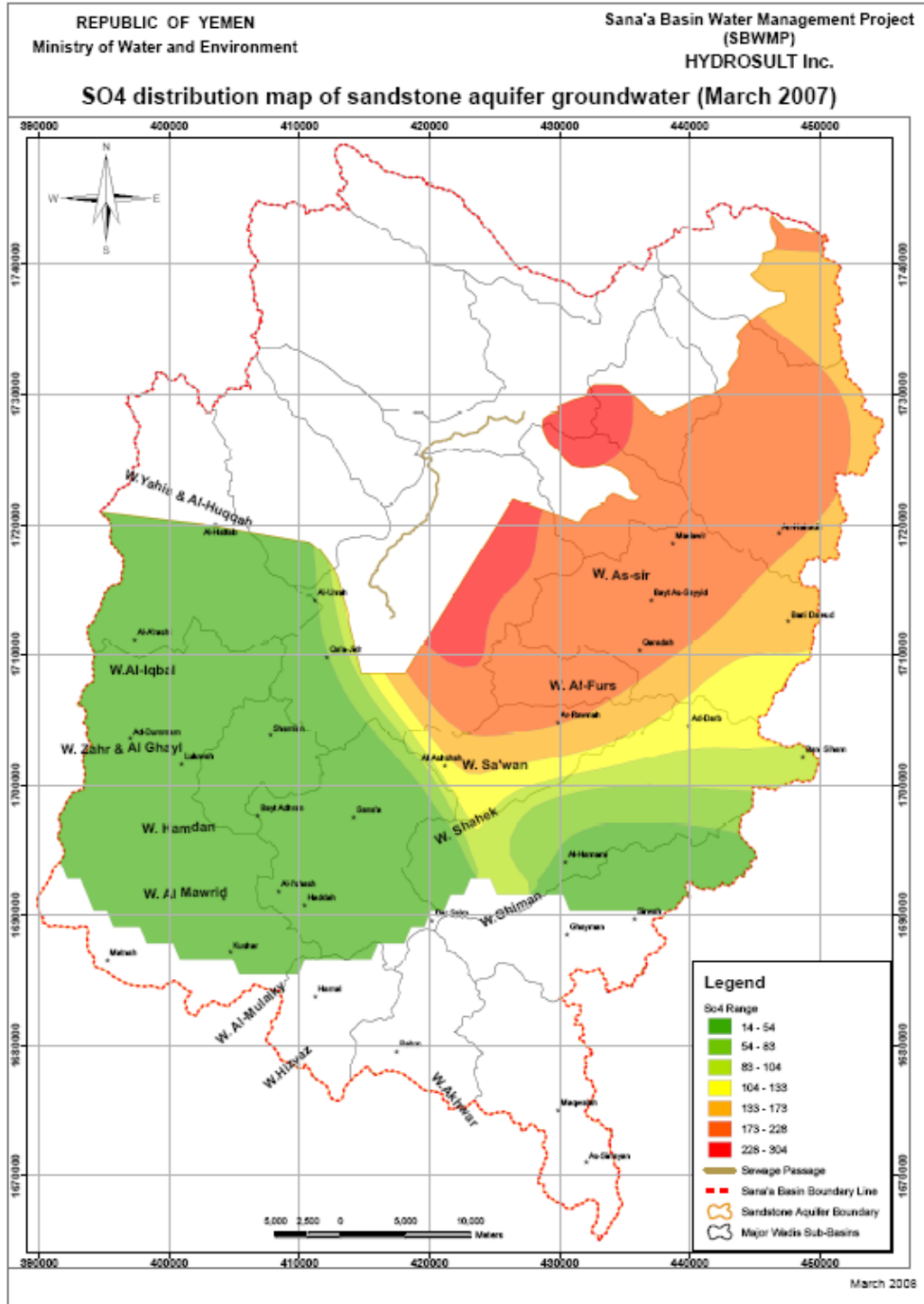


Figure 7-41 Sulfate distribution map of groundwater of the Tawilah sandstone aquifer in Sana'a Basin

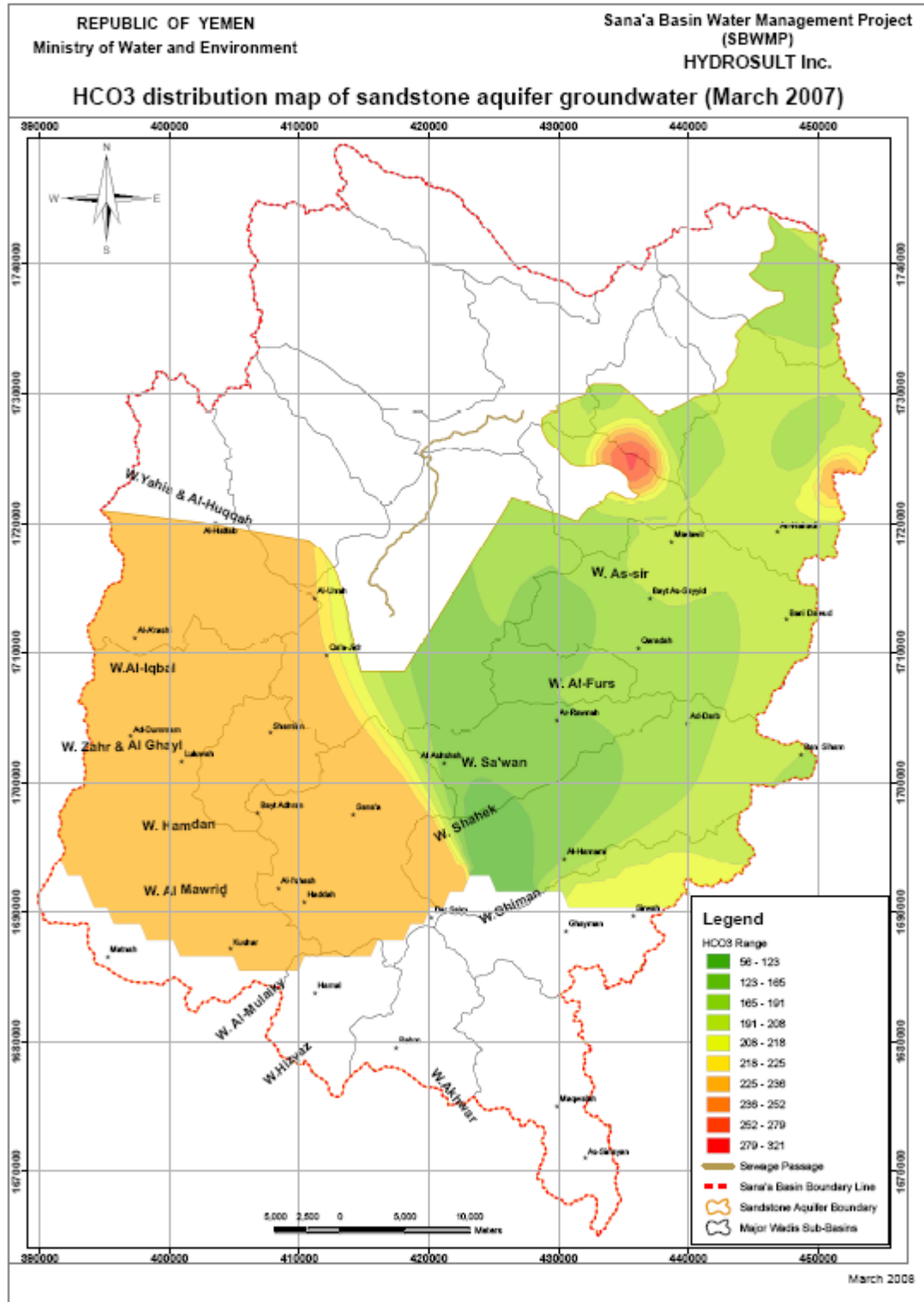


Figure 7-42 Bicarbonate distribution map of groundwater of the Tawilah sandstone aquifer in Sana'a Basin

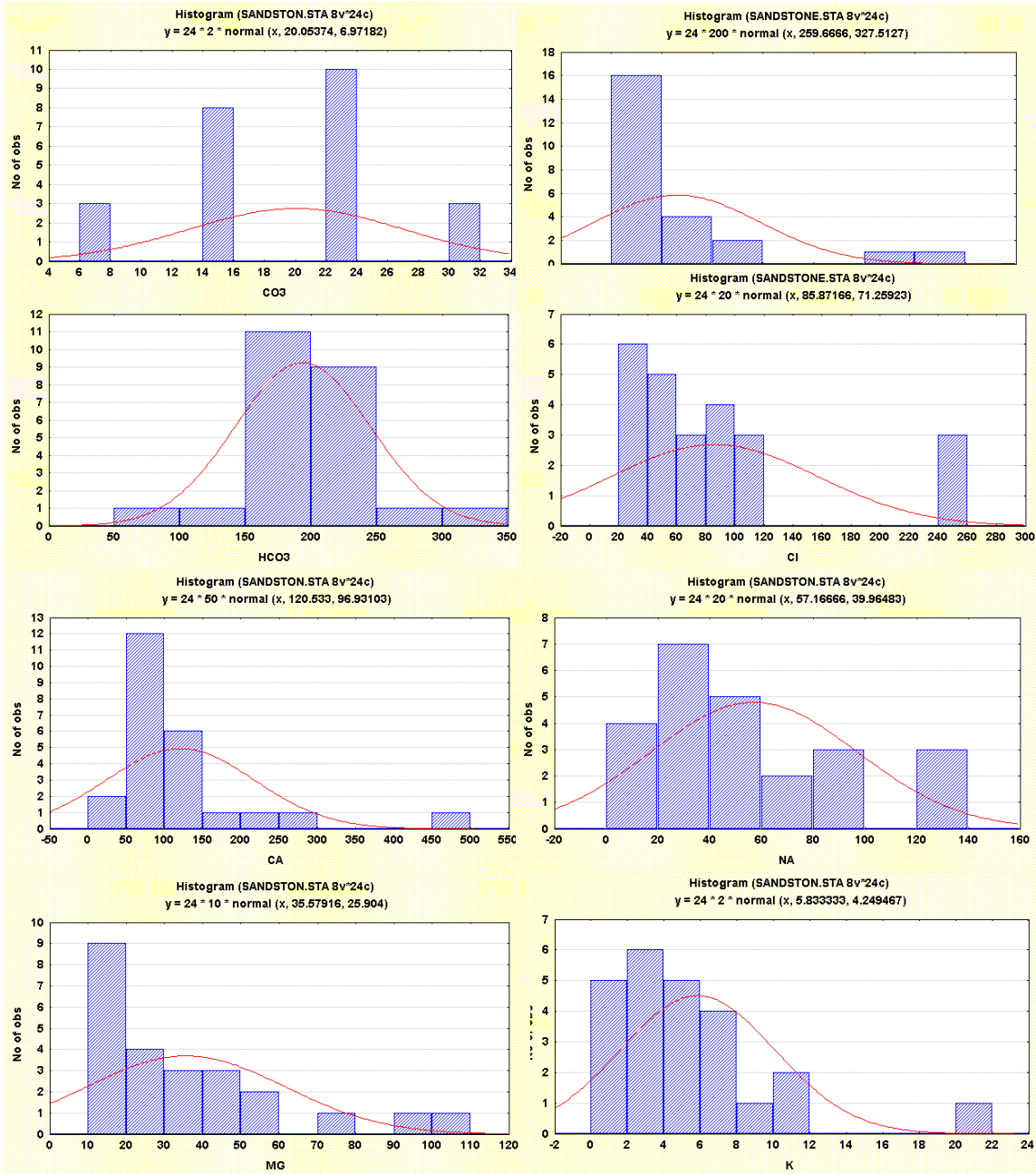


Figure 7-43 Graph showing normal distribution of groundwater ions of the Tawilah sandstone aquifer in Sana'a Basin

From the above discussion, it is clear that the main sources of ions in the fresh and brackish groundwater (shallow Tawilah sandstone zone) are local precipitation, surface and subsurface runoff waters interacting with aquifer materials and allowing the dissolution of evaporites or marine salts from the catchment area and terrestrial salts from the aquifer matrices. However, the main sources of ions in the fresh groundwater of the deep Tawilah sandstone zone is local precipitation in pluvial and post-pluvial times which have flushed the brackish groundwater in such aquifer. From the arithmetic mean values of different ions, one can predict the most effective ion to cause an increase of water salinity in the following orders:

- $\text{Na}^+ > \text{Mg}^{2+} > \text{Ca}^{2+}$ as cations
- $\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^-$ as anions

The more advanced stage $\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^-$ reflects the effect of leaching and dissolution of terrestrial and marine salts with some contribution of cation exchange. This is in complete agreement with normal distribution of all cations and anions (Figure 7-43).

7.4.4 Ion relationship and hydro-chemical coefficients

Five main groups are distinguished on the basis of ion relationships in groundwater of the sandstone aquifer at shallow and deep wells in Nihm and Gebel Zi Marmar, Bani Hushaish, El Gheras, Bani Matr and Hamadan areas.

A description of each of these groups is as follows:

- **Group 1:** $\text{Ca} > \text{Mg} > \text{Na}$ and $\text{SO}_4 > \text{HCO}_3 > \text{Cl}$ (21%), where $r\text{Na}/r\text{Cl}$ is less than unity for 40%. This is characteristic of groundwater samples no. HS 1, HS 2, HS 25, HS 27 and HS 126, which are fresh water type.
- **Group 2:** $\text{Ca} > \text{Mg} > \text{Na}$ and $\text{HCO}_3 > \text{SO}_4 > \text{Cl}$ (21%), where $r\text{Na}/r\text{Cl}$ is less than unity. This is characteristic of groundwater samples no. HS 105, HS 113, HS 124, HS 125 and HS 133, which are related to the fresh water type.
- **Group 3:** $\text{Ca} > \text{Mg} > \text{Na}$ and $\text{HCO}_3 > \text{Cl} > \text{SO}_4$ (13%), where $r\text{Na}/r\text{Cl}$ is less than unity. This is characteristic of groundwater samples no. HS 110, HS 146 and HS 21, which are related to the fresh water type. Two groundwater samples are related to this group, but with different anion relationships (SH 4 and SH 132).
- **Group 4:** having $\text{Ca} > \text{Na} > \text{Mg}$ and $\text{Cl} > \text{SO}_4 > \text{HCO}_3$ or $\text{HCO}_3 > \text{SO}_4 > \text{Cl}$ (17%), where $r\text{Na}/r\text{Cl}$ is less than unity. This is characteristic of groundwater samples no. HS 57, HS 141, HS 147 and HS 148, which are fresh water type.
- **Group 5:** having $\text{Na} > \text{Ca} > \text{Mg}$ and $\text{HCO}_3 > \text{SO}_4 > \text{Cl}$ or $\text{SO}_4 > \text{HCO}_3 > \text{Cl}$ (9%), where $r\text{Na}/r\text{Cl}$ is more than unity. This is characteristic of groundwater samples no. HS 28 and HS 85, which are fresh water type.

In brief, Groups 1-4 characterize most groundwater samples (72%), while Group 5 characterizes the other groundwater samples. Groups 1, 4 and 5 indicate the intermediate stage of hydro-chemical evolution in fresh groundwater types. Therefore, most groundwater samples (72%) exhibit a less advanced stage of mineralization where the metasomatic sequence are $\text{SO}_4 > \text{HCO}_3 > \text{Cl}$ and $\text{Cl} > \text{HCO}_3 > \text{SO}_4$. This is due to the effect of direct recharge by rainfall (500 mm/y) with some contribution of leaching, dissolution and cation exchange processes.

With respect to total salinity, it is found that the groundwater of this aquifer lies between fresh and brackish water types (TDS reaches 1,196 and 1,827 mg/l in wells HS 1 and HS 27 respectively). The hydro-chemical coefficients and assemblages of the hypothetical salts combinations of this groundwater indicate that the Tawilah sandstone aquifer is formed under continental conditions. The high concentration of HCO_3 indicates the effect of direct rainfall on this groundwater. The hydro-chemical coefficient ($r\text{Na}/r\text{Cl}$) is less than unity in most groundwater samples of this aquifer. This indicates that the groundwater is of meteoric origin and affected by leaching and dissolution of marine salts of the catchment area in the western boundaries of the Basin.

In conclusion, there is one main class of mineralization of groundwater in the shallow unconfined zone that acquires its quality either by leaching and dissolution of terrestrial salts from the aquifer matrix or by leaching and dissolution of marine salts from the catchment area (Gebel El Sama in the west). With regard to deep groundwater, it acquires its quality from leaching and dissolution of terrestrial salts from aquifer matrix, which is formed under continental conditions (El-Sayed et al 2001).

7.4.5 Distribution of total hardness

From data obtained (Table 7-17), it is clear that total hardness ranges from 93.71 and 1,119.5 **epm** with mean value of 373 **epm** in the fresh groundwater samples of the shallow unconfined zone, and from 230.5 and 857 **epm** in the fresh groundwater samples of the deep Tawilah sandstone aquifer. These data indicate an increase in total hardness with increasing water salinity (Figure 7-44). Also, the rate of increasing total hardness with water salinity is 1.8-fold, according to the change of water type from fresh to brackish water in the case of the shallow zone. This is mainly attributed to the effect of leaching and dissolution of terrestrial and marine salts leading to an increase of hardness, with particular importance given to the effect of NaCl concentration (effect of ionic strength) on increasing solubility of Ca^{2+} and Mg^{2+} in water (Freeze and Cherry, 1979 and Hem, 1989). This does not exclude the contribution of CO_2 , longer residence time, influence of salty water and cation exchange process.

With regard to total, permanent and temporary hardness relative to water salinity (TH/TDS, NCH/TDS and CH/TDS) % in the shallow Tawilah sandstone aquifer, the ratios obtained are 31%, 16% and 16% respectively in the fresh groundwater samples, and 68%, 5% and 28% respectively in the brackish samples of the deep Tawilah sandstone aquifer (Table 7-19). This means that the total, permanent and temporary hardness percentages of TDS changes according to the change of water type from fresh to brackish water due to the increase in soluble salts of brackish groundwater samples (10%) more than that of fresh groundwater samples (62%). This is confirmed by the rate of increase in total hardness, which is slightly less than that of water salinity. Consequently, the increase in groundwater salinity is due to the increase in soluble salts (NaCl and Na_2SO_4) more than that of hardness salts $\{\text{MgSO}_4, \text{CaSO}_4, \text{MgCl}_2, \text{CaCl}_2 \text{ and } \text{Ca}(\text{HCO}_3)_2\}$. Therefore, the increase in water salinity is due to increase of soluble salts (66% of TDS) more than that of permanent salts (17% of TDS) and temporary salts (17% of TDS), i.e. $(\text{NaCl} + \text{Na}_2\text{SO}_4, 66\%) > \{(\text{MgSO}_4 + \text{CaSO}_4 + \text{MgCl}_2 + \text{CaCl}_2, 17\%) = (\text{Ca}(\text{HCO}_3)_2, 17\%)\}$.

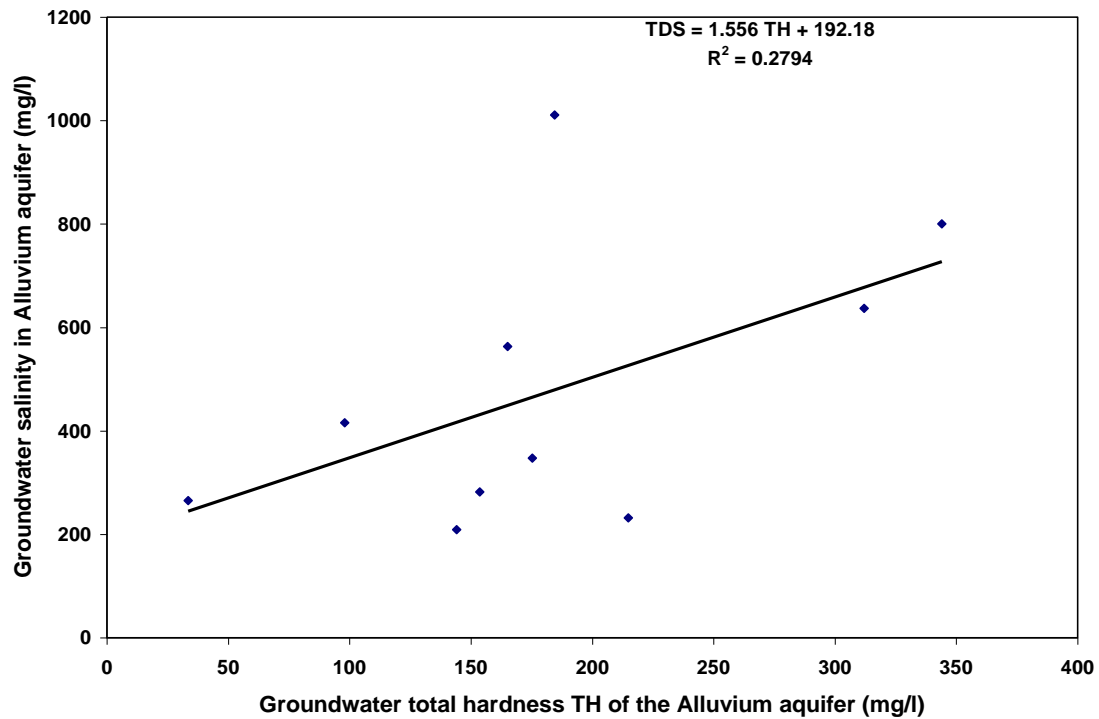
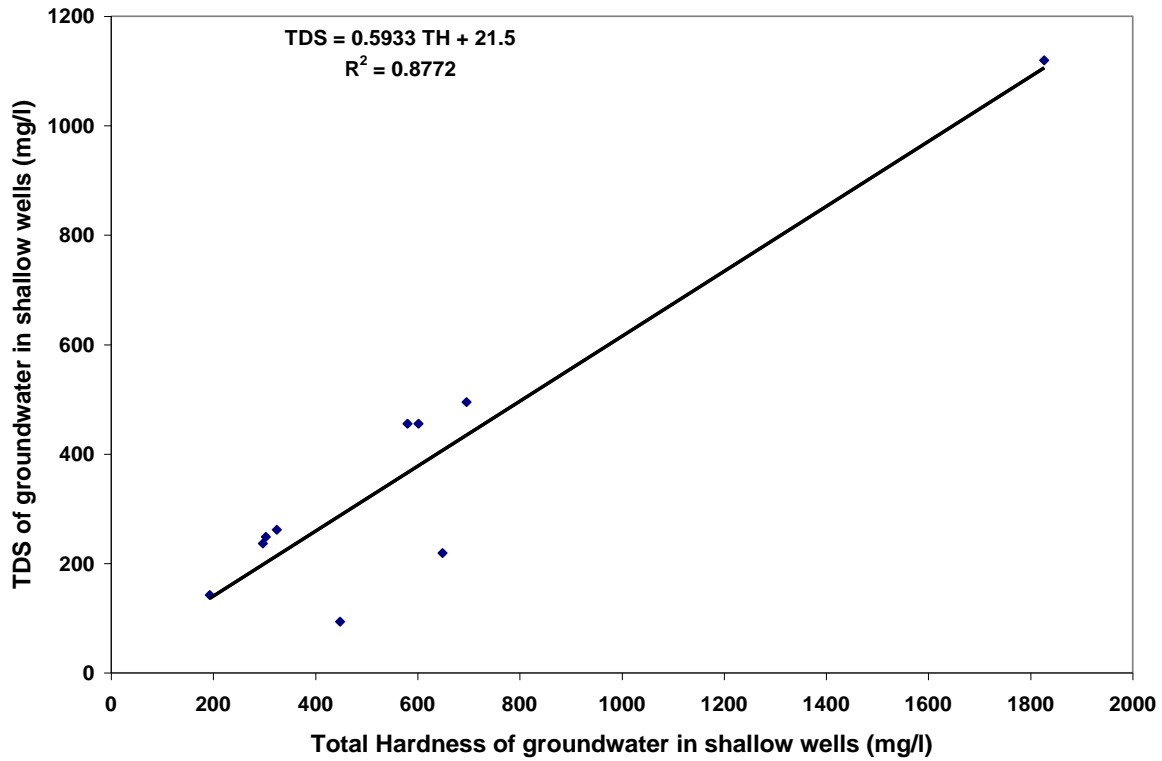


Figure 7-44 Graph showing relationship between TDS and total hardness in mg/l of groundwater of shallow (upper graph) and deep (lower graph) Tawilah sandstone zones in Sana'a Basin

For the deep Tawilah sandstone aquifer, the mean value of total, permanent and temporary hardness reached 419, 175 and 32 mg/l respectively in the fresh groundwater samples. The solution equilibrium reaction of Ca^{2+} and Mg^{2+} carbonates, which contributed to temporary hardness, is influenced by H_2CO_3 (CO_2 and H_2O) in percolating rainwater, Pco_2 , pH values and water temperature. This is generally reflected in temporary hardness in the shallow Tawilah sandstone aquifer, which contains (Ca + Mg) CO_3 materials in aquifer matrices. In other words, temporary hardness is significant in this aquifer. However, permanent hardness is enhanced by longer residence time and influences of salty water, sulfates and chlorides of calcium and magnesium increase in groundwater, i.e. permanent hardness (239 mg/l) is more than that of temporary hardness (195 mg/l) in all groundwater samples of the shallow Tawilah sandstone aquifer. With regard to groundwater samples of the deep Tawilah sandstone aquifer, the permanent hardness (175 mg/l) is far more than that of temporary hardness (32 mg/l).

In general, total and permanent hardness in deep groundwater samples are more than that of shallow groundwater samples, while temporary hardness in shallow groundwater samples is more than that of deep groundwater samples, reflecting the dilution effect of local rainfall and surface runoff water in the shallow Tawilah sandstone aquifer. In addition, the shallow Tawilah sandstone aquifer contains less carbonate materials than the deep Tawilah sandstone aquifer.

Table 7-19 Average and relative values of total, temporary and permanent hardness compared to water salinity of groundwater in the shallow and deep Tawilah sandstone zones

Water salinity classes								
Fresh water (TDS <1500 mg/l)								
TDS mg/l	TH mg/l	CH mg/l	NCH mg/l	(TH/TDS)%	(CH /TDS)%	(CH/TH)%	(NCH/TDS)%	(NCH./TH)%
1039	434	195	239	49	22	45	27	55
Brackish water (TDS =1500-5000 mg/l)								
TDS mg/l	TH mg/l	CH mg/l	NCH Mg/l	(TH/TDS)%	(CH/TDS)%	(CH/TH)%	(NCH/TDS)%	(NCH./TH)%
2414	690	299	391	33	16	43	17	57
Water salinity in the shallow Tawilah sandstone aquifer (TDS <1500 mg/l)								
TDS mg/l	TH mg/l	CH mg/l	NCH mg/l	(TH/TDS)%	(CH/TDS)%	(CH/TH)%	(NCH/TDS)%	(NCH./TH)%
1189	373	189	190	31	16	50	16	50
Water salinity in the deep Tawilah sandstone aquifer (TDS = 1500-5000 mg/l)								
TDS mg/l	TH mg/l	CH mg/l	NCH mg/l	(TH/TDS)%	(CH/TDS)%	(CH/TH)%	(NCH/TDS)%	(NCH./TH)%
616	419	175	32	68	28	42	5	77

- 1) Carbonate hardness or temporary hardness (CH% of TDS) = $[\text{Mg}(\text{HCO}_3)_2 + \text{Ca}(\text{HCO}_3)_2]$ salts as percent.
- 2) Non-carbonate hardness or permanent hardness (NCH% of TDS) = $[\text{MgSO}_4 + \text{CaSO}_4 + \text{MgCl}_2 + \text{CaCl}_2]$ salts as percent.

The wide variations of iron concentration from 0.002 mg/l to 0.32 mg/l with a mean value of 0.09 mg/l (SAWAS 1996) in the groundwater samples of the shallow Tawilah sandstone aquifer point to

considerable weathering process (Klitzsch 1978 and Klitzsch et al 1984). With regard to groundwater chemical equilibrium with non-carbonate minerals (iron minerals), all water samples of the shallow and deep Tawilah sandstone zones were supersaturated with respect to $\text{Fe}(\text{OH})_3$, goethite $[\text{Fe}_3\text{O}(\text{OH})\cdot\text{H}_2\text{O}]$, hematite (Fe_2O_3), maghemite (Fe_2O_3) and magnetite (Fe_3O_4). These minerals indicate that the aquifer is formed under continental conditions. Also, these minerals indicate that groundwater of the aquifer concerned was formed under oxidizing conditions, Hem (1989).

Most of the groundwater samples (92%) of shallow and deep Tawilah sandstone zones, have the assemblages of salt combinations (II and III) which reflect the effect of leaching and dissolution of terrestrial salts (continental facies groundwater) with some contribution of cation exchange processes, forming hypothetical salt combinations as follows:

- II-NaCl, Na_2SO_4 , MgSO_4 , $\text{Mg}(\text{HCO}_3)_2$, $\text{Ca}(\text{HCO}_3)_2$, where 51% of water samples of the shallow Tawilah sandstone aquifer have temporary hardness > permanent hardness $\{\text{Ca}(\text{HCO}_3)_2 > \text{CaMgSO}_4 \text{ salts}\}$ and 16% of water samples of the aquifer concerned have permanent hardness > temporary hardness $\{\text{CaMgSO}_4 > \text{Ca}(\text{HCO}_3)_2 \text{ salts}\}$.
- III-NaCl, Na_2SO_4 , MgSO_4 , CaSO_4 , $\text{Ca}(\text{HCO}_3)_2$, where 25% of water samples of the shallow Tawilah sandstone aquifer and all water samples of the deep Tawilah sandstone aquifer have permanent hardness > temporary hardness $\{\text{CaMgSO}_4 > \text{Ca}(\text{HCO}_3)_2 \text{ salts}\}$.

In this case, alkaline earths (Ca^{2+} and Mg^{2+}) in their sulfates and carbonates in solution replace alkalis on the surface of clay minerals in the aquifer matrix.

As a result of cation exchange processes, the increase of Na^+ concentration and decrease in Ca^{2+} and Mg^{2+} concentration in solution, lead to a considerable decrease in salts. This causes temporary and permanent hardness in the form of $\text{CaMg}(\text{HCO}_3)_2$ salts and CaMgSO_4 salts, respectively, while causing a considerable increase in water salinity but no change in pH and HCO_3^- content, because each mole of Ca^{2+} or Mg^{2+} adsorbed is replaced by 2 moles of Na^+ . The loss of Ca^{2+} and Mg^{2+} decreases the degree of water saturation of some groundwater samples with respect to both carbonate and gypsum minerals leading to ion activity products (IAP) of carbonate and gypsum minerals which became less than that of the solubility product constant (K_{sp}), Freeze and Cherry (1979).

For further elucidation of the data, the cation exchange index is employed where the cation exchange index is equal to $[\text{rCl}^- - \text{r}(\text{Na}^+ + \text{K}^+)] / \text{rCl}^-$.

This ratio has either negative or positive values. The negative value means that alkaline earths (Ca^{2+} and Mg^{2+}) in water replace alkalis ($\text{Na}^+ + \text{K}^+$) on the surface of clay minerals in the aquifer and vice versa in the case of a positive value.

From the computed values (Table 7-17), it is obvious that most of the groundwater samples (60%) of the shallow Tawilah sandstone zone and 31% of groundwater samples of the deep Tawilah sandstone zone have negative values of cation exchange index and vice versa in the rest of the groundwater samples of both shallow and deep Tawilah sandstone zones, which have positive values of cation exchange index, regardless of water salinity. In the former, alkaline earth (Ca^{2+} and Mg^{2+}) in water replace alkalis (Na^+ and K^+) on the surface of clay minerals in the aquifer matrices while, in the latter, alkalis (Na^+ and K^+) in water replace alkaline earth (Ca^{2+} and Mg^{2+}) on the surface of clay minerals in the aquifer matrices.

In conclusion, there is an increase in total, permanent and temporary hardness with increasing water salinity in groundwater samples of the shallow Tawilah sandstone zone. There is an increase in total and permanent hardness with increasing water salinity, and vice versa in the case of temporary hardness in groundwater samples of the deep Tawilah sandstone zone. About 51% of the analyzed groundwater samples of the shallow Tawilah sandstone zone show permanent hardness rather than temporary hardness, and vice versa in the case of the rest of the groundwater samples (49%) in the aquifer concerned. Notably, all groundwater samples of the deep Tawilah sandstone zone have permanent hardness rather than temporary hardness. This is mainly attributed to the effect of leaching

and dissolution of marine salts leading to an increase of hardness with particular importance given to the effect of NaCl concentration (effect of ionic strength) on increasing solubility of Ca^{2+} and Mg^{2+} in water (Freeze and Cherry, 1979 and Hem, 1989).

7.4.6 Sodium/chloride ratio ($r\text{Na}^+ / r\text{Cl}^-$)

The values of $r\text{Na}^+ / r\text{Cl}^-$ range from 0.8 to 1.59, with a mean value of 1.24, and from 1.1 to 1.14, with a mean value of 1.14 for groundwater samples of shallow and deep Tawilah sandstone zones in Sana'a Basin. The $r\text{Na}^+ / r\text{Cl}^-$ ratio of the majority of groundwater samples of the shallow unconfined zone (92%) and all groundwater samples of the shallow confined zone are more than unity. The increase in the concentration of Na^+ in these water samples reflects meteoric and deep meteoric water recharges where Starinsky et al. (1983) concluded that increasing Na^+ might have theoretically originated by dissolution of sodium-bearing silicates from the country rocks. The increase in Na^+ indicates the leaching and dissolution of terrestrial salts from the aquifer matrices. However, few groundwater samples from the shallow Tawilah sandstone aquifer (8%) have values of $r\text{Na}^+ / r\text{Cl}^-$ less than unity. The decrease in concentration of Na^+ may be attributed to the adsorption of sodium ions on the fine argillaceous sediments (Starinsky, 1983), in addition to the leaching and dissolution of marine salts from the catchment area.

In general, the mean values of $r\text{Na}^+ / r\text{Cl}^-$ decrease with total salinity increase (mean values for fresh and brackish waters are 1.4 and 1.22 respectively).

7.4.7 Groundwater classification

Results of the water quality analyses of the samples of the Tawilah sandstone aquifer were used as input data for the determination of groundwater types by using AQUACHEM Software. The output of the Piper diagram applying this program is given in Figure 7-45 and the water type is tabulated in Table 7-20.

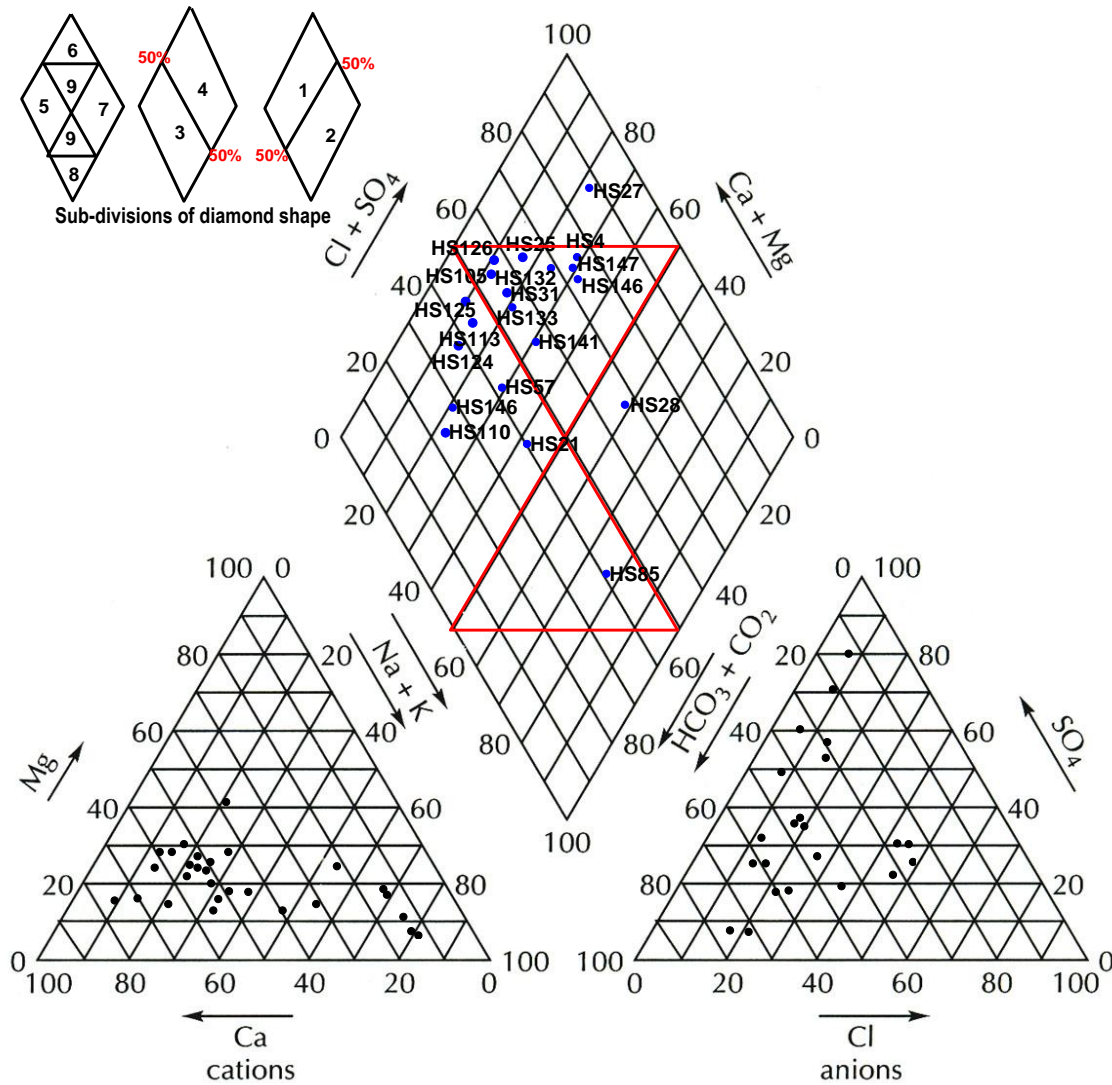


Figure 7-45 Classification of groundwater of the Tawilah sandstone aquifer according to Piper 1953

Figure 7-45 shows that 40% of the groundwater samples from the shallow Tawilah sandstone zone are located in sub-area 9 (Wells no. HS 25, HS 31, HS 85 and HS 126), where no one cation-anion pair exceeds 50 percent. However, 50% of the groundwater samples from this zone lie in sub-area 5 (wells no. HSc, HS 110, HS 124, HS 125 and HS 148), which is dominated by alkaline earths and weak acids (carbonate hardness and secondary alkalinity). The rest of the groundwater samples lie in sub-area 6 (wells no. HSAs, HAS' and HS 27).

Regarding groundwater samples from the deep Tawilah sandstone zone, the majority of the groundwater samples (54%) are located in sub-area 9 (wells no. HS 4, HS 105, HS 132, HS 133, HS 141, HS 146 and HS 147) while 23% of the groundwater samples lie in the sub-area 5 (wells nos. HSc, HS 110, HS 124, HS 125 and HS 148). The rest of the groundwater samples lie in sub-area 6. This means that few of the groundwater samples are influenced by direct rainwater recharge (shallow zone) and 20% are affected by continental conditions. The majority of groundwater samples (60%) located in sub-areas 7 and 9 have marine facies type.

In conclusion, Piper's trilinear diagram suggests that the groundwater of both the shallow and deep Tawilah sandstone zones in Sana'a Basin are of mixed origins of mineralization, where rainwater and salt water are the main sources of salt contribution. The feeding recharge sources are rainwater for the shallow zone and during pluvial times for the deep one, and subsurface flow, which dissolves the marine salts of the aquifer matrix and catchment area as well as a possible local contamination from adjacent marine salts. This stands in agreement with the hydro-chemical coefficients and hypothetical salts combinations (Table 7-17).

Table 7-20 Water type for the Tawilah sandstone aquifer water samples

Well ID	Water type	Water Type
HS25	Ca-HCO ₃ -SO ₄	1
HS110	Ca-Mg-HCO ₃ -Cl	1
HS113	Ca-Mg-HCO ₃ -Cl	1
HS120	Ca-Mg-HCO ₃ -Cl	1
HS102	Ca-Mg-HCO ₃ -SO ₄	1
HS104	Ca-Mg-HCO ₃ -SO ₄	1
HS34	Ca-Mg-HCO ₃ -SO ₄	1
HS106	Ca-Mg-Na-Cl-HCO ₃ -SO ₄	2
HS95	Ca-Mg-Na-Cl-SO ₄	2
HS100	Ca-Mg-Na-HCO ₃	1
HS107	Ca-Mg-Na-HCO ₃ -SO ₄ -Cl	1
HS121	Ca-Mg-SO ₄	2
HS90	Ca-Mg-SO ₄	1
HS91	Ca-Mg-SO ₄ -HCO ₃	1
HS99	Ca-Mg-SO ₄ -HCO ₃	1
HS108	Ca-Na-Cl-HCO ₃ -SO ₄	1
HS112	Ca-Na-Cl-SO ₄ -HCO ₃	2
HS24	Ca-Na-HCO ₃ -Cl	1

Well ID	Water type	Water Type
HS31	Ca-Na-Mg-Cl-SO ₄	2
HS96	Ca-Na-Mg-HCO ₃ -SO ₄ -Cl	1
HS115	Ca-Na-SO ₄	2
HS105	Ca-SO ₄ -HCO ₃	1
HS119	Mg-Ca-HCO ₃ -Cl	1
HS101	Mg-Ca-HCO ₃ -SO ₄	1
HS18	Na-Ca-SO ₄ -HCO ₃ -Cl	2

7.4.8 Cluster analysis of the Tawilah sandstone aquifer groundwater

Statistical analysis was carried out for the 23 available groundwater samples related to the Tawilah sandstone aquifer. Although the groundwater resource in this aquifer is the unique source for drinking, available data is minimal and cover only the northern sector of the aquifer. The southern part (almost half the area of the aquifer) has no data as the volcanic cover is very large and there are no wells which penetrate the Tawilah sandstone aquifer in this location.

7.4.8.1 Descriptive statistical analysis

Statistical analysis of data sets shows that linear regressions between variables are significant since the critical value of F, with 95% confidence level and 9 degrees of freedom is less than the estimated value. Table 7-21 shows the data of the descriptive analyses. The most striking results are the maximum of TDS, Ca⁺⁺, Mg⁺⁺, SO₄⁻ and Cl⁻ where they exceed the WHO standard (World Health Organization 1984) for most domestic use.

Table 7-21 Descriptive statistics of the groundwater chemical components analyzed for the Tawilah sandstone aquifer

	Total number	Minimum	Maximum	Mean	Standard Deviation	WHO Standard (1984) (Acceptable)
pH						
EC						
TDS	23	193	1,827	606.86957	370.60752	500
Ca	23	20.01	297.6	105.38435	64.140136	75
Mg	23	10.35	91.47	32.960435	21.841093	50

	Total number	Minimum	Maximum	Mean	Standard Deviation	WHO Standard (1984) (Acceptable)
Na	23	12	140	54.391304	40.965328	200
K	23	1	21	5.6521739	4.4375331	-
CO ₃	23	7.89	31.56	20.469565	6.7251019	-
HCO ₃	23	56.15	320.86	191.83522	52.431869	-
SO ₄	23	14	1,100	208.95652	240.34662	200
Cl	23	21.54	258.51	83.167826	73.187715	200

The correlation analysis between the different hydrogeochemical parameters shows that TDS is highly positively correlated with Ca, Mg, Na and SO₄ (0.81, 0.77, 0.73 and 0.91 respectively) and moderately positively correlated with Cl (0.6) and weakly correlated with CO₃ (0.29), indicating that the recharge to the Tawilah sandstone aquifer from rainfall is unlikely (Table and Figure). On the other hand, the inverse correlation between Ca, Mg, and Cl and pH (-0.24, -0.17 and -0.24 respectively) reflects the mixing process between two different groundwater sources.

Table 7-22 Correlation coefficient matrix between different ions concentrations in the Tawilah sandstone aquifer groundwater

		Well no.	PH	EC	TDS	Ca ⁺²	Mg ⁺²	Na ⁺¹	K ⁺¹	CO3 ⁻²	HCO3 ⁻¹	SO4 ⁻²	Cl ⁻¹
Well no.	Correlation Coefficient	1	0.025704	-0.0613	-0.07116	-0.27273	-0.24407	0.371231	-0.10882	0.363797	-0.21184	-0.15415	-0.00989
	Sig. (2-tailed)		0.907321	0.781144	0.746948	0.208013	0.261724	0.081156	0.621124	0.087924	0.331866	0.482513	0.964282
	N	23	23	23	23	23	23	23	23	23	23	23	23
PH	Correlation Coefficient	0.025704	1	-0.182	-0.21557	-0.2437	-0.1735	-0.17977	-0.24261	-0.17412	-0.19354	-0.1389	-0.24784
	Sig. (2-tailed)	0.907321		0.405899	0.323209	0.262478	0.428519	0.411761	0.264683	0.426853	0.376258	0.527334	0.254205
	N	23	23	23	23	23	23	23	23	23	23	23	23
EC	Correlation Coefficient	-0.0613	-0.182	1	0.984178	0.815126	0.809194	0.733927	0.736028	0.270885	0.243785	0.887791	0.719021
	Sig. (2-tailed)	0.781144	0.405899		1E-06	2.17E-06	2.94E-06	6.72E-05	6.25E-05	0.211224	0.2623	1E-06	0.000111
	N	23	23	23	23	23	23	23	23	23	23	23	23
TDS	Correlation Coefficient	-0.07116	-0.21557	0.984178	1	0.815419	0.778354	0.738195	0.7853	0.299132	0.18354	0.914752	0.666667
	Sig. (2-tailed)	0.746948	0.323209	1E-06		2.14E-06	1.22E-05	5.79E-05	9.05E-06	0.165571	0.401865	1E-06	0.000513
	N	23	23	23	23	23	23	23	23	23	23	23	23
Ca ⁺²	Correlation Coefficient	-0.27273	-0.2437	0.815126	0.815419	1	0.779644	0.312902	0.600755	0.104316	0.19891	0.743083	0.603708
	Sig. (2-tailed)	0.208013	0.262478	2.17E-06	2.14E-06		1.16E-05	0.146019	0.002435	0.635727	0.362885	4.86E-05	0.002287
	N	23	23	23	23	23	23	23	23	23	23	23	23
Mg ⁺²	Correlation Coefficient	-0.24407	-0.1735	0.809194	0.778354	0.779644	1	0.367276	0.66088	0.004194	0.349585	0.741107	0.564153
	Sig. (2-tailed)	0.261724	0.428519	2.94E-06	1.22E-05	1.16E-05		0.084705	0.000597	0.984849	0.102024	5.22E-05	0.005047
	N	23	23	23	23	23	23	23	23	23	23	23	23
Na ⁺¹	Correlation Coefficient	0.371231	-0.17977	0.733927	0.738195	0.312902	0.367276	1	0.550094	0.556717	0.089056	0.589224	0.640119
	Sig. (2-tailed)	0.081156	0.411761	6.72E-05	5.79E-05	0.146019	0.084705		0.006538	0.005795	0.68615	0.003092	0.001003
	N	23	23	23	23	23	23	23	23	23	23	23	23
K ⁺¹	Correlation Coefficient	-0.10882	-0.24261	0.736028	0.7853	0.600755	0.66088	0.550094	1	0.40595	0.003001	0.73641	0.466689
	Sig. (2-tailed)	0.621124	0.264683	6.25E-05	9.05E-06	0.002435	0.000597	0.006538		0.054607	0.989158	6.16E-05	0.024773
	N	23	23	23	23	23	23	23	23	23	23	23	23
CO3 ⁻²	Correlation Coefficient	0.363797	-0.17412	0.270885	0.299132	0.104316	0.004194	0.556717	0.40595	1	-0.12926	0.040888	0.471084
	Sig. (2-tailed)	0.087924	0.426853	0.211224	0.165571	0.635727	0.984849	0.005795	0.054607		0.556649	0.853046	0.023271
	N	23	23	23	23	23	23	23	23	23	23	23	23
HCO3 ⁻¹	Correlation Coefficient	-0.21184	-0.19354	0.243785	0.18354	0.19891	0.349585	0.089056	0.003001	-0.12926	1	0.13327	0.276193
	Sig. (2-tailed)	0.331866	0.376258	0.2623	0.401865	0.362885	0.102024	0.68615	0.989158	0.556649		0.544375	0.202064
	N	23	23	23	23	23	23	23	23	23	23	23	23
SO4 ⁻²	Correlation Coefficient	-0.15415	-0.1389	0.887791	0.914752	0.743083	0.741107	0.589224	0.73641	0.040888	0.13327	1	0.409889
	Sig. (2-tailed)	0.482513	0.527334	1E-06	1E-06	4.86E-05	5.22E-05	0.003092	6.16E-05	0.853046	0.544375		0.052081
	N	23	23	23	23	23	23	23	23	23	23	23	23
Cl ⁻¹	Correlation Coefficient	-0.00989	-0.24784	0.719021	0.666667	0.603708	0.564153	0.640119	0.466689	0.471084	0.276193	0.409889	1
	Sig. (2-tailed)	0.964282	0.254205	0.000111	0.000513	0.002287	0.005047	0.001003	0.024773	0.023271	0.202064	0.052081	
	N	23	23	23	23	23	23	23	23	23	23	23	23
Correlation is significant at the .01 level (2-tailed).													
Correlation is significant at the .05 level (2-tailed).													

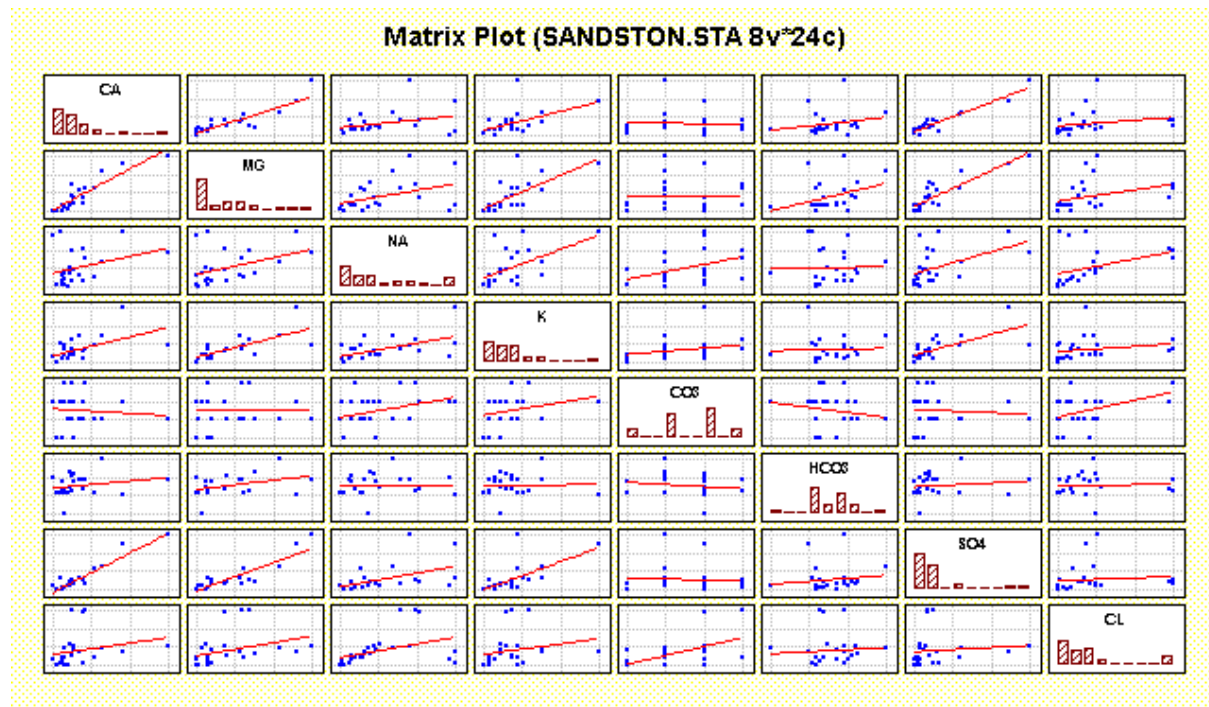


Figure 7-46 Linear regression between different ions in groundwater of the alluvium aquifer

7.4.8.2 Cluster analysis (Q- mode dendrogram)

The non-transformed data input analysis (Figures 7-47 and 7-48) and the transformed data (Figure 7-49) of hydrogeochemical analysis of the Tawilah sandstone aquifer are used in constructing the tree diagrams (Figures 7-47 to 7-49), which are classified into three clusters and four independent samples as follows:

Cluster A: includes 11 samples located in the eastern and western outcrops of the studied aquifer. This cluster is characterized by lower salinity (193-475 mg/l), lower calcium, magnesium, carbonate and bicarbonate content. The salinity may be attributed to evaporation and agricultural activity.

Cluster B: includes two samples (13 & 46) which are characterized by a higher salinity range than Cluster A (1,428-4,209 mg/l). The increase in salinity is due to high evaporation with precipitation.

Cluster C: represents the main cluster and includes 17 samples located in the southern and middle parts of the study aquifer, except sample no. 59, which is located in the northern part. This cluster is characterized by a higher salinity range than Clusters A & B (1,933-7,259 mg/l) and a higher SO_4^{--} content. Sample no. 12 (in the southern part) has the highest TDS, Ca^{++} , Mg^{++} , Na^+ , and Cl^- , which exceed the WHO & EHCW standards due to contribution of saline water flowing laterally from the adjacent aquifers as a result of high extraction rates and anthropogenic sources. Sample no. 13 (also in the southern part) has the highest value of SO_4^{--} , while sample no. 56 (in the middle part) has the highest value of F (SAWAS 1995), which exceeds WHO and EHCW standards due to agricultural activity and municipal wastes.

Sample no. 28 is an independent sample, which is characterized by very low salinity (199.9 mg/l). It is located in the northern part of the study area.

Sample no. 21 is an independent sample, also characterized by very low salinity (269.7 mg/l). This result is due to the presence of fresh water reservoirs in this location and high agricultural activity. It is also located in the northern part of the study aquifer.

Sample no. 19 is an independent sample, also characterized by very low salinity (271.4 mg/l).

Finally, **sample no. 17** is an independent sample, also characterized by very low salinity (313.4 mg/l) and very low nitrate content. It is also located in the northern part of the study area.

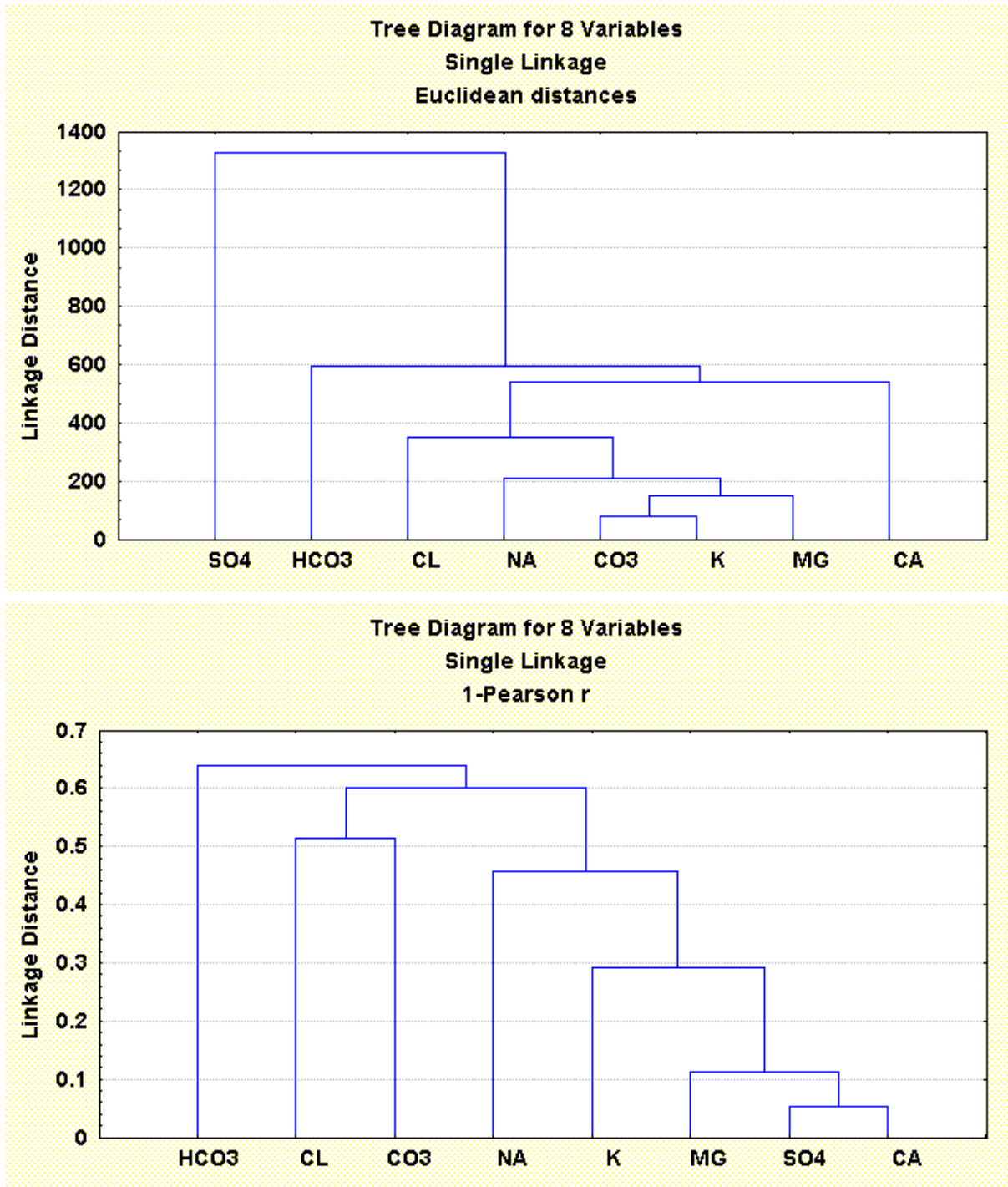


Figure 7-47 Horizontal icicle plot of the 8 non-transformed hydrogeochemical variables studied (R-mode) applying Euclidean distance method (upper figure) and 1-Pearson method (lower figure)

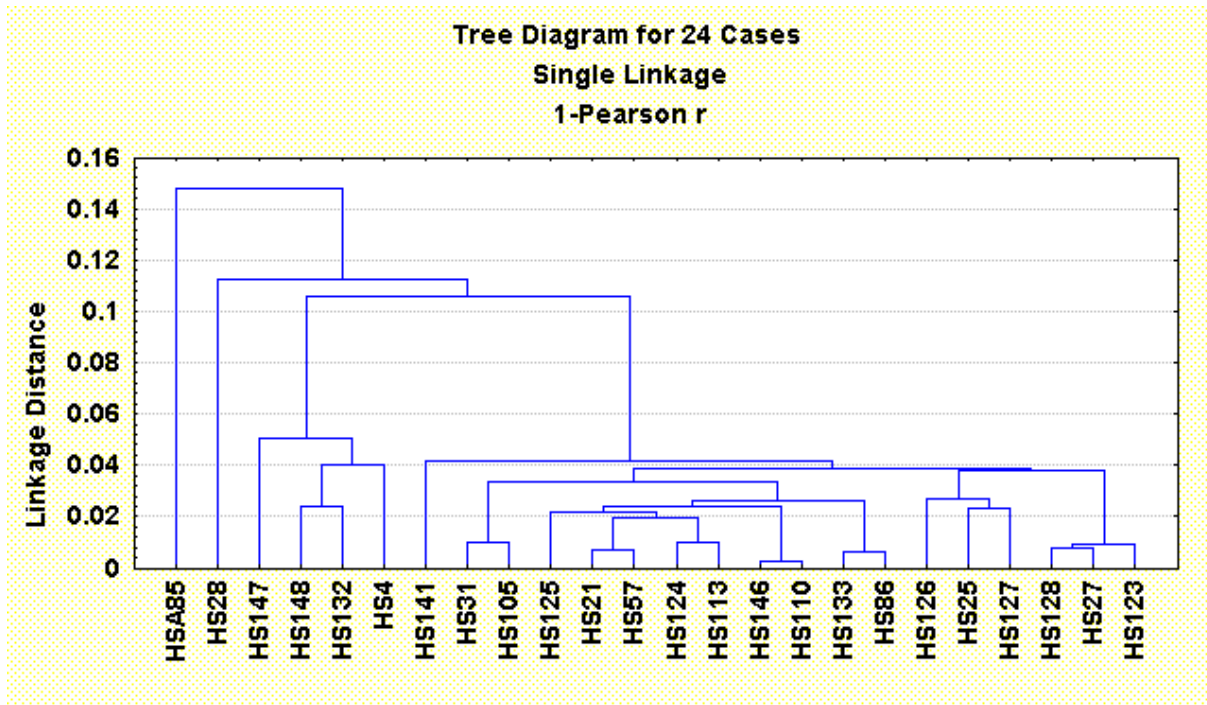


Figure 7-48 Vertical icicle plot of the 8 non-transformed hydrogeochemical variables studied and of 23 wells (Q-mode) applying 1-Pearson r method

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* * * * * H I E R A R C H I C A L C L U S T E R   A N A L Y S I S *
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Dendrogram using Average Linkage (Between Groups)

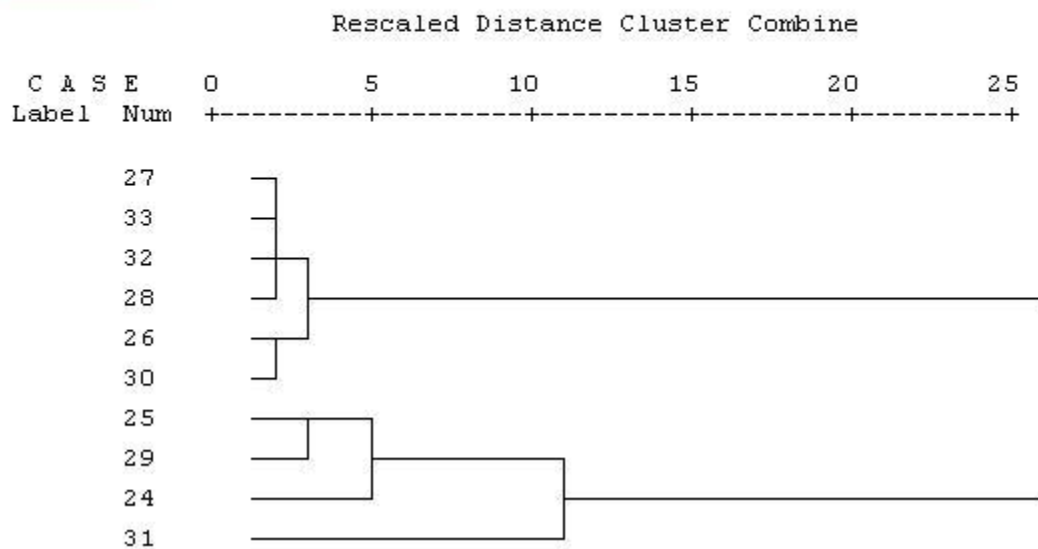


Figure 7-49 Dendrogram of the selected transformed groundwater data of the alluvium aquifer using average linkage

Table 7-23 List of wells sampled for water quality and their locations in the Amran aquifer

S.N	Well ID	Location	Sample_Date	UTM E (m)	UTM N (m)	Rim Elv (m)
1	HSA63	Al-Hyfa / ARHAB	3/1/2007	418913	1739978	2407
2	HSA65	Kulak / ARHAB	3/1/2007	421656	1740289	2379
3	HSA66	Aigaz / ARHAB	3/1/2007	424439	1738751	2375
4	HSA67	Bani Al-Hakam / ARHAB	3/1/2007	427306	1737420	2290
5	HSA68	Bani Sabare / ARHAB	3/1/2007	428859	1737137	2281
6	HSA69	AL-Mrahyb / ARHAB	3/1/2007	425724	1731589	2073
7	HSA70	Darb Oubaid / ARHAB	3/6/2007	419702	1731375	2160
8	HSA71	Al ganadiba / ARHAB	3/6/2007	418317	1731495	2186
9	HSA72	Bousaan / ARHAB	3/6/2007	421515	1730889	2124
10	HSA73	gahfal / ARHAB	3/6/2007	423760	1731279	2094
11	HSA74	Simnah / ARHAB	3/6/2007	426751	1729981	2031
12	HSA75	Al safiah / ARHAB	3/6/2007	427928	1730022	2028
13	HSA76	Al abwa'a / Al Swllban / ARHAB	3/6/2007	425304	1728396	2089
14	HS77	Al hayeathim /Nihm	3/7/2007	437787	1732133	1991
15	HS78	Al hayeathim /Nihm	3/7/2007	437008	1732149	2009
16	HS79	Al hayeathim /Nihm	3/7/2007	437909	1732005	1994
17	HS80	Al hayeathim /Nihm	3/7/2007	438198	1730745	2009
18	HS81	Al ghyll/Al hayeathim /Nihm	3/7/2007	437733	1730792	2010
19	HS82	Al raghwa/Al hayeathim /Nihm	3/7/2007	437433	1730165	2014
20	HSA77	Al kibsha'a / bani Al harith	3/7/2007	428717	1722095	2156
21	HSA80	El-zylah / ARHAB	3/10/2007	413979	1749744	2606
22	HSA83	Al-Hyfa / ARHAB	3/10/2007	417850	1740194	2423
23	HS83	Maswarah /Nihm	3/11/2007	446815	1740388	2139
24	HS84	Maswarah /Nihm	3/11/2007	450100	1740787	2173
25	HS85	Maswarah /Nihm	3/11/2007	449783	1741843	2171
26	HS88	Al -Kutby /Nihm	3/11/2007	448408	1744413	2198
27	HS89	Al -Kutby /Nihm	3/11/2007	447482	1744952	2195
28	HS90	Al -Kutby /Nihm	3/11/2007	446983	1744691	2201
29	HS91	Eyal Housin /Nihm	3/11/2007	448148	1740768	2116
30	HS93	Bani ghalib /Nihm	3/11/2007	445988	1742985	2215

Sample	Well ID	Location	Sample Date	UTM E (m)	UTM N (m)	Rim Elv (m)
31	HS95	Al -qadr /Nihm	3/11/2007	444245	1742667	2188
32	HS96	Wadi Mahaly /Nihm	3/12/2007	446690	1735446	2170
33	HS99	Al razoah /Nihm	3/12/2007	447790	1735787	2153

Sample	Well ID	Location	Sample Date	UTM E (m)	UTM N (m)	Rim Elv (m)
34	HS34	sanany /Nihm	3/12/2007	448854	1736073	2156
35	HS100	Ghaylamah /Nihm	3/12/2007	447830	1737774	2136
36	HS101	Al Ghaydah/Nihm	3/12/2007	444166	1739703	2094
37	HS102	Wadi Al- ma'ady /Nihm	3/12/2007	442135	1737739	2022
38	HS104	Wadi Al- ma'ady /Nihm	3/12/2007	441635	1737691	2019
39	HS106	Wadi Thajer /NIHM	3/13/2007	443383	1730190	2083
40	HS107	Wadi Thajer/Bani Asaem /NIHM	3/13/2007	444468	1729011	2089
41	HS108	Wadi Thajer /NIHM	3/13/2007	445208	1727894	2107
42	HS24	Al mahajer /NIHM	3/14/2007	433352	1724317	2127
43	HS112	KOULAQAH /NIHM	3/14/2007	438002	1727781	2054
44	HS115	Bani Qtra'an /Nihm	3/14/2007	434859	1731484	2093
45	HS117	Ghoubarah/Nihm	3/14/2007	440254	1735268	2012
46	HS119	Bani Zater/Nihm	3/14/2007	440747	1731266	2060
47	HS120	Bait Houmran/Nihm	3/14/2007	442159	1727703	2100
48	HS121	Qourymah/Nihm	3/14/2007	442170	1726064	2128
49	HS122	Qariah Aljarf /Nihm	3/15/2007	441564	1724984	2151
50	HS27	Bit Al anz /NIHM	4/10/2007	432478	1724413	2127
51	HS28	Bit Al anz /NIHM	4/10/2007	430758	1724836	2127
52	HSA 91	Shira'a /ARHAB	4/10/2007	429370	1725365	2066
53	HSA 92	Bani Jarmoz /ARHAB	4/10/2007	426167	1726223	2086
54	HSA 97	Aomarah /ARHAB	4/11/2007	417010	1726772	2207
55	HSA 102	Bit Al Euthari /Bani Al Harith	4/12/2007	419534	1723364	2167
56	HSA 103	Bit Duqaish /Bani Al Harith	4/12/2007	419477	1720943	2166

Sample	Well ID	Location	Sample Date	UTM E (m)	UTM N (m)	Rim Elv (m)
57	HSA 105	Bab Al Rawdah /ARHAB	4/14/2007	419380	1725310	2156
58	HSA 106	Al baglan /ARHAB	4/14/2007	419567	1730016	2156
59	HSA 107	Bit Swdi /ARHAB	4/14/2007	430467	1729702	2074
60	HSA 108	Markan /ARHAB	4/14/2007	430695	1730438	2105
61	HSA 109	Bani Al Hakam /ARHAB	4/14/2007	430402	1732830	2001

Table 7-24 Results of chemical analyses of groundwater samples from the Amran aquifer (March 2007)

Well ID	alt. (m)	depth (m)	flow (m³/day)	Temp	Ca²⁺	Mg²⁺	Na⁺	K⁺	Sum Cat.	COF	HCO3	SO4	Cl	Sum An.	Hydrochemical coefficients			DAR (eq/L)	Na/Ca (mg/L)	Hardness (L)
															Ca/Mg	Ca/Mg+K	Ca/Mg+K+Na			
HS463	X	257	287	meq/L	28.9	23.6	18	3	59.8	23.6	23.6	29	26.33	137	0.57	1.01	0.01	0.50	1437	149.10
				mg/L	1140	976	720	120	2956	23.6	23.6	29	26.33	137	0.57	1.01	0.01	0.50	1437	149.10
				%	62.1	22.44	18	3	23.67	23.67	23.67	30	28.72	137	0.57	1.01	0.01	0.50	1437	149.10
HS465	X	558	780	meq/L	13.9	14.9	13.9	1.2	43.9	14.9	14.9	14.9	14.9	5.57	0.97	1.68	0.01	0.50	1437	149.10
				mg/L	62.85	62.72	62	5.1	157.26	14.9	14.9	14.9	14.9	5.57	0.97	1.68	0.01	0.50	1437	149.10
				%	19.26	19.26	19.26	1.2	23.67	23.67	23.67	30	28.72	137	0.57	1.01	0.01	0.50	1437	149.10
HS466	X	612	340	meq/L	1.36	1.40	1.36	0.12	4.24	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				mg/L	5.56	5.60	5.56	0.48	17.36	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				%	19.26	19.26	19.26	1.2	23.67	23.67	23.67	30	28.72	137	0.57	1.01	0.01	0.50	1437	149.10
HS467	X	950	563	meq/L	1.36	1.40	1.36	0.12	4.24	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				mg/L	5.56	5.60	5.56	0.48	17.36	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				%	19.26	19.26	19.26	1.2	23.67	23.67	23.67	30	28.72	137	0.57	1.01	0.01	0.50	1437	149.10
HS468	X	701	419	meq/L	1.36	1.40	1.36	0.12	4.24	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				mg/L	5.56	5.60	5.56	0.48	17.36	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				%	19.26	19.26	19.26	1.2	23.67	23.67	23.67	30	28.72	137	0.57	1.01	0.01	0.50	1437	149.10
HS469	X	346	333	meq/L	1.36	1.40	1.36	0.12	4.24	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				mg/L	5.56	5.60	5.56	0.48	17.36	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				%	19.26	19.26	19.26	1.2	23.67	23.67	23.67	30	28.72	137	0.57	1.01	0.01	0.50	1437	149.10
HS470	X	712	413	meq/L	1.36	1.40	1.36	0.12	4.24	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				mg/L	5.56	5.60	5.56	0.48	17.36	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				%	19.26	19.26	19.26	1.2	23.67	23.67	23.67	30	28.72	137	0.57	1.01	0.01	0.50	1437	149.10
HS471	X	694	383	meq/L	1.36	1.40	1.36	0.12	4.24	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				mg/L	5.56	5.60	5.56	0.48	17.36	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				%	19.26	19.26	19.26	1.2	23.67	23.67	23.67	30	28.72	137	0.57	1.01	0.01	0.50	1437	149.10
HS472	X	1097	598	meq/L	1.36	1.40	1.36	0.12	4.24	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				mg/L	5.56	5.60	5.56	0.48	17.36	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				%	19.26	19.26	19.26	1.2	23.67	23.67	23.67	30	28.72	137	0.57	1.01	0.01	0.50	1437	149.10
HS473	X	832	520	meq/L	1.36	1.40	1.36	0.12	4.24	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				mg/L	5.56	5.60	5.56	0.48	17.36	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				%	19.26	19.26	19.26	1.2	23.67	23.67	23.67	30	28.72	137	0.57	1.01	0.01	0.50	1437	149.10
HS474	X	1840	1009	meq/L	1.36	1.40	1.36	0.12	4.24	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				mg/L	5.56	5.60	5.56	0.48	17.36	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				%	19.26	19.26	19.26	1.2	23.67	23.67	23.67	30	28.72	137	0.57	1.01	0.01	0.50	1437	149.10
HS475	X	2090	1440	meq/L	1.36	1.40	1.36	0.12	4.24	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				mg/L	5.56	5.60	5.56	0.48	17.36	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				%	19.26	19.26	19.26	1.2	23.67	23.67	23.67	30	28.72	137	0.57	1.01	0.01	0.50	1437	149.10
HS476	X	1304	761	meq/L	1.36	1.40	1.36	0.12	4.24	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				mg/L	5.56	5.60	5.56	0.48	17.36	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				%	19.26	19.26	19.26	1.2	23.67	23.67	23.67	30	28.72	137	0.57	1.01	0.01	0.50	1437	149.10
HS77	X	1014	572	meq/L	1.36	1.40	1.36	0.12	4.24	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				mg/L	5.56	5.60	5.56	0.48	17.36	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				%	19.26	19.26	19.26	1.2	23.67	23.67	23.67	30	28.72	137	0.57	1.01	0.01	0.50	1437	149.10
HS78	X	2330	1329	meq/L	1.36	1.40	1.36	0.12	4.24	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				mg/L	5.56	5.60	5.56	0.48	17.36	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				%	19.26	19.26	19.26	1.2	23.67	23.67	23.67	30	28.72	137	0.57	1.01	0.01	0.50	1437	149.10
HS79	X	1605	950	meq/L	1.36	1.40	1.36	0.12	4.24	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				mg/L	5.56	5.60	5.56	0.48	17.36	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				%	19.26	19.26	19.26	1.2	23.67	23.67	23.67	30	28.72	137	0.57	1.01	0.01	0.50	1437	149.10
HS88	X	782	429	meq/L	1.36	1.40	1.36	0.12	4.24	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				mg/L	5.56	5.60	5.56	0.48	17.36	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				%	19.26	19.26	19.26	1.2	23.67	23.67	23.67	30	28.72	137	0.57	1.01	0.01	0.50	1437	149.10
HS89	X	1327	752	meq/L	1.36	1.40	1.36	0.12	4.24	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				mg/L	5.56	5.60	5.56	0.48	17.36	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				%	19.26	19.26	19.26	1.2	23.67	23.67	23.67	30	28.72	137	0.57	1.01	0.01	0.50	1437	149.10
HS90	X	1163	634	meq/L	1.36	1.40	1.36	0.12	4.24	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				mg/L	5.56	5.60	5.56	0.48	17.36	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				%	19.26	19.26	19.26	1.2	23.67	23.67	23.67	30	28.72	137	0.57	1.01	0.01	0.50	1437	149.10
HS91	X	1363	733	meq/L	1.36	1.40	1.36	0.12	4.24	1.40	1.40	1.40	1.40	0.20	0.30	0.30	0.01	0.50	1437	149.10
				mg/L	5.56	5.60	5.56	0.48	17.36	1.40	1.40	1.40	1.40	0.20	0.30	0.30</				

7.5.1 Distribution of pH values

**pH Spatial Distribution in Limestone Aquifer
Hydrosult STudy (2007)**

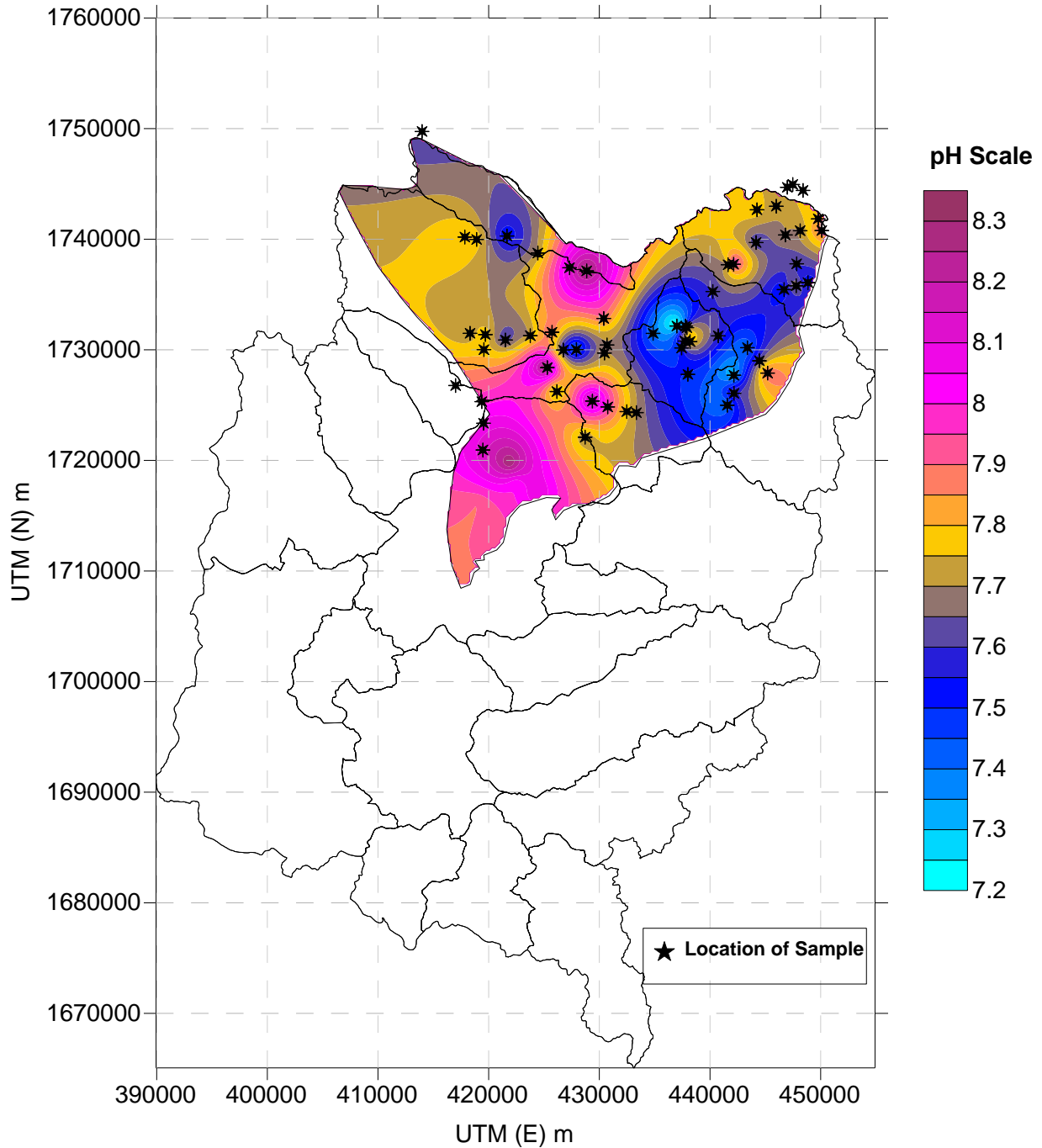


Figure 7-51 pH distribution map of the Amran limestone aquifer

Figure 7-51 presents the spatial distribution for the value of pH over the entire Amran limestone outcrop. The lowest value occurred within the boundary of Wadi Khulaga, while the highest value occurred mainly in Wadi Al-Kharid. In general, the pH values are found to be below the permissible limit of 8.5.

7.5.2 Groundwater salinity

Figure 7-52 presents the distribution of the TDS over the entire limestone aquifer. As shown in this figure, about 75% of the aquifer area has a value close to 400 mg/l, located mainly at the north-eastern part of the limestone aquifer. The value of TDS dramatically increases in the south-western part and reaches a value of 1,800 mg/l. In addition, there are some locations where the TDS reaches a value of 2,200 mg/l.

TDS Spatial Distribution in Limestone Aquifer Hydrosult STudy (2007)

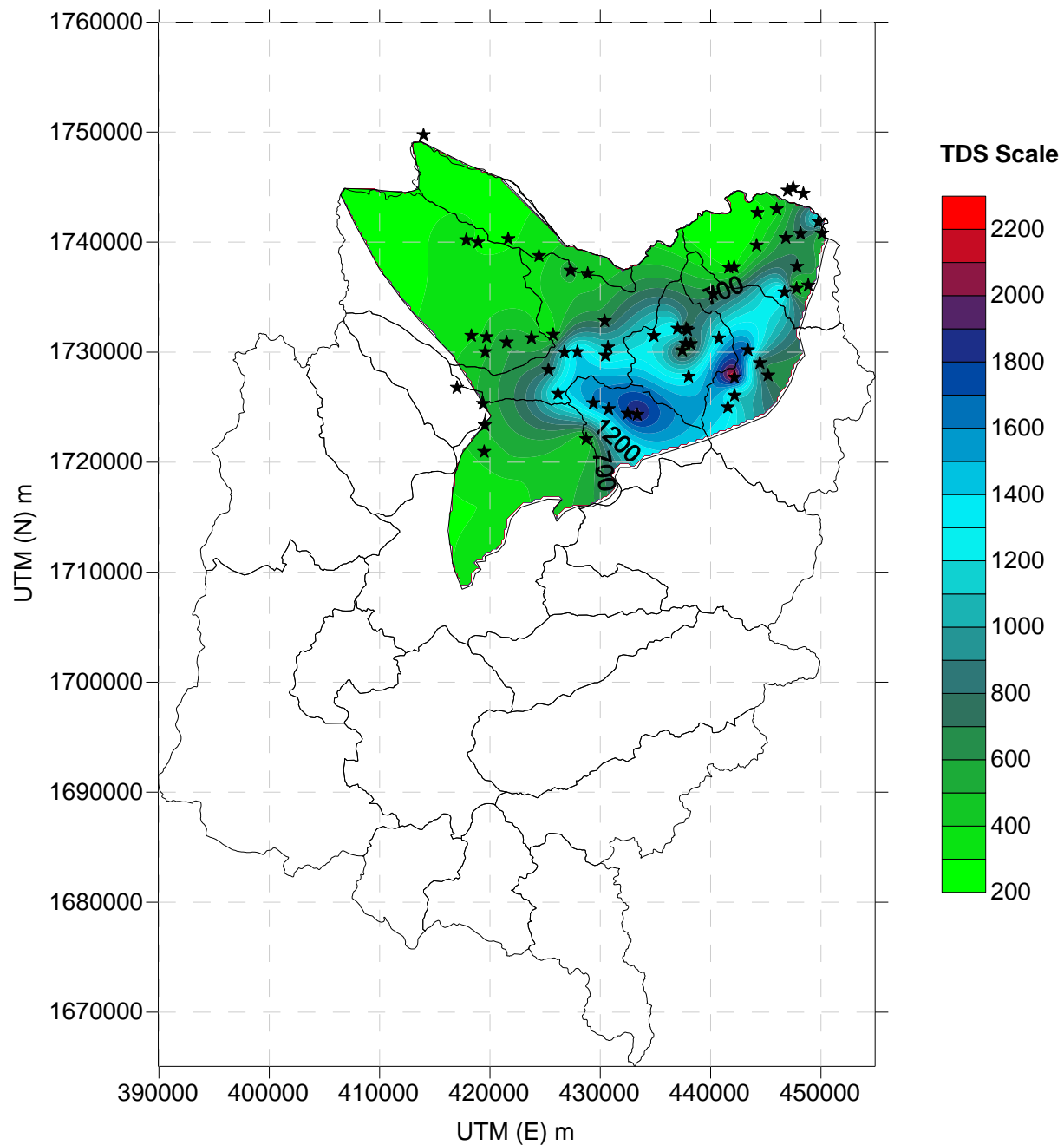


Figure 7-52 Iso-salinity map of groundwater of the Amran limestone aquifer

7.6 Evaluation of groundwater in Sana'a basin

The quality of water is as important as quantity for any evaluation of groundwater. Groundwater quality within Sana'a Basin is evaluated with respect to international standards. This evaluation deals

mainly with suitability of groundwater resources for drinking, domestic purpose, livestock, irrigation, industry and building needs.

7.6.1 Evaluation for drinking purposes

According to the international standards for drinking water (WHO, 1984), the groundwater in Sana'a Basin is classified into acceptable, permissible and unsuitable water for drinking as follows:

All selected groundwater samples from the alluvium aquifer are suitable for drinking except the groundwater sample from well HSA 108 with TDS 1,011 mg/l. In the case of the Tawilah sandstone aquifer, groundwater from HS 25, HS 31 and HS 27 in the shallow zone and groundwater from HS 105, HS 4, HAS (1,215, 1,126 and 2,770 mg/l respectively). The groundwater of the deep zone is not suitable for drinking, except groundwater from wells HS 21, HS 57, HS 147, HS 146, HS 141 and HS 113 which are acceptable (46%). 21% of groundwater from the volcanic aquifer (HS 139, HS 131, HSA 16 and HS 55) is unsuitable due to high salinity ranging from 1,338-2,010 mg/l) i.e. they are suitable for toilets and flushing. The rest of the groundwater extracted from this aquifer is suitable for drinking.

7.6.2 Evaluation for domestic purposes

Generally, water for domestic purposes should have low salinity. The hard water (water with high calcium and magnesium content) causes problems. In this case, detergents must be used instead of soap, with harmful effects and chemical pollution to other water sources. There are two kinds of water hardness:

Temporary hardness is a result of the presence of calcium and magnesium bicarbonate. Such water can be treated by distillation or by adding Ca(OH)_2 to precipitate CaCO_3 and to overcome the hardness. Permanent hardness is due to presence of chloride and sulfate ions. To test the permanent hardness, an ion exchange method can be used or the addition of sodium carbonate to precipitate Ca and Mg cations.

$$\text{T.H. concentration} = (\text{Ca} + \text{Mg}) \times 50 \text{ (epm)}$$

The limit of total hardness in laundry water is tabulated in Table 5-2.

According to these limits, all groundwater samples in the alluvium aquifer are unsuitable for laundry except HSA 99, which is considered as soft water (33.5 mg/l). With respect to Tawilah sandstone groundwater, only HS 85 is moderately soft water (93.7 mg/l) and the rest are considered as hard water i.e. unsuitable for laundry use. 16% of the groundwater samples from the volcanic aquifer exhibit soft water, 21% are permissible and the rest are hard water.

Table 7-25 Limits of total hardness in laundry water (values in epm)

Total hardness concentration	Kind of water	Evaluation for laundry use
Less than 60	Soft water	Excellent
From 60 - 120	Moderate water	Permissible
Greater than 120	Hard water	Unsuitable

7.6.3 Evaluation for livestock and poultry purposes

Water suitable for livestock has similar properties to those pertaining to quality of drinking water for human consumption. The principle criterion for evaluating water quality for livestock and poultry is **sulfate content**. By comparing the chemical analysis of the groundwater in the study area with the limits given in **this table**, the following can be deduced:

- Excellent water for all classes of livestock and poultry has TDS < 1,000 ppm. All alluvium groundwater wells except the groundwater sample from well HSA 108, with TDS 1,011 mg/l, are included in this category.
- Very satisfactory water for all classes of livestock and poultry has TDS: 1,000-3,000 ppm. Groundwater from the three aquifers in Sana'a Basin, without any exceptions, are included in this category.

7.6.4 Evaluation for irrigation purposes

Wilcox, L.V. (1948) and U.S. Salinity Laboratory Staff classification (1954) are the preferred methods used in evaluation of the groundwater of the alluvium, Tawilah sandstone and volcanic aquifers in Sana'a Basin for the purpose of irrigation. This classification is based on the salinity and sodium adsorption ratio (SAR) where:

$$SAR = Na^+ / (0.5(Ca^{++} + Mg^{++}))^{0.5}$$

Na⁺, Ca⁺⁺ and Mg⁺⁺ are in **epm**. U.S. Salinity Laboratory Staff (1954) have devised a system for classifying irrigation water in the form of a monogram, which is widely used for evaluation of water for irrigation purposes. This monogram consists of a plot of the electrical conductivity as a function of total dissolved solids, expressed by the horizontal axis against the (SAR) expressed by the vertical axis.

The high values of SAR imply a hazard of sodium replacing adsorption Ca⁺⁺ and Mg⁺⁺ and this replacement is damaging to soil structure. On the basis of TDS, water is divided into four classes (C1, C2, C3 and C4), and, on the basis of SAR, water is divided also into four classes (S1, S2, S3 and S4), giving a total of sixteen possible quality classes. The classification is shown in Table 7-26.

Table 7-26 Classification and description of conductivity and SAR

Class	SAR	Quality	Usage
S1	0 - 10	Low Na	Suitable for all soils.
S2	10 - 18	Medium Na	Preferable for coarse soils with good permeability.
S3	18 - 26	High Na	Side harmful effects for soils.
S4	26 - 100	Very high Na	Unsuitable for irrigation purposes.

According to this classification, the alluvium aquifer groundwater of Sana'a Basin can be classified as follows:

- **Medium salinity – low SAR** (C2-S1) includes samples no. 17, 19, 21 and 28 (in northern parts). This water is suitable and can be used for irrigation on almost all soils with little danger of development of harmful levels of exchangeable sodium.
- **High salinity – medium SAR** (C3-S2) includes only one sample (57) in the middle part of the study area. This water can be used on soils of moderate to good permeability; plants with moderate salt tolerance can be grown in most instances without special practices for salinity control.

- **Very high salinity – very high SAR** (C4 – S4) includes the most samples in all parts of the study area. This water is generally unsuitable for irrigation except for highly permeable soils with frequent leaching and highly salt-tolerant plants. Chemical amendments must be used for exchanging sodium ions from lightly sodium-affected soils.

According to this classification, the Tawilah sandstone aquifer groundwater of Sana'a Basin can be classified as follows:

- **Medium salinity – low SAR** (C2-S1) includes samples no. 17, 19, 21 and 28 (in northern parts). This water is suitable and can be used for irrigation on almost all soils with little danger of development of harmful levels of exchangeable sodium.
- **High salinity – medium SAR** (C3 – S2) includes only one sample (57) in the middle part of the study area. This water can be used on soils of moderate to good permeability; plants with moderate salt tolerance can be grown in most instances without special practices for salinity control.
- **Very high salinity – very high SAR** (C4 – S4) includes the most samples in all parts of the study area. This water is generally unsuitable for irrigation except for highly permeable soils with frequent leaching and highly tolerant plants. Chemical amendments must be used for exchanging sodium ions from lightly sodium-affected soils.

According to this classification, the volcanic aquifer groundwater of Sana'a Basin can be classified as follows:

- **Medium salinity – low SAR** (C2-S1) includes samples no. 17, 19, 21 and 28 (in northern parts). This water is suitable and can be used for irrigation on almost all soils with little danger of development of harmful levels of exchangeable sodium.
- **High salinity – medium SAR** (C3 – S2) includes only one sample (57) in the middle part of the study area. This water can be used on soils of moderate to good permeability; plants with moderate salt tolerance can be grown in most instances without special practices for salinity control.
- **Very high salinity – very high SAR** (C4 – S4) includes the most samples in all parts of the study area. This water is generally unsuitable for irrigation except for highly permeable soils with frequent leaching and highly tolerant plants. Chemical amendments must be used for exchanging sodium ions from lightly sodium-affected soils.