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Hydrochemical identification and salinity problem of ground-water in Wadi Yalamlam basin, Western Saudi Arabia

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Abstract

Wadi Yalamlam, located in the western province of Saudi Arabia, lies within a typical arid to semi-arid area. Within its drainage area of about 1600 km^2, the ground-water of its shallow alluvial aquifer is relatively high in salinity. The present study integrates hydrochemical, hydrogeological, and recharge estimation analyses to identify the process/processes, that led to the aquifer salinity. The results of chemical analysis indicate that the ground-water salinity is highly variable and inconsistent along the course of the wadi. This variability is probably due to the local hydrogeological conditions and to the intensive evaporation of effluent surface irrigation water that led to the precipitation of evaporites, e.g. calcite, dolomite and gypsum, especially affecting the ground-water at shallow depths. The recharge rate of approximately 20 mm $year^{-1}$—also plays a role in determining the risk of ground-water salinity in this aquifer.

Keywords: Arid region; Ground-water; Saturation index; Salinity; Saudi Arabia

1. Introduction

The Arabian Shield in Western Saudi Arabia is considered the most important recharge zone for the alluvial aquifers. Traversing the Shield are several wadis which are ephemeral in nature and have direct response to the

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sporadic rainfall. In such arid and semi-arid environments of limited water resources, ground-water constitutes a significant part of these resources. Further, in such environments, the ground-water chemistry evolves rapidly and the salinity goes up considerably, leading to restrictions in its utilization and limitations on the development and management of unconfined alluvial aquifers. Several factors cause the increase in ground-water salinity. Some of these factors are local, such as hydrogeological conditions, rate of natural recharge and irrigation, while others are regional in nature, including the aridity of the environment and the irregular and unpredictable occurence of rainfall (Eagelson, 1978, 1979).

Wadi Yalamlam is one of the important wadis in Western Saudi Arabia. While it receives more than 200 mm of annual rainfall, the aquifer in the wadi still has a ground-water salinity problem. This wadi is a part of the Arabian Shield, which is an extensive occurrence of Precambrian igneous and metamorphic rocks. These rocks contain appreciable amounts of minerals such as feldspars and micas which are thermodynamically unstable and tend to dissolve when in contact with water. These environments reflect the heterogeneities in recharge estimation and water quality assessment in time, as well as in space.

The purpose of the present study is to identify and discriminate among the local and regional causes of ground-water salinity, as well as to hydrochemically and hydrogeologically characterize the unconfined alluvial aquifer of Wadi Yalamlam in Western Saudi Arabia.

2. Methods

2.1. *Topography and geology*

The study area of Wadi Yalamlam is bound by latitudes 20°30′ and 21°10′N and longitudes 39°45′ and 40°30′E., lying about 125 km south-east of the city of Jeddah, and 70 km south of the city of Makkah (Fig. 1).

Geologically, this wadi is a part of the Arabian Shield extending from north to south parallel to the Red Sea (Fig. 2). This escarpment is one of the outstanding landscape features of Saudi Arabia. The Shield is composed of Precambrian crystalline, metamorphic and metavolcanic sedimentary rocks, with local Tertiary and Quaternary basalt flows. These rocks form the mountain ranges east of the Red Sea coastal plain (Brown et al., 1963; Wier and Hadley, 1975; Pallister, 1982; Moore and Al-Rehaili, 1989).

Loose Quaternary sediments fill the Wadi Yalamlam basin with a thickness ranging form 5 to 10 m in the upstream to more than 50 m in the downstream. These sediments consist of alternating layers of sand, gravel and clayey sand driven from the host rocks and constituting an ideal place for ground-water accumulation. In addition to this alluvial aquifer, field studies indicated that the bedrock of the basin is highly weathered and fractured also providing an ideal host for ground-water preservation (Subyani and Bayumi, 2001).

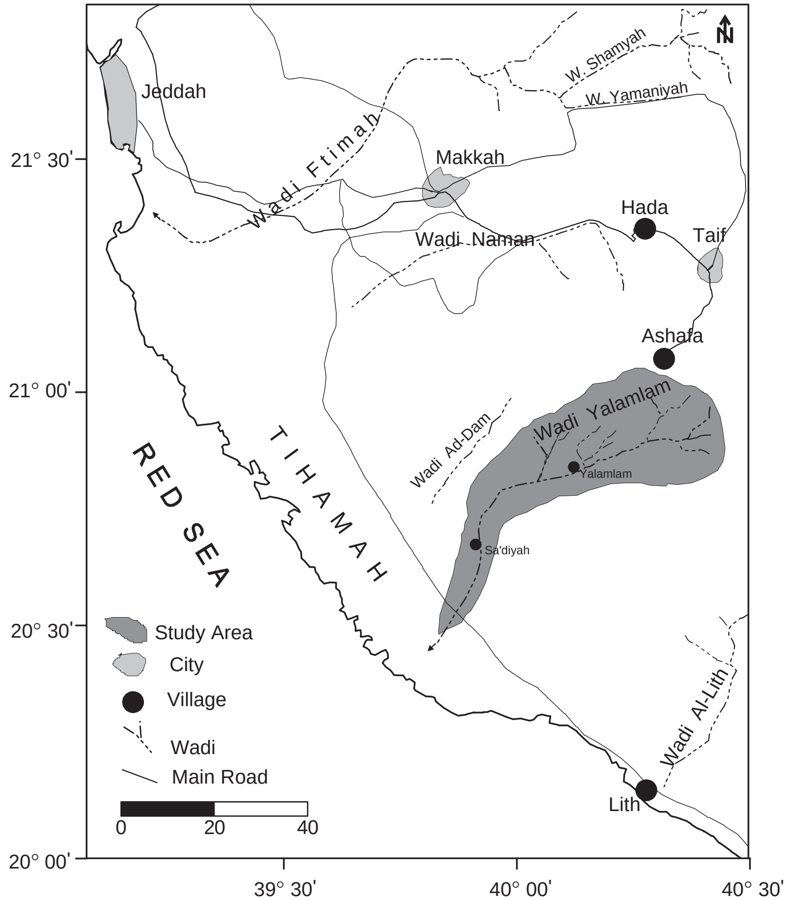

Fig. 1. Location map and geographic position of WADI Yalamlam.

Structurally, these units are intensively faulted and folded as a result of various tectonic activities and are dissected by distinctive north-west and north-east trending faults, some of which are occupied by ablitic and andesitic dikes. These geologic features are reflected in the topographic and morphometric characteristics of the area and, consequently, control the human population and activities therein. For instance, due to the upper wadi streams being virtually inaccessible, most of the population activities, such as grassing and the limited agricultural endeavors in the wadi, are concentrated around the middle and downstream areas at Yalamlam, Sa'diyah, and Almigat villages (Fig. 2).

Further, within the natural basin, topography is a controlling factor of the distribution of water flux-surface water, evaporation, infiltration, heat exchange and other ground–atmosphere interface processes; the quantitative assessment of these processes depends, therefore, on the topographic configuration of the basin.

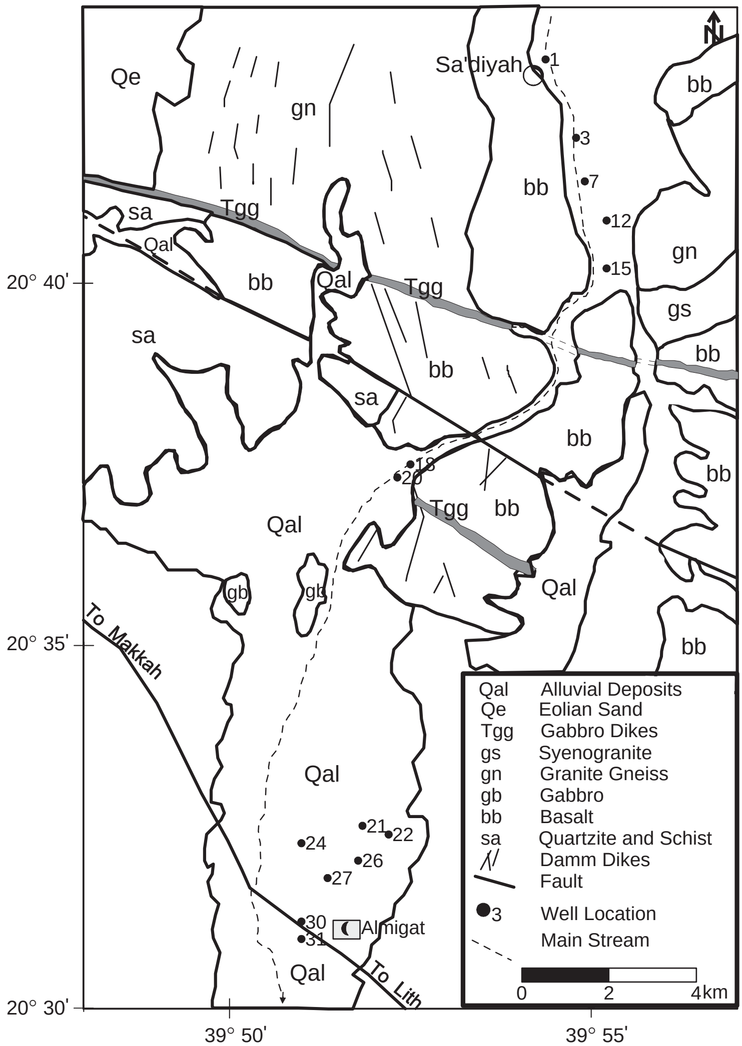

Fig. 2. Geologic map of Wadi Yalamlam.

2.2. Hydrogeology

Wadi Yalamlam drains a wide catchment area of about 1600 km^2 and flows to the Red Sea (Tihamah) (Fig. 1). The catchment area, starting from the Hijaz Escarpment, is characterized by a high amount of annual rainfall of more than 200 mm. In addition, surface water runs most of the year in some tributaries of the wadi. The subsurface investigations in Wadi Yalamlam indicate that the water-bearing formations consist of alluvial deposits overlying the weathered top zone of the basement rocks forming an unconfined aquifer. More than 30 large and small diameter wells exist within the main course of the wadi. The total daily abstraction from these wells is more than 1000 m^3.

Based on field observations, well survey records, and geophysical investigations carried out in the study area (Subyani and Bayumi, 2001), the thickness of the saturated alluvial deposits in the Sa'diyah area ranges between 6 and 12 m. The thickness of the water-bearing formations in the Almigat area, on the other hand, ranges between 15 and 38 m. Further, the depth to the water-table varies between 3–9 m in the upstream and 30–33 m in the downstream. These variations in the water table depth might be attributed to the effects of the bedrock surface nature and the occurrence of dikes (Table 1 and Fig. 2).

2.3. *Rainfall distribution and variability*

The climatological data used in this paper were collected from Aljerash (1989) and the Hydrology division of the Ministry of Water and Electricity (2000). The available rainfall records cover a period of 15–20 years (1980–1999). Some of the stations with long enough records of rainfall were chosen based on the following criteria: (1) that they provide a good spatial coverage of the region; (2) that they maximize the same monthly precipitation records; (3) that they have continuous monthly precipitation records; and (4) that they represent all different climatic conditions.

The mean annual rainfall distribution presented in Fig. 3 demonstrates the spatial variation of precipitation which strongly reflects the effect of topography, where the annual rainfall generally increases with elevation (orographic effect). Generally, the uppermost (eastern) part of the wadi catchment receives a considerably higher amount of rainfall—an average of about 220 mm/year near the Hijaz Escarpment—as compared to the lower (western) part of the wadi having an average of less than 100 mm/year near the Red Sea coast (Tihamah).

2.4. *Sample collection and analysis*

Thirteen ground-water samples were collected from the water wells distributed in the middle and lower parts of Wadi Yalamlam, particularly from wells used for domestic purposes, such as well No. 1 near the Sa'diyah village; well No. 20 for livestock, and the Ministry of Water well No. 22 for Almigat Mosque and surrounding villages; other wells used for irrigation purposes were also sampled. Sample locations are shown in Fig. 4. All water samples were taken after intensive pumping of the wells in order to avoid any local contamination or evaporation. The samples were analyzed for the major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, HCO_3^{-}, and SO_4^{2-}) in the laboratories of the Faculty of Earth Sciences, King Abdulaziz University. In addition, water temperature, electrical conductivity, and pH were measured in situ. Partial pressure of carbon dioxide (P_{CO_2}) and saturation indices for calcite (SI_{cal}), dolomite (SI_{dol}) and gypsum (SI_{gyp}) were also computed.

Table 1
Chemical analysis of major ions of ground-water samples in Yalamlam basin (mg/l)

Well no.	Water depth (m)	SO_4^-	Cl^-	HCO_3^-	Na^+	K^+	Ca^{2+}	Mg^{2+}	Temp (°C)	pH	EC (μs/cm)	TDS	P_{CO_2}	SI_{cal}	SI_{dol}	SI_{gyp}
1	4	456.1	448.8	151.5	98.5	18.4	317.3	50	24	7.3	2750	1540	−2.18	0.29	0.12	−0.66
3	5	696.5	503.6	305.1	283	6.06	308.5	74	25	7	2980	1880	−1.58	0.22	0.17	−0.56
7	4.5	782.2	580.4	427.5	330	7.3	405.6	31	24	6.8	3300	2564	−1.24	0.26	−0.25	−0.42
12	3.5	740.3	552.2	335.3	300	8	382.8	76.6	26	6.8	3420	2395	−1.35	0.14	−0.07	−0.48
15	3	680.8	419.5	187	170	17.4	303.4	91.4	23	6.9	3390	1900	−1.69	−0.08	−0.34	−0.56
20	9.5	438.8	506.9	176.9	335	12	143.1	75.4	24	7	3100	1738	−1.81	−0.28	−0.5	−0.99
21	32	468.4	543.7	206.6	302	15.8	160	84.5	25	7.1	3370	1781	−1.84	−0.08	−0.09	−0.93
22[a]	32	370.4	466.1	220.3	275	15.4	130	69.6	27	7.2	2700	1545	−1.91	−0.01	0.05	−1.07
24	32.5	624	643.9	220.3	340	25.9	194	117	26	7.2	3200	2165	−1.92	0.09	0.31	−0.79
26	30.5	450.6	598.9	274.2	328	32.2	190.6	74.3	25	7.3	3380	1950	−1.92	0.31	0.56	−0.89
27	33	469.2	500.6	213.4	258	15.4	176.8	82.2	26	6.9	3550	1716	−1.63	−0.22	−0.42	−0.89
30	33.5	504.6	557.5	199.7	290	15.8	171.7	95.4	25	7	3570	1835	−1.76	−0.17	−0.25	−0.89
31	33	475.8	535.1	213.4	285	15.4	171.7	86.9	25	6.9	3540	1783	−1.63	−0.23	−0.42	−0.9
Mean		550.6	527.5	240.6	276.5	15.7	235.0	77.5	25	7.04	3250	1930	−1.73	0.018	−0.087	−0.77
S.D.		134.8	62.3	75.9	69.4	7.2	94.8	20.9	1.13	0.18	290	312	0.251	0.212	0.318	0.210

[a] Ministry of Water Well.

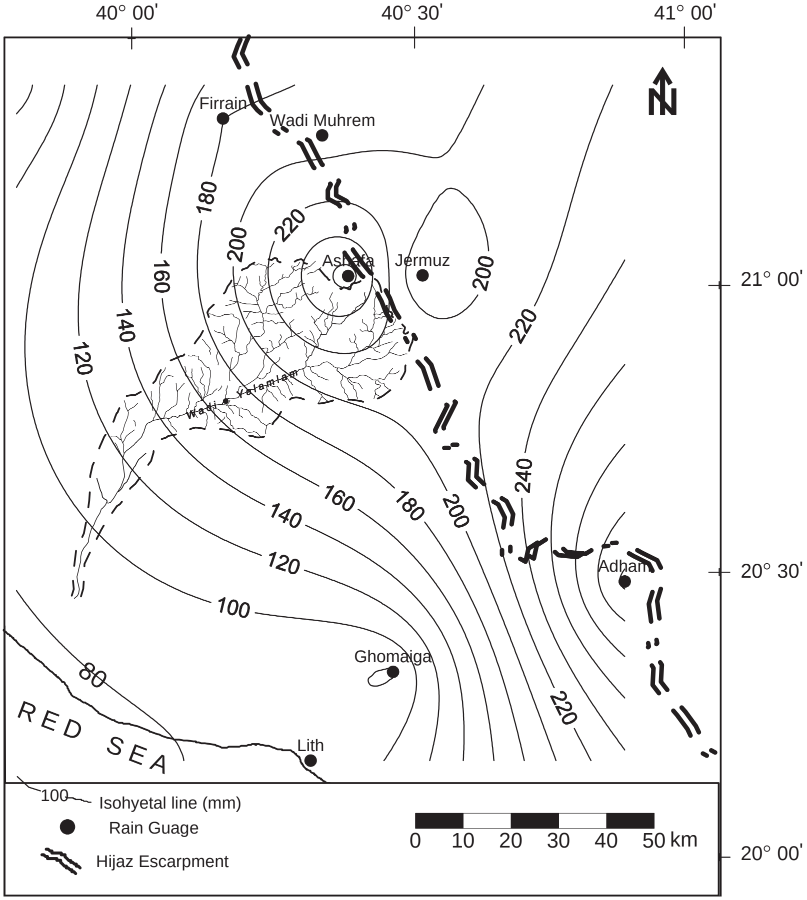

Fig. 3. Annual rainfall distribution over Yalamlam basin.

3. Results and discussions

Table 1 shows the major constituents of the ground-water, in addition to the total dissolved solids (TDS), field electrical conductivity (EC), pH, and temperature. TDS in ground-water vary from 1450 to 1835 mg/l with a mean and a standard deviation of 1930 and 1312 mg/l, respectively. Fig. 4 exhibits the regional distribution of TDS in the Wadi Yalamlam basin. The electrical conductivity (EC) of the ground-water varies from 2750 to 3570 μS/cm with a mean and a standard deviation of 3250 and 290 μS/cm, respectively. In order to decipher the water type, the Durov diagram was used, Fig. 5. Accordingly, Wadi Yalamlam is occupied by a Ca^{2+}–SO_4^{2-} water type in its middle parts and a Na^{+}–Cl^{-} water type in its lower parts. This ion exchange can be explained by the occurrence of clay media in the relatively deeper aquifer (Table 1). This simple dissolution or water type

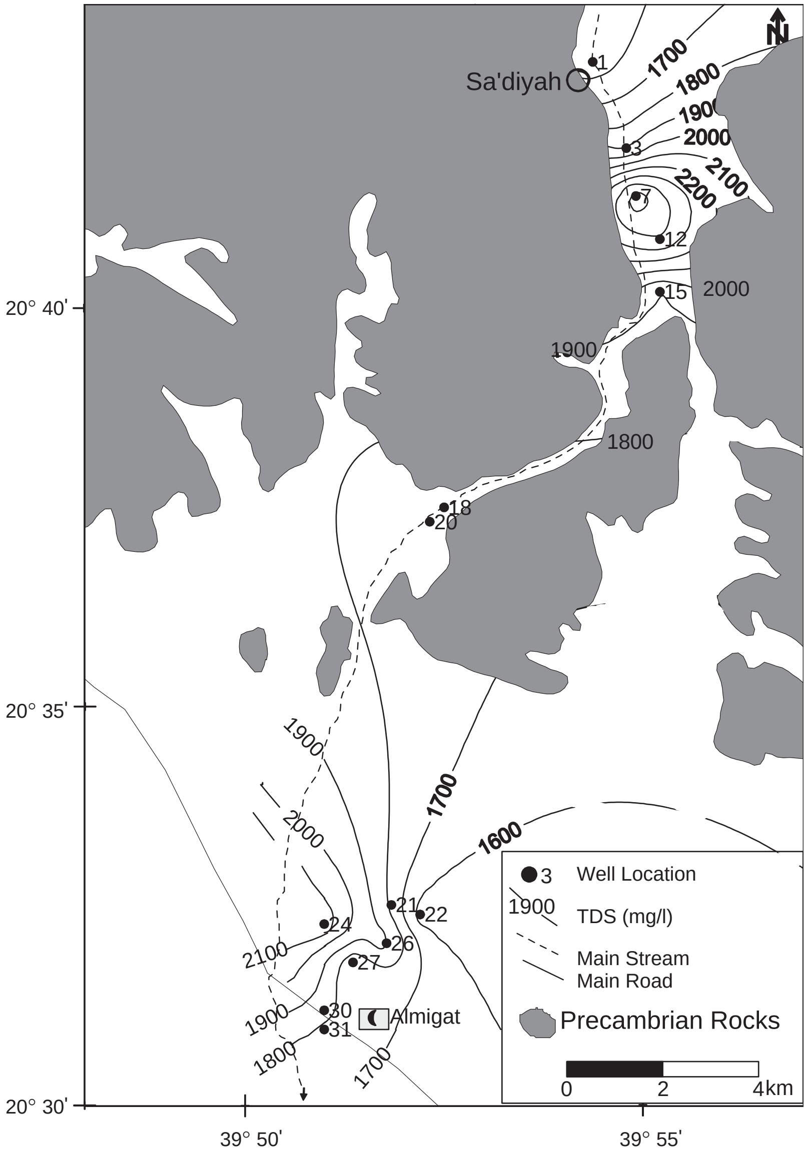

Fig. 4. Sample location and regional distribution of TDS in Wadi Yalamlam.

change from calcium sulfate to sodium chloride water type distinctly matches the general flow of ground-water (Lloyd and Heathcote, 1985; Viessman et al., 1996; Wanielista et al., 1997).

The ground-water chemistry exchanges matter with the various minerals and gases within an aquifer resulting in a dissolution or precipitation of

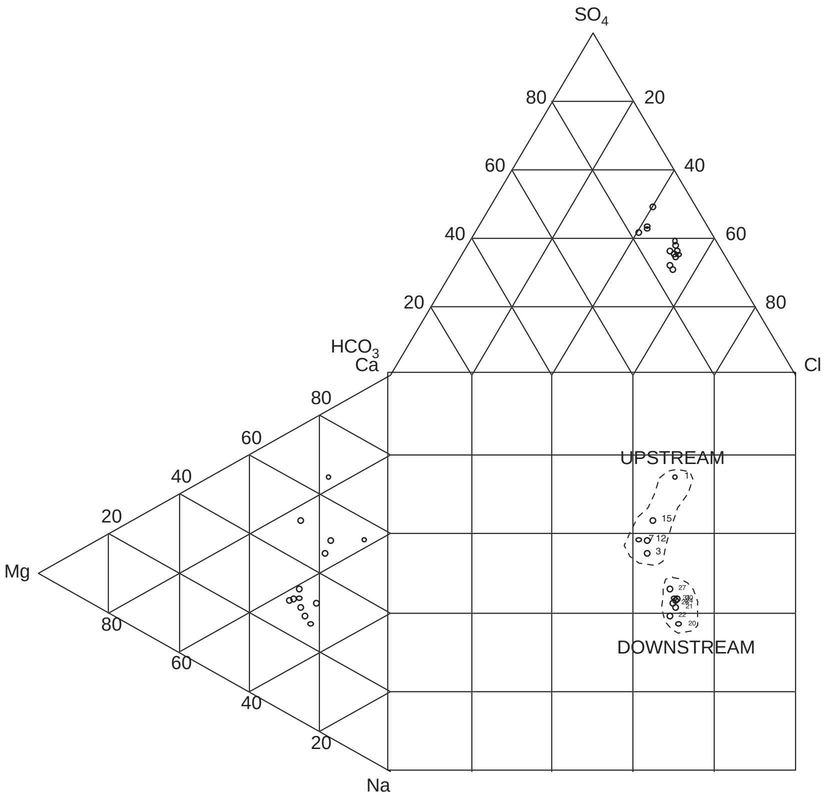

Fig. 5. Water types grouped using Durov diagram.

minerals. Equilibrium calculations are most commonly used to assess whether ground-water is in equilibrium with respect to one or more minerals. The saturation state of minerals in the water can be expressed by the saturation index (SI). When $SI < 1$, the minerals will dissolve, while they will precipitate when $SI > 1$.

SI indices of calcite and dolomite are calculated for the ground-water samples of Wadi Yalamlam as shown in Table 1. In the middle parts of the wadi, most of the samples have positive calcite and dolomite indices, indicating a slight oversaturation, while the samples representing the lower parts of the wadi have negative indices reflecting an undersaturation. In general, the mean for calcite and dolomite fluctuates about equilibrium ($SI = 0$). For gypsum, all indices are negative indicating that it is below the saturation state. Within the study area, the dissolution processes for calcite and dolomite would be considered with a relatively large reservoir of $CO_{2(g)}$ in the surficial zone. The high P_{CO_2} values (Table 1) provide dissolved CO_2. That means the H_2CO_3 supplies the imputes in the calcite and dolomite dissolution (Freeze and Cherry, 1979).

4. Origin of ground-water salinity

4.1. Irrigation effects

In the upper (eastern) part of the wadi, the ground-water extracted from wells in the main channel (wells 1, 3, 15, and 20) is not highly mineralized because these wells are used heavily for domestic and livestock purposes. Wells 7 and 12, on the other hand, are highly mineralized due to the effluent surface irrigation water and their being located along the edge of the wadi course (Table 1 and Fig. 2).

In the lower part of the wadi (wells 21–31, Table 1 and Fig. 2) the ground-water salinity is slightly lower than that in the upper part. This can be attributed to these wells being mostly used for domestic purposes and being away from the effluent surface irrigation water.

4.2. Water-table position

The aquifer of Wadi Yalamlam is unconfined and the water-table is not deep enough to be protected from salinity and pollution effects. However, the water-table depth in the upper part of the wadi ranges between 3 and 10 m which is shallow enough to be affected by the continuous evaporation causing mineral precipitation during the period between two runoff events. On the other hand, the water table depth in the lower part of the wadi is much deeper, ranging between 30 and 33 m, resulting in a reduced influence of evaporation compared to the upper part.

4.3. Ground-water movement

The effect of bedrock surface on ground-water flow may be significant, especially in a shallow alluvial aquifer. The bedrock with a set of barriers either supports or impedes the water flow system. In Wadi Yalamlam, the regional ground-water flow direction is towards the south and south-west following the general trend of the main wadi channel (Fig. 6). The gradient of the water level varies from one area to another depending on the pumping rates, hydraulic conductivity, and the cross-section of the aquifer. Near Sa'diyah village, the general gradient is 0.002 and the direction of flow is down the wadi towards the south. This gradient increases, however, in the central part of the study area to 0.008, possibly reflecting a reduction in the hydraulic conductivity of the aquifer material. This conclusion stems from the fact that pumping is low in this area and that the aquifer dimensions are greater compared to those in the upstream. The hydraulic gradient in the lower parts of the wadi is 0.011 and the flow direction is towards the southwest.

The ground-water flow is interrupted in many parts along the wadi course due to the presence of the basement rocks at and/or near the surface. This is especially clear immediately upstream of Sa'diyah village, where several igneous outcrops are encountered across the main wadi channel (Fig. 2). As is often in such a system, ground-water flow is likely to be affected and, consequently, ground-water appears

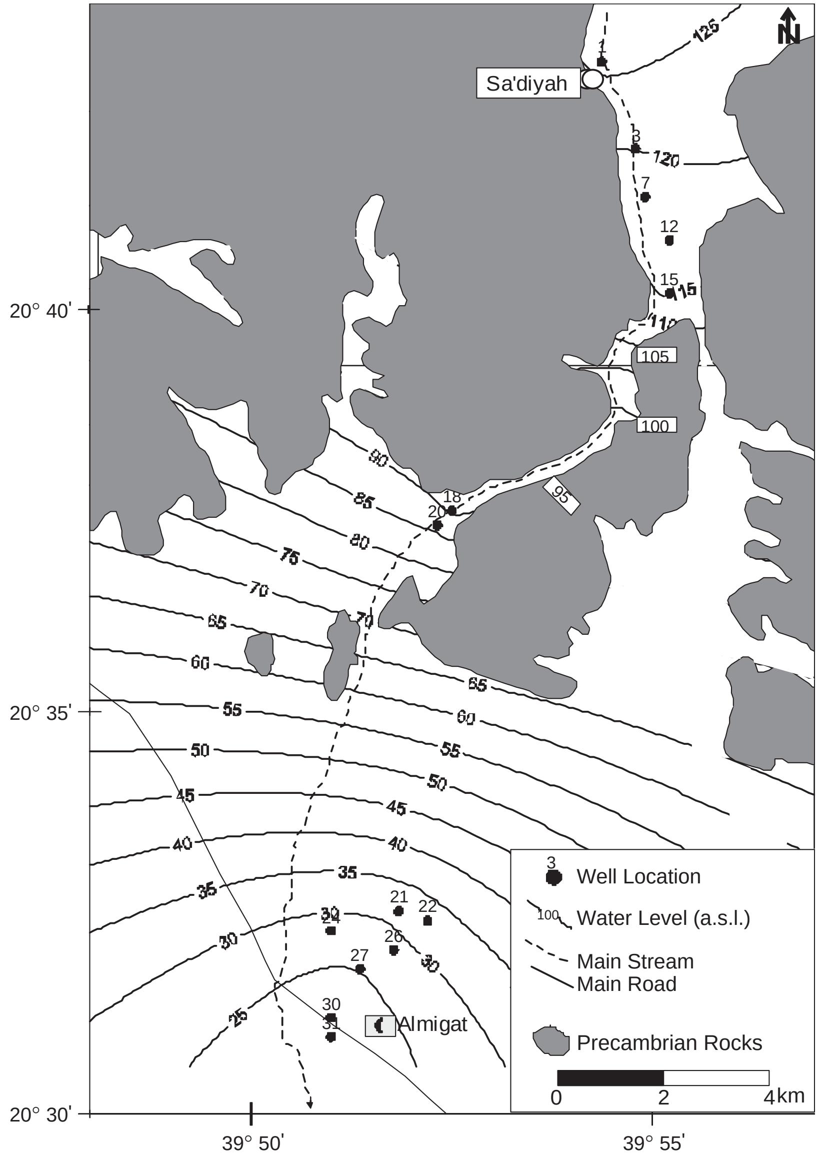

Fig. 6. Water level map.

at the surface forming perennial streams that disappear some 100 m downward of these barriers where they soak back into the ground. In the upper part of the wadi (wells 1–20), dikes and shallow bedrock form impediments to ground-water flow and tend to break the saturation zone into small basins, permitting more water-rock interaction to affect the water quality (Fig. 2). Consequently, the concentration of salts would be expected to increase at these localities. In the lower part of the wadi (wells 21–31), the alluvial thickness is more than 50 m and there is a consistency in the ground-water flow in this part. The salinity problem might therefore be attributed to the fine-grained materials in the aquifer formations.

4.4. Recharge rate

Floods occur frequently, because the uppermost part of the basin receives considerable amount of rainfall (average 275 mm year^{-1}; Shafa station) compared to 60 mm year^{-1} in the lower parts. The duration of flooding is extremely variable, ranging from 10 h to several days (local people communications). Direct infiltration from local rainfall is less significant, but probably occurs when heavy rainfall takes place.

Recharge to the alluvial aquifer occurs primarily from the infiltration of floodwaters. The infiltration through the wadi channels is controlled by the size of the floods, the grain size distribution, and the wettability of the soil surface. The recharge rate in this basin and other adjacent basins in Saudi Arabia and other arid parts of the world, using chloride mass-balance method, is about 10% of the annual rainfall (Allison, 1988, pp. 49–72; Wood and Sanford, 1995; Bazuhair and Wood, 1996; Wood et al., 1997; Wood, 1999; Love et al., 2000; Subyani and Bayumi, 2001; Edmunds et al., 2002). However, the chloride concentration was measured from rain-storm samples and that dry deposition was not included, in addition, the ground-water samples for chloride concentration were taken from the upper stream of the basin, where there is no human or agricultural activities, it is possible to deduce from the chloride-mass balance method that the recharge rate in Yalamlam basin is low (20 mm year^{-1}) in the upstream area. This implies further that a considerable amount of rainwater does not contribute to ground-water recharge but causes the precipitation of salt on the ground surface. In addition, the steep slope of the wadi surface increases the runoff velocity which reduces the rate of infiltration into the alluvium.

5. Conclusions

Wadi Yalamlam is one of the most important wadis in western Saudi Arabia. It drains a wide catchment area of about 1600 km^2 and flows to the Red Sea. Over the study area, rainfall occurs as thunderstorms of high intensity during local storms followed by dry periods. The chemical composition of the ground-water in the study area shows a randomly variable distribution of ground-water salinity. Two types of ground-water exist in the study area; these are calcium sulfate in the upper part and sodium chloride in the lower part of the wadi. The total dissolved solids (TDS) of the ground-water vary between 1450 and 1835 mg/l. The salinity origin can, generally, be divided into two main groups, as indicated in Fig. 5, representing shallow (wells 1–20) and deep (wells 21–31) water-tables (see Table 1).

In the case of shallow water-table, the existing salinity source seems to be the intensive evaporation of effluent surface irrigation water that led to the precipitation of salts. The bedrock surface topography and dikes act as impediments to ground-water movement. The recharge rate is also another factor contributing to the increase in water salinity (about 10% of annual rainfall).

For the deeper water-table in the lower part of the wadi, there is no direct recharge and the salinity problem might, therefore, be due to the fine-grained materials in the aquifer formations. Long distance flow of ground-water is another factor which increases the time span of soil–water interaction and, consequently, enhances the dissolution processes causing the ground-water to systematically acquire more dissolved constituents leading to increasing salinity.

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