Original article

Use of chloride-mass balance and environmental isotopes for evaluation of groundwater recharge in the alluvial aquifer, Wadi Tharad, western Saudi Arabia

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Abstract Groundwater recharge estimation has become a priority issue for humid and arid regions, especially in regions like Saudi Arabia, where the precipitation varies over space and time as a result of topography and seasonality. Wadi Tharad is a typical arid area in western Saudi Arabia. Within its drainage area of 400 km^2, the groundwater system shows a graded hydrochemical zonation from the hydrocarbonate in the upper reach to the chloride zone in the lower reach. The saturation index (SI) varies depending on the concentrations of carbonate minerals; the mean for calcite and dolomite is about in equilibrium (e.g., zero value). As halite and gypsum indices are negative, it is undersaturated. Isotopic compositions of H and O in the groundwater show that the groundwater recharge resources are mainly from meteoric water. The chloride-mass balance method was refined to estimate the amount of recharge, which is probably 11% of the effective annual rainfall. These results can be used to improve the accuracy of future groundwater management and development schemes.

Keywords Stable isotopes · Recharge · Saturation index · Arid regions · Saudi Arabia

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Introduction

In arid regions, groundwater is a significant part of the total water resources. To determine the safe yield of an aquifer, a reliable estimate of groundwater recharge is needed for sustainable groundwater resources management. In Saudi Arabia, there are no perennial rivers or surface water, and groundwater storage rates in alluvial aquifers depend on direct recharge of precipitation amounts. Wadi Tharad is one of the important wadis in western Saudi Arabia. Because of rapid economic growth and lack of precipitation, the use of groundwater resources has increased dramatically, and the groundwater extraction has four serious consequences: (1) significant water-level decline; (2) increasing groundwater salinity; (3) desertification of ranges and agriculture lands; and (4) human migration to major cities. The human activities (domestic and agricultural) can be sustained based on a good management of groundwater storage volumes without significant problems, especially, on the western regions along some wadi courses. However, recharge estimation in arid regions involves a large degree of uncertainty due to low rainfall and high evaporation.

Different methods can be used to estimate groundwater recharge, such as empirical approaches, water-balance techniques, the Darcy law in unsaturated zones, tracer techniques and others depending on data availability and the field situation (Eagelson 1979; Lerner and others 1990; Flint and others 2002; Edmunds and others 2002) during the last two decades. Carter and others (1994) summarize previous rain-fed groundwater recharge studies in semi-arid and arid regions around the world. The groundwater recharge percentages of these studies range from 1 to 30% of the local rainfall, and tracer techniques, such as environmental isotope and chloride-mass balance (CBM), have been commonly used in the overall domain of water resources development and management (Fritz and Fontes 1980; Wood and Sanford 1995; Wood and Imes 1995; Wood 1999; Shi and others 2000; Kattan 2001). In fact, the application of these relatively new techniques has played an important role in solving the envisaged hydrogeological problems that cannot be solved by conventional methods alone. Stable isotopes, oxygen-18 (^{18}O) and deuterium (D)

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are commonly used for flow-system tracing and climate reconstruction. The chloride-mass balance is used for groundwater recharge because of its conservative nature. Furthermore, the application of these techniques in the case of arid and semi-arid zones is very attractive as a tool for the identification of recharge and the quantitative evaluation of groundwater systems (IAEA 1980, 1983; Clark and Fritz 1997).

Over the past decades, the Saudi government and scientists have carried out much research on the assessment, development, utilization and conservation of water resources in a wadi system in western Saudi Arabia (Basmaci and Al-kabir 1988; Abdulrazzak and others 1989; Bazuhair and Wood 1996; Bazuhair and others 2002).

This study combines the systematic analysis of the hydrochemical types and hydrogeologic features of the wadi with isotopic geochemical methods for rainfall, surface water, and groundwater in Wadi Tharad, western Saudi Arabia. The objective is to elucidate the controls of groundwater quality evolution, recharge, circulation and mixing processes and, furthermore, to explain the mechanism of these processes from the environmental geochemistry standpoint.

Hydrogeology of the study area

Wadi Tharad, the most important tributary of Ranyah basin, is located in the western part of Saudi Arabia and bounded by latitudes 20°15′and 20°20′ N and longitudes 41°45′and 42°00′E. This wadi is a part of the Scarp-Hijaz Mountains of the Arabian Shield, which extend from north to south, parallel to the Red Sea. This escarpment is one of the outstanding landscape features of Saudi Arabia. Wadi Tharad originates from the Baha Mountains and disappears in the desert of middle Saudi Arabia (Fig. 1). Its drainage area is about 170 km^2 and the total length of the main channel is merely 20 km. The elevation of Wadi Tharad decreases from 2,500 to 1,350 m above the sea level (a.s.l.) from the Baha Mountains in the west to the mouth of the wadi in the east.

In terms of the geological characteristics, several investigators have discussed various aspects concerning the geology of Wadi Tharad (Brown and Jackson 1960; Greenwood 1975; Cater and Johnson 1986). Four principle units of Precambrian rocks (Ablah group) exist from the oldest to the youngest (Fig. 1). These units are:

1. the Qirshah Formation, which is composed of metamorphic basaltic and subordinate andesitic, dacitic and rhyolitic pyroclastics;
2. the Khutnah Formation, which includes siltstone and subordinate basaltic to andesitic flow rocks;
3. the Thurat Formation, which consists mainly of metamorphosed arkosic volcanic wacke and sandstone. In dierent parts of the area, these units are intruded by granodiorite and diorite plutons, and finally,
5. the loose quaternary sediments that fill the basin to a thickness of 5–10 m.

These sediments consist of alternating layers of sands, gravel and clayey sand that were derived from host rocks, and provide for groundwater storage. The bedrock of the basin is highly weathered and fractured, and is also an ideal place for groundwater storage. These units are intensively faulted and folded, and have a series of distinctive north–west and north–east-trending faults, some occupied by ablitic and andesitic dikes.

Rainfall in western Saudi Arabia can be described as scarce and unpredictable, but very extensive during local storms. The rate of evaporation is very high, on the average of 400 mm/year. There are no perennial streams. Wadi Tharad basin receives a considerable amount of rainfall, on the average of 450 mm/year (Fig. 2). Compared with other basins, it is mostly mountains and is within a subtropical zone. Runoff occurs most of the year, especially after rainfall events and flash floods occur in the winter and spring seasons (Şen 1983; Subyani 1997).

More than 70 large-diameter wells exist within the main course of Wadi Tharad. These wells have an average diameter of 5 m and the total depth ranges from 9 to 22 m. Most of these wells abstract groundwater from alluvial and fractured bedrock. The alluvial thickness ranges from 3 m in the upstream to 12 m in downstream. The depth to the water table is also variable, from 3 to 10 m, with no systematic variation along the wadi course. Figure 3 shows the complexity of the regional water flow and variation of the water table due to the bedrock surface nature, as well as the occurrence of faults and dikes (Alyamani 2000).

Sampling and methods

Twenty-six water samples were collected in July 2003, with major and minor ion constituent analysis as shown in Tables 1 and 2. Nineteen samples from the water-supplying wells are within the Quaternary and fractured aquifer, and seven samples are taken from running surface water in Wadi Tharad basin. Each water sample was analyzed to determine the concentration (milligram/liter) of major ions (SO_4^{2-}, Cl^-, HCO_3^-, CO_3^-, Na^+, K^+, Ca^{2+} and Mg^{2+}). These water samples were analyzed by using inductively coupled plasma mass spectrometry (ICP-MS) in the laboratories of the Faculty of Earth Sciences, Saudi Arabia. Water temperature, pH, and electrical conductivity (EC) are measured in the field. Saturation indices for calcite (SI_{cal}), dolomite (SI_{dol}), halite (SI_{hal}) and gypsum (SI_{gyp}) were also computed.

For environmental isotopes, 15 samples (5 from rainfall, 5 from groundwater and 5 from surface water) were selected to determine the isotopic composition of oxygen and hydrogen at the same time of the field study. The results are presented in Table 3. Oxygen-18 and deuterium were analyzed in the Laboratory of Isotope Geochemistry, Department of Geosciences, Tucson, Arizona, USA. Duplicate analyses of δD and $\delta^{18}O$ were with 0.1‰. Standard mean ocean water (SMOW) is adopted as a criterion for measuring H and O isotopic composition. Rozanski and others (1993) developed this SMOW by using the

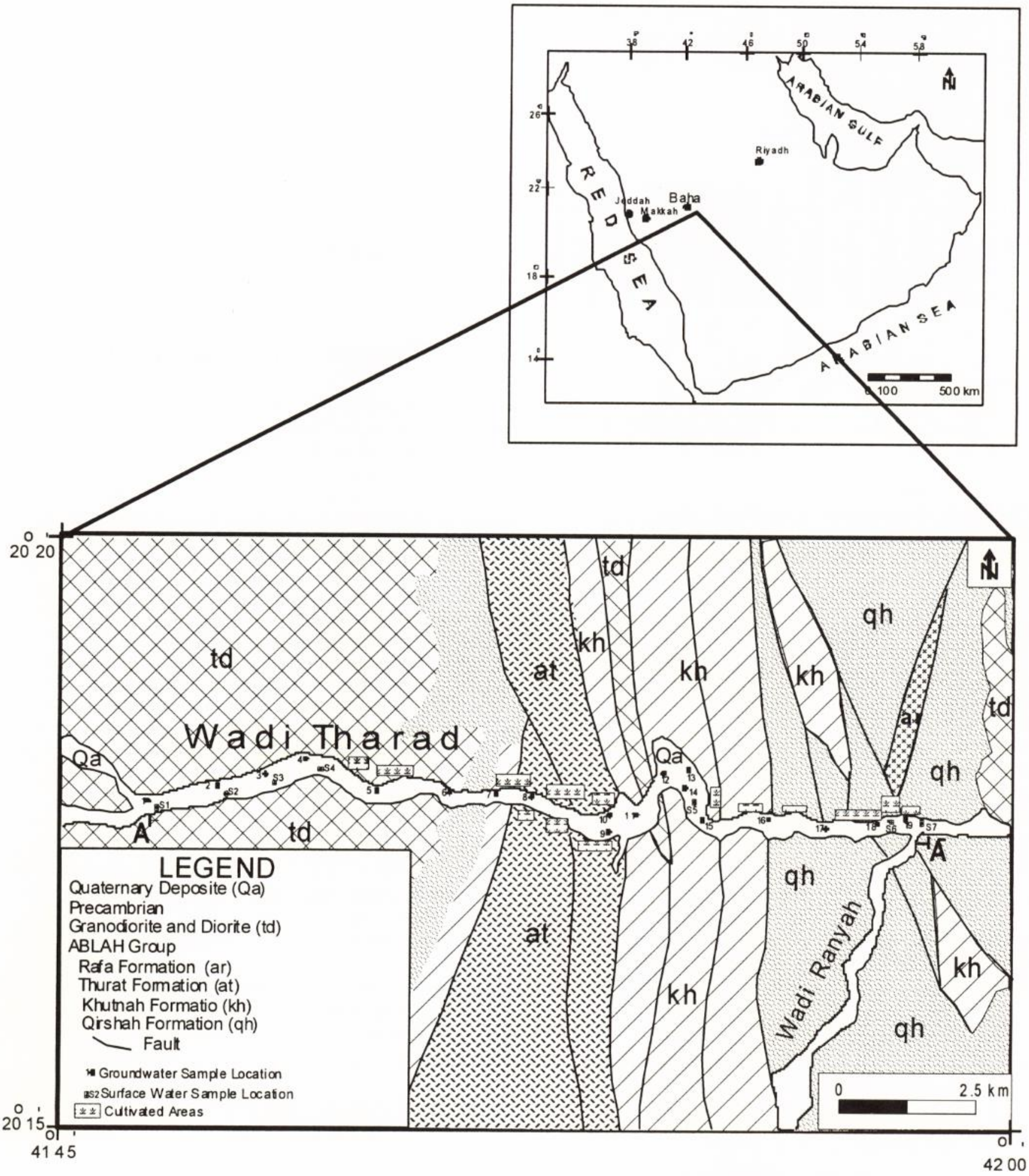


Fig. 1
Geological map of the study area and sampling points

global average precipitation data from IAEA/WMO (International Atomic Energy Agency and World Meteorological Organization) and defined the global meteoric water line (GMWL) as:

$$\delta^2H = 8.13\ \delta^{18}O + 10.8‰$$

The y-intercept value of 10 in the GMWL equation is called the deuterium excess value for this equation. It can be defined as $d=\delta^2H-8\delta^{18}O$. The precise value of the deuterium excess varies climatologically and geographically. Consequently, different equations have been derived from different regions. The global average of deuterium excess is 10, however, its values typically range from 0 to 20. The major controlling factors of d-excess, which operate on sea

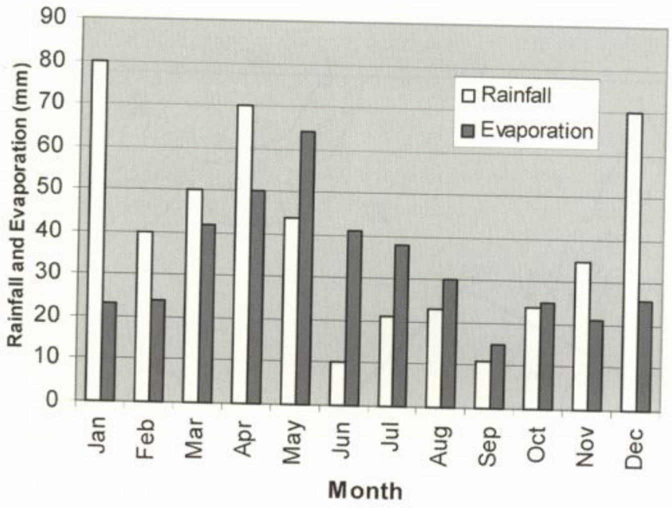


Fig. 2
Mean monthly rainfall and evaporation at Baha station (1980–2000)

surface, are relative humidity, varying temperature, and wind speed (Kondoh and Shimada 1997).

Furthermore, five rainfall samples were collected also at different times around the study area. Special treatment was given to the rainfall samples, which were selected for chloride ion concentrations. The chloride ion is used for recharge studies because of its conservative nature. The ion neither leaches from nor is absorbed by aquifer sediments, and it does not participate in any chemical reaction. Two principle types of recharge are recognized: water added by vertical percolation of rainfall through the unsaturated zone to groundwater and percolation to groundwater following runoff. In Wadi Tharad, under the assumptions that chloride is the conservative ion and rainwater the only source of chloride (Cl), the relation between rainfall and recharge (Ting and others 1998; Wood 1999) is established as:

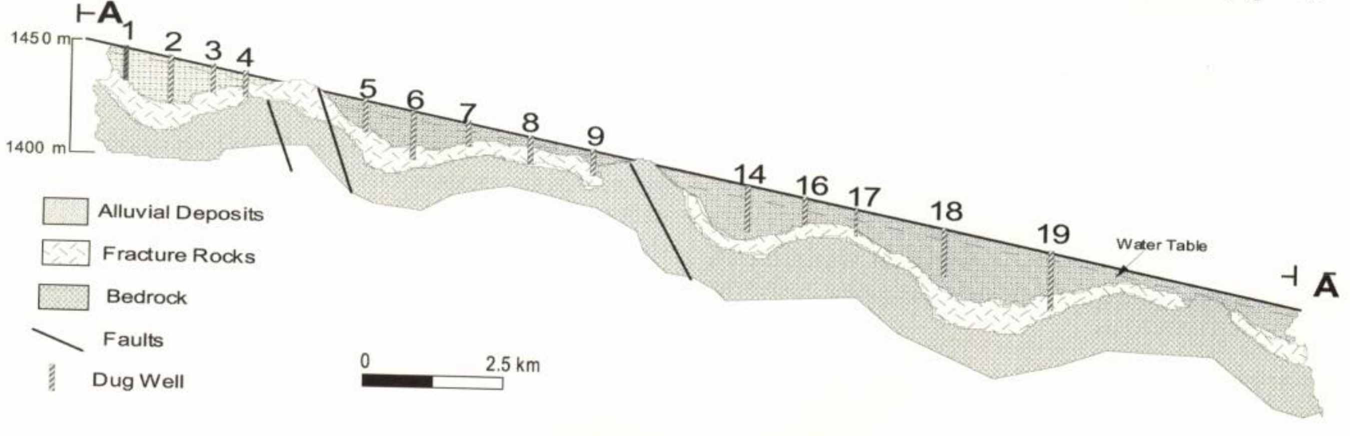
$$q = R_{\mathrm{eff}}\mathrm{Cl}_{\mathrm{p}}/\mathrm{Cl}_{\mathrm{gw}} \tag{1}$$

where q is the recharge (mm/year), R_{eff} is the effective rainfall (mm/year), Cl_{p} is the average chloride concentration of rainfall (mg/l), and Cl_{gw} is the average chloride concentration of groundwater. Due to the long-term aridity in the study area, effective rainfall is taken for winter and spring seasons (Fig. 2). However, this basic equation is refined by adding some statistical properties taking into account the temporal and spatial variation of these variables as (Subyani 1997, unpublished data)

$$\overline{\mathrm{q}} = \left(\overline{\mathrm{R}}\ \overline{\mathrm{Cl}}_{\mathrm{r}} + \hat{\rho}_{\mathrm{RCl_r}}\hat{\sigma}_{\mathrm{R}}\hat{\sigma}_{\mathrm{CL_r}}\right)/\overline{\mathrm{Cl}}_{\mathrm{gw}} \tag{2}$$

where $\hat{\rho}_{\mathrm{RCl_r}}$ is the correlation coefficient between the rainfall and its chloride concentration; $\hat{\sigma}_{\mathrm{R}}$ and $\hat{\sigma}_{\mathrm{CL_r}}$ are the standard deviations of rainfall and its chloride concentration measurements, respectively.

Fig. 3
Hydrogeological cross section of Wadi Tharad system



Zonation of hydrochemical types

Based on long-term observation of groundwater hydrochemistry, the hydrochemical types show an obvious zonation from the upper to lower reaches according to Lloyd and Heathcote (1985). It changes from HCO_3^- through to SO_4^{2-} and to Cl^- water. HCO_3^-–Ca^{2+} water is mainly in the upper reach where the recharge zone is located. Meteoric water infiltrates through the fracture rocks and alluvial deposits in some parts of the wadi (Fig. 4). At places of insufficient deposits, water appears on the surface and returns in a short time and distance to the aquifer. In the upper reach of the wadi, water reaction with rocks is very weak (rocks are mainly plutonics), which leads to a low mineralized hydrocarbonate water. In the middle reach of the wadi, where the metasediments are the host rocks, water is transformed to HCO_3^-–Ca^{2+}–Na^+ water. In the lower reach of the wadi, due to the reaction with metamorphic rocks, water is transformed to SO_4^{2-}–Na^+–Cl water (Fig. 5a).

As a result of surface-water chemistry, HCO_3^-–Na^+ type occurs along the narrow bank of the wadi in the upper reach, and changes to SO_4^{2-}–Cl^- type in the lower reach. This surface-water zonation is consistent with other groundwater types.

The hydrochemical features of groundwater and surface water are very complex because of the subsurface geology (alluvial and fractured aquifers). In addition, a high evaporation rate under an arid climate causes an increase in mineralization of surface and groundwater in short distances due to the reaction with host rocks (Fig. 5b).

Table 1
Chemical analysis of major cations and ions in Wadi Tharad. The samples S1 to S7 are from surface water (see Fig. 1)

Well no.	SO_4	Cl	HCO_3	Na	K	Ca	Mg	Temp	pH	EC	SI_{cal}	SI_{dol}	SI_{hal}	SI_{gyp}
S1	70	71.5	177	31	2.31	70	16	23.7	7.8	520	0.38	0.45	−1.99	−1.77
S2	102	117	156	40.2	3.12	76.2	21.4	22.5	7.45	680	−0.02	−0.28	−1.83	−1.6
S3	102	97.6	212	42.6	3.84	86	20.4	24.6	7.8	830	0.53	0.77	−1.79	−1.57
S4	89.6	80.2	221	40	3.32	86.4	19.5	22.1	7.5	790	0.23	0.11	−1.84	−1.61
S5	122	132	135	67.6	7.16	61.2	19.9	22.8	7.6	800	−0.03	−0.24	−1.84	−1.61
S6	176	139	178	81	6.12	80.2	28.2	23.6	7.3	910	−0.12	−0.36	−1.63	−1.4
S7	468	540	187	282	11.2	210	62.8	25.9	7.35	2150	0.26	0.34	−1.03	−0.82
1	42	57	198	24.2	3.38	62.8	12.4	24.3	7.59	531	0.2	0.04	−2.22	−2.0
2	79.2	88	221	44.8	3.92	96.4	21.4	27.1	7.83	862	0.65	1.03	−1.85	−1.64
3	72.4	99	194	39	3.8	72.8	18.5	26.7	7.65	711	0.32	0.41	−1.97	−1.76
4	57.6	81	145	36.8	3.76	47	18.3	28.1	7.26	850	−0.33	−0.7	−2.2	−2.0
5	73.6	99.3	185	50.2	4.34	62.8	22.4	25.5	7.6	710	0.17	0.24	−2.03	−1.81
6	79.6	105	182	54.2	3.72	41.6	23.6	29.3	7.3	700	−0.26	−0.37	−2.14	−1.94
7	68	87.1	185	38.8	3.46	56.2	18	28.5	7.2	680	−0.22	−0.55	−2.08	−1.87
8	86	101	179	47.4	3.4	59	21.8	25.3	7.5	750	0.03	−0.03	−1.99	−1.77
9	73.6	83.7	123	35.2	3.34	48.4	20.3	28.5	7.6	650	−0.06	−0.11	−2.09	−1.89
10	81.6	102	117	43.8	3.7	49.4	22.4	29.5	7.38	630	−0.29	−0.52	−2.05	−1.85
11	84	87.1	143	47.2	3.44	57.8	22.4	25.1	7.52	580	−0.06	−0.18	−2	−1.78
12	124	122	178	79	3.94	70.2	24.6	27.3	7.7	900	0.29	0.5	−1.79	−1.58
13	84.8	87.1	162	45	3.64	65.4	23.2	28.1	7.55	740	0.11	0.16	−1.95	−1.74
14	99.6	99.3	162	62.2	3.76	59.8	20.2	24.4	7.4	780	−0.13	−0.39	−1.92	−1.7
15	99.6	87.1	152	65.6	3.8	49.8	19	31.5	7.38	680	−0.16	−0.32	−1.96	−1.77
16	115	105	155	66	4.3	62.8	21.2	28.6	7.61	780	0.13	0.17	−1.84	−1.64
17	246	232	115	147	8.28	81.4	33.4	27.2	7.11	1150	−0.48	−0.98	−1.52	−1.31
18	508	410	150	346	8.64	114	52.6	24.5	7.45	1980	−0.02	−0.03	−1.22	−1
19	464	476	138	406	6.9	83.2	56.2	30.6	7.8	2230	0.24	0.7	−1.37	−1.17
Mean	141	147	167	87	4.64	73.5	25.4	26.4	7.51	907	0.039	−0.02	−1.85	−1.63
Median	87.8	100	170	47.3	3.78	64.1	21.4	26.3	7.51	765	−0.02	−0.03	−1.92	−1.7
St. dev	131	126	29.8	99.3	2.11	32.5	12.4	2.56	0.19	467	0.269	0.479	0.294	0.296
Coef. var	0.93	0.86	0.18	1.14	0.45	0.44	0.49	0.1	0.03	0.51	6.856	−20.3	−0.16	−0.18
Skew. co.	2.2	2.39	0.02	2.46	1.83	3.19	2.2	0.16	−.09	2.23	0.298	0.295	1.365	1.318

Table 2
Deuterium and Oxygen-18 compositions in the study area

Water type	Sample no.	$\delta^{18}O$ ‰	$\delta^{2}H$ ‰	d-excess
Rainfall	1	−2.62	−9.2	11.76
	2	−2.24	−7.32	10.6
	3	−2.22	−8.21	9.55
	4	−1.92	−5.48	9.88
	5	−1.48	−2.00	9.84
Surface water	S1	−1.8	−10	4.4
	S2	−1.7	−11	2.6
	S4	−2.0	−10	6
	S5	−1.4	−9	2.2
	S6	−1.8	−7	7.4
Groundwater	1	−2.8	−14	8.4
	3	−2.4	−13	6.2
	6	−1.9	−9	6.2
	12	−1.9	−10	5.2
	18	−2.0	−11	5

Table 3
Statistical summary of mean monthly rainfall and rainfall chloride concentration in Wadi Tharad

Month	Mean monthly rainfall (mm)	Rainfall Cl con (mg/l)
Jan	80	7.5
Feb	40	7
March	50	8
April	70	9.5
Nov	35	10
Dec	70	9
Sum	345	51
Average	57.5	8.5
Corr. Coef.		−0.07
STD	16.8	1.08

The behavior of ion concentrations in surface and groundwater, in general, are the same. However, in the final reach of the wadi, SO_4^{2-}, Cl^-, Na^+ and Ca^{2+} increase rapidly owing to the mixing of water with other tributaries (Fig. 1).

Results and discussion

The isotopes of oxygen $\delta^{18}O$ and hydrogen $\delta^{2}H$ are a sensitive tracer and widely used in studying the natural water circulation and groundwater movement. The isotope data of the rainfall, surface water and groundwater are presented in Table 2. The $\delta^{18}O$ and $\delta^{2}H$ of the rainfall samples in the Wadi Tharad area range between −2.62 to −1.48‰ and from −9.2 to −2.0‰, respectively. The average values of $\delta^{18}O$ and $\delta^{2}H$ in the rainfall are −2.1±0.38‰ and −6.442±2.54‰, respectively. The d-excess range between 9.55 and 11.76‰ indicates a seasonal isotopic variation due to different rainfall sources. The five rainfall samples define the best-fit line of $\delta^{2}H=6.51\ \delta^{18}O+7.21$. This relationship has a correlation coefficient of $r=0.97$ and a standard error of 0.72‰. This line closely resembles the SMOW line (Fig. 6).

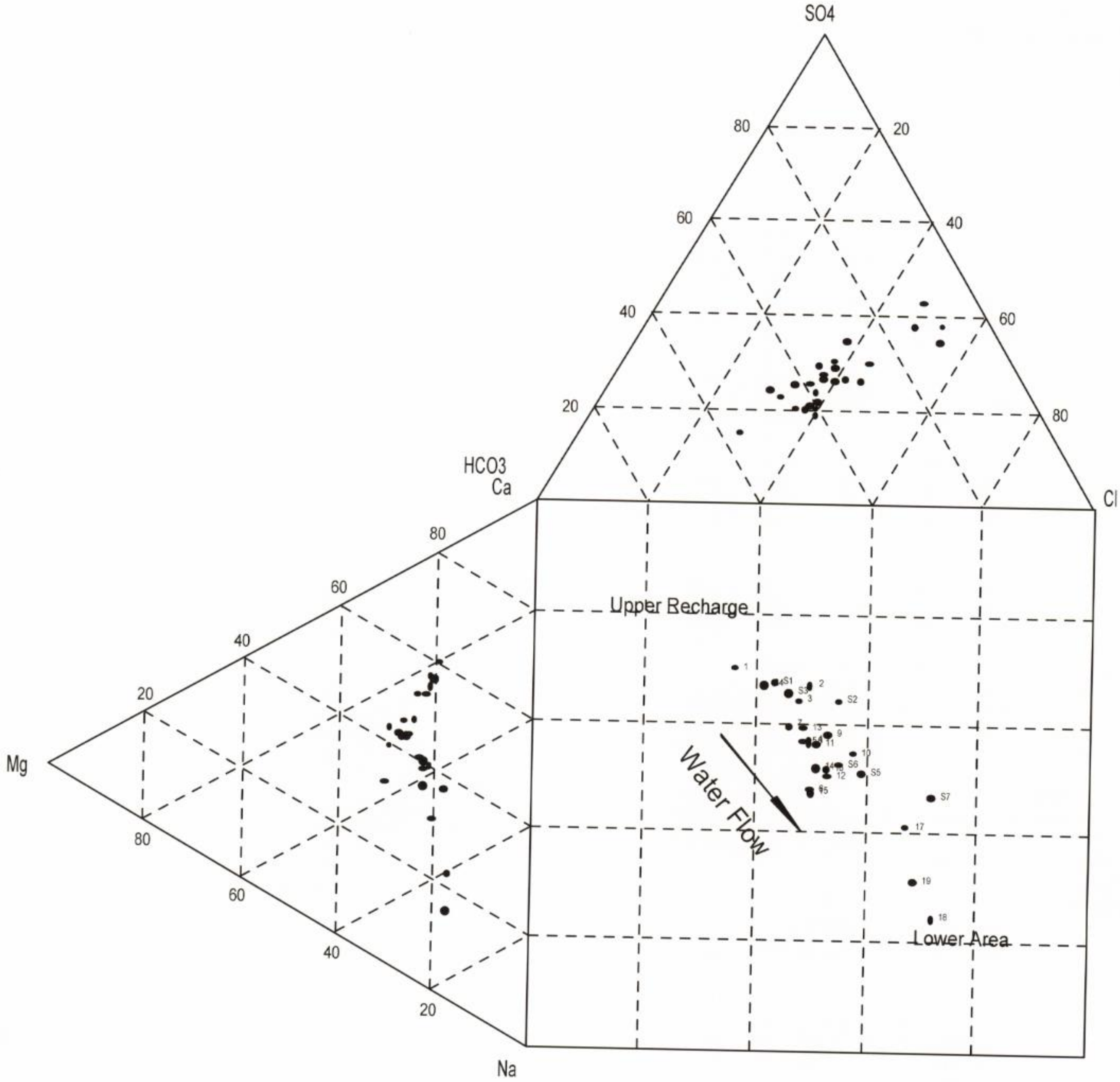


Fig. 4
Water types on Durov diagram

Wadi Tharad groundwater has $\delta^{18}O$ values in the range of -2.8 to -1.9‰ and δ^2H from -14.0 to −9.0‰. The average values of $\delta^{18}O$ and δ^2H in the groundwater are −2.2±0.35‰ and −11.4±1.85‰, respectively. The d-excess ranges between 5.0 and 8.4‰. The best-fit regression line of groundwater is $\delta^2H=5\ \delta^{18}O-0.4$. This relationship has a correlation coefficient of r =0.95 and a standard error of SD as 0.75‰ (Fig. 6).

The $\delta^{18}O$ and δ^2H compositions of surface water range between -2.8 to −1.9‰ and -14.0 to −9.0‰, respectively. The d-excess ranges between 2.2 and 7.4‰. The best-fit regression line of surface water is $\delta^2H=0.6\ \delta^{18}O-8.3$. This relationship has an insignificant correlation coefficient of r=0.1 and a standard error of estimate for SD as 0.75‰ (Fig. 6).

Distribution of $\delta^{18}O$ and δ^2H values of surface and groundwater has an obvious tendency for the average of $\delta^{18}O$ and δ^2H to increase from surface water to groundwater. Both surface and groundwater show shifting samples towards heavier values of $\delta^{18}O$, which is a typical phenomenon prior to recharge in semi-arid areas (Gat 1981). The strong evaporation in the summer recharge is the result of runoff flow over the hot landscape. As in an arid region, water can be lost by evaporation from the unsaturated zone or from the water table. Most samples show the evaporative losses.

The spatial distribution of isotopic compositions in Wadi Tharad shows the presence of several groundwater heads within the fractured networks and weathered zones of the

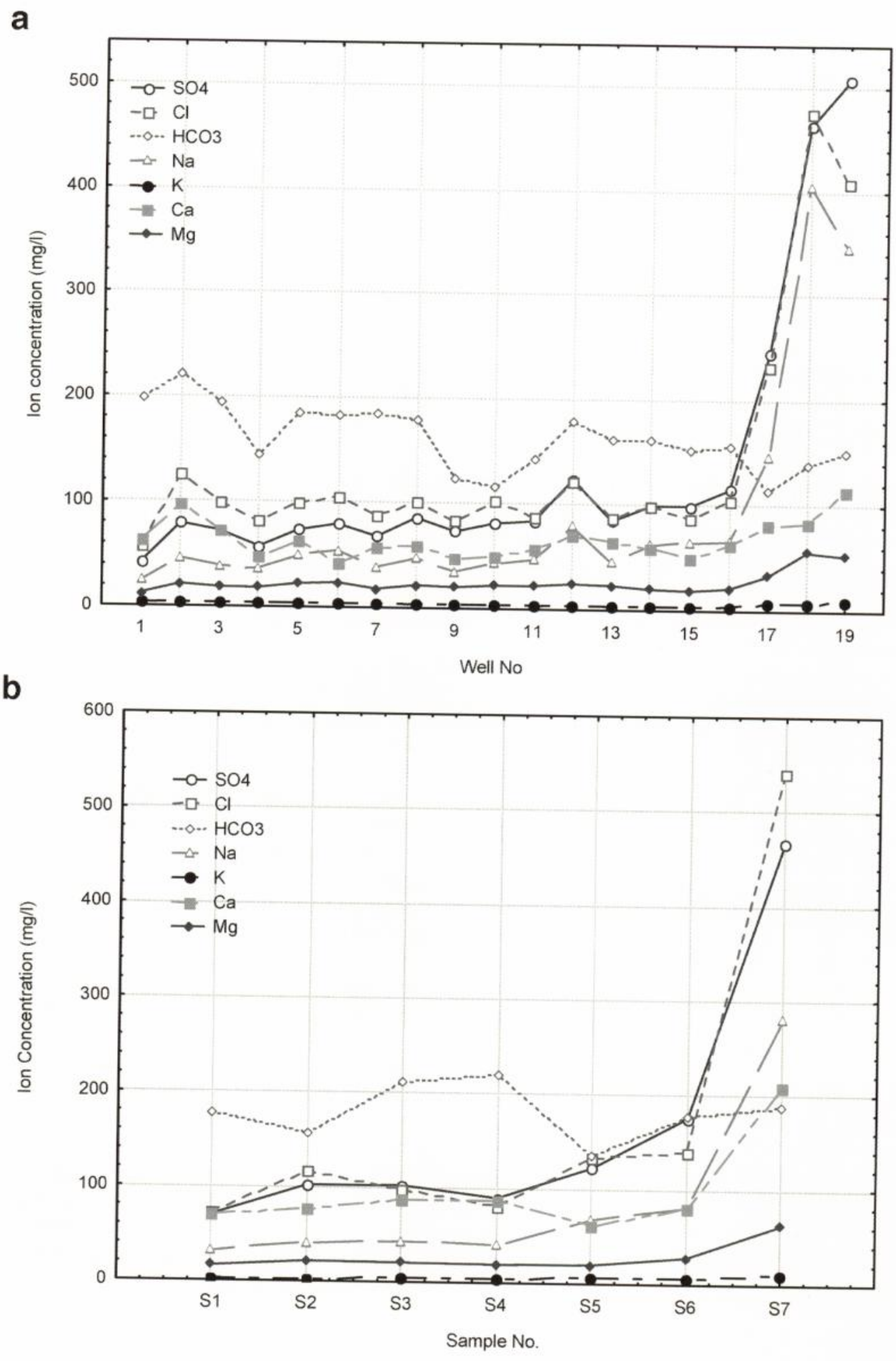


Fig. 5
a Major ion concentration of groundwater along wadi channel. **b** Major ion concentration of surface water along wadi channel

hard rock aquifer in the upstream reaches of the wadi. The random distribution of the lighter and heavy isotopes in the wadi course indicates that the wadi alluvial is the most productive aquifer system. However, the upper reaches of the wadi are the main recharge areas.

Chemical analysis (Table 1) and field investigations of groundwater and surface water indicates that there is no significant difference in ion concentrations (Fig. 5a,b). The water table is very shallow and surface water appears and disappears in some spots in the wadi depending on the alluvial thickness (Fig. 3). Thus it can be assumed that isotopic compositions are the same for groundwater and surface water. However, the best-fit regression line of groundwater and surface water is $\delta^2H=4.1\ \delta^{18}O-2.4$. This relationship has a correlation coefficient of $r=0.8$ and a standard error of estimate for SD as 1.3‰.

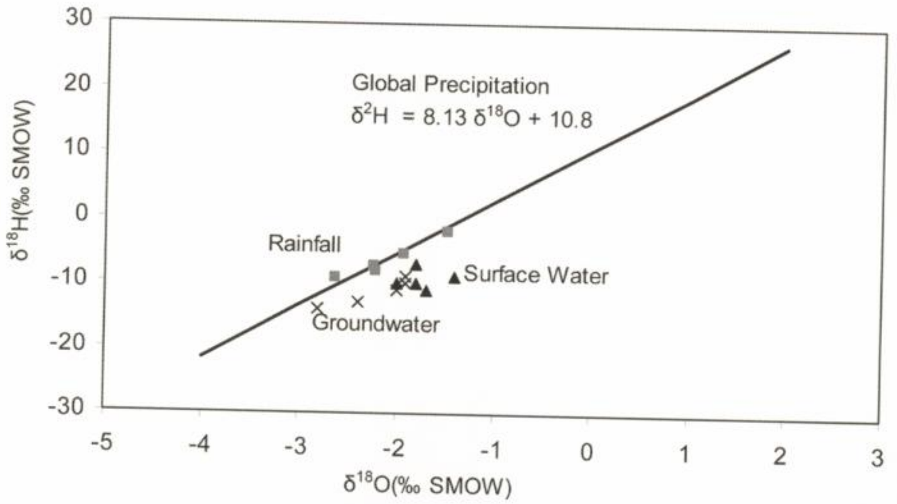


Fig. 6
Isotopic compositions of H and O in the study area

Groundwater chemistry exchanges matter with the various minerals and gases within the aquifer. It can be taken in the form of dissolution or precipitation of the minerals. Equilibrium calculations are most commonly used to assess whether the groundwater 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 the SI<1, the minerals will be dissolved; and when the SI is >1, the minerals will be deposited. SI indices of calcite and dolomite were calculated for the surface and groundwater in Wadi Tharad as shown in Table 2. About 60% of samples have positive calcite and dolomite indices, which are slightly oversaturated, where the rest of the samples are negatively unsaturated. In general, the mean for calcite and dolomite is about equilibrium (e.g., zero value). For halite and gypsum, all indices are negative, which indicates undersaturation (Freeze and Cherry 1989).

Conclusions

In Wadi Tharad, recharge takes place from intensive rainfall of short durations through the alluvial deposits and the weathered and fractured hard rocks of Baha Escarpment Mountain chain due to the steep gradient and low permeability of the hard rocks. Runoff plays a significant role in the hydrological balance as a source of recharge to the alluvial and fractured rocks. The random distribution of the lighter and heavy isotopes in the wadi course indicates that the wadi alluvial is also a most productive aquifer system. However, the upper reaches of Wadi Tharad are the main recharge areas for the high rate of groundwater recharge.

The chloride-mass balance method is applied to estimate the recharge flux for Wadi Tharad aquifers by using the best possible values of the three measured components, i.e., effective rainfall, chloride concentrations in rainfalls, and groundwater. Rainfall is highly variable in space as well as time in the study areas. However, effective monthly rainfall values correlated with monthly chloride concentration and the groundwater samples from the recharge area in the wadi are used. Cl concentrations in rainfall and groundwater are statistically evaluated (Table 3). Equation (2) is employed to calculate the recharge flux to the aquifer as:

$$\bar{q} = (57.5 * 8.5 - 0.06 * 16.8 * 1.08)/80 = 6.1 \text{ mm/year}$$

This value represents about 11% of rainfall, which is acceptable for arid and semi-arid regions. In addition, due to the negative and insignificant correlation between monthly rainfall and monthly chloride concentration (−0.07), Eq. 1 gives the same result as Eq. 2. The aquifer recharge in these areas is mainly from rainfall-runoff in the form of winter and spring storms in the adjacent Baha Escarpment Mountains. The main governing recharge factors in these areas are the high infiltration capacity of the unsaturated zone and the shallow water table depths, which are mainly composed of weathered and fractured rocks.

The hydrochemical types show an obvious zonation from the upper to lower reaches. It changes from HCO_3^- through to SO_4^{2-} and to Cl^- water. HCO_3^-–Ca^{2+} water is mainly in the upper reach where the recharge zone is located. About 60% of the samples have positive calcite and dolomite indices, which are slightly oversaturated, where the remainder of samples is negatively unsaturated. For halite and gypsum all indices are negative, which indicates unsaturation. The random distribution of the lighter and heavy isotopes in the wadi course indicates that the wadi alluvial is also a most productive aquifer system. However, the upper reaches of the wadi are the main recharge areas for the high rate of groundwater recharge. The chloride-mass balance method shows that 11% of the effective annual rainfall is recharged to the aquifer.

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