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# Hydrogeology and hydrochemistry of a shallow alluvial aquifer, western Saudi Arabia

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**Abstract** A hydrogeological and hydrochemical study was conducted on a shallow alluvial aquifer, Wadi Wajj, in western Saudi Arabia to assess the influence of protection measures on groundwater quality. The hydrochemistry was assessed up-gradient and down-gradient from potential contamination sources in the main city in dry and wet seasons prior to and after the installation of major drainage and wastewater facilities. Wadi Wajj is an unconfined aquifer where water is stored and transmitted through fractured and weathered bedrock and the overlying alluvial sediments. Natural recharge to the aquifer is about 5% of rainfall-runoff. Hydrochemistry of the aquifer shows temporal and seasonal changes as influenced by protection measures and rainfall runoff. Both groundwater and runoff showed similar chemical signature, which is mostly of chloride-sulfate-bicarbonate and sodium-calcium type. Groundwater downstream of the city, though of poorer quality than upstream, showed significant improvement after the installation of a concrete runoff tunnel and a wastewater treatment plant. Concentrations of many of the groundwater quality indicators (e.g., TDS, coliform bacteria, and nitrate) exceed US Environmental Protection Agency drinking-water standards. Heavy metal content is, however, within allowable limits by local and international standards. The chemical analyses also suggest the strong influence of stream runoff and sewage water on the groundwater quality.

**Résumé** Une étude hydrogéologique et géochimique a été menée sur l'aquifère phréatique alluviale Wadi Wajj dans l'Ouest de l'Arabie Saoudite afin d'évaluer l'influence de mesures de protection sur la qualité de l'eau souterraine. L'hydrogéochimie de l'eau a été étudiée en amont et en

aval de sources potentielles de contamination dans la ville principale, pendant les saisons sèches et humides, avant et après l'installation de réseaux majeurs de drainage et d'eaux usées. L'aquifère Wadi Wajj est libre, l'eau est stockée et s'écoule dans les sédiments alluviaux et dans le socle fracturé et altéré sous-jacent. La recharge naturelle de l'aquifère représente 5% des eaux de pluie et de ruissellement. L'hydrogéochimie de l'eau de l'aquifère montre que les changements saisonniers et temporaires sont influencés par les mesures de protection et par le ruissellement des eaux pluviales. L'eau souterraine et l'eau de ruissellement ont présenté le même faciès chimique, de type bicarbonatée-sulfatée-chlorée et calco-sodique. En aval de la ville, l'eau souterraine, bien que de moins bonne qualité qu'en amont, a présenté une nette amélioration après l'installation d'un système de récupération et d'une station de traitement des eaux usées. Les concentrations de plusieurs paramètres indicateurs de la qualité de l'eau (tels que la charge totale dissoute, les coliformes, et les nitrates) dépassent les normes de potabilité de l'eau de consommation de l'agence américaine de la protection de l'environnement. Les teneurs en métaux lourds en revanche n'excèdent pas les normes locales et internationales. Les analyses chimiques indiquent aussi l'influence importante de l'écoulement par ruissellement et des eaux usées sur la qualité de l'eau souterraine.

**Resumen** Un estudio hidrogeológico e hidroquímico fue hecho en un acuífero somero de Wadi Wajj, en Arabia Saudi oeste para evaluar la influencia de medidas de protección en la calidad del agua subterránea. La hidroquímica fue evaluada gradiente-arriba y gradiente-abajo de las fuentes potenciales de contaminación de la ciudad principal durante las estaciones seca y lluviosa, antes y después de la instalación de sistemas principales de drenaje y aguas servidas. Wadi Wajj es un acuífero no-confinado donde el agua es almacenada y transmitida a través de roca fracturada y meteorizada, y los sedimentos aluviales que le sobreyacen. La recarga natural del acuífero es de cerca del 5% de la precipitación-escorrentía. La hidroquímica del acuífero muestra cambios temporales y estacionales influenciados por las medidas de protección y la escorrentía de precipitación. Ambas, agua subterránea y escorrentía mostraron composición química similar, siendo mayoritariamente de tipos cloruro-sulfato-bicarbonato y sodio-calcio. El agua subterránea aguas arriba de la ciudad, aunque de calidad

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más pobre que aguas abajo, mostró significativa mejoría después de la instalación de un túnel de concreto para escorrentía y una planta de tratamiento de aguas servidas. Las concentraciones de muchos de los indicadores de calidad de agua subterránea (e.g., STD, coliformes, y nitrato) exceden los estándares de la Agencia de Protección Ambiental USA para agua potable. El contenido de metales pesados está, sin embargo, dentro de los límites permisibles de los estándares locales e internacionales. Los análisis químicos también sugieren la fuerte influencia de la escorrentía y aguas residuales en la calidad del agua subterránea.

**Keywords** Alluvial aquifers · Hydrochemistry · Groundwater management · Groundwater protection · Saudi Arabia

## Introduction

In a typical arid country like Saudi Arabia, groundwater is the major source of water for most uses. The availability and quality of groundwater resources have been affected by activities and projects associated with rapid development in the kingdom during the past several decades. Groundwater conservation and protection measures have been generally overlooked in the majority of the practices. Environmental Impact Assessment (EIA) studies have been implemented as a requirement for new projects only recently.

Most of the groundwater resources in Saudi Arabia exist in two main sources: deep nonrenewable groundwater in aquifers located mostly in the sedimentary cover engulfing the Arabian Shield (a region of Precambrian basement covering about the western third of Saudi Arabia), and renewable groundwater in fractured Precambrian basement and shallow alluvial aquifers located mostly in the western and southwestern parts of the country. Shallow alluvial aquifers, restricted mainly to major *wadis* (a wadi is a dry river bed with seasonal runoff) are the major source for water in western Saudi Arabia. Water from these aquifers is used for irrigation and domestic purposes, and for most of the rural areas, for drinking. Though limited in quantity, groundwater in the shallow alluvial aquifers can be replenished more frequently and more rapidly than the deep sedimentary, mostly confined, aquifers. However, these aquifers are sensitive to human activities because of the shallow water table coupled with frequent runoff, and proximity of the aquifers to major cities and towns with large population densities. Therefore, groundwater contamination is always a possibility in shallow alluvial aquifers in the vicinity of major cities.

Wadi Wajj is a major drainage system in western Saudi Arabia. The wadi collects rainfall runoff from the highlands south and west of Taif during rainy seasons and flows northeastward through the city and ends in the interior plains (Fig. 1). With a length of 110 km, Wadi Wajj is underlain by a shallow alluvial aquifer of limited lateral extent. Groundwater from the aquifer is the main source for irrigation and some domestic uses in the area.

Downstream of the city, the Wadi Wajj hosts several agricultural and municipal activities that can be a source of contamination to the aquifer such as poultry farms, private agricultural farms, a wastewater treatment plant with related activities, and settlements along the wadi banks. Part of Taif sewage system and storm runoff releases water just north of the city to the downstream part of the wadi.

This study was aimed mainly at evaluating both the aquifer hydraulic characteristics and the groundwater hydrochemistry and variation in groundwater quality both upstream and downstream of the city to assess the influence of the protection projects. The groundwater quality of the aquifer and its suitability for drinking and irrigation purposes was also assessed.

## Study area

The study area is located in the Taif region of western Saudi Arabia and is roughly bounded by latitudes 21°00' and 21°30'N and longitudes 40°15' and 40°35'E (Fig. 1). Saudi Arabia lies within one of the world's great desert belts which are characterized by high temperatures and semi-arid to extremely arid conditions. There are no permanent streams, but frequent runoffs do occur where storm water in flash floods is funneled through wadis, and the floods seldom flow for more than a few days continuously. The average annual precipitation is around 268 mm and the average temperature range is 20–39°C in summer and 6–29°C in winter. Topographic elevations in the study area range from 1,400 to more than 2,000 m above sea level (masl) with a relief of about 15 m/km from SW to NE.

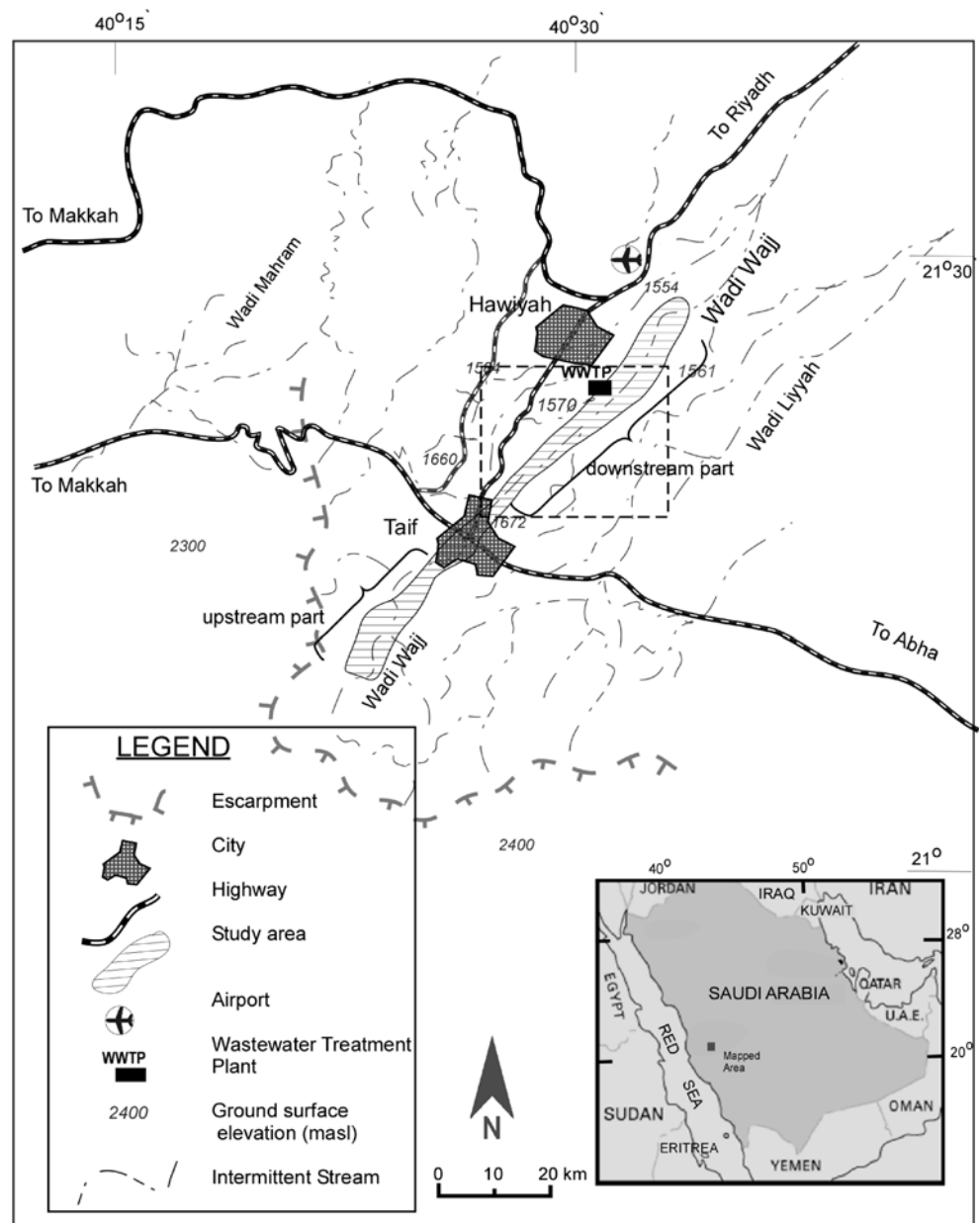
## General geological setting

The study area is part of the Arabian Shield, which is made up of Precambrian igneous and metamorphic rocks. The dominant rock units present in the area are metamorphosed lavas and volcanoclastic rocks (Moore and Al-Rehaili 1989). The surface geologic units of the area are divided into three parts: metamorphic belt, granites, and dikes in addition to Quaternary deposits in low lands (Andreasson et al. 1977; Ghurm 1980). Amphibolite-schist is the oldest rock within the Wadi Wajj area. The upper reaches of the wadi are dominated by quartz mica schists and the lower reaches area is dominated by granitic rocks. Numerous dikes of granitic compositions intrude older igneous and metamorphic rocks. Wadi Wajj floor is filled by coarse to fine-grained sediments, and depth to the bedrock varies from a few meters to about 20 m.

## Hydrogeology

Wadi Wajj drainage basin is a fourth order catchment, according to the classification originally described by

**Fig. 1** Location map of the study area; *inset map* shows the general location of the city of Taif in western Saudi Arabia. Area within the *dashed square* is shown in a separate map (for the locations of water samples see [Electronic supplementary material](#))



Horton (1945) and revised by Strahler (1957). In this classification, the order of a stream indicates the position of a particular stream section in the hierarchy of a stream network. A first-order system is a single stream that has no tributaries feeding it, and a second-order stream forms at the junction of a first-order stream and so forth. The catchment area of Wadi Wajj is narrow, typical of drainage systems in mountainous areas, with a total area of about 1,605 km<sup>2</sup>. The catchment area of the upstream part alone (south of the city of Taif) is about 803 km<sup>2</sup>.

The general hydrogeology of the area has been studied by several investigators. Al-Saqaaby (1974) and Al-Hajri (1974) studied the geology and hydrogeology of upper Wadi Wajj and the surrounding areas. Italconsult (1967) studied the characteristic of the aquifer for water supply. A relatively detailed hydrogeologic study was conducted on the aquifer by Ghurm (1980). Aborizaiza et al. (1989)

covered the watershed of Wadi Wajj in a study of the water resources potential of the western region of Saudi Arabia. Abdulrazzak et al. (1992) studied the natural groundwater recharge in some wadis of western Saudi Arabia including Wadi Wajj. None of the available literature discussed the influence of the protection measures on the groundwater quality or the hydrochemical variations of the aquifer.

#### **Aquifer framework and hydraulic characteristics**

Field surveys were conducted to study the geology, measure groundwater levels in more than 30 hand-dug wells, and to collect sediment samples for grain-size analysis. A few pumping tests were also performed for permeability calculations. Wadi Wajj is a shallow unconfined aquifer which consists mainly of two hydrologically connected layers: (1)

the highly permeable and highly porous alluvium deposits that consist mainly of gravels and sands, and (2) fractured and weathered crystalline rocks at the bottom of the aquifer. The dense un-weathered crystalline rocks form the bedrock of the aquifer.

The thickness of the alluvial deposits varies from a few meters to about 20 m. The aquifer has a limited lateral extent. The saturated thickness of the alluvium changes throughout the aquifer due to variation in bedrock topography and lateral extent of the aquifer. Groundwater is stored and transmitted through the fractured and weathered bedrock and the overlying alluvial deposits. The average S–N topographic gradient of the wadi is about 10 m/km.

The wadi-fill in the study area is moderately to poorly sorted and is composed mostly of fine to coarse-sized sand. Hydraulic conductivity ( $K$ ) estimated from the grain-size distribution curve using the Hazen method (Fetter, 2001) ranges between 20 and 54 m/day, which lies in the range expected for similar environments (Anderson and Woessner 1995; Domenico and Schwartz 1998; Fetter 2001). Two pumping tests yielded hydraulic conductivity values of 10 and 40 m/day which is also comparable to the hydraulic conductivity estimation using the Hazen method. The hydraulic gradient in the study area varies between 0.02 and 0.08, with an overall average gradient of 0.03. Depth to the water table ranges from 4 to 20 m below ground surface and gradually approaches the ground surface in the lower reaches.

Discharge from the aquifer takes place through pumping and inter-basin flow and by evaporation in places where the water table is close to the ground surface. The upstream part of the wadi is the principal area of recharge but surface recharge can also take place in other parts of the aquifer. Wadi Wajj carries water for a few days, but most water is lost through direct infiltration and evaporation. Even in seasons of no rainfall, runoff of some magnitude is observed in the wadi. This additional runoff comes, most probably, from leaks in the sewage system and septic tanks. The shallow water table and coarse alluvial deposit increase the chances of direct recharge to the alluvial aquifer from runoff. Estimation of direct runoff is discussed below.

### Recharge estimation

In arid and semi-arid regions, the recharge component in any groundwater balance assessment presents difficulties for direct measurement in the field. Recharge to shallow alluvial aquifers usually occurs from infiltration of surface runoff through the wadi bed (Abdulrazzak et al. 1992). The amount of recharge is dependent on the frequency of rainfall-runoff which is characterized by large temporal and spatial variations. About 9–58% of the mean annual runoff converts to recharge in different wadis of Saudi Arabia (Abdulrazzak et al. 1992). This large variation of recharge expressed as a percentage of runoff can be due to a combination of the estimation methodology, characteristics of wadi-bed material, depth to water table, available storage and soil moisture condition. Wood (1996) estimates

that recharge rate in arid and semiarid areas typically ranges from 2 to 4% of average precipitation. Comparatively, shallow alluvial aquifers are expected to have higher recharge rates as a percentage of runoff due to their high hydraulic conductivities and shallow water tables. Average annual rainfall in the study area is 268 mm and gross runoff for the upstream catchment (from field measurements) is  $35.8 \times 10^6 \text{ m}^3/\text{year}$  (Ghurm 1980). Thus 16.6% of rainfall volume flows as runoff.

Two simple methods of recharge estimation are commonly used for arid and semi-arid regions; the water budget (WB) and the chloride mass balance (CMB). The WB method is an arithmetic solution of the hydrologic equation;

$$\text{INPUT} - \text{OUTPUT} = \text{CHANGE IN STORAGE} \quad (1)$$

The input includes natural and induced recharge, and the output includes evapotranspiration, pumping and base-flow outside the basin. Natural recharge is usually estimated by accounting for all other components in Eq. (1) above. It was not possible to apply the WB method for recharge estimation in this study due to lack of records of abstractions from the aquifer and difficulty in estimating the base-flow out of the aquifer.

The CMB method, which provides a direct estimation procedure of the groundwater recharge, is based on the assumption that the chloride concentrations in the rainfall and recharge are in steady state balance, i.e., input is equal to output without chloride storage change during a time period. The CMB method has been shown to yield regional values of groundwater recharge comparable to those obtained by physically based methods, given that certain assumptions and conditions are met (see Wood 1996 for a review of the method).

The CMB method requires only knowledge of annual precipitation, chloride concentration in precipitation and chloride concentration in groundwater. The fundamental equation of CMB method was proposed by Wood and Sanford (1995);

$$Q = \frac{R \times Cl_{\text{wav}}}{Cl_{\text{gw}}} \quad (2)$$

where,  $Q$ =recharge flux ( $L T^{-1}$ ),  $R$ =average annual rainfall ( $L T^{-1}$ ),  $Cl_{\text{wav}}$ =weighted average chloride concentration in rainfall ( $ML^{-3}$ ),  $Cl_{\text{gw}}$ =average chloride concentration in groundwater ( $ML^{-3}$ ),  $M$ =mass unit,  $L$ =length unit, and  $T$ =time unit.

The regional precipitation-weighted chloride concentration of the mountainous area along the western edge of Saudi Arabia ranges from 6 to 12 mg/l (Bazuhair and Wood 1996); a value of 9 mg/l is considered for this study. Average chloride concentration in groundwater from the upstream part of the Wadi Wajj aquifer is 210 mg/l. From CMB Eq. (2) Wadi Wajj has a recharge of 4.8% of precipitation. However, since the CMB calculation above is based only on data from the upstream part, the recharge rate is expected to be more in the lower parts of the

aquifer as more runoff is observed due to sewerage leaks and irrigation return.

## Hydrochemistry

### Methodology

Downstream water samples were collected from the stream runoff and groundwater wells during two field visits in the wet and dry seasons of 2003 (May and August, respectively). Sampling was done in accordance to the US Environmental Protection Agency guidelines (EPA 2004), and strict consideration was given to individual parameter holding time criteria as outlined by the American Public Health Association (APHA 1995). A total of 51 samples were collected, five of which were from surface runoff along the wadi and the rest from groundwater wells. Electrical conductivity (EC), pH, temperature, dissolved oxygen (DO) and salinity were measured in situ. In the laboratory alkalinity and chloride were measured using titration method. Alkalinity, reported as mg/l of CaCO<sub>3</sub> is multiplied by a factor (the ratio of the equivalent weights of bicarbonate to calcium carbonate) to calculate bicarbonate concentration. A spectrophotometer was used to analyze phosphorous, silica and sulfate content of the samples. Induced Coupled Plasma Mass Spectrometry (ICPMS) was used to measure arsenic (As), boron (B), calcium (Ca<sup>2+</sup>), cadmium (Cd<sup>2+</sup>), cobalt (Co<sup>2+</sup>), iron (Fe<sup>2+</sup>), potassium (K<sup>+</sup>), magnesium (Mg<sup>2+</sup>), manganese (Mn<sup>2+</sup>), sodium (Na<sup>+</sup>), lead (Pb<sup>2+</sup>), strontium (Sr<sup>2+</sup>), and zinc (Zn<sup>2+</sup>).

Coliform bacteria was detected using a presence-absence (P-A) procedure (APHA 1995).

Standard quality control/ quality assurance methods were used to ensure accuracy in both sampling and laboratory procedures and few samples were excluded from reporting for failing the accuracy criteria. Upstream data were obtained from Al-Thobaity and Al-Shaibani (personal data, 2003), and old geochemical results for both upstream and downstream are taken from Ghurm (1980).

### Current hydrochemical characteristics

The current hydrochemical characteristics of the aquifer are described generally in this section before addressing the hydrochemical variations with time, location, and season. Table 1 is a summary of the geochemical analysis results from this study and the literature. The 2003 data represent the current conditions (Table 2, map of sample locations is provided as [electronic supplementary material](#) with this article). Average groundwater temperature is comparable to the ambient local air temperature (24°C) and has small variation along the groundwater flow path. The higher values of EC are associated with wells away from the main wadi channel, probably indicating a longer residence time, and less circulation with the alluvial aquifer. A linear correlation exists between EC and total dissolved solids (TDS) for the analyzed samples with a mathematical approximation of TDS (mg/l)=0.78 EC (µS/cm).

Although pH values are in the usual range of natural groundwater (Hem 1985), they are relatively low. The

**Table 1** Comparison of the chemical analyses for both groundwater and surface water samples, upstream and downstream of Taif; values are mean concentrations in mg/l, unless indicated otherwise

	Upstream groundwater		Downstream groundwater		Downstream runoff		
	1978 <sup>a</sup>	2003 <sup>b</sup>	1978 <sup>a</sup>	2003 <sup>c</sup>	2003 <sup>c</sup>		
				Wet <sup>d</sup>	Dry <sup>e</sup>	Wet	Dry
TDS	530.6	837	3,149	2,685.4	2097.1	778	1,032
Electrical conductivity (µS/cm)	816.3	1,423	4,844	3,097.5	2,996.1	1,415	1,477
pH				6.50		6.7	
T (°C)				24.5		24.3	
Sodium	47.9	126.7	502.1	335.7	388.7	189	195
Potassium	3.7	7.25	11.1	28.3	14.3	18	11
Calcium	111.7	116	444.7	175.1	137.3	82.4	70
Magnesium	12.6	39.1	77.8	65.6	85.5	33	44
Sulfate	103.3	161.2	607.1	439.05	471.9	200	233
Chloride	110.3	210	1,163.6	555.3	574.4	165	222
Nitrate	NA	78	NA	180.4	60.6	102	56.3
Bicarbonate	264.3	163.7	295.8	211.1	270.1	323.1	243.8
Alkalinity	NA	163.7	NA	170.9	229.2	265.0	200.0
Pb (ppb)	NA	<1	NA	0.25	NA	0.022	NA
Iron	NA	0.05	NA	1.91	ND	0.022	ND
Coliform bacteria (per 100 ml)				93.9	NA		
Biological oxygen demand (BOD)				2.7			5.00
Dissolved oxygen (DO)				0.3			0.04

ND no detection; TDS total dissolved solids; ppb parts per billion.

<sup>a</sup> Ghurm (1980)

<sup>b</sup> Al-Thobaity and Al-Shaibani (2003)

<sup>c</sup> This study

<sup>d</sup> Wet season of 2003

<sup>e</sup> Dry season of 2003

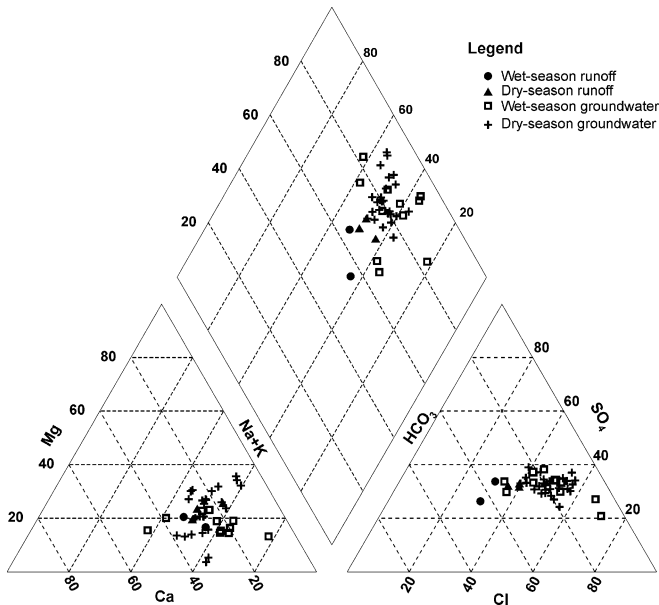
**Table 2** Chemistry of groundwater and runoff in 2003; values are concentrations in mg/l, unless indicated otherwise

Sample no.	Sample no. on map	T (°C)	EC $\mu\text{S}/\text{cm}$	TDS	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Na <sup>+</sup>	K <sup>+</sup>	Cl <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	HCO <sub>3</sub> <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>
Dry-GW-02	1	NA	2,300	1,610	168	38	265	12	340	430	274	46
Dry-GW-03	2	NA	2,200	1,540	136	14	332	13	400	310	274	50
Dry-GW-04	3	NA	2,300	1,610	93	77	280	12	420	320	262	46
Dry-GW-05	4	NA	4,800	3,360	227	187	535	30	1,020	730	329	91
Dry-GW-06	5	NA	3,700	2,590	162	126	450	27	800	530	262	68
Dry-GW-07	6	NA	2,400	1,680	80	89	295	12	428	370	256	54
Dry-GW-08	7	NA	4,200	2,940	178	135	490	27	868	590	262	71
Dry-GW-09	8	NA	2,000	1,400	130	35	260	11	352	310	244	53
Dry-GW-10	9	NA	2,800	1,960	75	107	345	12	508	400	274	77
Dry-GW-11	10	NA	2,700	1,890	34	113	370	10	464	440	274	66
Dry-GW-13	11	NA	3,000	2,100	34	128	395	11	516	460	311	68
Dry-GW-14	12	NA	2,400	1,680	77	79	335	11	408	440	250	50
Dry-GW-15	13	NA	2,400	1,680	88	86	290	14	400	360	323	49
Dry-GW-17	14	NA	2,200	1,540	120	46	325	14	404	350	317	46
Dry-GW-19	15	NA	1,650	1,150	98	42	210	12	256	270	262	47
Dry-GW-20	16	NA	1,800	1,260	96	50	250	12	304	310	274	45
Dry-GW-22	17	NA	1,750	1,225	80	58	225	12	280	310	250	46
Dry-GW-23	18	NA	3,500	2,450	144	118	440	13	700	530	293	80
Dry-GW-24	19	NA	2,100	1,470	128	41	310	12	440	310	244	50
Dry-GW-26	20	NA	2,150	1,505	68	65	315	11	400	320	244	54
Dry-GW-27	21	NA	2,250	1,575	120	60	295	11	460	300	244	66
Dry-GW-28	22	NA	3,000	2,100	164	74	370	12	620	460	152	73
Dry-GW-29	23	NA	2,500	1,750	128	67	340	11	520	420	152	63
Dry-GW-32	24	NA	2,800	1,960	212	50	380	16	650	360	317	64
Dry-GW-33	25	NA	6,800	4,760	440	29	1,030	28	1,340	1,150	439	68
Dry-GW-34	26	NA	4,500	3,150	54	179	645	19	832	740	427	48
Dry-GW-37	27	NA	5,500	3,850	283	183	605	16	1,164	900	232	47
Dry-GW-38	28	NA	4,300	3,010	203	159	465	12	840	740	201	108
Dry-RO-01	29	NA	1,280	896	64	38	155	11	170	190	219	70
Dry-RO-002	30	NA	1,500	1,050	48	51	220	11	240	240	250	52
Dry-RO-003	31	NA	650	455	64	11	125	16	130	90	244	33
Dry-36 (treated wastewater)	32	NA	800	560	28	10	185	15	116	150	244	19
Wet-GW-02	33	24	1,350	1,030	89	37	297	25	215	267	297	187
Wet-GW-03	34	24.4	1,080	850	48	23	194	17	178	181	239	75
Wet-GW-04	35	24.8	8,120	7,076	1,013	278	816	21	2,618	940	329	600
Wet-GW-06	36	22.9	1,560	3,023	36	25	111	9	271	305	194	106
Wet-GW-07	37	23.1	1,500	1,806	140	48	190	15	299	291	226	107
Wet-GW-08	38	25.2	2,320	1,826	278	59	286	13	468	511	246	142
Wet-GW-10	39	23.3	1,490	1,138	45	20	153	16	271	234	110	89
Wet-GW-11	40	25.1	7,310	6,736	237	139	999	131	1,984	751	213	341
Wet-GW-12	41	24.5	4,590	3,980	105	83	521	50	1,329	701	110	145
Wet-GW-13	42	24.3	2,470	1,324	46	27	157	11	496	401	174	141
Wet-GW-14	43	25.4	2,610	2,040	11	15	161	28	543	387	220	101
Wet-GW-15	44	23.7	1,790	1,396	54	33	145	5	346	298	142	129
Wet-RO-01	45	25.7	1,300	768	54	22	99	6	150	203	252	120
Wet-RO-09	46	22.9	1,530	788	110	44	280	30	180	197	394	83
EPA maximum limit for drinking water (EPA 2004)			NA	500	NA	NA	200	NA	250	250	NA	10 (as N)

Dry dry season; Wet wet season; RO runoff; GW groundwater; NA not available

relatively low pH might be due to the oxidation of organic carbon which produces CO<sub>2</sub>. In the absence of carbonate minerals in the aquifers, which is generally the case throughout the study area, CO<sub>2</sub> would lower pH (Kehew 2001). Nitrification can also reduce pH. High calcium concentration may be due to the presence of plagioclase feldspar in the sediment originating from surrounding igneous rocks and also from contamination by agricultural and industrial effluent. Concentrations of bicarbonate more than 200 mg/l are not uncommon in groundwater (Matthes 1982; Hem 1985). Given the fact that no carbonate rocks exist in the area, the possible sources of bicarbonate include presence of organic matter in the groundwater which is oxidized to produce carbon dioxide, which in

turn promotes dissolution of minerals. This weathering enriches groundwater in Ca, Mg, and bicarbonates. Weathering of silicate minerals may also be accounted as a source for bicarbonate, in addition to cations such as Ca and Mg, especially for upstream samples. Chloride is usually a major indicator of septic system pollution (Alhajjar et al. 1990). High chloride (and sodium) concentration can also result from dissolution of soil and rock minerals and/or evapotranspiration of the runoff and irrigation water resulting in the concentration of salts. Based on the data and local geology, it can be said that high chloride concentration is more likely the result of percolation of septic water and sewage waste in addition to evapotranspiration.



**Fig. 2** Piper diagram for major ion composition ( $\text{meq l}^{-1}$ ) of groundwater and runoff samples in the downstream part of the study area

Nitrate is probably the most commonly used indicator of contamination of groundwater from septic systems. Nitrate is produced during the final stage of decomposition of organic matter (Carter and Sneed 2001) and is the most prevalent form of nitrogen in groundwater (Hem 1985). Samples taken from wells located on the flood plain have nitrate concentrations of 340–600 mg/l. The area is heavily cultivated and irrigated. Sewerage leaks are

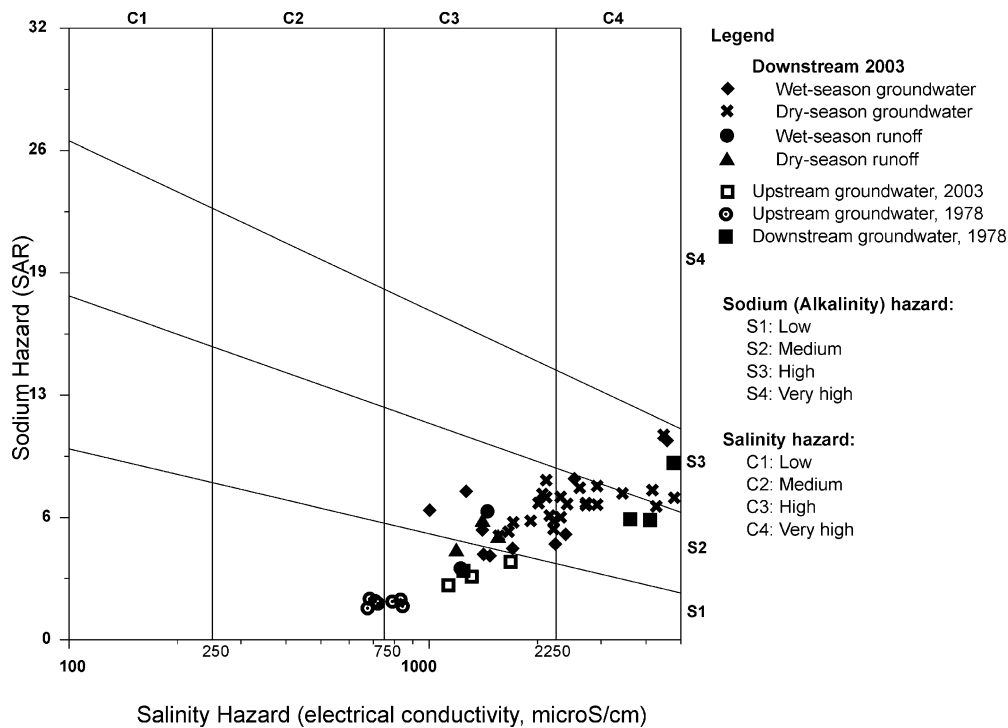
common, and poultry farms exist on the flanks of the wadi. Therefore, high nitrate concentration in the study area’s groundwater is a strong indication of direct contamination of the aquifer from these sources.

Groundwater samples collected downstream of the wastewater treatment plant (see Fig. 1 for the treatment plant location) showed high sulfate concentrations resulting probably from the combined effect of evapotranspiration and effluents from irrigation return and the wastewater treatment plant (the discharge outlet was also sampled). Coliform bacteria count in the collected samples was in the range of no detection to about 250 per 100 ml of water and was found to be higher just downstream from the city.

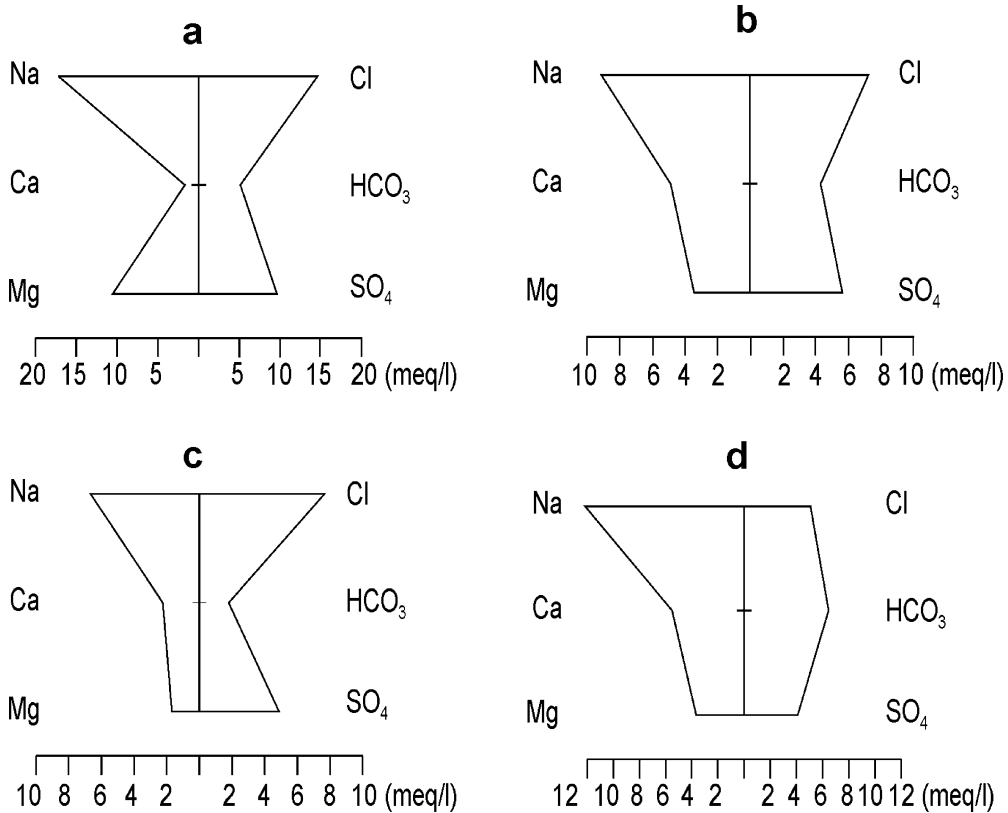
Figure 2 is a Piper diagram representation of the chemical analysis conducted in 2003. Almost all the samples fall in one zone indicating a similar chemical signature. The cation composition of the waters ranges from Na+K dominated through a mix of Mg+Na+K dominated. The anion compositions are chloride dominated. This indicates that water within the alluvial aquifer is of alkaline type with prevailing sulfate and chloride type. During the wet season Ca,  $\text{SO}_4$  and  $\text{HCO}_3$  domination increases. The cation composition probably varies as a result of the differences in the chemistry of the rocks with which the waters come into contact and the loading history and locations of contaminants.

### Water quality assessment

Most of the downstream groundwater and runoff samples exceed the limits for drinking water for major constituents



**Fig. 3** Wilcox diagram of salinity and sodium adsorption ratio (SAR) hazards for all samples



**Fig. 4** Stiff diagram of four representative samples from the 2003 downstream data **a** dry season groundwater, **b** dry season runoff, **c** wet season groundwater, and **d** wet season runoff

according to international and local standards (WHO 1998; PME 2004). However, heavy metals are within allowable limits, except for iron where it exceeds the limit in a few samples.

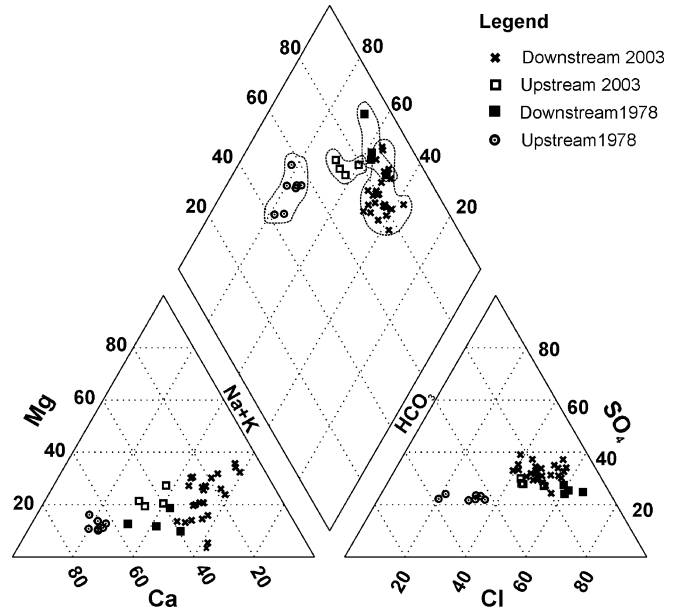
Salinity and Sodium Adsorption Ratio (SAR) are two main criteria to evaluate irrigation water. Salinity hazard, measured by electrical conductivity, and sodium (SAR) hazard, measured as the proportion of sodium to calcium and magnesium ions in a sample are the axes of a Wilcox plot, a diagram used to classify irrigation waters (Hounslow 1995). Based on this classification, the downstream groundwater of the study area has medium to high sodium hazard and high to very high salinity hazard (Fig. 3). Upstream groundwater is of better quality for irrigation (Fig. 3).

**Hydrochemical variation**

*Seasonal variation*

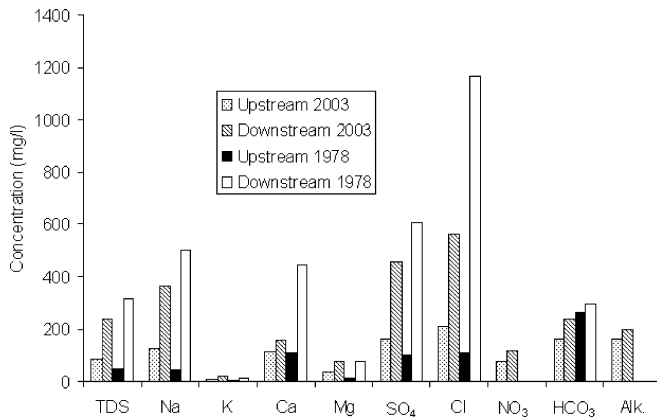
Seasonal variation of the water hydrochemistry can also be depicted in Fig. 2, which shows four groups of the 2003 downstream water samples: (1) groundwater in dry season, (2) groundwater in wet season, (3) runoff in dry season, (4) and runoff in wet season. The aquifer is divided into upstream and downstream parts with respect to Taif. The influence of rainfall on the runoff chemistry is obvious. Sodium, potassium, and chloride concentrations are reduced, as well as the overall TDS. Groundwater

samples are affected as well during the wet season indicating a fast recharge of groundwater from runoff (Fig. 4). Nitrate concentrations are generally higher in wet season samples compared to dry season samples reflecting the influence of the cultivation and irrigation period. Water



**Fig. 5** Piper diagram for major ion composition ( $\text{meq l}^{-1}$ ) of groundwater samples collected from both upstream and downstream in 2003 and 1978





**Fig. 6** A histogram plot to compare between the groundwater geochemistry in the upstream and downstream parts of the aquifer in the years 1978 and 2003. Nitrate and Alkalinity were not measured in 1978 samples; TDS scale is divided by 10

samples of the wet season are diluted by the rain falling prior to sample collection, and therefore, lower concentrations are found for many parameters.

#### *Spatial variation*

The groundwater quality of the upstream part of the aquifer (south of the city of Taif) should represent the background (natural) quality compared to the downstream part. Despite some agricultural development in the upstream area, it is located up-gradient from the main anticipated contamination sources. Four upstream groundwater samples were collected and analyzed during the summer of 2003 (Althobaity and Al-Shaibani 2003, personal data). Old data (1978) exist for groundwater quality of both upstream and downstream of the wadi (Ghurm 1980). Despite the questionable quality of the old data because of cations and anions that do not balance in

terms of equivalent weights, they are shown here for their historical significance and for general comparison.

Figure 5 is a Piper diagram of groundwater chemical analyses in two different years, 1978 and 2003, and Fig. 6 is a histogram that shows the average concentrations for some constituents for both upstream and downstream in both years 1978 and 2003. Upstream groundwater type changed from mostly calcium-bicarbonate in 1978 to a mixed cation-Cl type in 2003, suggesting simple dissolution or mixing of water. There is a clear increase in Na+K and SO<sub>4</sub> concentration from upstream to downstream of the aquifer (S–N of the city). It must be remembered, however, that there is a long time span between the two analyses and differences in collection, handling, analysis, and interpretation methods between the two studies.

#### *Temporal variation*

Table 1 lists the 1978 and 2003 geochemical analyses both upstream and downstream of the city; temporal variation is also shown in Fig. 5. Surprisingly, the downstream groundwater is of better quality in 2003 than in 1978, an observation from which two important conclusions can be drawn. First the aquifer water has been diluted by a better quality runoff; a major drainage project was completed after 1980 where an underground tunnel transports wadi runoff from upstream (south of the city) to downstream (just north of the city limits), causing less mixing between the clean runoff and the sewage from leaks within the city limits. Second, construction of the wastewater treatment plant helped reduce the amount of raw sewage water percolating to the aquifer. The upstream water type did not change much from 1978 to 2003; there is a slight increase in chloride-sulfate and an increase in calcium-sodium percentages from 1978 to 2003. However, from 1978 to 2003, in the lower parts of the aquifer, the water type

**Fig. 7** Runoff from sewerage leaks, irrigation drainage and septic tanks discharges in the Wadi Wajj during the dry season



changed from chloride-sulfate-calcium-sodium to chloride-sulfate-bicarbonate-sodium-calcium.

## Discussion and conclusions

A hydrogeological and hydrochemical study was conducted on a shallow alluvial aquifer in western Saudi Arabia. Recharge rate to the aquifer was estimated based on the chloride mass balance method and was found to be slightly higher than previous estimates in the literature. Hydrochemistry of the aquifer is compared for the upstream and downstream parts (up-gradient and down-gradient from Taif city) for two different years, and for two different seasons. The groundwater flow system under study can be classified as local flow according to the classification set forth by Toth (1963). In this system the aquifer is permeable with a relatively uniform lithology. Therefore, little change in chemical composition is expected as a result of the evolution of water chemistry along the flow path. Most of the downstream samples have generally higher concentrations of the different chemical constituents, including nitrate. Therefore, the elevated concentration from upstream to downstream strongly indicates the influence of sources other than, or in addition to, natural evolution due to contact between groundwater and surrounding rocks. Strong indicators of contamination include nitrate, chloride, phosphate, coliform bacteria, and low pH. The source of contamination can be attributed to incidental or induced infiltration of sewage water, wastewater treatment effluent (downstream of the treatment plant), leachate from poultry farm wastes, leakage from sanitary sewers, and surface contamination of wells with sewage water during floods (Fig. 7). The above sources collectively represent the sources of contamination and it is beyond the scope of this study to quantify the levels of contamination caused by individual sources.

Downstream groundwater quality improved from 1978 to 2003 as a result of two major drainage system and wastewater projects. Shallow alluvial aquifers are the main source of water for domestic and agricultural purposes in western Saudi Arabia. The amount of groundwater stored is relatively limited, but is renewable due to infiltration from frequent rainfall runoff. Annual rainfall in western and southwestern Saudi Arabia ranges from 250 to 500 mm. Dictated by their hydrogeologic settings, these aquifers are vulnerable to contamination; therefore, more effective monitoring programs need to be installed, and conservation and protection measures should be applied. Environmental impact assessment (EIA) studies are required by law for all new major projects that can adversely affect the quality of groundwater. Projects prior to the EIA requirement should be reviewed and, if necessary, modified.

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