

A GIS approach for the assessment of groundwater quality in Wadi Rabigh aquifer, Saudi Arabia

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Abstract A classification approach has been implemented in the present work by integrating traditional water sample analysis methods and Geographic Information System (GIS) capabilities in order to classify zones with acceptable groundwater quality for drinking. GIS extrapolation capabilities with their multi-conditional layering facilities were integrated together in order to assess in the determination of areas suitable for drinking purposes. This technique was implemented in Wadi Rabigh, Western Saudi Arabia, due to its significance as one of the most promising areas in the Western Province in the Kingdom of Saudi Arabia, owing to the establishment of King Abdullah Commercial City and King Abdullah University for Science and Technology (KAUST) nearby. Results show that only a limited area in the aquifer can be used for domestic purposes. This area is located in two separate patches in the upstream part of the aquifer while most of the aquifer water is categorized as brackish which might be used for agriculture purposes to a certain extent. The downstream area of the aquifer is very saline due to sea water intrusion effect.

Keywords Rabigh area · Groundwater quality · GIS · TDS · Concentration · WHO

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Introduction

One of the critical problems that hinder the sustainable development in developing countries located in arid zones, such as in Saudi Arabia, is the lack of renewable water resources. Groundwater is the most important natural resource utilized for drinking, irrigation, and industrial activities in such areas. This resource can be optimally used and sustained only when quantity and quality of groundwater is properly assessed (Kharad et al. 1999). However, groundwater can be vulnerable to contamination from a range of land use features and aquifer characteristics. Thus, assessment of groundwater quality at different parts of aquifer is an important task for proper groundwater sustainable management.

Due to the difficulty of carrying out water quality studies and investigations where groundwater comprehensive data are not readily available owing to the difficulty in acquiring information about aquifer characteristics in inadequately instrumented aquifers and the inaccessibility of some areas, hydrogeologists started to use new technologies to perform this type of work. One of the most prominent of these is utilizing the facilities and capabilities of Geographic Information System (GIS) in such investigations. This technique has been utilized efficiently in the last decade or so, for different purposes related to groundwater quality assessment. Many of these applications are carried out according to governmental and private sector requirements, by utilizing GIS in the map classification of groundwater quality, based on correlating total dissolved solids (TDS) values with some aquifer characteristics (Butler et al. 2002) or land use and land cover (Asadi et al. 2007). Other studies have used GIS as a database system in order to prepare maps of water quality according to concentration values of different chemical constituents, such as in

Skubon (2005); Yammani (2007) and Bilgehan and Berk-tay (2008). In such studies, GIS is utilized to locate groundwater quality zones suitable for different usages such as irrigation and domestic (Yammani 2007). A similar approach was adapted by Rangzan et al. (2008) where GIS was used to prepare layers of maps to locate promising well sites based on water quality and availability. However, describing the overall water quality condition in an integrated manner is difficult, due to the spatial variability of multiple contaminants and the wide range of indicators (chemical, physical, and biological) that could be measured (Babiker et al. 2007). These authors proposed a GIS-based groundwater quality index method which synthesizes different available water quality data (e.g., Cl, Na, Ca) by indexing them numerically relative to the World Health Organization (WHO) standards.

The present work addresses the issue of using GIS in groundwater quality assessment in a comprehensive and integrated way, by means of an integrated approach that combines the concentration effect of different chemical constituents in groundwater aquifer utilizing GIS multi-conditional layering capability. Layers of different chemical constituents in the Rabigh aquifer were conditionally over-imposed according to the permitted WHO standards, utilizing GIS capability.

Geographical and hydrogeological setting

Geographical setting

Wadi Rabigh is located in Makkah Province in the Western region of Saudi Arabia; about 150 km north of Jeddah city (Fig. 1). Its catchment is one of the largest catchments in the western coastal plain of the Kingdom of Saudi Arabia. It extends from the Arabian Shield outcrops in the east to the Red Sea coast in the west. The study area, however, covers about 2,690 km² and is confined to the lower part of the catchment which lies between 39°00', at the city of Rabigh, and 39°30'E longitudes and 22°40' and 23°05'N latitudes where the potential of groundwater availability is great.

Climate setting

The climate of the study area is categorized as arid and has a desert climate which is dry and hot throughout the year. However, transitional zones between Mediterranean and monsoon climates predominate in winter and early spring. Mean temperature ranges between 30 and 34°C during summer and between 20 and 24°C during winter (Bindagji 1980). Rainfall is very irregular and it increases from the coastal plain toward the mountains. Annual average rainfall

varies between 50 and 100 mm (Sogreah 1970). However, annual minimum rainfall may not exceed few millimeters at the downstream area and the annual maximum rainfall may exceed 250 mm in the catchment upstream area about 700 m above mean sea level. Relative humidity ranges between 30 and 75% and evaporation rate is very high in the area and ranges between 200 and 500 mm monthly depending on the seasons.

Hydrogeological setting

The upper reach of Wadi Rabigh catchment lies within the plateau of the Harrat Rahat lava flows and Precambrian outcrops at the Hijaz escarpment. Its shape is long where tributaries meet the main channel at intervals along its length and has a decreasing width toward its lower reaches. Generally it has a relatively narrow and long main valley course. The length of the main Wadi channel is about 116 km starting from the catchment outlet to nearly the edge of the selected area. However, the average length of the selected area of the catchment is 77 km while the width of the catchment at this area ranges from 28 to 53 km (Fig. 2). The elevation of the area starts at few meters at the sea coast and rises up to 1,200 m above mean sea level at few isolated peaks in the east. However, the elevation of the heads of the tributaries reach more than 500 m above sea level, and the valleys then slope down to 40 m at the catchment outlet onto the coastal plain. Basin average slope is 0.074 m/m and the main stream slope is 0.0034 m/m.

Few wells were found dug into fractured bedrocks along wadis in the upstream areas which flows toward the main Wadi Rabigh (Fig. 3). At some stream junctions, level of groundwater was found on the surface at the edge of the mountain ridge surrounding the main stream course, creating locations of very pleasant oasis in the area. The bedrock in these locations is less than 2 m deep near the mountains at the stream edge (Table 1). At the southern and south eastern parts of the catchment, many wadis drain into Wadi Rabigh and about 5 km downstream from this point, Wadi Al Khaniq, from south, joins Wadi Rabigh where the latter spreads over a wide area at Al Haqqaq village where Al Hawmah spring appears (Fig. 2). Two main wadis meet at Al Nuwabi village and flow downstream where they join Wadi Rabigh at about 17 km upstream of Rabigh city. It seems that the junction point at Al Nuwabi village has a great potential of groundwater as the depth of wells reached about 45 m below the surface. Finally, at about 5 km upstream of the city of Rabigh in the north-east direction dry wadis meet the main Wadi Rabigh where the area surrounding these wadis is very dry and there is no indication of groundwater potential in it.

Fig. 1 Location of study area

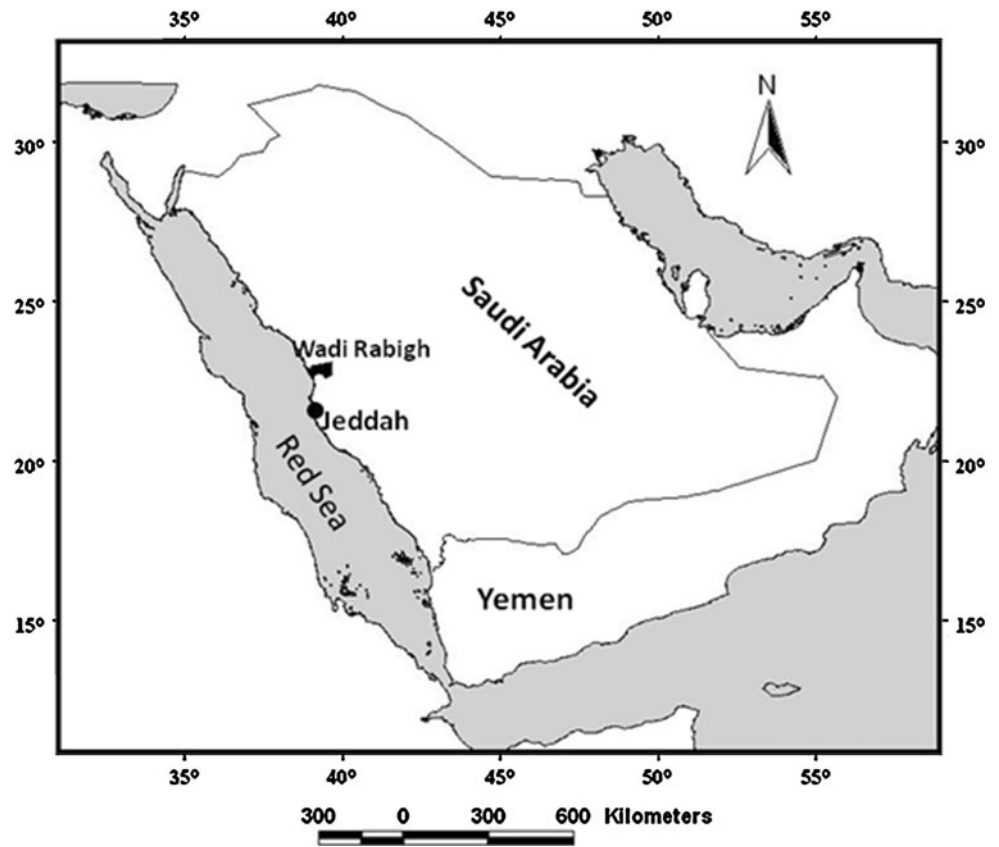
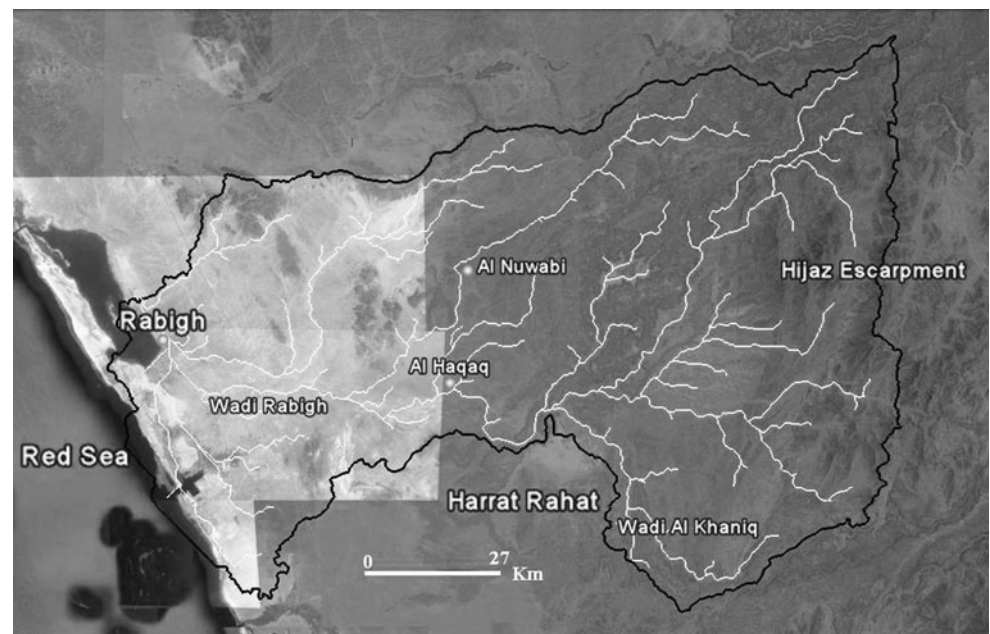


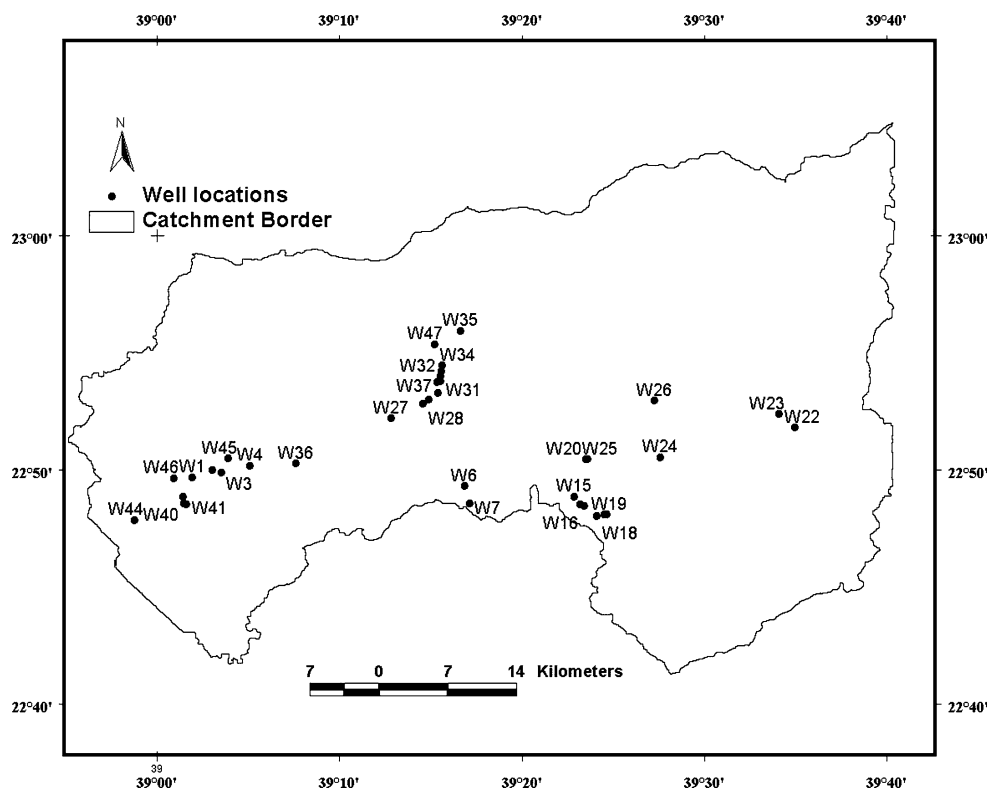
Fig. 2 Wadi Rabigh hydrogeology



The geological formation of the study area may be divided into three main geological entities; these are: Late Proterozoic rocks, Tertiary rocks which cover the western part of the area and they occur in low hills rising above the coastal plain, and Quaternary deposits which cover large area of the coastal plain and consist of alluvial gravel

which range from few to several meters in thickness. The latter contains the main aquifer in the area. The upper reach of the catchment lies within the plateau of the Harrat Rahat lava flows and Precambrian outcrops at the Sarawat escarpment. At the upstream of the study area, the bedrock depth is less than 2 m near the mountains at the stream

Fig. 3 Locations of studied wells in Wadi Rabigh



edge, however, a great potential of groundwater was found at Al Nuwabi village as the depth of wells reached about 45 m below the surface in the alluvium deposits (wells 28, 29, 30, 31, 32, 33, 34, 35, and 47 in Table 1 and Fig. 3).

Methodology

Determination of groundwater quality spatial distribution and its suitability to different purposes in Wadi Rabigh aquifer has been studied by integrating water chemical analysis techniques with GIS capability for spatially analyzing and distributing the results of chemical concentrations statistically for major constituents. This procedure starts with collecting and analyzing water samples from most of the operating and accessible wells in the study area and the results were then introduced to an adapted GIS approach to over impose these data in a special manner in order to locate areas with different water characteristics with respect to chemical constituents in the area. Chemical analysis results of a certain chemical constituent were spatially interpolated in the aquifer by utilizing Kriging method available in GIS software. Layers (maps) of the spatial distribution for all utilized constituents were prepared by this method. Produced layers of the major chemical components in the aquifer were overlaid (over-imposed) conditionally according to WHO acceptable standards for drinking in different scenarios. As a result,

new GIS layers, that combine more than one constituent, were produced to show the adequate locations for drinking water in the groundwater aquifer, based on different combinations of the extent of major chemical components, as explained in detail below.

Sampling and analytical methods

In general, water can be considered suitable for drinking if it is free from unacceptable physical properties like color, or turbidity, in addition to unpleasant taste or odor. It should also be chemically safe for human consumption. In this article, the standard for drinking water which is published by the World Health Organizations (2008) which is described in Table 2 is adopted.

More than 40 wells and spring locations were investigated from which about 34 water samples were collected from all accessible and operational wells during the field visits. These wells, however, represent most of the dug wells in the aquifer and they present a complete well inventory in the area (Table 1). Information and locations of visited wells which were obtained using GPS technology and up to date instruments for in situ measurements as shown in Fig. 3 and Table 1.

Collected water samples were taken following intensive pumping of the wells in order to avoid any local contamination or change in the water chemistry caused by evaporation or gas exchange in the well itself. In addition, all

Table 1 Well inventory and characteristics in the study area

Well no.	Latitude	Longitude	Total depth (m)	Depth to water table (m)	pH	EC ($\mu\text{S}/\text{cm}$)
1	22° 48.69	39° 1.920	9.5	7.35	9,690	5,964
2	22° 49.107	39° 3.012	10.0	8.70	16,590	12,008
4	22° 49.347	39° 5.092	7.30	6.0	7,270	4,818
6	22° 48.22	39° 16.850	39.0	3.9	9,510	6,254
7	22° 47.242	39° 17.125	On surface	On surface	2,450	1,474
16	22° 47.216	39° 23.171	13.90	10.60	3,030	2,206
18	22° 46.584	39° 24.097	11.60	8.40	2,045	1,380
19	22° 46.666	39° 24.639	12.00	11.40	1,622	1,158
20	22° 49.669	39° 23.521	Bed rock 2.0 m	On surface	3,380	2,112
21	22° 46.657	39° 24.521	12.70	8.90	1,803	1,226
22	22° 51.427	39° 34.967	16.60	15.03	1,477	1,032
23	22° 52.165	39° 34.106	28.70	22.00	2,370	1,664
24	22° 49.791	39° 27.592	19.40	15.40	1,688	1,272
26	22° 52.883	39° 27.250	Bed rock 5.2 m	4.55	3,050	1,880
27	22° 51.932	39° 12.813	17.60	10.20	12,500	8,274
28	22° 52.728	39° 14.586	45.13	11.60	6,415	4,828
29	22° 52.948	39° 14.902	15.50	15.10	1,600	1,014
30	22° 53.304	39° 15.397	18.45	11.10	3,140	2,236
31	22° 53.948	39° 15.544	18.80	16.80	3,700	2,872
32	22° 54.485	39° 15.562	31.10	18.84	1,533	1,038
33	22° 54.216	39° 15.529	21.45	19.20	3,720	2,774
34	22° 54.804	39° 15.625	30.40	28.90	1,110	734
35	22° 56.711	39° 16.619	22.20	16.50	5,440	612
36	22° 49.452	39° 07.617	7.60	6.00	27,400	18,656
37	22° 53.916	39° 15.358	21.00	15.00	5,440	4,076
s1	22° 49.676	39° 23.584	Bed rock 2.5 m	2.0	2,610	1,536
40	22° 47.653	39° 1.414	10.0	5.3	12,390	8,576
41	22° 47.212	39° 1.604	10.0	5.35	14,960	10,118
42	22° 47.283	39° 1.486	10.0	5.1	18,760	13,480
43	22° 47.283	39° 1.486	10.0	3.2	19,110	12,578
44	22° 46.349	38° 58.797	10.0	1.0	86,000	67,302
45	22° 49.735	39° 3.923	10.90	6.9	31,600	20,024
46	22° 48.936	39° 1.089	10.0	6.45	8,910	5,878
47	22° 55.973	39° 15.210	23.5	17.2	1,099	736

the water samples were collected in close polythene bottles of 1 l volume which were washed several times with water from the well itself. Physicochemical parameters such as electrical conductivity (EC), pH, and groundwater temperature were measured in situ using portable equipment such as Digital EC-meter, WTW D 812, Weilheim Type and Digital pH-meter Kinck, 651-2 Portamess 2Type.

Samples were analyzed in the laboratory to determine the concentration of major ions including Ca, Mg, Na, K, HCO_3 , Cl, and SO_4 in addition to TDS. Major cations (Ca, Mg, Na, and K) were determined using ICP-Optical Emission Spectrometer, while the anions were determined as follows: Cl by volumetric titration using AgNO_3 and K_2Cr , HCO_3 was determined by Portamess using HCl,

phenolphthalein, methyl orange, and SO_4 was determined by precipitation as barium sulfate (BaSO_4) by adding Jelserin and NaCl solution to the samples. A summary of the results of the chemical analysis data are presented in Table 3. The accuracy of the chemical analysis of groundwater samples was checked and ionically balanced by calculation of the cation–anion balance in terms of equivalent per million (epm).

It can be noticed from the chemical analysis in Table 3 that concentration of the Na content is the highest concentration amongst the other cations. However, Ca content was found to have the second highest concentration and the third is belonging to Mg. The main reason for having Na and Ca in large concentrations is because of the

Table 2 Comparison between the ranges of compositions of groundwater in the study area and WHO Standard for drinking water (WHO 2008)

Parameter	Range in study area	WHO range	Samples within the WHO range
TDS (mg/l)	612–16,780	1,000	4
PH	7.16–8.32	6.5–8.5	30
EC ($\mu\text{s}/\text{cm}$)	1,123–24,500	1,400	1
Ca ⁺⁺ (mg/l)	35.27–2,106.22	500 as CaCO ₃	16
Mg ⁺⁺ (mg/l)	10.46–352.64	–	–
Na ⁺ (mg/l)	40–4,800	200	11
K ⁺ (mg/l)	2.49–72.39	–	–
HCO ₃ ⁻ (mg/l)	36.21–316.83	–	–
SO ₄ ⁻ (mg/l)	60.09–3,026.91	400	12
Cl ⁻ (mg/l)	181.51–7,819.74	250	4

Table 3 Results of water samples chemical analysis (mg/l)

Well no.	Ca	Mg	Na	K	HCO ₃	SO ₄	Cl	TDS
1	622.44	133.03	1,250	16.5	162.69	1,228.21	2,198.64	5,964
2	1,270.54	303.27	1,950	72.39	259.49	1,610.18	5,018.47	12,008
4	554.31	24.32	975	19.64	299.82	448.64	2,059.81	4,818
6	152.3	233.47	1,660	19.49	195.23	1,117.08	2,533.55	6,254
7	89.78	50.83	250	14.56	210	272.48	523.12	1,474
16	211.62	112.84	300	6.416	202.2	520.26	612.56	2,206
18	131.66	69.53	130	7.73	156.9	298	388.85	1,380
19	113.43	53.5	125	4.135	237.06	194.28	289.8	1,158
20	140.28	75.39	370	23.22	208.8	411.6	749.81	2,112
21	124.25	59.1	95	7.99	201.55	220.62	336.54	1,226
22	105.41	39.88	55	1.85	249.83	154.76	244.12	1,032
23	169.54	57.4	160	2.46	208.8	207.45	530.1	1,664
24	159.72	49.73	60	6.58	205.17	279.89	282.49	1,272
26	104.21	60.8	370	21.34	153.28	311.99	706.21	1,880
27	800.4	66.39	1,950	19.15	189.86	2,449.84	2,585.61	8,274
28	491.78	134	630	13	274.59	959.03	1,551.09	4,828
29	36.07	15.08	320	13.54	417.18	197.57	180.47	1,014
30	261.72	74.66	345	23.82	198.71	603.41	590	2,236
31	408.82	82.69	195	8.34	201.98	597.64	821.58	2,872
32	128.26	31.62	85	5.11	155.77	141.59	320.47	1,038
33	424.85	80.99	347	25.76	183.61	754.05	763.54	2,774
34	131.46	7.78	85	4.63	128.99	69.97	237.74	734
35	96.21	10.46	40	5.77	143.89	60.09	182.38	612
36	2,404.8	308.86	3,120	67.49	77.86	1,116.26	9,023.61	18,656
37	468.94	116.01	55	9.73	184.82	1,235.62	1,106.44	4,076
s1	68.14	50.11	310	18.57	217.24	198.39	587.64	1,536
40	765.53	65.66	1,990	8.406	263.79	2,779.95	2,261.11	8,576
41	989.98	104.58	1,980	17.31	162.69	2,413.62	3,765.62	10,118
42	1,170.3	189.7	3,250	5.004	127.83	2,598.84	5,483.58	13,480
43	893.78	299.14	2,610	1.164	154.56	3,202.25	4,563.86	12,578
44	986.97	2,188.8	21,150	2.173	74.37	4,541.59	35,573.84	67,302
45	1,963.9	432.9	3,610	2.255	81.35	1,866.19	9,717.73	20,024
46	513.02	155.65	1,310	4.469	156.88	1,118.73	2,273.26	5,878
47	132.26	10.94	50	5.925	185.93	74.91	196.09	736

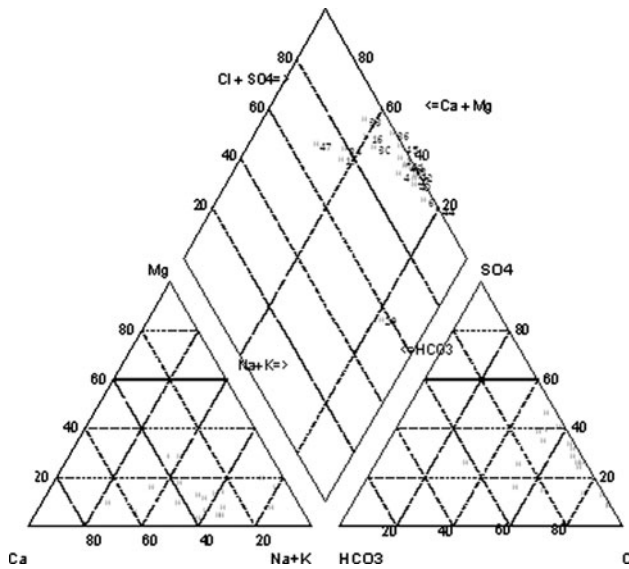


Fig. 4 Trilinear Piper diagram for the chemical compositions of the groundwater samples

surrounding igneous rocks which have been metamorphosed at various locations along the Wadi. Also, it can be seen that the highest Na value of 22,000 mg/l was found at well 44 at the downstream area near the seafront. On the other hand, Cl concentration represents the highest anion concentration in the groundwater in the study area. The second highest anions in concentration is SO₄ while the third highest anions concentration is of HCO₃. Also, the highest Cl value of 35,000 mg/l was found at well 44 at the downstream area near the seafront. The high concentration of Na and Cl at well 44 shows the effect of sea water on the groundwater aquifer due to sea water intrusion into the fresh aquifer groundwater as a result of excessive pumping. Considerable amount of Na and Cl concentrations may be contributed, however, to evaporation processes in the area as evaporation rate is very high as explained above. The chemical analysis of these constituents indicates that the general trend for ionic concentrations for groundwater in Rabigh aquifer area can be written as follows:

$$\text{Na} > \text{Ca} > \text{Mg}$$

$$\text{Cl} > \text{SO}_4 > \text{HCO}_3$$

Results of the chemical analysis of the collected groundwater samples were plotted on the Piper trilinear diagram (Fig. 4) in order to illustrate the overall chemical composition and hydrochemical characteristics of the groundwater which reflects the hydrochemical facies of these samples. This figure shows the hydrochemical characteristics of the plotted samples on the basis of major ions dominance. It indicates that all the groundwater samples are characterized by the dominance of strong acids Cl and SO₄, over weak acid HCO₃. Moreover, many of the groundwater samples are dominated by alkaline earths, Ca and Mg which exceed alkalis, Na and K. The rest of the groundwater samples are characterized by the dominance of alkalis over alkaline earths. This ionic dominance could be related to the provenance of the studied aquifer and the mineralogical composition of the aquifer matrix. Samples 19, 29, and 47 show increase of HCO₃ content where it is represented in their chemical type. The increase of HCO₃ content in these groundwater samples may be attributed to agricultural return flow where dissolution of carbonate minerals precipitated in the soil by the effect of high evaporation rates is the common process in such arid agricultural area. However, sample 29 shows an obvious increase in Na and K contents which is possibly due to cations exchange where Na is released and Ca and Mg are removed from the aqueous phase.

A statistical correlation analysis has been carried out on these variables. The results of the correlation analysis which are shown in Table 4 give an indication that almost all constituents are positively related to one another except for HCO₃ which is negatively related with all other constituents. The highest correlation is found between TDS and Cl, Na, and Mg. This shows that these three constituents are the major contributors to TDS value in the aquifer and they represent the most salts in the aquifer groundwater. This is also represented in the form of the high correlation between Na, Mg, and Cl in Table 4. This

Table 4 Correlation matrix for different water quality constituents

	Ca	Mg	Na	K	HCO ₃	SO ₄	Cl	TDS
Ca	1							
Mg	0.36388	1						
Na	0.401329	0.985355	1					
K	0.471622	-0.0289	-0.03987	1				
HCO ₃	-0.4456	-0.40798	-0.40244	0.049473	1			
SO ₄	0.606087	0.683922	0.746014	0.006235	-0.34496	1		
Cl	0.50646	0.981901	0.988228	0.034882	-0.45314	0.733522	1	
TDS	0.552002	0.97023	0.983948	0.049862	-0.45109	0.791209	0.995659	1

finding is also supported by the GIS analysis as shown in the next sections below.

GIS methodology

In terms of chemical constituent concentrations in the Wadi Rabigh groundwater aquifer, it was noticed (Table 3) that there are four elements that have considerable influence; these are Na, Ca, SO_4 , and Cl. A procedure was adapted here in order to locate suitable areas for drinking water with respect to the most effective chemical constituent individually as well as collectively, based on the recommended range by WHO and GIS capability. Suitable areas are produced as maps prepared by utilizing GIS facilities combined with statistical extrapolation techniques. Distributed measured values for the 34 wells are extrapolated according to their concentration levels by Kriging technique and areas of concentration below the accepted range are lumped together in one area. Prepared layers of acceptable areas with a certain chemical constituent was over-imposed by one or more layers and extrapolated in the same manner in order to show the resultant effect or extent of these layers combined together. The layers that show the extent of acceptable area for drinking by integrating the effect of the four most influencing chemicals (Na, Ca, SO_4 , and Cl) were over-imposed and a new layer was produced (four-parameter concentration layer). This layer shows the suitable drinking area in the groundwater aquifer including

the effect of all effective chemicals. Another layer was produced that shows the extent of suitable areas for drinking by including the effect of only the two most effective chemicals (Cl and SO_4) (two-parameter concentration layer). The last adapted scenario is made by creating a layer with the extent of suitable area for drinking based on the effect of TDS concentration only. The three produced layers were compared to each other and analyzed as shown in the next sections.

Results and discussion

Determination of suitable drinking area in the groundwater aquifer in Wadi Rabigh was done initially based on the concentration level recommended by WHO of the individual major chemical constituents in the water. Figures 5, 6, 7, and 8 show the extent of the areas that have suitable ranges of chemical concentration for drinking for the individual major-ions Na, Ca, SO_4 , and Cl, respectively. It is observed that suitable areas for drinking water with respect to the concentration of Na and SO_4 are found in almost the same location in the upstream area of the catchment, while suitable areas with respect to Ca concentration is located in the downstream area. However, the suitable area for drinking with respect to Cl concentration is very small and can be represented by two confined areas (patches) in the middle and in the upstream parts of the

Fig. 5 Suitable area for drinking with respect to Na concentration

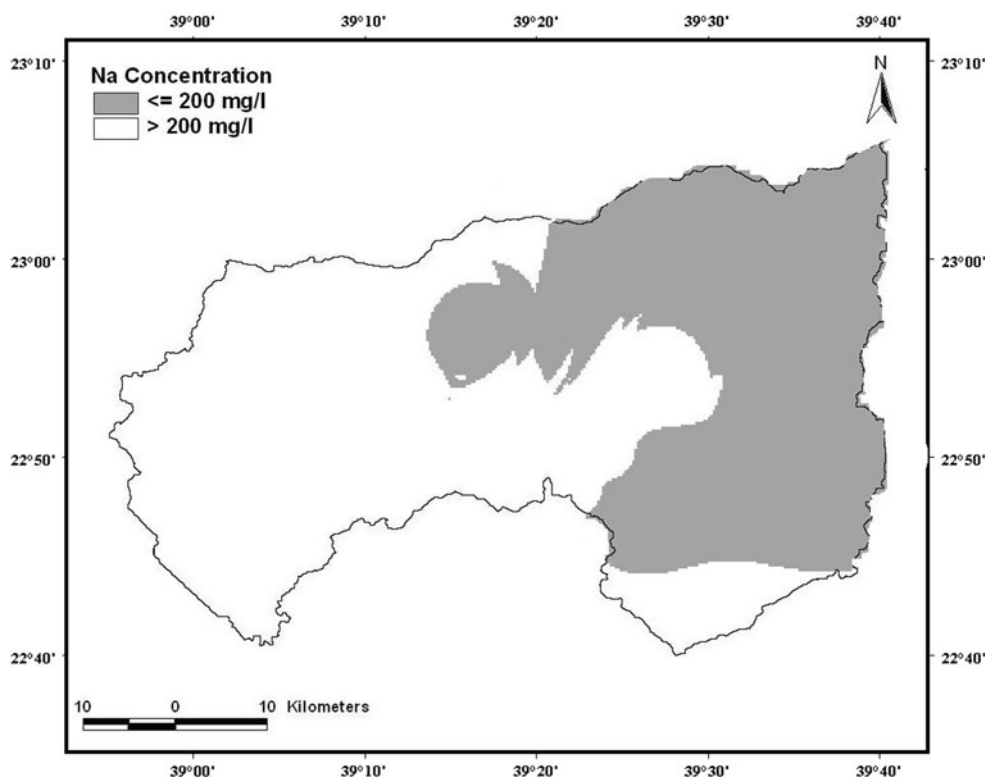


Fig. 6 Suitable area for drinking with respect to Ca concentration

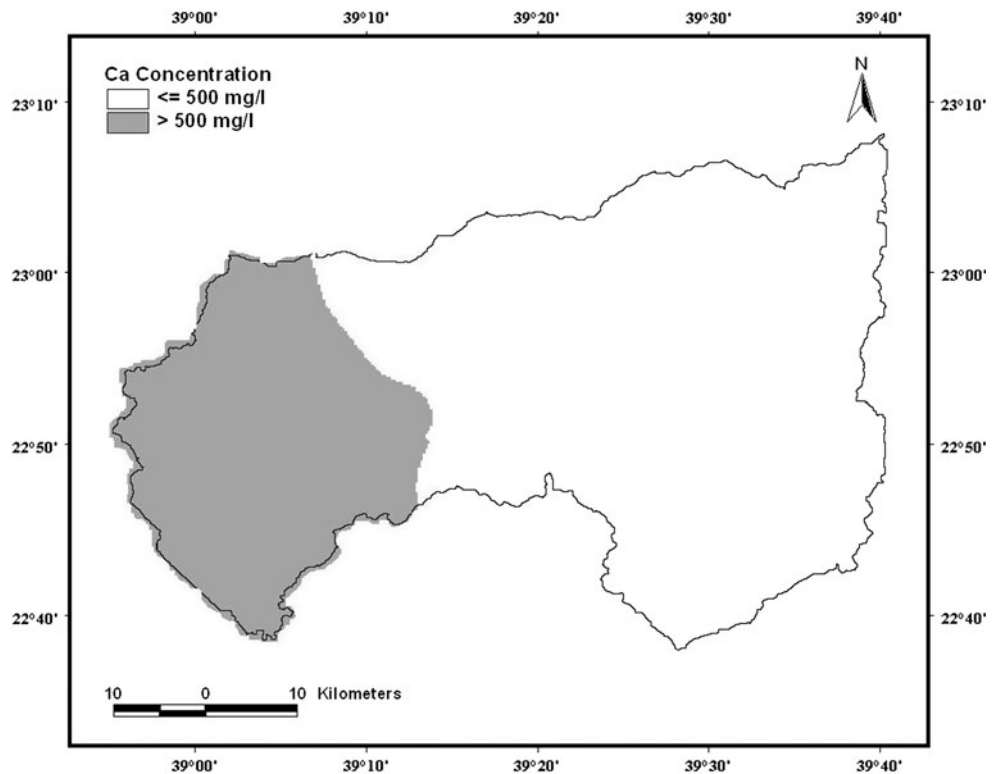
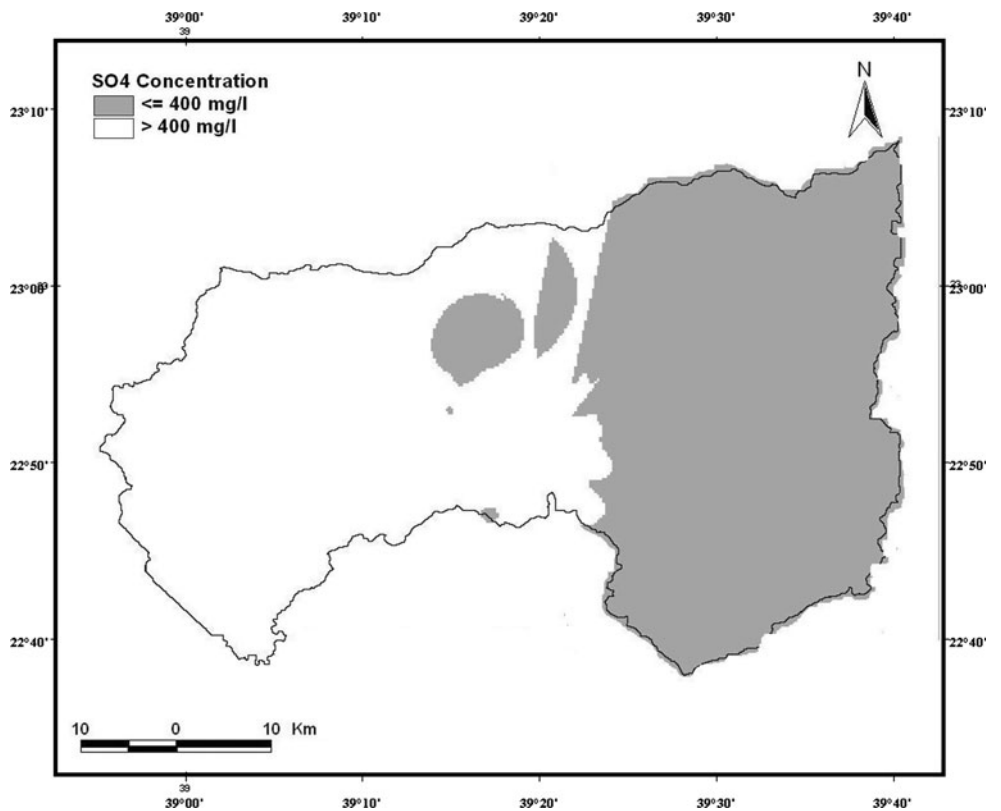


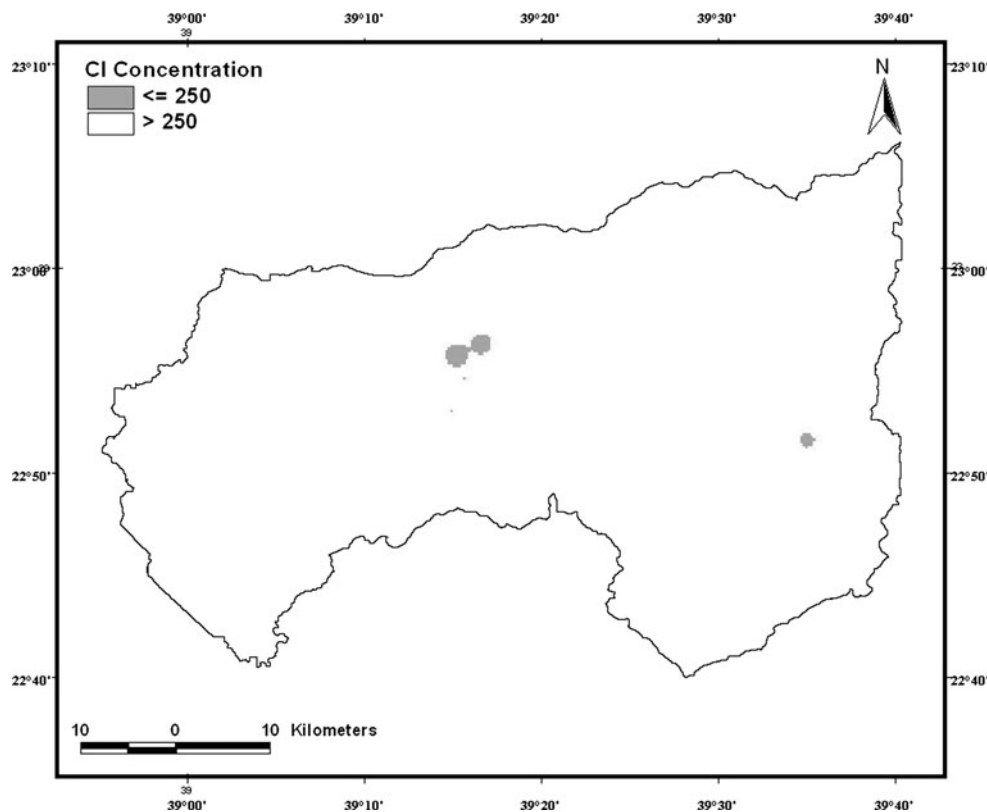
Fig. 7 Suitable area for drinking with respect to SO₄ concentration



catchment. This shows that the Cl is the determinant chemical constituent for the determination of suitable areas for drinking water production, which reflects the influence

of the saline sea water on the aquifer and the effect of evaporation in the area. It was found that due to restricted WHO drinking limits of Cl concentration; only small

Fig. 8 Suitable area for drinking with respect to Cl concentration



patches located at the upstream part of the aquifer seem to be suitable for drinking. Similar effect in terms of location and areal extent can be re-produced using TDS concentration; if GIS extrapolation techniques with TDS conditional WHO limits for drinking were observed.

However, determination of suitable areas for drinking should include the effect of all major chemical components acting together rather than the effect of the individual constituents. The ability of GIS to combine the effect of these components in one map is utilized. The layers that show the extent of acceptable area for drinking by integrating the effect of the four most influencing parameters (Na, Ca, SO₄, and Cl) were over-imposed and a new layer was produced. A map that includes the effect of the four parameters acting together was prepared. The values of these parameters were over imposed conditionally according to the individual acceptable concentration of these chemicals according to WHO standards. Only areas that meet the set conditions will appear as acceptable areas. The resultant layer (map) of overlaying the four parameters shows the extent of the suitable area for drinking (Fig. 9). This map is almost a replica of the Cl concentration effect alone, although the extents of areas in general were slightly reduced. However, since the major constituents are Cl and SO₄ a two parameter map was produced in the same manner. This map (Fig. 10) shows a similar extent of the suitable area for drinking which shows the influence of

these two constituents on groundwater characteristics of the aquifer.

Since TDS values are strongly correlated with the major constituents as shown by the statistical analysis, the influence of TDS concentration on the drinking areal extent was also plotted using GIS capabilities (Fig. 11) controlled by WHO limits. This area covers a similar range as the two and four parameter maps, although there is a slight change in the areal extent between these maps and the TDS concentration map which shows smaller areas in the case of TDS. This map was imposed on the channel network and aquifer boundary (Fig. 12) which shows that the acceptable area for drinking is only found in the upstream area at the wadi passing by Al Nuwabi village. The rest of the wadi has groundwater of poorer quality which cannot be used for drinking purposes but might be used for agriculture purposes to a certain extent.

Summary and conclusions

A procedure that integrates the traditional groundwater sampling analysis methods and GIS capabilities combined with statistical extrapolation and conditional overlaying techniques was adapted in order to locate the suitable areas at the Rabigh groundwater aquifer for drinking purposes. It is observed that the promising area with groundwater

Fig. 9 Suitable area for drinking with respect to four parameters concentration

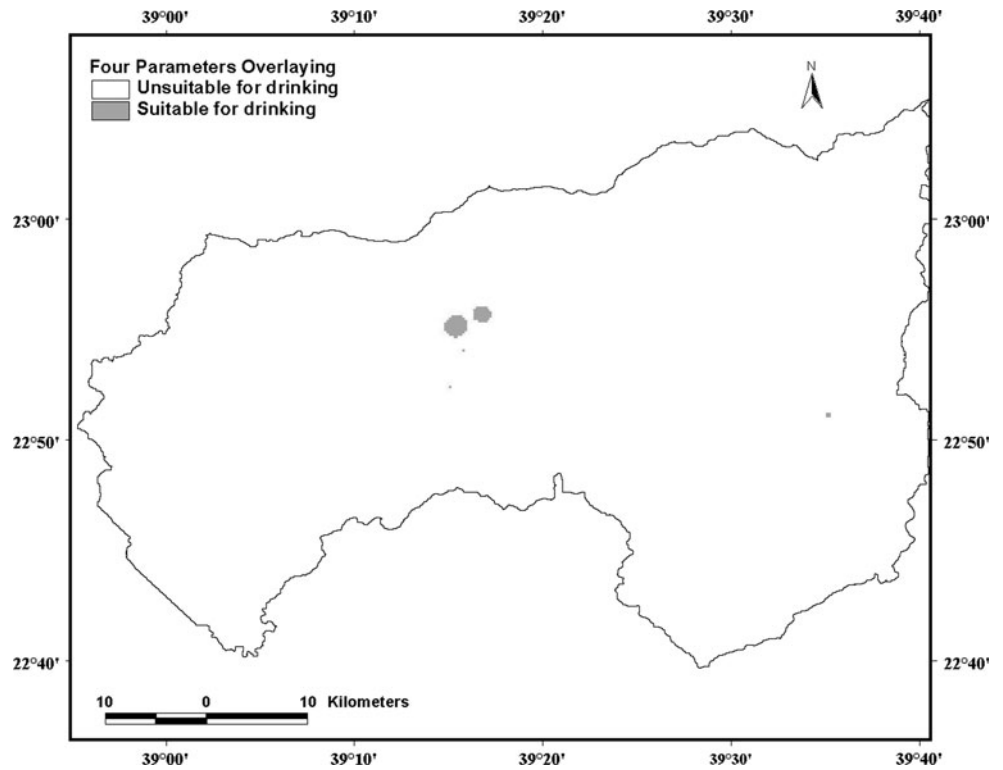
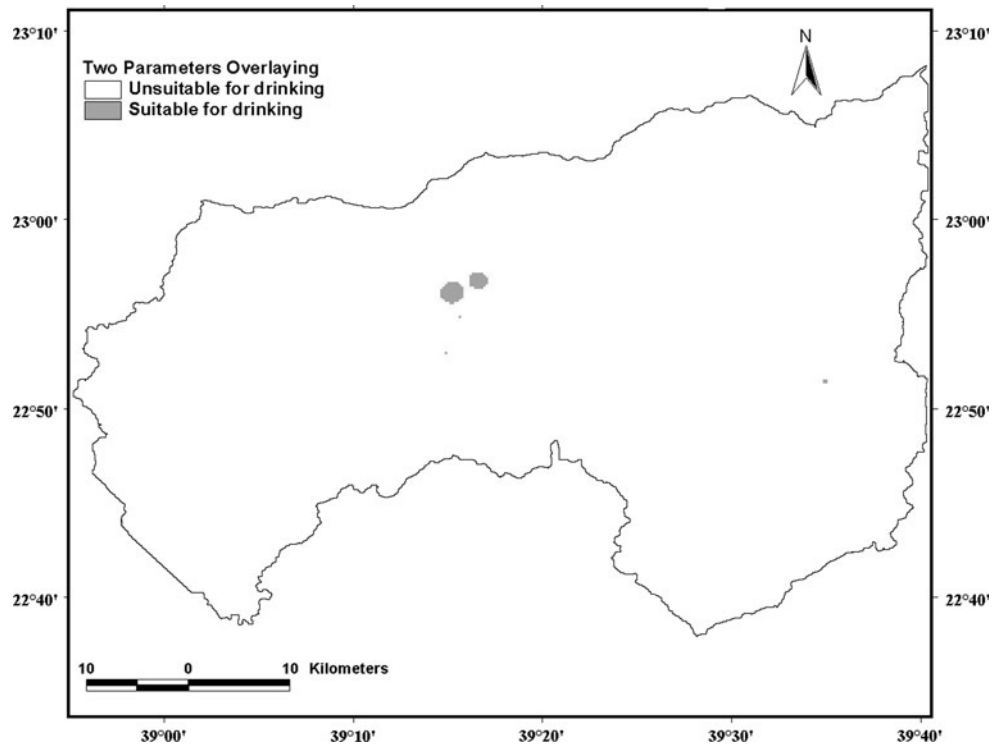


Fig. 10 Suitable area for drinking with respect to two parameters concentration



potential in the aquifer can be found in two locations. The first is located downstream of Haqqaq spring toward the junction with Al Nuwabi branch where the thickness of the saturated zone ranges from 10 to 16 m and the second is located at Al Nuwabi Wadi, where the thickness of the

saturated zone ranges from 20 to 35 m. The total dissolved solids (TDS) in groundwater varies from 734 to 67,302 mg/l where large values are located close to the sea coast where sea water is dominant. It can be drawn that there are two major players in the TDS concentration; these

Fig. 11 Suitable area for drinking with respect to TDS concentration

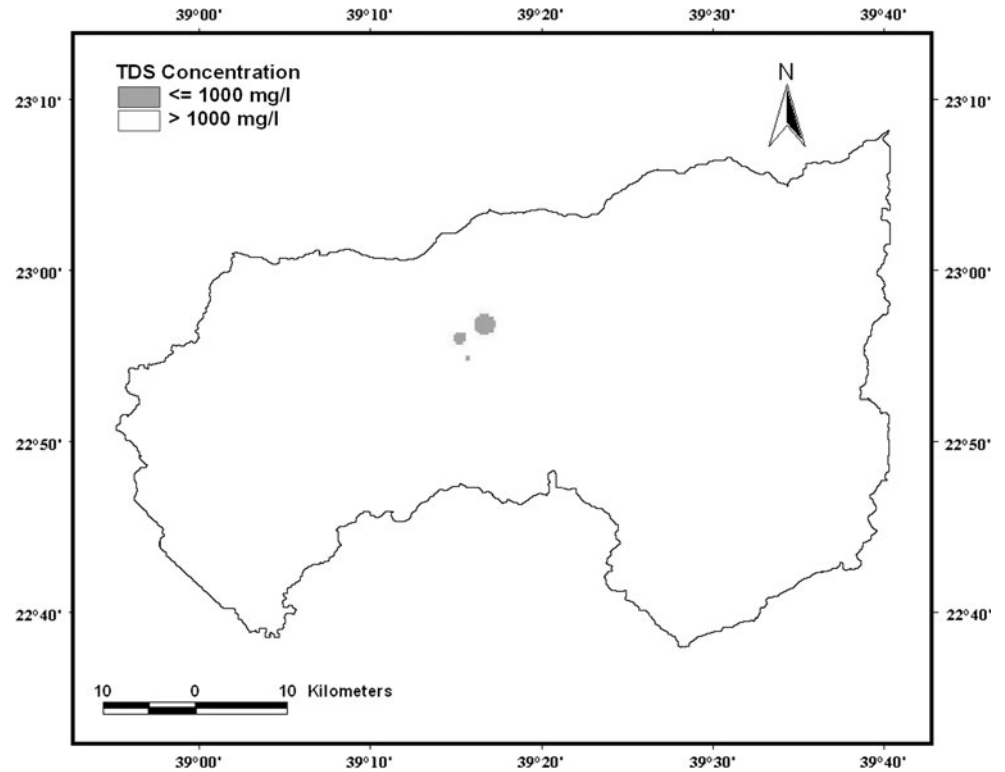
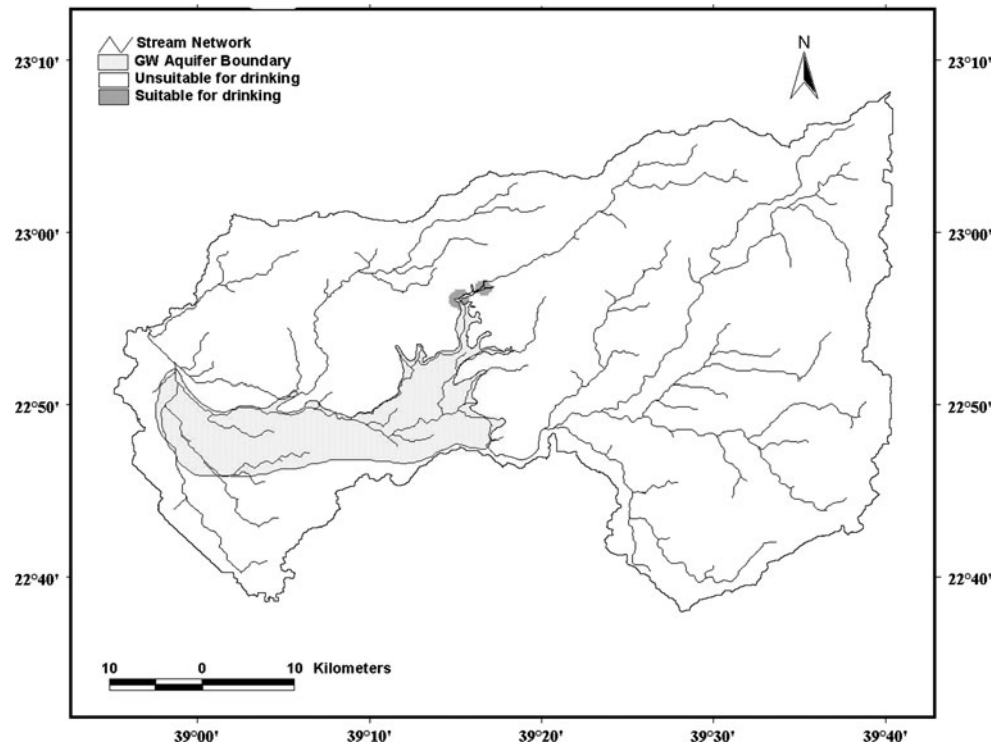


Fig. 12 Overlaying suitable area for drinking, aquifer boundary, and channel network



are salt water at seafront at the downstream area and the fresh water at the upstream area. Salt water effect extends up to about 6 km away from the seafront. On the other hand, effect of fresh water flowing from upstream area extends up to about 15 km from the top aquifer boundary at

different level. The bulk of the water in the study area can be classified as brackish water, however, groundwater upstream of Al Nuwabi Wadi can be considered as fresh water. Comparing the chemical analysis results at this location with WHO standard, for drinking water, indicates

that water at this area can also be used for drinking purposes. However, water of most of the study area can be used for agricultural purposes only, except areas close to the sea coast where water is more saline.

It was noticed that there are four elements in the groundwater aquifer which have significant concentration and can be considered the most effective in terms of the determination of suitable location for drinking water pumping; these are Na, Ca, SO₄, and Cl. The areal extent of each of these elements was determined by GIS statistical extrapolation techniques. It is observed that the extent of the suitable area for drinking with respect to Na and SO₄ concentration is similar and located in the upstream area. On the other hand, the suitable area for drinking with respect to Ca concentration is located in the most downstream area close to the seafront and extends about 10 km upstream. However, it was found that the determinant factor for drinking suitability is the concentration of Cl which is located as small patches at the upstream area of the aquifer on the wadi Al Nuwabi branch. By combining the effect of either the four parameters (all significant elements), the two parameters (Cl and SO₄), or TDS, similar results were obtained using the suggested technique in this paper which reflects the influence of Cl high concentration on the other parameters. It can also be drawn that Cl concentration is the major factor that makes up the TDS in the aquifer groundwater and plays an important role in the determination of areas suitable for drinking in the Rabigh aquifer.

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