

Effects of sewage waste disposal on the groundwater quality and agricultural potential of a floodplain near Jeddah, Saudi Arabia

Faisal Rehman¹ · Tariq Cheema¹

Received: 25 May 2015 / Accepted: 20 January 2016 / Published online: 31 March 2016
© Saudi Society for Geosciences 2016

Abstract The area of Wadi Bani Malik located to the east of Jeddah (Kingdom of Saudi Arabia) is commonly known as Al Misk Lake. It is one of the many floodplains present along the dry wadi beds. As the floodplains are cultivable areas irrigated by the shallow groundwater present in the alluvium, the quality of groundwater must be investigated before determining its irrigation potential. Historically, the area of Al Misk Lake remained a dumping ground for untreated sewage for many years. Although this activity has been abandoned, but leaching of contaminants might have contaminated the groundwater, and it is not clear how much of the area of Al Misk Floodplain has been compromised. To determine the effects of sewage waste disposal on the groundwater quality, this study was undertaken to evaluate the irrigation potential of the area. The investigation focused upon the hydrogeological and geophysical studies whereby 19 groundwater samples obtained from dug wells were analyzed, geochemically. Results of chemical analysis show that all the wells are contaminated with high concentration of major ions. Electromagnetic survey carried out at the site revealed that the longitudinal extent of the plume (in the direction of groundwater flow) is much larger than perpendicular to flow. Sodium adsorption ratio, salinity hazard, and sodium percentages were found to be much higher than the irrigation water quality standards thus making the Al Misk Lake area unsuitable for irrigation purposes.

Keywords Groundwater quality · Sewage waste disposal · Agricultural potential · Floodplain

Introduction

The Kingdom of Saudi Arabia (KSA) has an area of about 2.25 million km² making KSA as one of the largest countries of the Arabian Peninsula. KSA depends on three kinds of water resources; non-renewable groundwater resources, renewable water resources, and desalinated seawater. Only a small part of the country receives sufficient precipitation allowing a water supply that depends on water renewable resources. Sea water desalination source is limited in the coastal areas due to the transportation cost so a large part of the country rely on the non-renewable resources that were recharged before thousands of years or more (Al-Saud et al. 2011). However, KSA is one of poorest in term of renewable water resources. Although, the total groundwater resources of KSA are estimated to be around 2259 billion m³ (Al-Shayaa et al. 2012; Aly et al. 2013), an over-extraction of groundwater in order to meet the domestic and agricultural water demand has disturbed the balance of aquifers in many parts (Al-Hasawi and Hussein 2012). This disturbance is caused as a result of an increase in the number of groundwater wells. It is estimated that over a period of 15 years (from 1982 to 1997), the number of groundwater wells increased from 26,000 to 86,000 thus over-abstracting the groundwater resource (Elhadj 2004).

In last 30 years, enormous extraction of groundwater from limited country reserves has benefited the agriculture sector in KSA. The agriculture sector remains the highest water consumption sector in KSA that uses approximately 85–90 % of total water consumption (Al-Kahtani and Ismaiel 2010; Al-Zahrani 2009; Alzahrani et al. 2012). As most of

✉ Tariq Cheema
cheema123@hotmail.com

¹ Faculty of Earth Sciences, King Abdulaziz University, Jeddah, Saudi Arabia

the agriculture sector fulfils its irrigation requirements by making use of non-renewable groundwater resource, the benefits harvested on the expense of an intensive use of groundwater raises new challenges (Abderrahman 2002). Cultivated land in Saudi Arabia increased from 1971 to 1992; that is from 400,000 to 1,620,000 ha. Numerous measurements were taken to recover the quality and productivity of aquifers due to which in 1993, this cultivated area started reducing and reached in 2000 about 1,210,000 ha (Abderrahman 2002).

About 50 % of irrigation in KSA depends upon shallow unconfined groundwater aquifers developed in valley basins that sometimes dry out due to a small amount of rainfall (Alkolibi 2002), and water shortage is the main problem facing the agriculture sector (Al-Shayaa et al. 2012). Cultivable area is approximately 2 % of the total land area (Shetty 2003). Some of the cultivable areas are located along the dry river beds (wadis) on either side of wadis that can be considered as floodplains.

Floodplains are generally lands most subject to repetitive floods, positioned contiguous to rivers and streams (Hadadin et al. 2013). This is an area of land adjacent to a stream or river that stretches from the banks of its channel to the base of the enclosing valley walls and experiences flooding during periods of high discharge. Floodplains are significant source of groundwater, also able to hold excess amount of water and normally comprise of permeable geological sediments. Floodplains are significant source of soil nutrients and hence possible for agricultural purposes, specifically in developing countries where public lives very near to floodplain systems (Dan-Azumi 2011).

The area of Wadi Bani Malik located to the east of Jeddah is commonly known as Al Misk Lake. It is one of the many floodplains present along the wadi beds near Jeddah. Lately, the area of Al Misk Lake has been under investigation for several purposes. For example, its flood potential and the associated dangers as a result of its close proximity to Jeddah has been studied for various return periods by Ewea (2010). By simulating the floods, Ewea (2010) put forward a conceptual model for estimating the threat associated with Al Misk Lake and suggested the procedures for flood mitigation. Ewea (2010) recommends that the integrated management of the Al Misk Lake be carried out for reducing the negative effects on the environment. By using the ground water flow modeling and GIS technology, Elfeki et al. (2011) calculated the expected travel time of 50 years for the groundwater contaminant plume formed as a result of dumping of untreated sewage at Al Misk Lake to the Red Sea.

The integrated management of Al Misk Lake requires evaluating the agricultural potential of this floodplain. The rationale for looking at the agricultural potential of Al

Misk Lake originates from its location in the outskirts of Jeddah that would reduce the transportation cost from farm to market. However, the presences of an alluvial aquifer in the close proximity to the floodplain would warrant a hydro-geochemical study for determining the groundwater quality. As the area is known to be a dumping ground for untreated water, its effects on the groundwater quality need to be evaluated before making any decisions on the agricultural potential of the Al Misk Area. In order to study the effects of waste disposal on the groundwater quality and the agricultural potential of this floodplain, a groundwater investigation was carried out. The investigation focuses upon documenting the changes that has taken place as a result of this disposal using hydrogeological, geochemical, and geophysical techniques.

Material and methods

Study area

The study area is located about 40 km to the east of Jeddah. Jeddah is one of the largest cities in Saudi Arabia with a population of over 3 million. Groundwater and rainfall resources are not enough to fulfil the requirement of population so desalination water is supplied to meet the demands of people. The approximate water consumption is 200 l per capita per day. On average, 80 % of potable water used for urban purposes proceeds to the environment as waste water (Ewea 2010). About 70–85 % of Jeddah area is not linked to sewerage pipelines; waste water collected in underground cesspools is transported by tanker trucks to the dumpsites (Elfeki et al. 2011; Ewea 2010; News 2013; Zafar 2013). One of the dumpsites is Al Misk Lake area where the whole Jeddah domestic sewage was dumped without any treatment for more than 10 years. The dumping started back in mid 90s and continued until 2008 (Sharif 2008). It was estimated that during this period, more than 800 tankers dumped 40,000 m³ of waste water into the lake every day (Elfeki et al. 2011; Ewea 2010). A flood control dam was built which was supposed to contain the plume; however, its effectiveness is yet to be proven. Figure 1 shows the location of the study area.

Geology of study area

Geology of study area is shown on the geological map of the Makkah quadrangle which is situated in the west central portion of Arabian Shield bordered by the Red Sea. Makkah quadrangle covers major cities of Makkah, Jeddah, and Taif. Study area comprises of igneous and metamorphic rocks (Fig. 2). Major rock units present are diorite, quartz diorite,

Fig. 1 Location of the study area

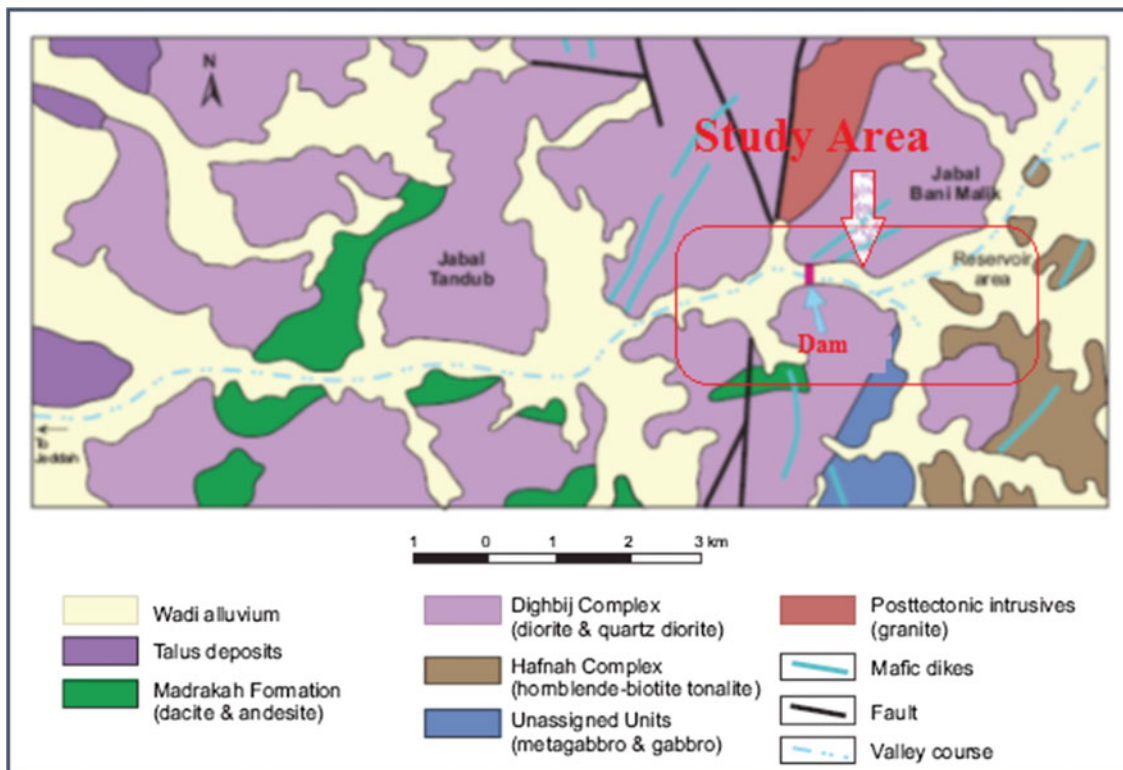


Fig. 2 Geological map of study area (modified after Ewea (2010))



Fig. 3 Location of the wells in study area

gabbro, metagabbro, andesite, hornblende, and wadi alluvium. Major faults in the study area strike northeast-southwest direction (Ewea 2010; Moore and Al-Rehaili 1989).

Alluvial sand with comparatively high permeability can be identified as main aquifer in the study area with basement rocks measured as aquiclude. A study of groundwater levels

Table 1 Concentration of major ions in study area

Well No	Ca ⁺⁺ mg/l	Mg ⁺⁺ mg/l	Na ⁺ mg/l	K ⁺ mg/l	SO ₄ ⁻ mg/l	CO ₃ ⁻ mg/l	HCO ₃ ⁻ mg/l	Cl ⁻ mg/l	Total hardness	TDS mg/l	E.C (mS/cm)	Salinity mg/l
S.1	721.4	291.8	6540	35.3	4407.8	1128	1040.6	6745	2999.98	21,300	25.4	15.5
S.2	1763.5	632.3	8960	37.4	2872.2	72	268.4	15,975	7001.23	30,880	45.9	29.9
S.3	1442.8	681	9800	15.4	5523.5	180	152.5	14,910	6399.3	31,003	43.7	27.5
S.4	961.9	340.4	8639	22.3	8645.5	360	183	8520	3800.76	27,900	33.5	21.1
S.5	2484.9	680.9	12,220	48.9	1175.3	10	61	23,785	9004.33	40,799	66.3	45.1
S.6	561.1	0.486	3120	7.4	2430.4	240	244	3195	1404.79	10,008	12.49	7.3
S.7	1122.2	438.2	4780	28.8	3546.6	60	237.9	7455	4602.22	17,890	22.5	13.6
S.8	1282.5	1605.1	17,900	320	4707	600	915	29,820	9787.392	57,240	92.5	66.4
S.9	1202.4	437.7	4171	26.6	2513.4	153	256.2	7277.5	4800.81	16,277	21.3	12.9
S.10	1042.0	729.6	4600	18.8	3328.5	120	366	7810	5596.56	18,199	22.8	14
S.11	160.3	972.8	3000	11.18	724.3	96	195.2	6745	4389.28	12,222	18.56	11.1
S.12	1683	535	4740	25.2	3938.5	120	305	8165	6401.16	20,111	25.6	15.7
S.13	3767.5	875.5	6540	20.1	2113.4	108	155.5	17,040	13,008.38	30,800	42.3	27.2
S.14	1923.8	632.32	8800	24.9	6100	93.6	135.4	13,845	7402.01	31,690	41.8	27
S.15	1282.5	438.7	5200	7.41	4226.7	216	24.4	7810	5005.07	19,330	24.9	15.3
S.16	2084.1	486.4	8642	34.1	3179.6	240	244	15,265	7204.64	30,401	41.4	26.5
S.17	1923.8	535.5	7600	26.5	3362.1	121.2	304.3	13,490	7005.05	27,500	37	23.4
S.18	2885.7	583.6	8200	20.6	2978	121.3	182.3	16,685	9607.05	31,705	44.4	28.7
S.19	1282.6	291.8	6180	6.1	3866.5	121.4	121.6	9230	4402.88	21,219	27.2	16.8

explains that the general groundwater flow direction is toward the sea (Ewea 2010).

Hydrogeochemical sampling

A groundwater well survey was conducted in order to collect the field hydrogeological parameters and to identify the groundwater wells for geochemical analysis. The field parameters included measuring top of casing, depth to water table, electrical conductivity (EC), salinity, temperature, and the pH. A standard Solinst® probe (with the necessary attachments) was used for this purpose. Nineteen water samples were collected for major ions analysis. The samples were collected in 1-L polyethylene bottles after 30 min of pumping. The bottles were washed with deionised water prior to sampling. The samples were sealed and transported to the laboratory for geochemical analysis that was performed by following standard procedures (APHA 2005). A QA/QC protocol was followed to ensure no contamination during sampling. This included the inclusion of a travel blank, field blank, and a field duplicate sample for analysis. Figure 3 shows the location of water samples. The locations were carefully selected to represent the

groundwater quality to the upstream as well as to downstream of the dam.

Geophysical survey

In support of the hydrogeological investigation, geophysical survey was carried out. Frequency domain electromagnetic survey was selected for this purpose. The selection was based upon the usefulness of this method in delineating the groundwater and soil contaminant zones and in demarcating the spread and horizontal extent of a leachate plume by several other investigators (Campbell and Fitterman 2000; Danielsen et al. 2003; McQuown et al. 1991; Zhang and Wang 2011). Electromagnetic data was acquired along a profiles located downstream to the dam axis by using frequency domain electromagnetic instrument EM34-3XL with 10 m coil separation. The coil separation was selected so that it could thoroughly investigate a depth of 7.5 to 10 m. The profiles location was selected to determine the effectiveness of the dam in delineating the plume. Data was recorded manually and GPS was used to acquire latitude and longitude values.

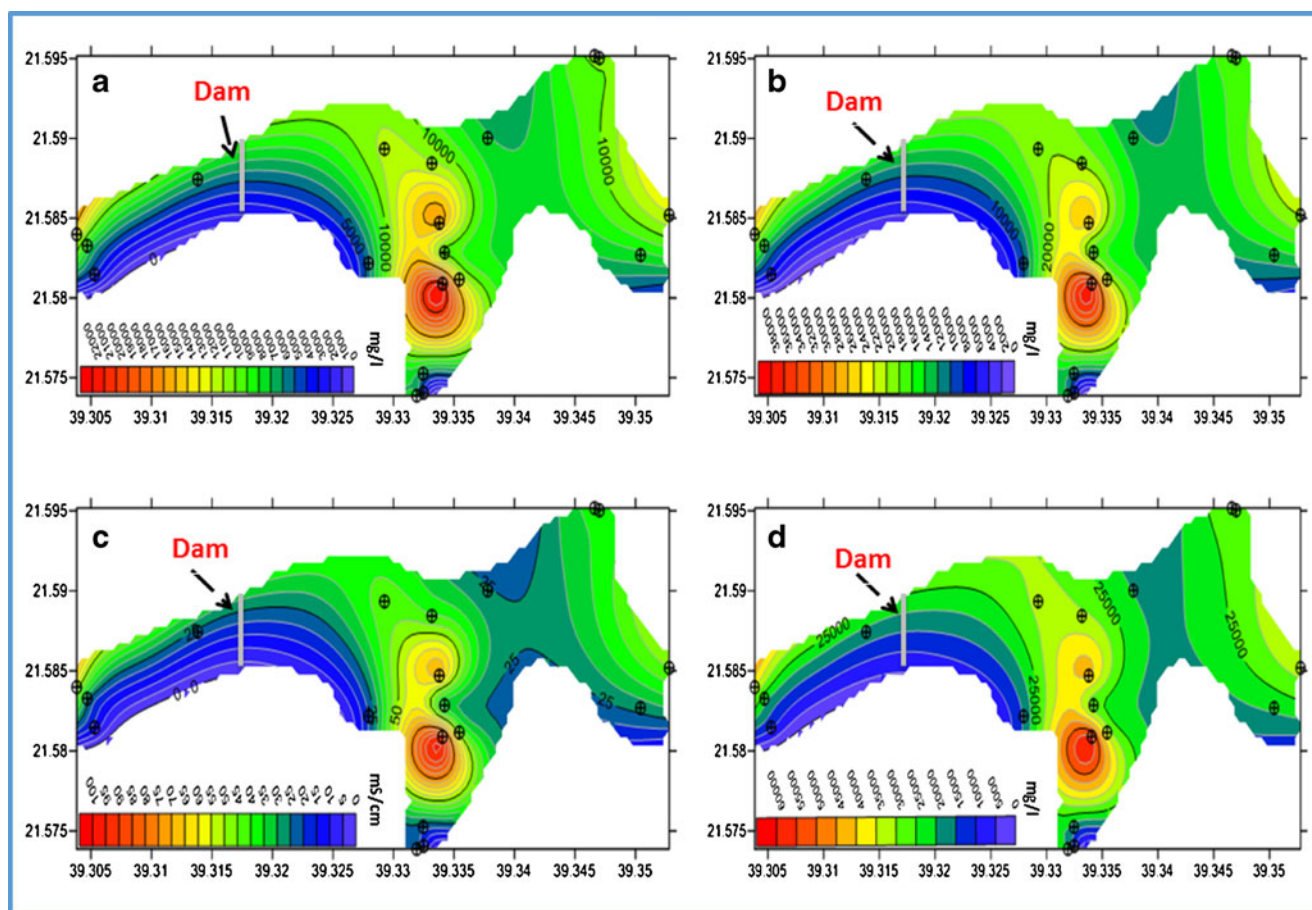


Fig. 4 Distribution of total cations (a), total anions (b), electrical conductivity (c), and total dissolved solids (d) in the study area (black circles show sampling locations)

Fig. 5 Ground water flow direction in study area

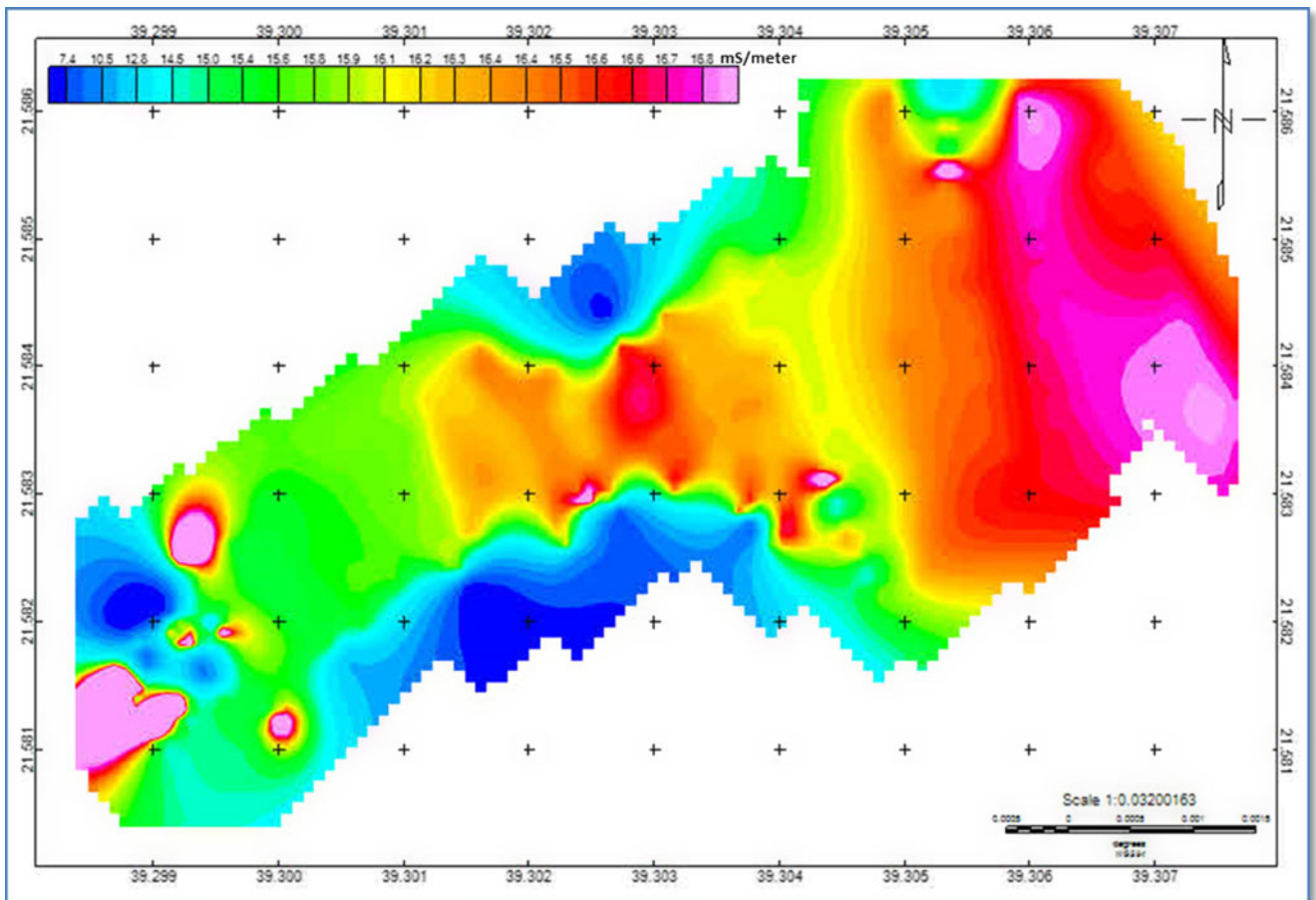
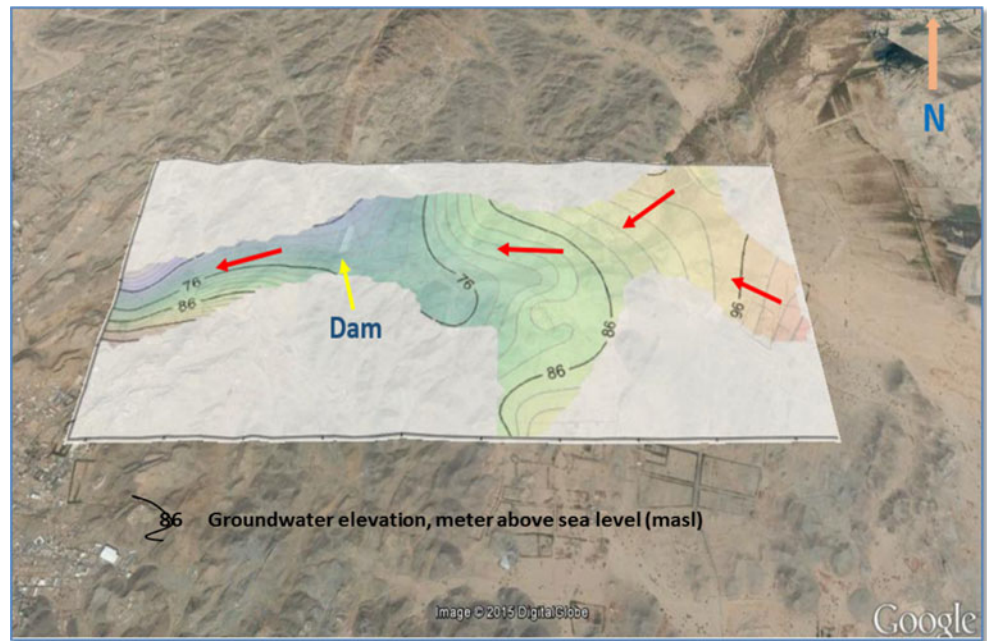


Fig. 6 Electromagnetic conductivity map with 10 m separation

Table 2 Maximum acceptable concentration of various ions in the drinking water and wastewater reuse for agricultural purposes (Environment 2011; WHO 2006)

Ions	Concentration in drinking water (KSA)	Wastewater reuse for agriculture (KSA)	Average of ions present in study area
Calcium	200	230	1556.77
Magnesium	30–150	–	588.92
Sodium	200	–	7349.05
Sulfate	250–500	600	3665.24
Chloride	250	100	12,303.55
Total hardness	300	–	6306.47
TDS	1500	2000	26,130.21

Then, data was contoured by using Oasis montaj software (Geosoft® version 7.0.1) to get electrical conductivity map.

Agricultural potential calculations

To investigate further the possibility of using the contaminated groundwater present at Al Misk Lake for agricultural purposes, salinity index, sodium adsorption ratio, and sodium percentage analysis were performed.

The crop productivity salinity hazard (or salinity index) is the most significant criteria for water quality that can be calculated from electrical conductivity values. The salts are generally initiated from high saline water table or dissolved minerals in the groundwater. For irrigation purposes, water with electrical conductivity values less than 700 µS/cm is considered as good (Narany et al. 2014).

Sodium adsorption ratio (SAR) influences the permeability of the soil and its presence in high concentration lead to the development of alkaline soil. Soil converted to compact

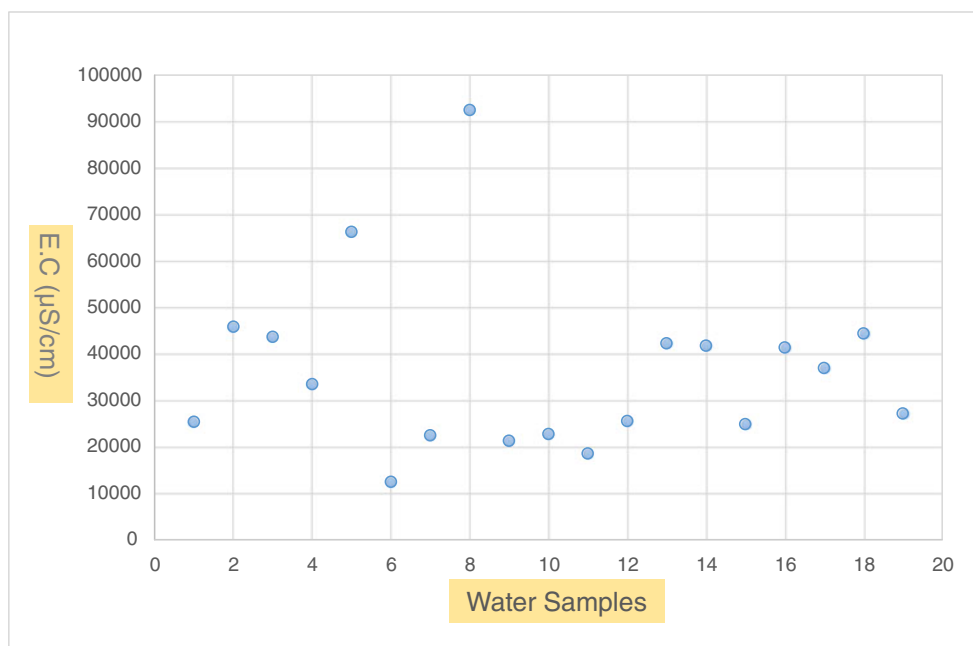
and hard when dry and progressively impervious to water penetration therefore the physical soil structure is damaged and becomes inappropriate for growth of plants. It is measured by the relative concentration in milli-equivalent per litre (meq/l) of sodium, calcium, and magnesium (Narany et al. 2014). The effect of relative cations adsorption on sodium accumulation in the soil specifies the SAR, and it is calculated by using Eq. (1):

$$SAR = Na / \{ (Ca + Mg) / 2 \}^{1/2} \tag{1}$$

Sodium percentage is a useful method for determining the suitability of groundwater for agricultural purposes (Wilcox 1955). Sodium percentage is the concentration of sodium in irrigation water and used to categorize the chemical composition of groundwater. It can be calculated by using Eq. (2), and all the ion concentrations are in meq/l:

$$Na\% = \{ (Na + K) * 100 \} / (Ca + Mg + Na + K) \tag{2}$$

Fig. 7 Salinity index for groundwater samples for study area



Results and discussion

Geochemical analysis

Table 1 shows the results of a hydrogeochemical analysis performed on all the 19 groundwater samples. This includes the concentration of major cations such as calcium, magnesium, sodium, and potassium (Ca^{++} , Mg^{++} , Na^+ , K^+) and anions such as sulfate, carbonate, bicarbonate, and chloride (SO_4^- , CO_3^- , HCO_3^- , and Cl^-) along with total hardness and total dissolved solids (TDS). Electrical conductivity and salinity values measured directly at the groundwater wells are also given in Table 1.

The values of almost all the parameters were found to be the highest in groundwater sample taken from Well No S.8 and the lowest in S.6. In order to understand the spatial distribution of geochemical parameters across the entire study area, Fig. 4a–d was plotted for the total cations, total anions, electrical conductivity, and total dissolved solids, respectively. As expected, they all have the same pattern.

The highest concentration contours for all the parameters were consistently found for Well No S.8, lowering somewhat to the north (S4) and south (S11) and emerging again at the northwest (S1, S2) of the figure. The lowest concentration was found for well No. S.6 downstream to the flood control dam. When compared with the prevalent groundwater flow direction (Fig. 5), it was found that the groundwater wells located away from the main wadi course (S10, S11, S12) upstream to the dam showed much lower concentrations as compared to the wells located near the main wadi (S5). The highest concentration found at S.8 was further investigated by studying the earlier images dating back to 2000 to 2010 of Google Earth®. In the earlier images of the Al Misk Lake, S.8 location corresponded to the area where depth of the untreated sewage and the residence time were found to be maximum. This situation could have served as the point source for groundwater contamination. The spreading of plume might have degraded the groundwater quality of the entire area.

Table 3 Classification of water quality on the basis of electrical conductivity (Handa 1969; Narany et al. 2014)

EC ($\mu\text{s}/\text{cm}$)	Water salinity	Classification	Percentage
0–250	Low (excellent quality)	Class I	–
251–750	Medium (good quality)	Class II	–
751–2250	High (permissible quality)	Class III	–
2251–6000	Very high	Class IV	–
6001–10,000	Extensively high	Class V	–
10,001–20,000	Brines weak concentration	Class VI	10.5 %
20,001–50,000	Brines moderate concentration	Class VII	79.0 %
50,001–100,000	Brines high concentration	Class VIII	10.5 %
>100,000	Brines extremely high concentration	Class IX	–

Table 4 Classification of water quality on the basis of sodium adsorption ratio (Narany et al. 2014; Todd 1959)

Value of SAR	Water quality	Percentage
<10	Excellent	–
10–18	Good	–
19–26	Doubtful	16 %
>26	Unsuitable	84 %

The major direction of groundwater flow is to the west that corresponds with the general direction of surface water flow. However, in the vicinity of S.8, the shape of the potentiometric contours indicates that the groundwater flow is to the north-northeast. It is believed that the northerly direction of groundwater flow from S.8 might have transported the contaminants to the EW trending the main wadi course. Much stronger flushing action near the main wadi course might have diluted the concentration of contaminants to some extent. As the source is not persistent (no more untreated sewage is being dumped), the processes of dispersion and diffusion will further attenuate the plume and will result in lower concentrations with time (Freeze and Cherry 1979). However, the concentrated flow within the thalweg remains the major direction of contaminant transport.

Geophysical analysis

Electromagnetic map with 10 m separation (Fig. 6) shows that most of the area (from green to pink color) reflects high conductivity for a zone of 7.5 to 10 m maximum achievable depth. High conductive zones represent the presence of contaminants in the groundwater. The most prominent conductive zone is aligned NS to the east of the area and also along the wadi course where it tapers off while going further downstream to the dam. A structural geological survey carried out at the field showed NS trending fault zones where it is less likely for the trapped contaminants to disperse/diffuse with the surrounding areas. The descending conductivity values while

Table 5 Classification of water quality on the basis of sodium percentage (Narany et al. 2014; Wilcox 1955)

Sodium percentage	Water quality	Percentage
<20	Excellent	–
20–40	Good	–
40–60	Permissible	11 %
60–80	Doubtful	68 %
>80	Unsuitable	21 %

going further downstream to the dam axis represent a much larger longitudinal dispersivity (α_L) in the main direction of flow as compared to transverse dispersivity (α_T) perpendicular to the flow. This is proven by the presence of the lowest conductivity values (blue color) on either side of the main wadi course. These zones represent the presence of boulders and impervious basement rocks. This is the zone considered to be an aquiclude by Ewea (2010). Two circular “highs” found to the southwest part of the map correspond to the presence of a temporary earthfill dam that has recently been removed.

Maximum acceptable concentrations (MAC) of different elements in drinking water for KSA are given in Table 2. The MAC of sulphate, chlorides, and total dissolved solids for waste water to be reused for agricultural purposes are also given in this table. The average concentrations of various ions present at Al Misk Lake are much higher than the drinking water or wastewater reuse. For example, the concentration of calcium and sulphate at Al Misk Lake was found to be six to seven times higher than the MAC of wastewater reuse. The

total dissolved solids were found to be as high as 13 times when compared with the wastewater reuse standards of KSA.

Agricultural potential

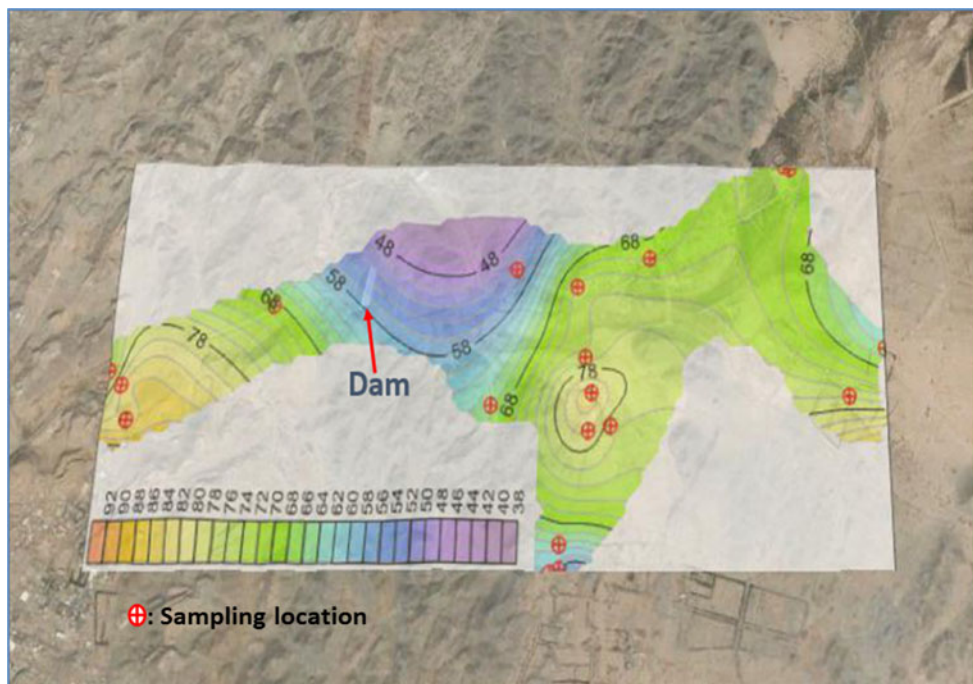
For the salinity index, water with electrical conductivity values less than 700 $\mu\text{S}/\text{cm}$ is considered as good for irrigation purposes (Narany et al. 2014).

None of the water samples lie in this range (Fig. 7). In the study area, 10.5 % of water samples fall in class VI with the equal percentage of samples in class VIII. The rest of the samples (79 %) belong to category VII (Table 3). This category is classified as brines with high concentration (Narany et al. 2014).

In term of sodium adsorption ratio (SAR), about 16 % water samples classified in the doubtful category and 84 % in unsuitable class in case of groundwater used for irrigation purposes (Table 4).

Classification of water quality on the basis of sodium percentage shows that none of water samples from the study area is classified in the excellent or good quality class. Only 11 % water sample are classified in permissible class, whereas about 68 % lie in doubtful and 21 % in unsuitable quality for irrigation purpose class (Table 5). The doubtful and unsuitable areas remain in the neighbourhood of S.8 and along the main wadi course (Fig. 8). It can be seen that the dam has very little effect on the containment of the plume because of the presence of the permeable deposits below the dam foundation. The permissible areas represent the aquiclude located in the vicinity of the basement rocks.

Fig. 8 Sodium percentage in the study area



Conclusion

On the basis of the results of hydrogeological, geochemical, and electromagnetic surveys carried out at the Al Misk Lake Floodplain, it is concluded that the groundwater quality at the study area has degraded. This degradation is caused by the plume emanating from the untreated sewage disposal at Al Misk Lake. The longitudinal and transverse extent of the plume mapped by the hydrogeological and geophysical surveys revealed that the contamination has spread to almost all the cultivable areas of the Al Misk Floodplain. Sodium adsorption ratio, salinity hazard, and sodium percentages were found to be much higher than the irrigation water quality standards thus making the Al Misk Lake Floodplain unsuitable for irrigation purposes. It is recommended that the possibility of planting salt-tolerant species be looked at for any future studies at Al Misk Lake.

References

- Abderrahman, W (2002) Should intensive use of non-renewable groundwater resources always be rejected?: intensive use of groundwater: challenges and opportunities, p. 191–203
- Al-Hasawi, Z., and Hussein, K (2012) Groundwater investigation in Rabigh Governorate, West of Saudi Arabia, *Global Advanced Research Journal of Environmental Science and Toxicology*, v. 1, no. 4, p. 72–79
- Al-Kahtani, S.H., and Ismaiel, S.M. (2010) Groundwater irrigation management in the Kingdom of Saudi Arabia: A case study of Al-Wajid aquifer, *Journal of US-China Public Administration*, v. 7, no. 12, p. 54–65
- Al-Saud, M., Teutsch, G., Schüth, C., and Rausch, R (2011) Challenges for an integrated groundwater management in the Kingdom of Saudi Arabia, *International Journal of Water Resources and Arid Environments*, v. 1, no. 1, p. 65–70
- Al-Shayaa, M.S., Baig, M.B., and Straquadine, G.S. (2012) Agricultural extension in the Kingdom of Saudi Arabia: Difficult present and demanding future, *The Journal of Animal and Plant Sciences*, v. 22, no. 1, p. 239–246
- Al-Zahrani, K.H., 2009 Sustainable development of agriculture and water resources in the kingdom of Saudi Arabia, *in Proceedings Conference of the International Journal of Arts and Sciences 2009*, Volume 1, p. 3–37
- Alkolibi, F.M. (2002) Possible effects of global warming on agriculture and water resources in Saudi Arabia: impacts and responses *Climatic change*, v. 54, no. 1–2, p. 225–245
- Aly, A., Alomran, A., Alwabel, M., Almahaini, A., and Alamari, M (2013) Hydrochemical and quality of water resources in Saudi Arabia groundwater: A comparative study of Riyadh and Al-Ahsa regions *Proceedings of the International Academy of Ecology and Environmental Sciences*, v. 3, no. 1, p. 42–51
- Alzahrani, K.H., Muneer, S.E., Taha, A.S., and Baig, M. B (2012) Appropriate cropping pattern as an approach to enhancing irrigation water efficiency in the Kingdom of Saudi Arabia: JAPS, *Journal of Animal and Plant Sciences*, v. 22, no. 1, p. 224–232
- APHA (2005) Standard methods for the examination of water and wastewater, 21st edn. American Public Health Association, Washington, DC
- Campbell, D. L., and Fitterman, D. V., Geoelectrical methods for investigating mine dumps, *in Proceedings Proceedings of the Fifth International Conference on Acid Rock Drainage*. SME, Littleton, CO2000, p. 1513–1524.
- Dan-Azumi JJ (2011) Agricultural sustainability of smallholder floodplain agricultural systems: a case study of Fadama areas in North-Central Nigeria, Doctor of Philosophy. University College, London
- Danielsen, J.E., Auken, E., Jørgensen, F., Søndergaard, V., and Sørensen, K.I. (2003) The application of the transient electromagnetic method in hydrogeophysical surveys: *J Appl Geophys*, v. 53, no. 4, p. 181–198
- Elfeki, A., Ewea, H., and Al-Amri, N (2011) Linking groundwater flow and transport models, GIS technology, satellite images and uncertainty quantification for decision making: Buraiman Lake Case Study Jeddah Saudi Arabia, *International Journal of Water Resources and Arid Environments*, v. 1, no. 4, p. 295–303
- Elhadj, E. (2004) Camels don't fly, deserts don't bloom: an assessment of Saudi Arabia's experiment in desert agriculture: Occasional Paper, no. 48, p. 6
- Environment, P. o. M. a., 2011, National Ambient Water Quality Standards for KSA, 1409-01.
- Ewea, H (2010) Hydrological analysis of flooding wastewater lake in Jeddah: Saudi Arabia, *Journal of King Abdel Aziz Univ: Met., Env. & Arid Land Agric faculty*, v. 125–142, no. 9
- Freeze RA, Cherry JA (1979) *Groundwater*, 604 pp. Prentice-Hall, Englewood Cliffs, NJ
- Hadadin, N., Tarawneh, Z., Shatanawi, K., Banihani, Q., and Hamdi, M. R. (2013) Hydrological analysis for floodplain hazard of Jeddah's drainage basin Saudi Arabia, *Arabian Journal for Science and Engineering*, v. 38, no. 12, p. 3275–3287
- Handa, B., Description and classification of media for hydro-geochemical investigations, *in Proceedings Symposium on ground water studies in arid and semiarid regions*, Roorkee1969
- McQuown, M., Becker, S., and Miller, P., Subsurface characterization of a landfill using integrated geophysical techniques, *in Proceedings The 5th national outdoor action conference on aquifer restoration, ground water monitoring and geophysical methods 1991*, p. 933–946
- Moore T, Al-Rehaili M (1989) Geologic map of the Makkah Quadrangle: Sheet 21D, Kingdom of Saudi Arabia, Ministry of Petroleum and Mineral Resources. Deputy Ministry For Mineral Resources, Publication, Jeddah, SA.
- Narany, T.S., Ramli, M.F., Aris, A.Z., Sulaiman, W.N.A., and Fakharian, K. (2014) Groundwater irrigation quality mapping using geostatistical techniques in Amol-Babol Plain, Iran: *Arabian Journal of Geosciences*, p. 1–16
- News, A. (2013) Sewage networks in Jeddah very poor. (<http://www.arabnews.com/news/458680>): Jeddah, Arab News
- Sharif AA (2008) Sewage lake threatens Jeddah. *The National, UAE* <http://www.thenational.ae/news/uae-news/environment/sewage-lake-threatens-jeddah>
- Shetty, S. (2003) Kingdom of Saudi Arabia Future Vision of the Saudi Economy Agriculture and Water Resources Management: Issues and Options; A World Bank Discussion Paper
- Todd D (1959) *Groundwater hydrology*. Wiley, New York
- WHO, 2006, A compendium of standards for wastewater reuse in the eastern Mediterranean region: Geneva: WHO.
- Wilcox, L. (1955) *Classification and use of irrigation waters*
- Zafar, S. (2013) Waste Management in Jeddah (<http://www.ecomena.org/waste-management-jeddah/>)
- Zhang, S., and Wang, X. (2011) Delineation of groundwater and soil contamination using EM survey at an industrial abandoned site *Journal of Environmental Science and Engineering*, v. 5, no. 5, p. 545–549