Research Article

Faisal Rehman, Hussein M. Harbi, Tahir Azeem, Abbas Ali Naseem, Muhammad Fahad Ullah, Saif ur Rehman, Omar Riaz, Faisal Rehman*, and Helmy S. O. Abuelnaga

Shallow geophysical and hydrological investigations to identify groundwater contamination in Wadi Bani Malik dam area Jeddah, Saudi Arabia

<https://doi.org/10.1515/geo-2020-0176>

received March 22, 2020; accepted June 17, 2020

Abstract: The integration of geophysical techniques with hydrological investigation is frequently used for solving different geological and environmental problems including groundwater quality and exploration and seismic vulnerability assessment. In this research, the shallow geophysical techniques comprising of electrical resistivity profiling, vertical electrical sounding, and ground magnetic were used to identify the contaminated areas lying in the upstream and downstream of Almisk Lake in Jeddah. The chemical analyses of water samples collected from the wells located in the downstream and upstream areas were used to support these results as an increase in the total dissolved solids (TDS) shows a decrease in the resistivity value. The results of geophysical techniques and hydrochemical analyses show that the TDS values are significantly higher in the upstream area of dam than those of the downstream, which

suggests that the contaminating source is lying in the upstream of the reservoir. Moreover, the dam was not completely successful to block the contamination because of improper base. The hydrochemical analysis and geophysical results clearly indicate that the groundwater is not suitable for drinking and irrigation purposes.

Keywords: groundwater contamination, hydrogeophysics, hydrochemical analyses, total dissolved solids

1 Introduction

Geophysical techniques and hydrogeological studies are the pivotal tools to detect and study the different environmental problems caused by the drinking and waste water, and the integrated geophysical methods with a hydrogeological investigation can impeccably delineate the contaminated, partly affected, and virgin area. The integration also provides insight into the future potential and venerable subsurface areas to be affected by lateral and vertically downward movement of contaminants [1–4].

Many researchers used the integration of different geophysical methods in dealing with mapping of waste disposal areas and characterization of bedrocks to delineate fractures and faults through which transportation of contaminants takes place in the subsurface and nature of contaminants. Subsurface contamination can occur in different ways like intrusion of saltwater, seepage from buried waste, and groundwater pollution of soil through the landfill or direct contamination [5–8]. Ground magnetic method is the most widely used technique to identify the major subsurface structural elements such as faults, fractures which facilitate contaminant spreading [9]. Electrical resistivity profiling (ERP) provides valuable information on resistivity of subsurface material which will be used to create 2D and 3D resistivity models. The variation in resistivity values provides probable direction of landfill leachate flow in subsurface [10–14].

The present research is executed by the integration of different shallow geophysical methods and chemical

* **Corresponding author: Faisal Rehman**, Department of Earth Sciences, University of Sargodha, Sargodha, Pakistan, e-mail: mail.faisalrehman@gmail.com

Faisal Rehman: Department of Earth Sciences, Quaid-i-Azam University Islamabad, Islamabad, Pakistan, e-mail: faisalrehman_atd@yahoo.com

Hussein M. Harbi: Geophysics Department, King Abdulaziz University, Jeddah, Saudi Arabia, e-mail: hharbi1@kau.edu.sa

Tahir Azeem: Department of Earth Sciences, Quaid-i-Azam University Islamabad, Islamabad, Pakistan, e-mail: tahir2rd@yahoo.com

Abbas Ali Naseem: Department of Earth Sciences, Quaid-i-Azam University Islamabad, Islamabad, Pakistan, e-mail: abbasali@qau.edu.pk

Muhammad Fahad Ullah: Department of Earth Sciences, University of Sargodha, Sargodha, Pakistan, e-mail: mfahad_awan@yahoo.com

Saif ur Rehman: Institute of Geology, University of the Punjab, Lahore, Pakistan, e-mail: saifurrehman5@gmail.com

Omar Riaz: Department of Earth Sciences, University of Sargodha, Sargodha, Pakistan, e-mail: omarriazpk@gmail.com

Helmy S. O. Abuelnaga: Nuclear Materials Authority, P. O. Box 530, El-Maadi, Cairo, Egypt, e-mail: helmysosman@yahoo.com

analysis of groundwater samples to detect the contamination in the groundwater and sources of contamination. Integrated geophysical methods including ground magnetic method, ERP, and vertical electrical sounding (VES) were carried out around the catchment area of Wadi Bani Malik dam (Al Misk Lake area Figure 1) to determine the contamination in groundwater and source of contamination. The study area has been used as Jeddah's waste disposal site and abandoned for over 10 years but leaching out contaminants is a problem [2,15,16].

1.1 Location and geology of the study area

The study area is located about 40 km in the east of Jeddah that is one of the major cities in Saudi Arabia (Figure 1). For more than past 10 years, wastewater has been collected in underground cesspools and then it is transported to the Wadi Bani Malik area through tankers [15,17]. Wadi Bani Malik is one of the most important structures of the area in terms of its size. It covers an area of 519 km² with a maximum altitude of 500 m. The study area consists of alluvial aquifer with small stream branches merging into mainstream channel of the Wadi. It is an arid region with tropical type of climate. Precipitation is less than 250 mm/year while the summer temperature often reaches 48°C [18]. The drainage of the Wadi is semi-rectangular to dendritic type with its catchment area is mushroom shaped [19]. Lake Al Misk is formed in the upstream area of the Wadi and is the dumping site of the sewage of Jeddah City. Around 1,200 tankers dump the sewage water in the lake which has significantly increased in the size of the lake.

Wadi Bani Malik excellently crops out a thick sequence of volcanic, plutonic, and volcanoclastic rocks. These rocks are grouped into seven main units including Madrasah Formation, unassigned metagabbro and gabbro, Dighbij complex, Kamil diorite and quartz diorite, Hafnah complex, unassigned syenogranite and quaternary deposits, and mafic dykes (Figure 2). The study area crops out the rocks of Madrasah Formation and is characterized by basic and intermediate volcanic and related volcanoclastics which are metamorphosed to greenschist and amphibolite facies. These rocks are intruded by granite, granodiorite, and diorite [20].

2 Materials and methods

2.1 Methodology

In this work, the study area was divided into two areas (Area-1 and Area-2) depending upon the accessibility of the area (Figure 3). Area-1 covers the whole area lying along the downstream, and Area-2 includes the area located along the upstream of the lake/dam. The shallow geophysical techniques including ground magnetic, ERP, and VES were used as primary techniques to collect the data. Results of geophysical techniques were compared with the hydrogeological studies and chemical analysis of water samples collected from the wells.

ERP data were acquired along seven profiles and named as ERP-1, ERP-2, ERP-3, ERP-4, ERP-5, ERP-6, and ERP-7 (result of ERP-1 is not used in this article). Six VES were performed in the area; VES-4, VES-5, and

Figure 1: Location map of the study area.

Figure 2: Geological map of Wadi Bani Malik area (Moore and Al-Rehaili 1989 [20]; Rehman *et al.* 2016d [21]).

VES-6 were performed in Area-1 and VES-1, VES-2, and VES-3 in Area-2. In both the areas, magnetic data were acquired along North-South trending profiles having 5 m distances between stations and 20–30 m between profiles depending upon the accessibility of area (Figure 4). ERP and VES data were collected in the study area [15,16] along with ground magnetic data [1]. *In situ*, hydrogeological studies were made using a standard Solinst probe which includes the measurement of electrical conductivity (EC), salinity, water depth, and total dissolved solids (TDS).

3 Results and discussion

3.1 Vertical electrical sounding

The VES data were plotted in RES1DVES software. The data were used to demarcate the different lithological

layers and their thickness in the study area. VES data of the study area show the presence of four distinct lithological layers including surface layer, sandy layer, alluvial layer (mixed gravelly and sandy layer with minor clays), and basement boulder, from surface to bottom, respectively. The maximum depth of the investigation of VES is about 25 m in both Area-1 and Area-2. The thickness of interpreted layers varies significantly from point to point in the study area. The thickness of uppermost surface layer is nearly consistent in Area-1 and Area-2, and its thickness is less than 1 m. The lower sandy layer is thicker in upstream Area-2 as compared to Area-1. The thickness of sandy layer varies from 10 to 15 m in Area-2 and 4 to 11 m in Area-1. Sandy layer is underlain by alluvial layer that varies from 1.9 to 2.25 m in thickness in Area-2 and 1.9 to 13.9 m in Area-1. The lowermost gravelly layer consisting of basement boulders is thickly developed in Area-2, and its thickness ranges from 12.2 to 20 m. In upstream Area-1, the thickness of the lowermost layer varies from 7.8 to 12.2 m.

Figure 3: Location of upstream and downstream of the study area.

Figure 4: Location of magnetic data (red lines), electrical resistivity profiles (blue lines), and vertical electrical soundings on both sides of the dam.

3.2 Electrical resistivity profiling

Resistivity profiling of the study area indicates pronounced variation in resistivity values of upstream and downstream areas. Resistivity variations with depth are used to develop

the resistivity profiles of different aforementioned lithological layers. The minimum resistivity values of 1.6 (Ωm) were recorded in the sandy layer of VES-4 while maximum resistivity values of 10577.2 (Ωm) were calculated in the uppermost surface layer of VES-5 of Area-1.

3.3 Correlation of VES and ERP data

Among the total six VES points, five VES were acquired near or at same points of ERP except the VES-6. The VES and ERP show good mutual correlation in uppermost layers including uppermost surface layer and lower sandy layer except the VES-6. The uppermost surface layer is generally highly resistive and is mutually comparable to a great extent; however, its values are variable in Area-1 (123.1 Ωm at VES-4 to 10577.2 Ωm at VES-5) and Area-2 (243.1 Ωm at VES-3 to 3749.7 Ωm at VES-1). The lower sandy layer is generally characterized by the very low resistivity values in both Area-1 (1.5 Ωm at VES-4 to 14.3 Ωm at VES-6) and Area-2 (3.8 at VES-3 to 9.4 at VES-1). The lower sandy layer shows very low resistance and indicates filling of saline water. The third alluvial layer exhibits a very diverse resistivity (very low to low except the VES-6) and does not show good correlation. In contrary to alluvial layer, the lowermost gravelly layer is generally very resistive layer and shows good mutual correlation between VES and ER data.

3.3.1 Area-1

The VES-4 was carried out about 21 m away from the site of ERP-2 and about 113 m from the starting point of the same site. VES and ERP show a good mutual correlation in terms of thickness and variation in resistivity with depth (Figure 5). A low resistive sandy contaminated

layer is marked up to 5 m depth that is followed by a thin sandy layer with relatively high resistivity values as compared to upper contaminated layer. However, no resistivity information is available below this sandy layer. Similarly, VES-5 and ERP-4 also exhibit a good mutual correlation. VES-5 was performed at the same location as of ERP-4 and about 403 m from the starting point of ERP-4. VES and ERP data of these profiles show the presence of a low resistive sandy contaminated layer below high resistive surface layer that extends to depth of 11.5 m. This contaminated layer is further underlain by a relatively high resistive layer consisting of sandy sediments.

In contrary to these, the data of VES-6 were acquired 6.5 m away from the site of ERP-5 and about 100 m away in the east of starting point of aforementioned profile. In comparison with the above-mentioned profiles, VES-6 and ERP-5 are characterized by the missing low-resistivity contaminated layer below the high-resistivity surface layer. The sandy layer beneath the high resistive surface layer shows relatively high values of resistivity as compared to the other profiles of downstream and indicates low level of contamination in the water of this layer possibly because of the uplift of resistive block at this location.

3.3.2 Area-2

VES-1 was conducted 34 m away from the site of ERP-7 and about 715 m away from the starting point of ERP-7

Figure 5: Correlation diagram of geophysical techniques on the downstream (Area-1) of the dam in Wadi Bani Malik area Jeddah, Saudi Arabia. (a) Electrical resistivity tomography, (b) vertical electrical sounding, and (c) total intensity magnetic map.

(Figure 6). In both sections, surface high resistive layer is followed by a very low resistive sandy layer that extends up to the depth of about 16 m. The very low values of resistivity show high levels of contamination in this layer and indicate the presence of saline water. The data of VES-2 were acquired 12 m away from the location of ERP-6 profile, and it was located about 280 m away from the starting point of ERP-6. The data of VES-2 and ERP-6 indicate a very low resistive sandy layer with contaminated/saline water underneath the high resistive surface layer. It also shows a good correlation up to the lower sandy layer. This contaminated sandy layer is further replaced with a high resistive layer with increasing depth.

3.4 Correlation between VES results and magnetic intensity

The VES profiles acquired from the study area are located in the different magnetic areas and they show consistency and correlation with magnetic anomaly data of the study area (Figure 5).

3.4.1 Area-1

Among the three VES profiles of Area-1, the site of VES-4 is located in the high magnetic value area. High magnetic

values are generally manifested by the presence of hard rocks of basement affinity in geological environments. The data of VES-4 profile are strongly consistent and identical with the magnetic intensity map of the area and show that the basement boulders/hard rocks of basement are present at very shallow depth (Figure 5).

The outcrop data collected from the vicinity of VES-4 site also confer the presence of same material as interpreted in the profile of VES-4. Remaining two VES profiles including VES-5 and VES-6 were acquired from the areas of moderate and low magnetic intensities. These profiles are also consistent with the magnetic intensities and are characterized by the presence of basement rocks/boulders at deeper levels in subsurface. Furthermore, the location of VES-6 is located along the drainage trend in Wadi which represents down thrown hanging wall of a normal fault.

3.4.2 Area-2

Among the total three VES profiles of Area-2, sites of two VES profiles including VES-1 and VES-3 are located in the low magnetic area as compared to the third profile VES-2 which lies in the high-magnetic intensity area (Figure 6). The results of VES profiles are consistent with the magnetic intensity map. The VES-2 profile clearly indicates the presence of the basement rock/boulder layer at shallow depth as compared to other profiles of Area-2.

Figure 6: Correlation diagram of geophysical techniques on the upstream (Area-2) of the dam in Wadi Bani Malik area Jeddah, Saudi Arabia. (a) Electrical resistivity tomography, (b) vertical electrical sounding, and (c) total intensity magnetic map.

3.5 Correlation of ERP and hydrogeological parameters

Results of electrical resistivity profiles are compared with the results of *in situ* hydrogeological parameters of water samples of different monitory water wells located in the downstream and upstream areas of the study area (Figure 7).

Among the *in situ* hydrological parameters, EC and depth of water table were used for the correlation with ER profiles. Well-1 that is located in the upstream Area-2 is characterized by 25.4 mS/cm value of EC that is very low as compared to Well-2 of Area-1 where it is calculated as 45.9 mS/cm.

Furthermore, the depth of water table in both well is also variable. The water table was recorded at the depth of 3.05 m in Well-1, and the depth of water table in Well-2 is estimated about 0.8 m that is quite shallow. Water table is recorded in the sand layer lying below the surface layer in both wells. The distance between these two wells is just 125 m, but their EC values and depths of water table show significant variation in quality of water and depth of host layer. The high value of EC in Well-2 shows the higher levels of contamination in groundwater in the Al Misk lake area in the downstream of dam as compared to upstream area. Furthermore, the storage of water in upstream of dam significantly elevated the water table to shallow depth through the seepage.

The nature of contamination can be investigated by the hydrochemical analysis; however, the accelerated levels of contamination in water are caused because of the dumping of untreated sewage water of Jeddah city in

the dam. In comparison with downstream area, the lower EC values and less contamination in upstream area are the results of different factors like non-continuous nature of source and attenuation processes like adsorption. As this source is non-continuous, the contaminants had to travel through the unsaturated area to reach the receptor (groundwater). Further, the attenuation processes like adsorption significantly reduced the concentration of contaminants which result in the lowering of EC values. Moreover, three wells are also present along the profile of VES-7 at distances of 75, 280, and 515 m from the aforementioned profile with water depths of about 3.27, 3.51, and 1.15 m, respectively. Geophysical results show that the top of most part of sandy layer is contaminated with salt. This layer is variable in thickness, and generally, its thickness tends to increase northward. The results of hydrogeological parameters support the geophysical results. This layer has different contaminant concentration and TDS.

4 Conclusion

The integration of the geophysical technique results along with hydrological investigations is one of the most widely used methodologies for solving any geological or environmental problems. In the current study, the integration of geophysical results and hydrological investigations provided indubitable outcomes. The geophysical techniques comprised of ground magnetic method and VES and ERP. The VES and ERP data are in good mutual

Figure 7: Correlation between electrical resistivity tomography and groundwater analysis results [21].

correlation. The VES profiles show consistency and correlation with magnetic anomaly data of the study area. The integration of geophysical techniques helps in identifying the contaminated layers in subsurface. Moreover, groundwater samples were collected for chemical analysis. The results of chemical analyses of water samples collected from the wells located in the downstream and upstream areas also supported geophysical findings. The integration of geophysical techniques and hydrochemical analyses suggests that the contaminating source is lying in the upstream of the reservoir. The hydrochemical analysis clearly indicates that the groundwater is not suitable for drinking and irrigation purposes.

References

- [1] Rehman F. Environmental hazard evaluation of Almisk lake, using integrated geophysical techniques. Jeddah, Saudi Arabia: King Abdulaziz University; 2016 (unpublished), in Geophysics Department.
- [2] Rehman F, Cheema T, Abuelnaga HS, Harbi HM, Atef AH, Lisa M. Interpretation of groundwater chemistry data using multivariate statistical techniques. *Glob Nest J*. 2016;18(3):665–73.
- [3] Hudson E, Kulesa B, Edwards P, Williams T, Walsh R. Integrated hydrological and geophysical characterisation of surface and subsurface water contamination at abandoned metal mines. *Water Air Soil Pollut*. 2018;229(8):256.
- [4] De Carlo L, Berardi M, Vurro M, Caputo MC. Geophysical and hydrological data assimilation to monitor water content dynamics in the rocky unsaturated zone. *Environ Monit Assess*. 2018;190(5):310.
- [5] Pellerin L. Applications of electrical and electromagnetic methods for environmental and geotechnical investigations. *Surv Geophys*. 2002;23(2–3):101–32.
- [6] Appiah I, Wemegah DD, Asare VDS, Danuor SK, Forson ED. Integrated geophysical characterisation of Sunyani municipal solid waste disposal site using magnetic gradiometry, magnetic susceptibility survey and electrical resistivity tomography. *J Appl Geophys*. 2018;153:143–53.
- [7] Giang NV, Kochanek K, Vu NT, Duan NB. Landfill leachate assessment by hydrological and geophysical data: case study NamSon, Hanoi, Vietnam. *J Mater Cycles Waste Manag*. 2018;20(3):1648–62.
- [8] McLachlan PJ, Chambers JE, Uhlemann SS, Binley A. Geophysical characterisation of the groundwater–surface water interface. *Adv Water Resour*. 2017;109:302–19.
- [9] Rehman F, Abdelazeem M, Gobashy MM, Harbi HM, Abuelnaga H. Application of magnetic method to define the structural setting controlling the contaminated area of Wadi Bani Malik, east Jeddah, Saudi Arabia. *Boll Geofis Teor Appl*. 2019;60:1.
- [10] Al-Sayed E, El-Qady G. Evaluation of sea water intrusion using the electrical resistivity and transient electromagnetic survey: case study at Fan of Wadi Feiran, Sinai, Egypt. in *EGM 2007 international workshop*; 2007.
- [11] Martínez-Pagán P, Faz A, Aracil E. The use of 2D electrical tomography to assess pollution in slurry ponds of the Murcia Region, SE Spain. *Near Surf Geophys*. 2009;7(1):49–61.
- [12] Maurya PK, Rønde VK, Fiandaca G, Balbarini N, Auken E, Bjerg PL, et al. Detailed landfill leachate plume mapping using 2D and 3D electrical resistivity tomography-with correlation to ionic strength measured in screens. *J Appl Geophys*. 2017;138:1–8.
- [13] Van Hoorde M, Hermans T, Dumont G, Nguyen F. 3D electrical resistivity tomography of karstified formations using cross-line measurements. *Eng Geol*. 2017;220:123–32.
- [14] Akingboye AS, Ogunyele AC. Insight into seismic refraction and electrical resistivity tomography techniques in subsurface investigations. *Rud Geol Naft Zb*. 2019;34(1):93–111.
- [15] Rehman F, Abuelnaga HS, Harbi HM, Atef AH. Application of vertical electrical sounding and water analysis for study the contaminated area at Al Misk lake, Eastern Jeddah, Saudi Arabia. *Nat Environ Pollut Technol*. 2016;15(1):311.
- [16] Rehman F, Abuelnaga HSO, Harbi HM, Cheema T, Atef AH. Using a combined electrical resistivity imaging and induced polarization techniques with the chemical analysis in determining of groundwater pollution at Al Misk lake, Eastern Jeddah, Saudi Arabia. *Arab J Geosci*. 2016;9(4):286.
- [17] Ewea HASA. Hydrological analysis of flooding wastewater lake in Jeddah, Saudi Arabia. *Meteorol Environ Arid Land Agric Sci*. 2010;21:1–144.
- [18] Almazroui M, Dambul R, Islam MN, Jones PD. Principal components-based regionalization of the Saudi Arabian climate. *Int J Climatol*. 2015;35(9):2555–73.
- [19] Qari MH. Geomorphology of Jeddah Governate, with emphasis on drainage systems. *Earth Sci*. 2009;20:1.
- [20] Moore T, Al-Rehaili M. Geologic map of the Makkah quadrangle, sheet 21D. Kingdom of Saudi Arabia, Saudi Arabian Directorate General of Mineral Resources Geoscience Map GM-107C, scale. 1(2,50,000); 1989.
- [21] Rehman F, Abuelnaga HSO, Harbi HM, Cheema T, Atef AH. Using a combined electrical resistivity imaging and induced polarization techniques with the chemical analysis in determining of groundwater pollution at Al Misk lake, Eastern Jeddah, Saudi Arabia. *Arab J Geosci*. 2016;9:286.