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ORIGINAL PAPER

Hydrogeological characterization of low permeability medium for conceptualization of a mine site in Eastern Turkey

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Abstract

The mining site in Eastern Anatolia of Turkey were encounter a significant risk of slope instability within the operational area. One of the processes that govern slope stability is the pore water pressure distribution. The conceptualization and characterization of porous media serve as fundamental prerequisites for the implementation of numerical methods aimed at predicting pore water distribution. This study aims to characterize the hydrogeological properties of water bearing rocks in the active mining site in Eastern Anatolia of Turkey. A total of 21 wells and drill holes were drilled in the study area to conduct in-situ tests, monitoring, and sampling. The large diameter wells drilled in surrounding the carbonate rocks were to determine the groundwater flow and boundary conditions and also wells tapped metasediments and diorite unit for hydraulic testing. The lugeon tests and installation of vibrating wire piezometers were carried out at small diameter drill holes to obtain localized hydraulic conductivity of metasediments and diorite at different depths and monitoring pore water pressure distribution along some critical cross-sections. The results obtained from these tests are used for developing hydrogeological conceptual model for groundwater flow. The results of in-situ tests show that the metasediment and diorite units act as a single hydrostratigraphic unit. The metasediments and diorite have high total porosity and low specific yield indicating that the pore water is retained by electrostatic forces in the medium and it resists flow due to low hydraulic conductivity. The vertical variation in hydraulic conductivity values indicates that the medium is highly heterogeneous.

Keywords Hydrogeological Properties · Characterization · Vibrating Wire Piezometer · Lugeon Test · Hydrogeological Conceptual Model

Introduction

The presence of groundwater at mine sites threatens efficient and safe mining operations (Beale and Read 2013; Connelly and Gibson 1985; Fernandez-Rubio and Lorca 1993; Peksezer-Sayit et al. 2015). Especially, slope instability in open pit mines is one of the major issues that are caused by groundwater (Ferreira Filho et al. 2021; Kolapo et al. 2022; Sullivan 2013; Zevgolis et al. 2019). The effect of groundwater on cut slopes and importance of the prediction of pore-water pressure distribution for slope stability have been extensively discussed in the literature on the basis of case studies (Mustafa et al. 2012; Ng and Pang 2000; Perrone et al. 2008; Rahardjo et al. 2001; Schnellmann et al. 2010; Zhan et al. 2022; Zhang et al. 2023) and well synthesized by Beale and Read (2013) and Read and Stacey (2009). Excessive pore-water pressure reduces the shear strength of the slope forming material and may lead to slope failure (Abramson et al. 2001; Argunhan-Atalay et al. 2021; Chen et al. 2004; Gardner et al. 1999; Huvenne et al. 2002; Nian et al. 2023; Solak et al. 2017; Ulusay et al. 2014; Xia et al. 2015). To reduce the excess pore-water pressure of material that form the slope, dewatering and/or depressurization is widely used (Argunhan-Atalay et al. 2021; Beale and Read 2013; Preene 2015; Read and Stacey 2009; White et al. 2004). Designation of the dewatering and depressurization system is dependent on thorough understanding of the hydrogeological setting (Beale and Read 2013). Application of the mentioned methods efficiently requires a detailed characterization of the hydrogeological setting of the mine site.

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The incorporation of the pore pressures into a geotechnical slope-stability analyses for a critical slope is often conducted by the use of an Ru value (i.e., the ratio expressing the pore water-pressure as a fraction of the vertical earth pressure), the use of a phreatic (water table) surface and the use of a pore-pressure distribution field (Beale and Read 2013). The Ru value is the simplest and the least accurate method that is usually conducted assuming fully saturated (Ru=1) media generally resulting in conservative estimates for the slope stability analyses. The use of a phreatic surface assumes hydrostatic conditions and fails to describe pore pressure distribution when there are significant vertical flow gradients. The use of a pore-pressure field that includes the horizontal and vertical distribution of pore pressures is the best practice and require the installation vertically discretized piezometers and the construction of a numerical hydrogeological model along the critical slopes considered. The construction of the numerical model on the other hand requires the characterization, conceptualization, calibration, and verification stages. The approach taken in this study is the latter method which required intensive field characterization work providing reliable conceptual hydrogeological models that formed the basis for developing and calibrating the numerical hydrogeological models for each section. The modeling part is reported in detail elsewhere (Argunhan-Atalay et al. 2021).

This paper demonstrates hydrogeological conceptualization and characterization of a mine site affected by slope stability problems. The study area consists of a series of side-by-side open pits where the ore is mainly extracted from metasediment and diorite units. Tests have revealed that the metasediment and diorite exhibit similar geotechnical properties such that high total porosity but low effective porosity and therefore high specific retention. This, in turn causes porewater to be retained by electrostatic forces in medium and to resist to flow (Bear 2012; Domenico and Schwartz 1997) which makes it highly challenging to depressurize slope material. The occurrence and distribution of groundwater in the site was investigated using combined techniques such as drilling, in-situ testing, and monitoring. The work has been done on selected four cross-sections representing the critical slopes of the main pit.

Study area

The study area is located in Eastern Anatolia Region of Turkey. The mine site is surrounded by high carbonate rock masses whose altitude reaches 2500 m asl in the south and 1500 m asl in the north of the mine site. Due to company policies, the name and exact location information of the mine kept confidential.

The geological setting of the region has been studied by Ozgul et al. (1981). Based on lithostratigraphy, structural development and geological evolution, Ozgul et al. (1981) have described three major structural units in the region. These units are, from bottom to top, Keban Unit, Munzur Dağı Unit and Ovacık Unit. The mine site is located within Munzur Dağı Unit. The geological setting of the mine site consists of three main lithologies: carbonate rocks (limestone and marble), metasediments and diorite (Fig. 1). The carbonate rocks are characterized by mainly shelf-type carbonates, and it has been continuous without a significant change in facies. The metasediments are described as metamorphic rocks which originated from mainly clastic deposits. The diorite unit is a highly altered plutonic rock unit crop out at the mine site and generally caused contact metamorphism in the carbonate rocks (Alacer Gold 2013). Metasediments and diorite are the main two lithological units where the mined ore exists. Mine site has three active operating pits, namely the Manganese pit, the Marble pit, and the Main pit. Currently, mining activities are intensified in the eastern edge of the Main pit and also slopes that are critical in terms of stability appear to be concentrated in this region. The Golder (2014) and Golder (2015) reports on stability analysis conducted in the Main pit shows that the north and south sides of the pit are developed at 25 degrees to 30 degrees. Stability analysis results mostly demonstrate high safety factor against deep failure surfaces, while few analysis shows a greater risk of slope failure in weathered and altered metasediments and diorites.

Terrane Geoscience Inc. was conducted a comprehensive study in 2018 about structural mapping of the mine site (Terrane 2018). According to this study, there are two major fault sets and several minor sets covering the study area. The South Çöpler Fault and several sub-parallel faults are the first major fault set. The second major set is the North Çöpler Fault is described as E-W trending, steeply dipping and bisect the Manganese pit.

The mine site is in the Eastern Anatolia of Turkey. Generally, the climate is cold and wet in winter, hot and dry in summers. The meteorological data obtained from WS05 (situated in mine site) show that average annual precipitation and air temperature is around 400 mm and 12 °C respectively. Precipitation occurs almost all through the year.

Groundwater seepages are observed mainly at shear zones. The occurrence of groundwater and positive pore water pressure are the main threat for stability of slopes particularly at these zones. To resolve the groundwater related problems at slopes, dewatering and/or depressurization methods are mainly preferred (Argunhan-Atalay et al. 2021; Chen et al. 2004; Huvenne et al. 2002; Solak et al. 2017; Ulusay et al. 2014). However, representative site characterization and conceptualization are essential for the application of these method efficiently. Four critical cross-sections

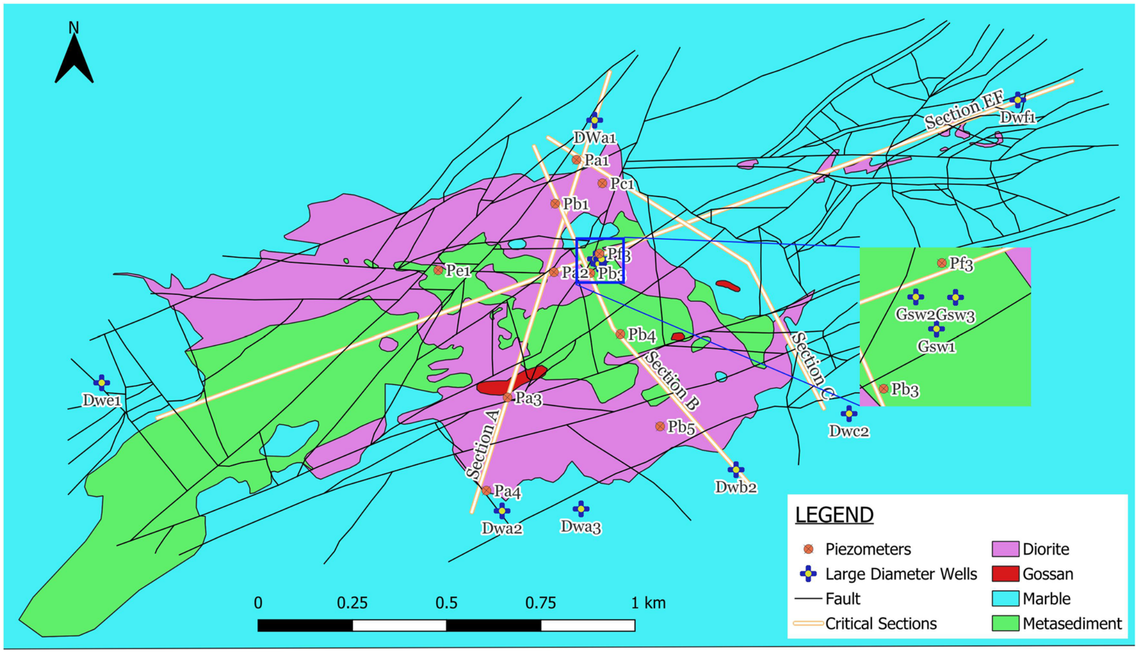

Fig. 1 Geology map of the mine site

were determined along which the occurrence and distribution of pore pressures were required. The field data regarding hydraulic properties and pore water pressure distribution have been obtained along these critical cross-sections (Fig. 1). Details of data acquisition including techniques used to characterize the site, such as drilling process, in-situ tests and analysis are given in the following paragraphs.

Materials and methods

Drilling holes and wells

To obtain the hydrogeological properties of lithological units, a total of 11 small diameter (PQ which is 3.34 inches in diameter) drill holes and a total of 10 large diameter wells (17.5 inches in diameter) were drilled in the designated critical cross-sections (Fig. 1). The small diameter wells have been cored to specify the geotechnical properties of lithological units. Also, during the drilling process of small diameter wells, lugeon tests were conducted at each well to obtain permeability profile on the critical cross-sections. Following the drilling, vibrating wire piezometers (VWP) were installed at different depths to measure the pore water pressure at different zones of lithological units. It is seen that in Fig. 1, some wells do not coincide with corresponding critical sections (e.g. Pe1, Pb5). The reason for this is that the conditions of the mining area can change quickly and sometimes drilling could not be done at the planned points. In such cases, the wells are drilled as close as possible to the planned points.

In addition to the small diameter drill holes, seven out of 10 large diameter wells were drilled into carbonate rocks and three wells (groundwater sampling wells) into metasediments and diorite to characterize the groundwater conditions. The main purpose of drilling seven large diameter wells was to determine the hydraulic head values at both ends of cross-sections in the carbonate rocks surrounding the mine site to define the hydraulic boundary conditions. The aim of drilling three groundwater sampling wells is tapping three different permeable zones in the metasediments and diorite. Water samples were collected from these zones to determine the origin and recharge areas of the groundwater in different depths by using stable isotope analysis. The aim of stable isotope analysis is to determine the water source and recharge areas which is very important for judging whether there is a hydraulic connection between the metasediments and diorite unit.

Hydraulic head distribution along critical sections were monitored in both large-diameter wells and small-diameter drill holes. A contact gage was used for monitoring on a weekly basis in all wells from September 2017 to July 2018, followed by monitoring on a monthly basis.

Geotechnical characterization

Carbonate rocks, metasediments and diorite are the three main lithology exposed in the mine site. Hydrogeologically, metasediments and diorite are impermeable units compared to carbonate rocks. For regional scale, this classification, based on the lugeon test results, was assumed sufficient to characterize the regional groundwater flow system. Although these units have low permeability, the total porosity and specific retention are high. This results in high pore water pressure due to the lack of significant groundwater movement.

The 11 small diameter holes were used to obtain geotechnical data from cores; a representative geotechnical log of small diameter drill hole is given in Fig. 2. In logs, the lithological description of metasediment and diorite is made in detail to include faults, clay zones, skarn, gossan, quartzite etc. Similarly, texture was defined as massive, brecciated, foliated, sheared, fault etc. The grain size was classified as very fine/aphanitic to very coarse. Porosity of lithological units has been classified as non-porous to highly porous or with vuggy porosity. Permeability values obtained from lugeon tests were converted to hydraulic conductivity value in m/s and plotted next to RQD values.

Lugeon test

The Lugeon test is one of the in-situ tests applied to determine hydraulic conductivity values especially in fractured rock mass (Tesema and Ekmekci 2019). The test is the most frequently used method to obtain the variation of the hydraulic conductivity in vertical profile, especially in heterogeneous media. Lugeon tests have been conducted in 11 small diameter drill holes. Test intervals were set up to 2 m to obtain a high-resolution characterization. The design and the application of the test were completed according to Houlsby (1991). Five pressure stages were applied at each test interval for at least 10 minutes and the water intake has been recorded regularly. In case of significant difference in water intake records, the test prolonged another 10 minutes to ensure the quasi steady-state conditions. The readings were evaluated in Lugeon Unit (Lu) for each of the five pressure stages. The lugeon values were then converted to hydraulic conductivity values (m/s) according to Houlsby (1991) and Roeper et al. (1992).

Pumping test

Determination of aquifer characteristics (e.g. Transmissivity, Storativity, Hydraulic Conductivity) is the main purpose of characterization studies. Pumping test is one of the widely applied in-situ tests to determine aquifer characteristics (Butler Jr 1990; Fetter 2001; Kruseman et al. 1970; Mishra et al. 2013; Walton 1970). Pumping tests have been planned to obtain hydraulic characteristics of the carbonate rock aquifer and the metasediments-diorite unit. Tests were carried out in six wells. These are Dwa-3, Dwb-2, Dwf-1,

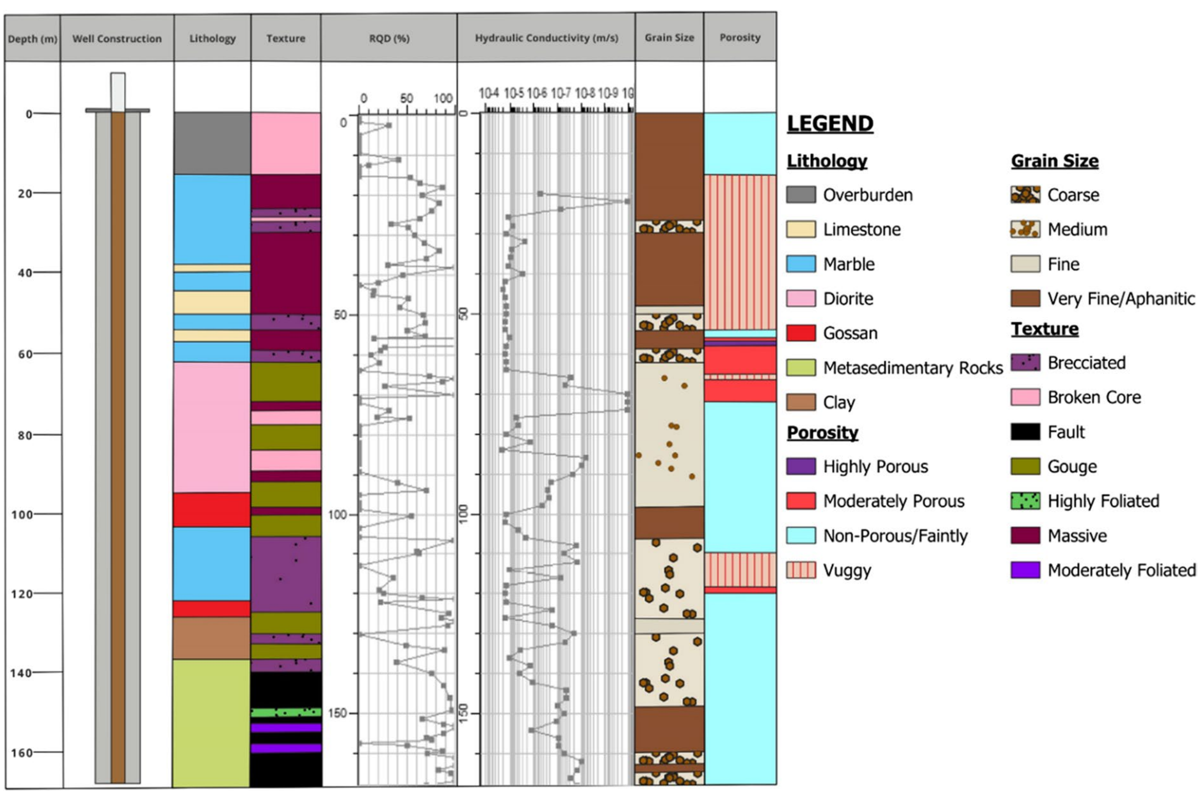

Fig. 2 Geotechnical/hydrogeological logs for well Pa1 (Ekmekci et al. 2018)

GSW-1, GSW-2 and GSW-3 wells. The test could not be conducted in other wells drilled in the carbonate rock unit because they were dry.

Instrumentation with vibrating wire piezometers

A total of 36 vibrating Wire Piezometers (VWP) were installed at different depths in small diameter drill holes to obtain the pore water pressure distribution at the study site. The VWPs were calibrated before installation and installed in fully grouted boreholes. The grouting material is prepared according to ASTM D5092 which consists of mix of water-cement and bentonite. Contreras et al. (2008) and Vaughan (1969) discussed that the pore water pressure measurement error is insignificant even if there is too much difference between grout permeability and ground permeability. The readings in kilopascal (kPa) were converted for barometric pressure and finally, hydraulic head values in meters above sea level (masl) were calculated using pressure head and elevation head values for each VWPs.

Stable isotope analysis

Stable isotopes provide useful tools to determine the possible recharge area and to explain the process affecting the groundwater flow system (Fackrell et al. 2020; Gat 1996; Toulier et al. 2019). A total of 78 samples were collected from wells, rainwater, surface water and springs. The sampling was not limited to the mine site, but it was performed on a regional scale. The analysis was done in the Stable Isotope Laboratory of Hacettepe University by Liquid Laser Analyzer of Los Gatos Inc.^{TM}.

Result and discussion

Fracture/karstic zones

Logging the large diameter wells in carbonate rocks that are fractured and partially karstified has been problematic due to loss of drilling mud. The circulation has been lost and therefore no cuttings have come out of the hole, and it is important to state that the complete loss of the drilling mud starts at a certain depth which indicates the presence of a karstic cavity/conduit. The estimates made over the elevation zones where complete loss of drilling mud starts may indicate karstic level.

According to the overall assessment, elevation of karst is around 1150 masl in the northern part of the mine, while it is around 1250 masl in southern part. In eastern and western parts, karstic zone elevation is estimated around 1050 masl and 1200 masl respectively. However, it is not clear that those zones indicate a productive karst aquifer or not.

Geotechnical characterization

The geotechnical logging was conducted in 11 small diameter drill holes to characterize the metasediments and diorite units. In the logs, detailed lithological description of metasediments and diorite is given with other information such as RQD, grain size, porosity, and hydraulic conductivity values.

The primary (intergranular) porosity of the diorite is very low, whereas it may be higher than 5 % in the massive metasediments. The altered metasediments and diorite have similar and higher intergranular porosity. The intergranular pores are saturated with water and due to their low hydraulic conductivity, the pore water is not easily drained by gravity forces. Fracture porosity has also developed in the metasediments and diorite. Due to high porosity and low specific yield, nearly all of the pore water is retained by electrostatic and capillary forces in the material. It resists flow because of the low hydraulic conductivity. Permeability values obtained from lugeon tests plotted next to RQD values. In general, RQD values are inversely related to permeability values. High RQD values are generally matching up with massive and foliated textures, on the other hand, brecciated and fault texture types are correlated with low RQD values. Grain size and porosity does not show variation in general so that in almost all piezometer wells, preponderant types are fine and very fine for grain size, non-porous and vuggy for porosity. It is important to note that several zones in the lithological logs have been described as faults. Faults are one of the main structural elements that control groundwater flow. Therefore, their existence, continuity in terms of depth and length, their width, the filling material, and its permeability need to be defined for a representative hydrogeological characterization. In the geotechnical logging practice, the number of fractures per geotechnical length has also been defined. Overall data shows that metasediment and diorite units have similar number of fractures, and these units were characterized by a mean fracture frequency (FF) of 15.24 fractures per run length in meters. Descriptive statistics of fractures for the drill holes are given in Table 1. In the table, all piezometer wells except Pb3 showed similar characteristics. The coefficient of variation of individual drill holes is generally very high. This suggests that the lithological unit is far from being homogeneous. The fracture frequency was correlated with the permeability values obtained from lugeon tests. Although in general, the two parameters are found to be compatible, they are not in some zones, where the fractures are filled with thick residue clayey material.

Lugeon test

In the study area, 882 lugeon tests were performed in 11 piezometer wells. The test range is set to 2 m to achieve a

Table 1 Descriptive statistics of fracture frequency per run length recorded in geotechnical logs

Piezometer ID	Min	Max	Mean	Standart Dev.	Cv (%)
Pa1	0.0	43.0	14.7	13.0	88.4
Pa2	0.0	40.4	21.3	11.8	55.5
Pa3	0.0	40.0	26.3	16.0	60.8
Pa4	0.0	41.0	24.2	13.3	54.9
Pb1	0.0	83.0	21.0	15.5	73.7
Pb3	0.0	3.6	0.7	0.8	108.2
Pb4	0.0	64.0	10.6	14.1	132.2
Pb5	0.0	80.0	7.0	13.5	194.2
Pc1	0.0	79.0	3.4	8.7	255.3
Pe1	0.0	27.0	10.3	8.0	77.3
Pf3	0.0	43.3	17.1	15.3	89.8
All Data	0.0	83.0	15.2	15.2	99.9

high-resolution characterization. The tests are constructed and applied as described in the previous parts of the paper. Lugeon (Lu) values were converted to hydraulic conductivity (m/s) values by assuming a constant radius of influence. The Lugeon values were evaluated in critical sections to characterize the medium. Histograms of the results have shown significant vertical changes of permeability in the wells. Example histograms showing the results of a piezometer well Pa4 in the study area are given in Fig. 3. Values greater than 50 Lu were carefully evaluated and marked in red on histograms. Overall, the permeability decreases with depth. According to the results, medium characterized the first 30-50 m depth from the surface has high permeability, medium-low permeability between about 50-120 m and low-very low in sections deeper than 120 m. In general, high permeability values were obtained in shear zones at shallow depths. On the other hand, low-very low permeability values were calculated at depths greater than 100 m.

The evaluation of Lugeon test results according to lithologies has shown that metasediments and diorite units have similar hydrogeological characteristics and can be accepted as a single hydrostratigraphic unit. The statistics of the Lugeon test results in Lu and in m/s for each well are given in Table 2 and Table 3 respectively. The coefficient of variation in small diameter drill holes are very high, values changing between %33-%518, indicating a great heterogeneity. The Lugeon test results were drawn on the critical cross-sections as hydraulic conductivities (m/s) for the hydrogeological characterization. Cross-section A is given as an example in Fig. 4. Two large diameter wells were also drilled in the carbonate rocks at the both end of cross-section. On these wells, representative groundwater measurements were put as blue marks. At various depths, there are some permeable zones that can be observed. However, it is not clear that the permeable zones belong to the same extensive zone.

Pumping test

In order to obtain hydraulic characteristics of carbonate rocks and the metasediments-diorite units, pumping tests were conducted at six large diameter wells. A list of the tests performed in the large diameter wells are summarized in Table 4. As shown in the table, constant discharge has continued only couple of hours and a long recovery period has followed. The hydraulic conductivity values changing between E-08 to E-10 m/s. Hydraulic conductivity values converted from transmissivity values indicate a low permeability medium. The results obtained from pumping tests are lower than the lugeon tests. It is an expected result because lugeon test represents more local characterization. The pumping tests are representative for larger scales. A fracture in the close vicinity of the packer test zone may give high permeability for the short test period. Pumping tests are more representative for the area of influence of the well. As can be seen in Table 4, model types were fitted to the graphs representing the unconfined and/or leaky aquifers. This was also confirmed by geological and hydrogeological field observations.

Also, hydraulic head measurements from VWPs prove that these sections are also unconfined in general. Similar results from different models for the same aquifer type have given similar results which confirms the interpretation above. The metasediments-diorite unit may be under unconfined conditions at the uppermost section where the material is altered and intensely fractured. As revealed by the packer tests, a permeable zone is underlined by a less permeable zone. Another permeable zone beneath this low permeability zone may form a leaky or confined aquifer. However, the hydraulic heads measured at the VW piezometers suggest that these sections are also unconfined in general.

Hydraulic head distribution on critical cross-sections

A total of 36 VWPs have been installed to characterize the pore water pressure distribution along the critical cross-sections. The vertical change in pore water pressure in metasediments-diorite unit has been recorded at the VWPs installed at different depths in the drill holes located along the critical cross-sections. The pressure heads measured at each VWP installed in drill holes were illustrated on cross-sections to give an idea on the actual pore water distribution with respect to the current situation and the ultimate pit bottom topography. A representative cross-section is given in Fig. 5. As seen in the figure, downward hydraulic gradient exists in Pa1, and Pa4, while in Pa2, the gradient is upward between VWP-3 (third piezometer of Pa2)

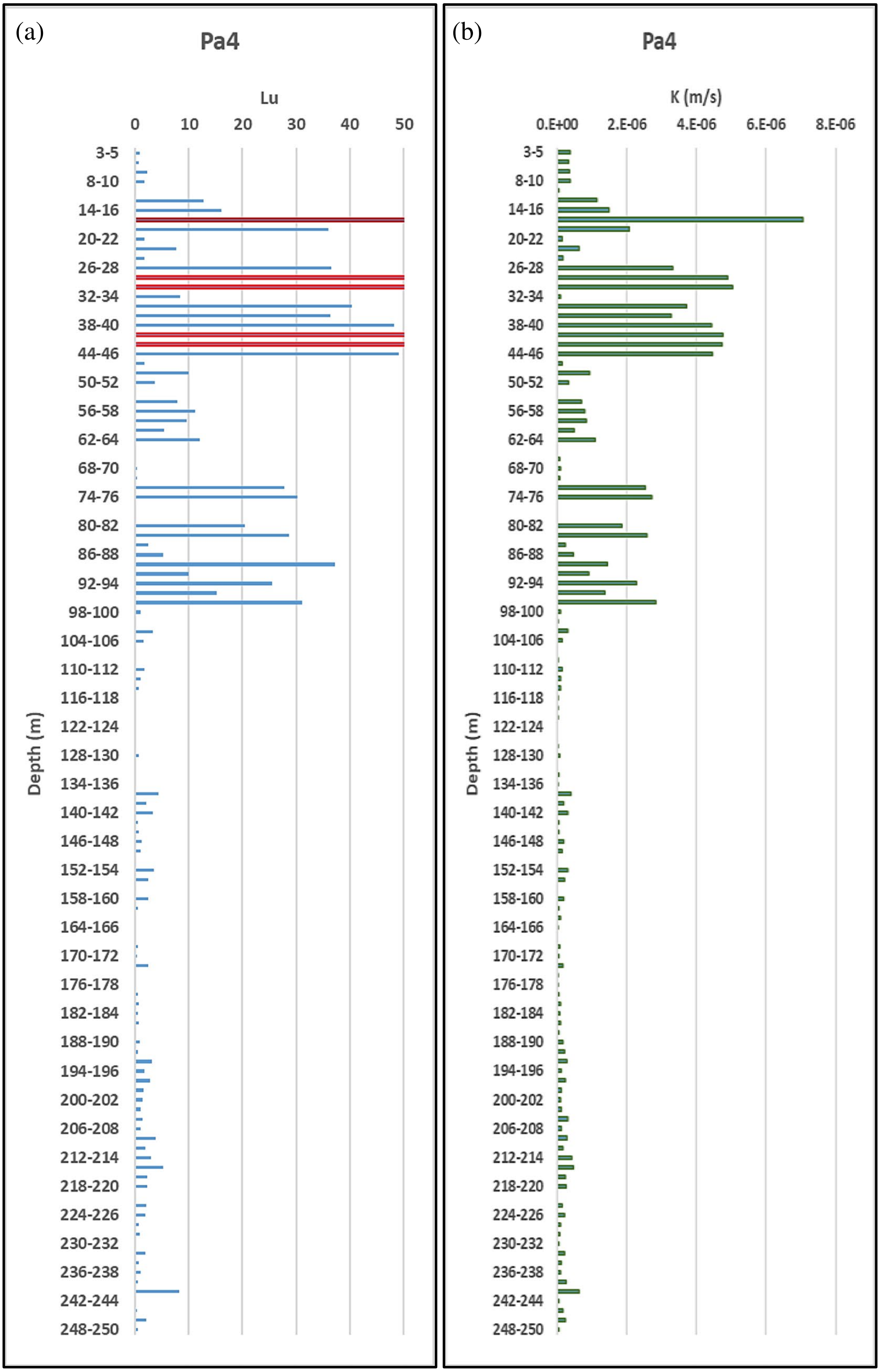

Fig. 3 Depth-wise histograms of permeability (Lu) (**a**) and hydraulic conductivity (m/s) (**b**) of drill hole Pa4 (Ekmekci et al. 2018)

Table 2 Summary of basic statistics of permeability values obtained for each drill hole in Lu

Piezometer ID	Min	Max	Mean	Geo Mean	Harmonic Mean	Standard Dev.	Cv (%)
Pa1	0.001	358.55	61.76	5.85	0.02	75.07	121.6
Pa2	0.001	160.43	10.89	1.14	0.03	34.19	314.1
Pa3	0.001	136.77	20.26	3.32	0.01	38.18	188.4
Pa4	0.001	76.46	6.97	0.91	0.02	14.13	202.7
Pb1	0.029	1.71	0.66	0.53	0.36	0.37	56.5
Pb3	0.001	3.71	0.71	0.32	0.04	0.79	111.0
Pb4	0.030	521.64	17.59	0.80	0.42	90.99	517.4
Pb5	0.427	3.15	1.41	1.33	1.26	0.51	36.1
Pc1	0.001	150.05	4.66	0.12	0.00	21.65	464.7
Pe1	0.001	52.96	2.22	0.62	0.01	7.17	322.8
Pf3	0.187	104.55	12.28	5.46	2.14	16.44	133.9

Table 3 Summary of basic statistics of permeability values obtained for each drill hole in m/s

Piezometer ID	Min	Max	Mean	Geo Mean	Harmonic Mean	Standard Dev.	Cv (%)
Pa1	1.00E-10	2.02E-05	5.21E-06	5.08E-07	1.82E-09	6.18E-06	118.7
Pa2	1.00E-10	1.48E-05	1.07E-06	1.03E-07	3.25E-09	3.31E-06	310.3
Pa3	1.00E-10	1.21E-05	1.80E-06	2.92E-07	1.15E-09	3.24E-06	180.0
Pa4	1.00E-10	7.05E-06	6.28E-07	1.18E-07	1.55E-09	1.25E-06	199.2
Pb1	1.32E-08	1.44E-07	6.06E-08	5.18E-08	4.28E-08	3.22E-08	53.1
Pb3	1.00E-10	3.39E-07	6.54E-08	3.34E-08	4.77E-09	7.03E-08	107.5
Pb4	3.70E-09	5.10E-05	1.77E-06	7.33E-08	4.02E-08	9.14E-06	518.0
Pb5	3.82E-08	2.71E-07	1.28E-07	1.22E-07	1.15E-07	4.22E-08	33.0
Pc1	1.00E-10	1.37E-05	4.27E-07	1.38E-08	4.68E-10	1.96E-06	458.3
Pe1	1.00E-10	8.05E-06	2.89E-07	6.36E-08	1.35E-09	1.10E-06	378.7
Pf3	2.42E-08	9.64E-06	8.28E-07	3.93E-07	1.91E-07	1.34E-06	162.1

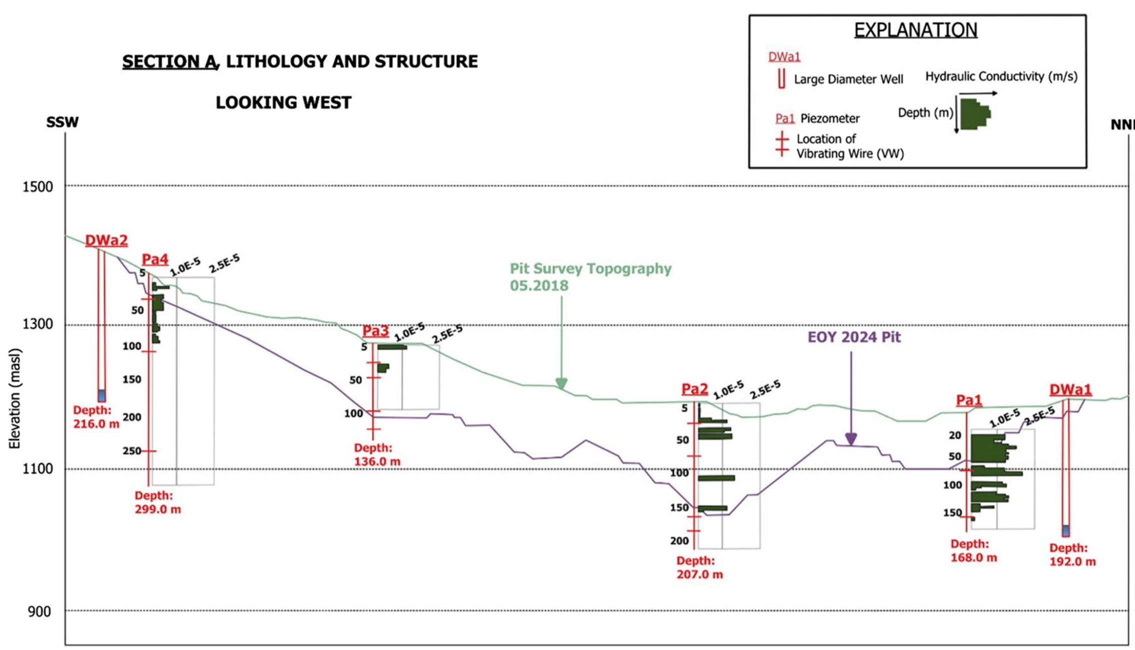

Fig. 4 Permeability results plotted on drill holes for cross-section A (Ekmekci et al. 2018)

Table 4 Pumping test information and test results for large diameter wells (Tayyar 2020)

Well ID	Pumping Phase Duration	Total Duration of Test	Average Discharge Rate (L/s)	Methods	Aquifer Parameters		Geo. Mean of T and K	
					T (m2/s)	K (m/s)	T (m2/s)	K (m/s)
Dwf-1	2 h 30 min	8 days	0.62	Moench (1997)	4.15E-07	9.55E-09	4.15E-07	9.55E-09
				Cooper-Jacob	2.76E-06	3.39E-08		
Dwb-2	4 h 52 min	3 days	0.71	Theis	2.18E-06	2.68E-08	1.96E-06	2.42E-08
				Theis Recovery	1.26E-06	1.56E-08		
Dwa-3	45 min	30 days	0.44	Moench (1985)	8.31E-08	2.08E-09	8.31E-08	2.08E-09
				Moench (1997)	5.67E-08	8.12E-10		
GSW-1	2 h 27 min	12 days	0.58	Moench (1985)	1.68E-08	2.40E-10	6.69E-08	9.58E-10
				Theis Recovery	3.15E-07	4.51E-09		
GSW-2	4 h 45 min	6 days	0.58	Moench (1985)	8.40E-08	4.90E-10	6.47E-08	3.78E-10
				Theis Recovery	4.99E-08	2.91E-10		
GSW-3	1 h 35 min	14 days	0.63	Moench (1985)	1.54E-08	2.73E-10	8.86E-08	1.57E-09
				Theis Recovery	5.10E-07	9.05E-09		

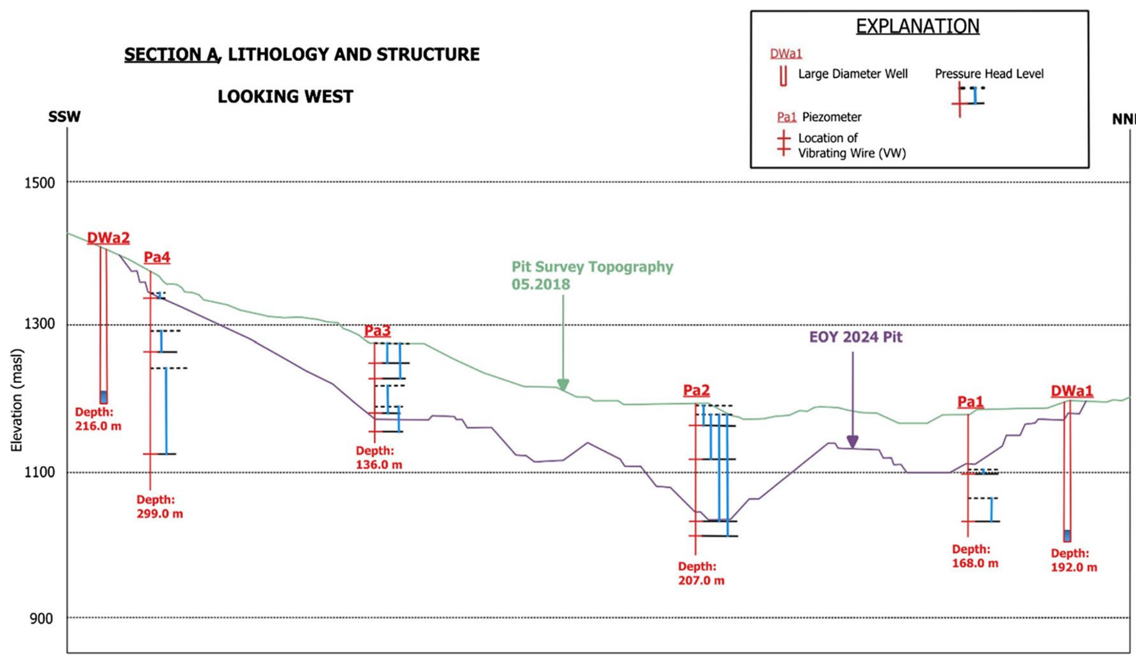

Fig. 5 Pressure heads recorded at VWPs on cross-section A (Ekmekci et al. 2018)

and VWP-4 (fourth piezometer of Pa2) only. Similarly, in Pa3, again an upward gradient is observed between VWP-2 (second piezometer of Pa3) and VWP-1 (first piezometer of Pa3). The figure also suggests that the gradient is not uniform in the vertical profile confirming the heterogeneity of the medium. At the south-west part of the section in Fig. 5, hydraulic head distribution forms groundwater divide and it can be seen better in the conceptual model. In general, a downward hydraulic gradient was observed in almost all piezometers, but the gradient is not uniform.

Stable isotope analysis

The results of the stable isotope analysis showed that the deuterium and oxygen -18 (O-18) is characterized by a deuterium (D) excess of 14. The local meteorological water line (LMWL) was obtained from the equation of D=8(O-18) +14. The graph of oxygen-18 vs deuterium is given in Fig. 6. The plots of rainwater were shown as green dots, and the groundwater were shown as blue dots. The rainwater

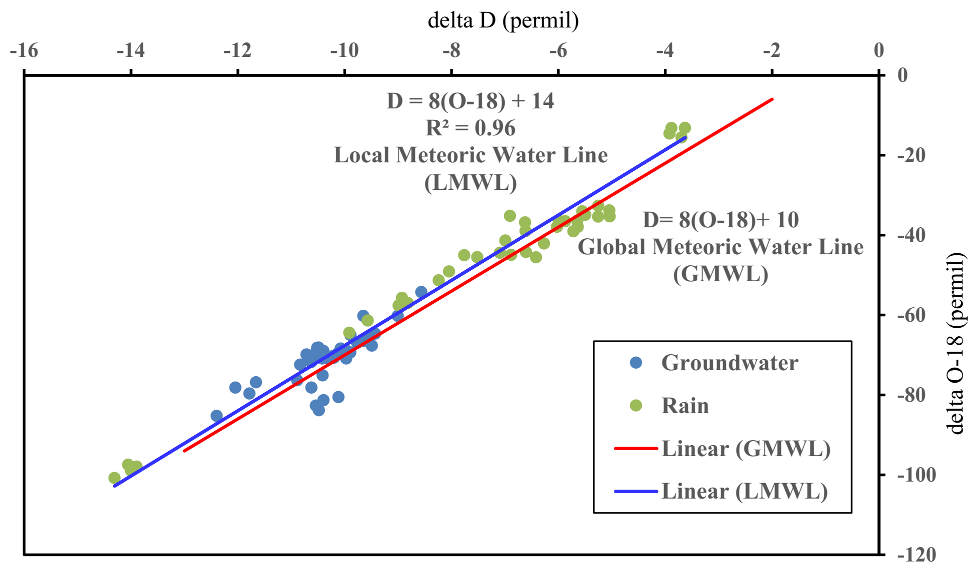

Fig. 6 Plot of D-O-18 and the meteoric water line for the study area (Ekmekci et al. 2018)

plots over a wide range. Rain may be quite rich with respect to heavy isotopes which indicates the summer rain and while the winter rain is much depleted and forms one of the end members. As can be seen in the figure, the groundwater plots between winter rain and the warmer period rain suggesting that groundwater is mainly recharged by spring rains.

The elevation–stable isotope regression equations were derived for both oxygen-18 and deuterium (Fig. 7). From both equations, different elevation estimations were obtained (Table 5). The results show that the metasediments and diorite are recharged from between 1230 masl and 1400 masl on average. Even with the highest area considered, the recharge area falls within the slopes of the carbonate rocks surrounding the mine site.

Hydrogeological conceptual model of mine site

The groundwater system of the mine site consists of carbonate rocks surrounding the metasediments and diorite units in the center. The in-situ tests and measurements showed that the metasediments and diorite units act like single hydrostratigraphic unit compared to carbonate rocks. A general expectation of groundwater system of the mine site is that the carbonate rocks supply inflow toward center of the mine. However, ore drillings on the southern side of the mine have shown that a diorite intrusion acts like an impermeable barrier against groundwater flow (Fig. 8). According to the cross-section given in Fig. 8, the southern carbonate rock mass is divided into two parts: the larger part forming the main carbonate rock aquifer. The small part between the diorite intrusion and the metasediments cropping out at the mine site has small area for recharge. In this part one should not expect thick saturated zone. Most probably the thin saturated zone is being discharged toward the west to contribute to the springs at the flood plain of the Karasu River. This model also explains the dryness of the wells drilled in carbonate rocks in this part of the area as discussed in the previous sections.

Based on the available and recently obtained data, a hydrogeological conceptual model was constructed on a cross-section, which can be regionalized to represent the mine site (Fig. 9). The metasediments and diorite have high total porosity and low specific yield indicating that the pore water is retained by electrostatic forces in the medium and it resists flow due to low hydraulic conductivity. The vertical change in the hydraulic conductivity values suggests that the medium is heterogeneous.

The medium consists of different water bearing levels. The shallow layers are in under unconfined conditions and deeper layers are in leaky conditions. A hydraulic divide is also noted around the Pa4 piezometer which causes groundwater flow to take place to SSW and NNE directions. This interpretation was concluded as a result of piezometer readings.

Conclusion

Slope stability issues in mining operations pose significant challenges, necessitating rigorous assessment and management strategies to mitigate potential hazards and ensure safe and sustainable extraction practices. The meticulous consideration of pore water pressure is paramount in assessing and mitigating slope instability risks. Conceptualization and characterization porous media are essential before employing numerical methods to estimate the pore water distribution. This research seeks to delineate the hydrogeological characteristics of water bearing rocks within the

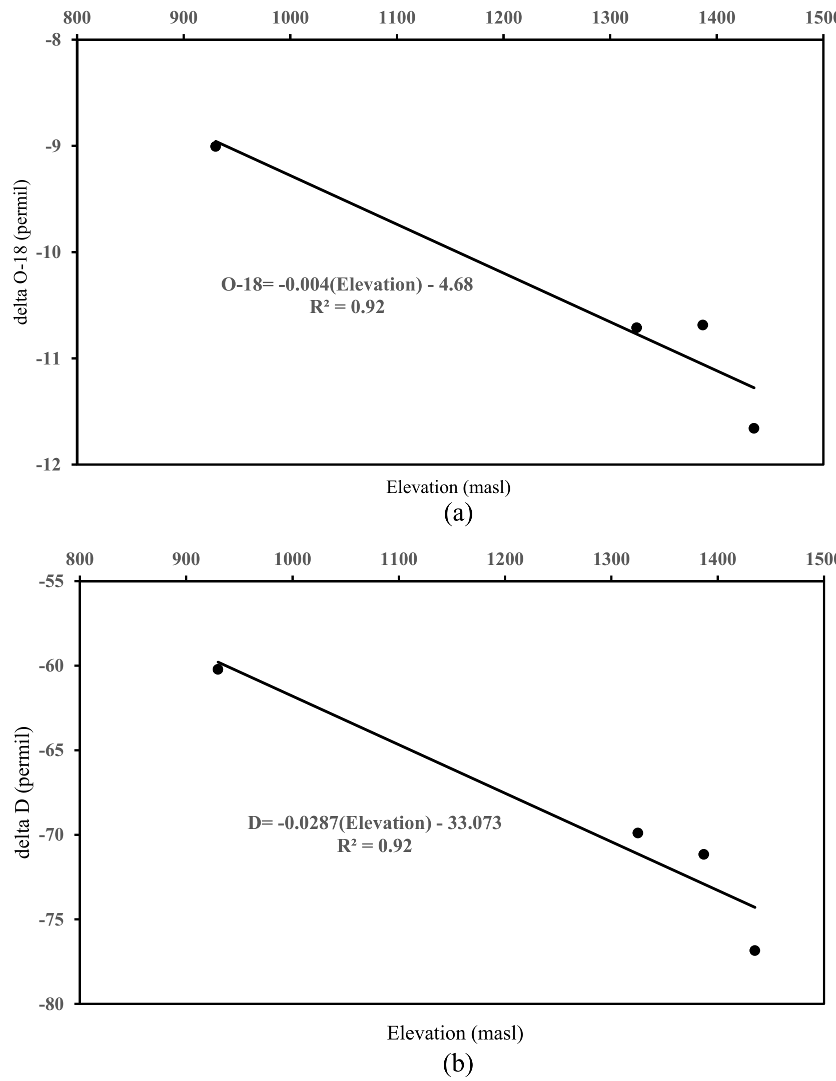

Fig. 7 Regression between elevation and stable isotope a) oxygen-18, b) deuterium (Ekmekci et al. 2018)

Table 5 Estimated recharge areas for groundwater in the mine site using O-18 and D (Ekmekci et al. 2018)

Sample	Date	d O-18 (per mil)	dD (permil)	Recharge Elevation (m)	
				O-18	D
Pf3	10/28/2017	-10.51	-68.20	1267	1225
DWf1	11/10/2017	-10.49	-68.16	1262	1224
Pa3	12/6/2017	-10.23	-70.50	1205	1305
Pa1	12/31/2017	-10.63	-71.78	1292	1350
Pb1	2/5/2018	-10.89	-76.34	1348	1509
Pb3	3/3/2018	-10.21	-70.26	1202	1297
Pb4	2/22/2018	-9.89	-69.37	1132	1266
DWb2	3/28/2018	-9.89	-65.03	1132	1115
GSW-1	6/1/2018	-10.11	-80.57	1181	1656
GSW-2	6/5/2018	-10.39	-81.34	1241	1683
GSW-3	6/12/2018	-10.48	-83.83	1260	1770

operational mining area located in Eastern Anatolia, Turkey. Large diameter pumping wells were drilled in the surrounding carbonate rocks to determine the groundwater flow and boundary conditions along some critical cross-sections. Large diameter wells were also drilled in the mine site for hydraulic testing of the metasediments and diorite. Constant rate pumping tests and monitoring of groundwater levels were conducted at each large diameter well. Furthermore, twelve diamond core drilling were done in the mine site and a total of 36 vibrating wire piezometers were installed at different depths for monitoring pore water pressures. Lugeon tests were applied on these wells to determine localized hydraulic conductivity of diorite and metasediments at different depths.

The results obtained from these tests are used for developing hydrogeological conceptual model for groundwater flow. The results of in-situ tests show that the metasediment and diorite units act as a single hydrostratigraphic unit. The vertical variation in hydraulic conductivity values indicates

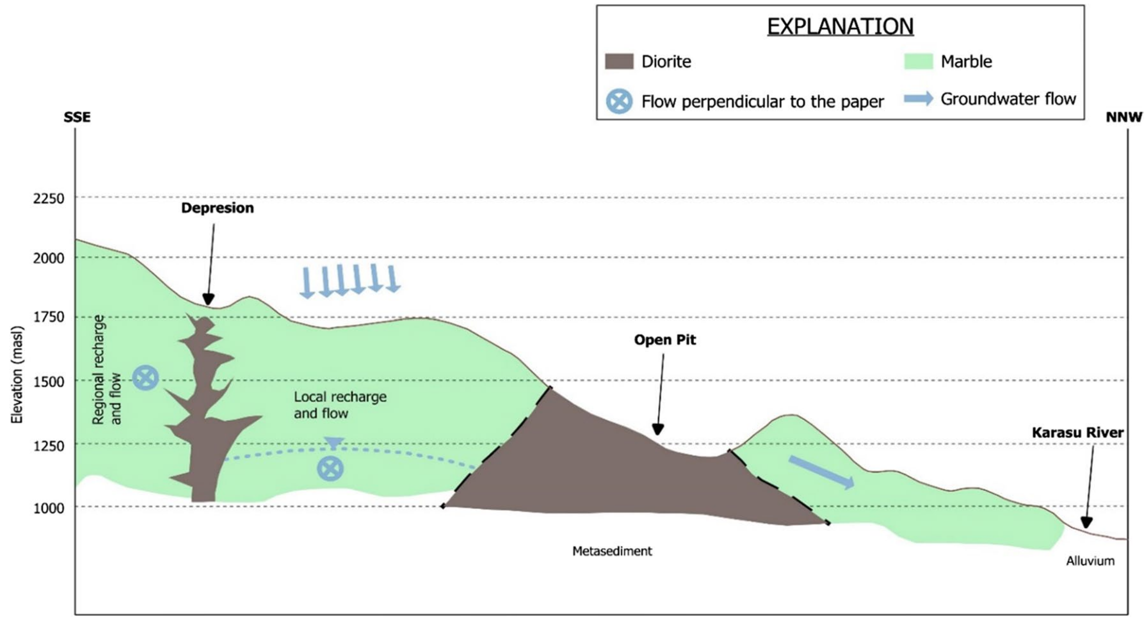

Fig. 8 Hydrogeological cross-section demonstrating the role of diorite intrusion in regional groundwater flow (Ekmekci et al. 2018)

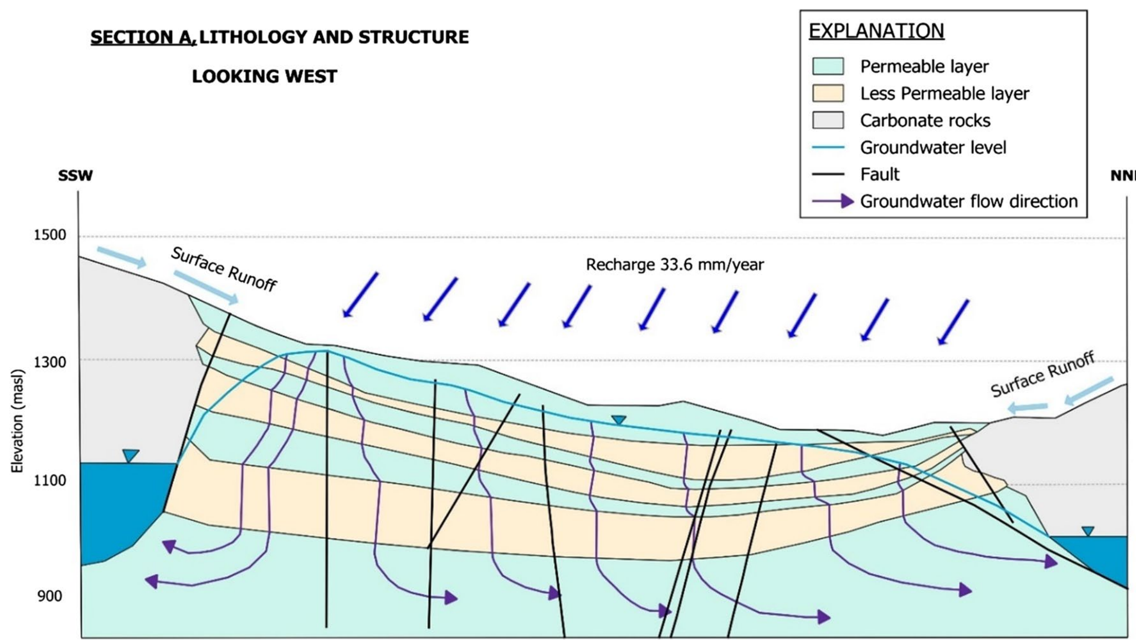

Fig. 9 Hydrogeological conceptual model for the flow domain on cross-section A (Ekmekci et al. 2018)

that the medium is highly heterogeneous. The carbonate rock was thought of as a major aquifer in the mine site. However, research results have shown that the carbonate unit does not contain groundwater in significant amount because of diorite intrusion at the highland in the south of the mine site. The intrusion acts like a hydrogeological barrier to groundwater flow and also it explains the dry carbonate rock mass surrounding the mine site.

According to the geotechnical analysis, metasediments and diorite units have high total porosity and low specific yield, meaning that the metasediments and diorite unit holds pore water against gravity. Upper sections of metasediments and diorite have higher permeability than lower sections. Decreasing permeability profile can be observed with depth which indicates a sort of perched aquifer formation in the site. Faults were found to be among the most important structural elements that control occurrence and flow of groundwater in the mine site. Although no direct hydrogeological characterization was possible, distribution of pore water pressure monitored by vibrating wire piezometers have clearly revealed the fact that a great majority of the faults function as impermeable barriers.

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Declarations

Competing Interests The authors declare no competing interests.

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