Stable Isotope Techniques as a Tool in Hydrogeological Conceptualisation of Ayazmant Mine Site (NW Turkey)

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Abstract
Ayazmant mine site is situated in the near vicinity of a dam reservoir being utilized for drinking and irrigation purposes. The mine is planned to be extracted by combination of two methods: open pit mining followed by underground mining. Most part of the operations will take place below the groundwater level. Preliminary hydrogeological assessment has revealed that the groundwater system is in connection with the dam reservoir. Prediction of groundwater inflow to both the open pit and the underground galleries and calculation the ratio of reservoir water in the inflow were the major questions. Numerical modeling was the methodology selected to be followed to achieve these objectives. Reliability of the numerical model is based on the accuracy of the hydrogeological model of the site. Hydrogeological conceptualization requires detailed geological hydrological and hydrogeological information. These studies give sufficient information on the occurrence, potential, availability and flow of groundwater systems. However, knowledge of interactions with different water bodies requires information on the flow path and velocity of a particle in the system. Isotopic constituents of water bodies provides this information. Particularly, stable isotopes are very useful in tracing the origin of the waters, mixing processes and interactions. This technique was used in conceptualization of the hydrogeological system in the mine site. The hydrogeological conceptual model suggested that the groundwater system is recharged mainly from highlands but also in connection with the dam reservoir. The water level fluctuation in the reservoir affects the interaction between the groundwater system in the mine site and the reservoir.

Key words: Ayazmant mine, conceptual model, hydrochemistry, stable isotope

Introduction
Occurrence of groundwater in mine sites is of major concern due to its two opposing impacts on mining activities. Particularly in arid and semi-arid areas, groundwater in most cases is the major source that can be used to meet the need for water at mine sites for different purposes such as process water and site water supply. On the other hand, mining commonly requires large excavations below the water table where groundwater inflow to excavations may cause serious problems of dewatering and depressurization (Kumar Deb 2014). Regardless of type of the problem, whether related to shortage or excess of groundwater, construction of a representative conceptual hydrogeological model has an essential role in achieving practical and effective solutions (ASTM 2000). However, conceptualization and characterization of groundwater systems, particularly in geologically complicated areas is not straightforward and various techniques need to be applied in combination with conventional methods. The combined use of hydrogeochemical and isotopic techniques is proved to provide an effective tool in this regard (Yurtsever 1995, Geyh 2000). The value of this tool stems from the fact that it contributes to the understanding of how the groundwater occurs and circulates by tracing the water starting from the recharge area until it reaches a point of interest in the flow domain (Clark and Fritz 1997, Aggrawal et al 2005). This knowledge is of significant importance in construction of a representative conceptual model of the site. This technique was applied in a mine site located in northwest of Turkey (fig.1). The area where the mine is located is environmentally sensitive because the mine site is bordered by a dam reservoir utilized also for drinking purposes. Mining operations, therefore should be planned to minimize if not remove its impacts on quantity as wells quality of water resources that exist in the area of influence of the mine.

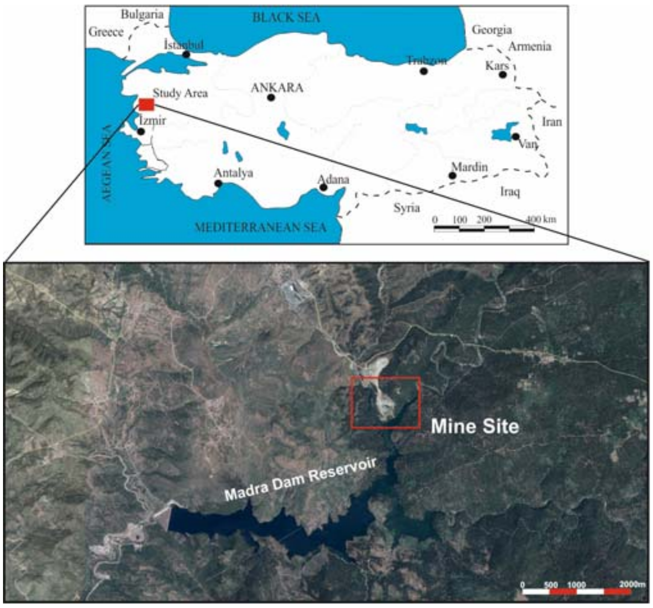


Figure 1 *Location Map of the Study Area.*

Hydrogeological Characteristic of Lithological Units

The Ayazmant iron-copper mine is of contact-metasomatic/scarn type mineralization within plutonic rock mass [Jeopark 2011]. Geologically, the site is located on the edge of the Kozak Pluton which has been intruded during Late Oligocene-Early Miocene in one of the ten horst-graben systems that have been developed as a consequence of intensive tensional tectonics affected the region during Neogene (Oyman 2010). The pluton has been intruded through the Kınık metamorphic basement. The basement is composed of metabasitic complex including limestone and sandstone blocks of Permian age. The mine site is dominated by hornfels, granatfels, granodiorite prophyry, arenaceous granodiorite, split and endoscarn. The ore constitutes hematite, magmatite, chalcopyrite and limonite (fig.2)

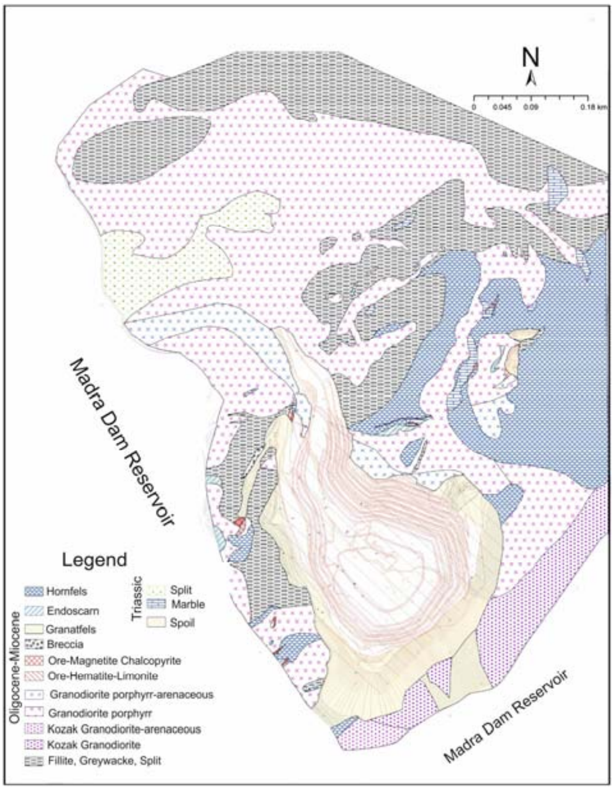
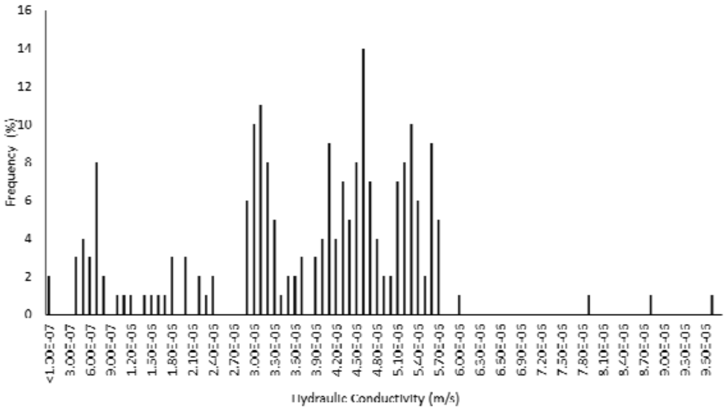


Figure 2 *Geological Map of the Mine Site (after Jeopark, 201)*

The intrusive magmatic rocks in the area are intensively fractured (fig.3a) and in some places are weathered, particularly along major faults intersecting the mine site. The rocks have gained secondary porosity and permeability owing to the intensive fracturing, forming a fractured hard rock aquifer. Hydrogeological characterization of the hard rock aquifer was achieved by a) fracture analysis and b) insitu well tests. Four fracture systems were identified on outcrops in the site. Based on fracture spacing and aperture measurements the total porosity of the hard rock aquifer was calculated as 0.018. The effective porosity was estimated as 0.010 on the basis of annual change of groundwater level in piezometers installed around the pit. The high effective porosity is due to fact that the intersecting fractures create a high degree of connectivity in the domain. The recharge in this calculation was obtained from water budget calculations as explained below. More than 140 packer tests were performed in 6 boreholes to characterize the rock for permeability and hydraulic conductivity. Although changed spatially, the hydraulic conductivity found to concentrate between $3x10^{-6}$ m/s ile $5.9x10^{-6}$ m/s (fig. 3b), with a geometric average of $3.2x10^{-6}$ m/s. This value suggests that the hard rock aquifer may yield significant groundwater flow into the pit and galleries.

a



b

Figure 3 *a) Frcature Systems b) Distribution of Hydraulic Conductivity in the Mine Site*

Hydro-Meteorology

Northern Aegean (Mediteranean) climatic conditions prevail in the Ayazmant mine site. Hydrographically, the site is located on the ridge separating two major tributaries of the Madra dam reservoir. The drainage areas of the tributaries at the mine site are 19.4 km^2 and 90 km^2, respectively. The shape of the basin and the drainage network pattern is controlled by the position of the Kozak Pluton and the permeability and erodibility of lithological units. The basin is rectangular in shape with 15 km length and 7.5 km width.

The long-term average annual precipitation onto the area is calculated as 635 mm. Precpitation is mainly rainfall and it occurs mostly in winter months from November to February. The rest of the year is dry (fig. 4). More than half of the rainfall was found to return to the atmosphere by evapo-transpiration. The water budget calculations showed that more than half (51 %) of the rainfall was found to return to the atmosphere by evapo-transpiration, 41 % of the rainfall makes the surface runoff which ultimately flows to the Madra reservoir and the rest (0.08 %) infiltrates to form recharge the hard rock aquifer.

Occurrence and Flow of Groundwater

Relatively high fracture permeability of the hard rock mass allows significant occurrence and flow of groundwater. Groundwater level measurements were performed in 9 piezometers installed at the site along two water years to cover dry and wet periods. The coefficient of variation of groundwater levels in the piezometers did not exceed 5 %, suggesting no significant seasonal effect. Based on this fact, a groundwater contour map was prepared to demonstrate the areal distribution of the hydraulic head and the direction of groundwater flow in the site. The map is given in Figure 5.

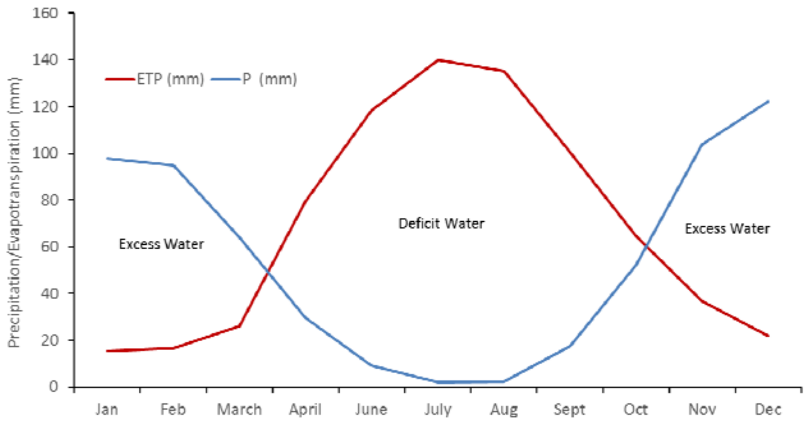


Figure 4 *Monthly Variation of Precipitation and Potential Evapotranspiration in the Study Area.*

As seen in figure 5, there is a prominent groundwater divide passing through the open pit, and the general groundwater flow direction occurs from north to south, to the reservoir. The groundwater contours bend and make a "v" in the southwest, indicating a higher permeability zone along anortheast-southwest line. This line was found to correspond exactly to one of the major fault lines.

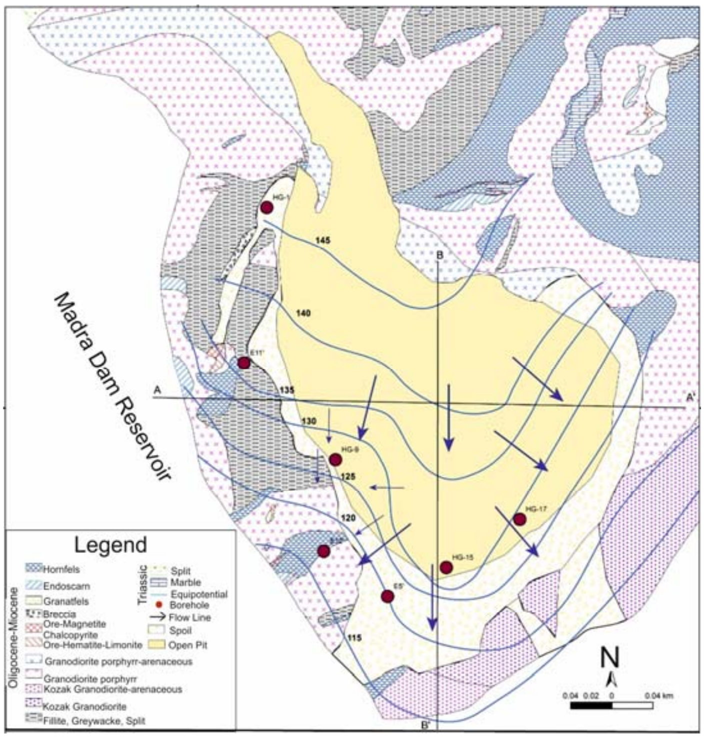


Figure 5 *Distribution of Hydraulic Head in the Site.*

In addition to groundwater level measurements and the hydraulic conductivity variation with depth, hydrochemical measurements and analyses have indicated that the hard rocks form a single and unconfined aquifer, and the aquifer is in connection with the dam reservoir at the periphery of the open pit. This finding is important to consider for safe mining operations.

Need for a Representative Hydrogeological Conceptual Model

The ore deposit is to be mined at two major phases; first as open pit mining to a certain elevation of pit bottom and by underground galleries excavated from the ultimate pit bottom. The plutonic (dominantly granodiorite and hornfels) rocks are fractured and jointed such that they have gained moderately high secondary permeability. The mine site is surrounded by surface water bodies from the east, west and the south. Two streams in the east and west of the site join the dam lake in the south. The elevation of the ultimate bottom of the open pit will be about 90 meters below the maximum level of the dam lake. The mine site is situated on a secondary groundwater divide where the groundwater level is about 30 m higher than the lake, which makes the groundwater flow to the streams and the lake in natural (pre-mining) conditions. The galleries will also be excavated below the groundwater level and the dam lake level. Thus, the major concern was to estimate the groundwater flow into the open pit and the ingress to the galleries at different stages of mining to prevent any probable adverse impact. Analytical and/or numerical methods are applied to predict the groundwater inflow to excavations. For both methods, construction of a representative hydrogeological model is essential. A hydrogeological appraisal was performed based on hydrostratigraphic definition of litohological units, core drilling and in-situ tests, and hydraulic head observations. A preliminary hydrogeological conceptual model was constructed to explain the occurrence of groundwater at the site. However, this study could not produced all information required in conceptualization of the groundwater system in terms of recharge-discharge relations and surface water-groundwater interactions; an essential knowledge for definition of the boundary conditions needed in analytical and/or numerical analyses. Hydrogeochemical and stable isotope techniques were used to obtain this information.

Stable Isotope Hydrology

Various water points representing surface waters and groundwater were sampled for hydrogeochemical and stable isotope analyses. Some basic physio-chemical properties such as temperature, specific electrical conductivity, total dissolved solids, dissolved oxygen, pH and oxidation-reduction potential of waters were also measured on site by a multi-probe. Samples were analysed at registered laboratories for some trace elements as well as major ions and for stable isotopes, namely oxygen-18 ($\delta^{18}O$) and deuterium (δD). In addition to samples collected from the site and its near vicinity, seasonal springs located at different altitudes were also sampled to quantify the altitude effect on stable isotopes. $\delta^{18}O$ in water samples was found to vary between -1.91 and -6.95 permil, concentrating around -5 and -6 permil (fig 6a). Similarly, δD ranges between -22.06 and -40.91 permil with a concentration around -35 permil (fig. 6b). The relationship between oxygen-18 and deuterium forms a regression line whose slope is 8 with an interception of y-axis (deuterium) known as the deuterium excess (DE) (Craig 1961). The DE indicates the evaporation kinetics in the source area of the precipitation, but also changes when the water is subjected to evaporation. The deuterium excess in the water samples collected at the site varies between -6.81 and 16.98 with a representative value around 15.7 (fig.7). The negative DE of the sample from the sump in the pit, indicates excessive evaporation.

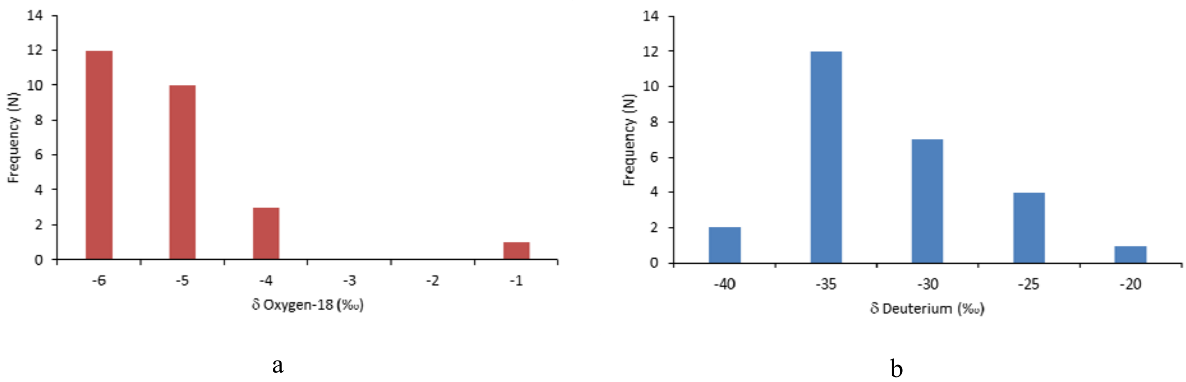


Figure 6 *Distribution of a) Oxygen-18 and b) Deuterium in Water Samples.*

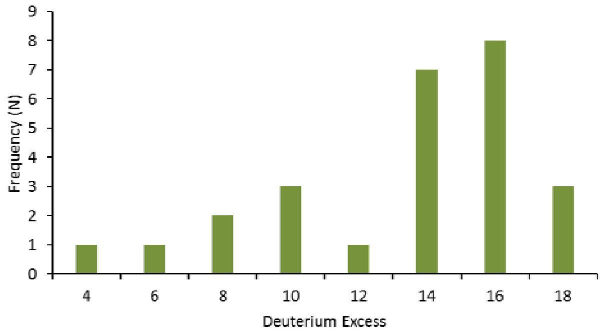


Figure 7 *Distribution of a) Oxygen-18 and b) Deuterium in Water Samples.*

The regression equation representing the global precipitation is given as $\delta D=8O^{18}+10$. The equation for the site, known as local meteoric line is found as $\delta D=8O^{18}+16$. The surface waters and the water collected from the sumps at bottom of the pit, plot on a evaporation line (fig.8).

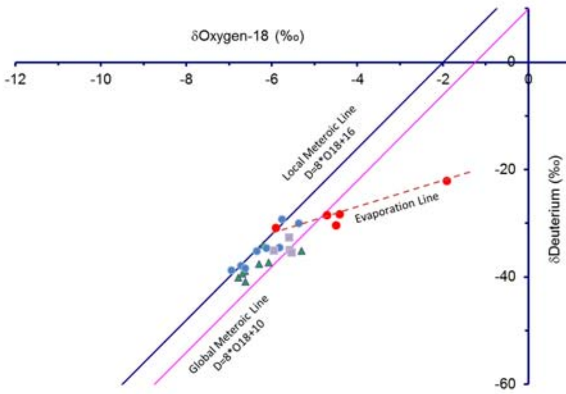


Figure 8 *Meteoric Lines Obtained from Isotopic composition of Water Samples.*

A plot of $\delta^{18}O$ vs altitude suggested that the precipitation is depleted with respect to this isotope at a rate of 0.33‰ per 100 m of change in altitude (fig.9). Using this information, the recharge area of the groundwater at the mine site was found to be located at higher elevations (450-480 m amsl) and at a distance of about 8 km from the mine site. The direct recharge from precipitation over the mine site was found insignificant compared to the regional recharge. Based on this information the hydrogeological model of the mine site was completed with a clear definition of the site-specific water balance and boundary conditions.

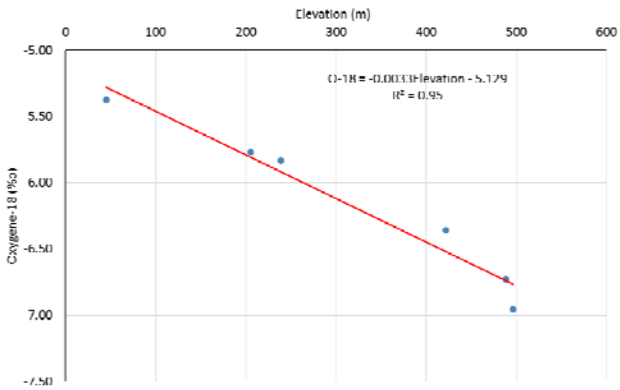


Figure 9 *Change of Oxygen-18 of Precipitation With Elevation.*

Hydrogeological Conceptual Model

Based on the information obtained from hydrological, hydrogeological and evaluation of isotope data, a hydrogeological conceptual model was constructed for the mine site. According to the model, an unconfined, fractured hard rock aquifer exists in the mine site. The aquifer is mainly recharged from the highlands and the recharge from direct precipitation is insignificant. The annual recharge from highlands is about 5.5 x 10^6 m^3. This amount is less than 10 % of the total precipitation. More than 40 % of the precipitation is direct runoff at the surface and contributes to the dam reservoir. The dam reservoir forms the southern, southeastern and southwestern boundaries of the flow domain at the mine site. A block diagram illustrating the hydrogeological conceptual model is given in Figure 10.

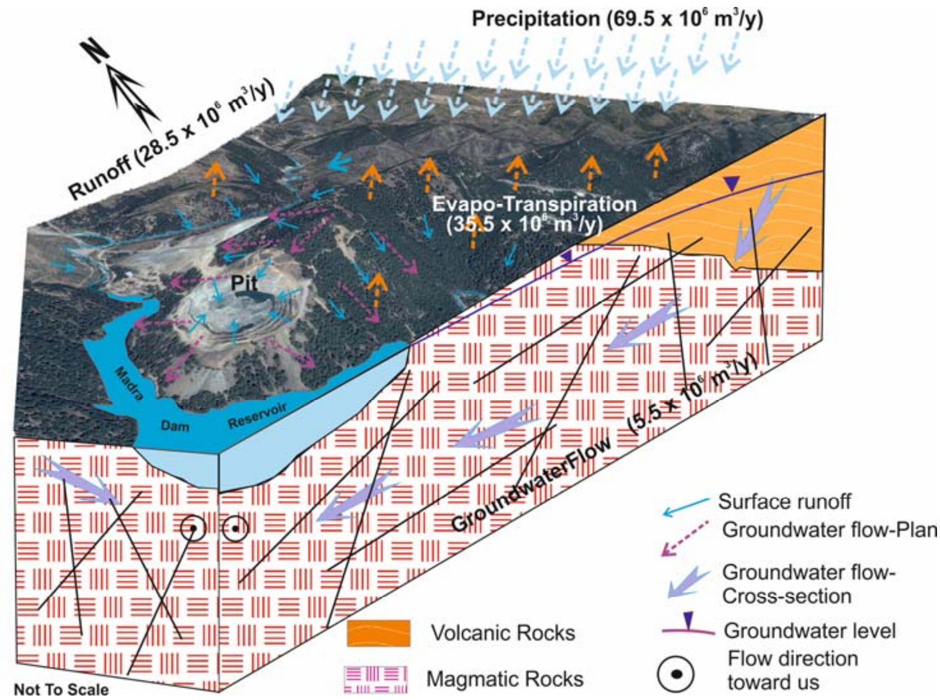


Figure 10 *Block Diagram Illustrating the Hydrogeological Coceptual Model at the Mine Site.*

Conclusions

Mining commonly requires large excavations below the water table where groundwater inflow to excavations may cause serious problems of dewatering and depressurization. Regardless of type of the problem, whether related to shortage or excess of groundwater, construction of a representative conceptual hydrogeological model has an essential role in achieving practical and effective solutions. However, conceptualization and characterization of groundwater systems, particularly in geologically complicated areas is not straightforward and various techniques need to be applied in combination with conventional methods. The use of isotopic techniques is proved to provide an effective tool in this regard. The value of this tool stems from the fact that it contributes to the understanding of how the groundwater occurs and circulates by tracing the water starting from the recharge area until it reaches a point of interest in the flow domain. This knowledge is of significant importance in construction of a representative conceptual model of the site.

Having been bordered by a dam reservoir, the Ayazmant mine site was studied in detail to construct a hydrogeological conceptual model that is required for further numerical analyses. The magmatic rocks were found to form a single, unconfined aquifer that may yield significant groundwater inflow to the mine site. Stable isotope analyses of water samples collected from the mine site and the surrounding area revealed that the recharge of the aquifer occurs at highlands at a distance of about 8 km from the mine site. In some of the sampled piezometers, the mixing with reservoir water was detected, suggesting that the water ingress should be expected from the bordering dam reservoir.

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References

Aggarwal PK, Gat JR, Froehlich KFO (2005) Isotopes in the Water Cycle; Past, Present and Future of a Developing Science. Springer Ed. 381pp.

ASTM (2000) Standard Guide for Conceptualization and Characterization of Groundwater Systems, D5979 – 96, 35p.

Clark I D and Fritz P (1997) Environmental Isotopes in Hydrogeology. Lewis Publishers, Boca Raton, FL, 352 p.

Craig H (1961) Isotopic variations in meteoric waters, Science, 133, pp. 1702– 1703.

Deb P K (2014) An Introduction to Mine Hydrogeology, Springer Briefs in Water Science and Technology, 58 p.

Ekmekçi M and Açıkel Ş (2015) Hydrogeological Appraisal Ayazmant Mine Site: Implications for Underground Mining Activity. HU-UKAM Report for BILFER Mining Co., 76 pp.

Geyh M (2000) Environmental Isotopes in the Hydrological Cycle: Principles and Applications. Vol. 4, Groundwater, Saturated and Unsaturated Zone, IAEA Publ. Vienna, 177p.

Jeopark (2011) Geology and Reserve Estimation of Iron-Copper Ore Deposit in Karahayıt (Ayvalık-Balıkesir) (İr: 489). BILFER Mining Report. 98 pp.

Oyman T (2010) Geochemistry, mineralogy and genesis of the Ayazmant Fe-Cu skarn deposit in Ayvalik (Balikesir), Turkey: Ore Geology Reviews, 37, pp. 175-201.

Yurtsever Y (995) An Overview of Conceptual Model Formulations for Evaluation of Isotope Data in Hydrological Systems. IAHS Publ. no 229, pp. 3-12.