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TECHNICAL ARTICLE

Assessment of Open Pit Dewatering Requirements and Pit Lake Formation for the Kışladağ Gold Mine, Uşak, Turkey

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Abstract The Kışladağ gold mine (Uşak, Turkey) has operated since 2006 and is projected to close by 2030, leaving a large open pit. We quantified dewatering requirements during the operational period, predicted pit lake formation during the post-closure period, and assessed the likely impacts on groundwater resources. Groundwater inflow into the pit during 17 years of mining was calculated using analytical and numerical models. The analytical model yielded lower inflow rates because it does not account for groundwater that will be released from storage. Post-closure, pit lake water balance calculations show that the system will reach equilibrium 585 years after dewatering ceases and that lake levels will stabilize at 816 m above sea level (masl). Further analysis indicated that 830 masl is a critical level, below which the pit will behave as a sink; above that, it will be a flowthrough system that could possibly affect downgradient groundwater quality.

Keywords Groundwater · Numerical modeling · Lake-budget

Introduction

Bulk mining, which generally requires deep excavations that are completed below the static groundwater level, can impose a significant environmental impact on groundwater resources. To provide safe and stable conditions for mining during the operational period, the excavation area must be dewatered. Mine dewatering can modify the water balance in a region, and can affect the existing water sources, the natural wetlands and the balance of aquifer systems (Fernandez-Rubio and Lorca 1993). Furthermore, as soon as dewatering ceases after the closure of such operations, the water table tends to recover to its original position. Groundwater flow into the pit, together with the direct precipitation and surface runoff, contributes to the formation of a pit lake (Castendyk and Eary 2009). Hydrogeology determines how rapidly open pit mines fill with groundwater after closure, and also influences the final steady-state water budget of the lake that is formed (Gammons et al. 2009). The time for a pit lake to reach steady state and the hydrologic interactions of the lake with its surrounding groundwater regime depend on many physical processes that control the pit lake hydrodynamics, including its shape and orientation and climatic conditions (Huber et al. 2008; Miller et al. 1996). Under natural conditions, large open pit lakes can take a very long time (decades to centuries) to fill with water.

Two main types of equilibrium can form when a pit lake reaches steady state: terminal conditions and flowthrough conditions. These final states of the system, and also the transitions between them are defined by Braun (2002) and Niccoli (2009) as follows: Under *terminal conditions*, groundwater flows into the pit and outflow occurs only as evaporation. This type of pit lake is common in arid areas, where evaporation rates exceed influx rates, causing the lake to function as a hydraulic terminal sink (McCullough et al. 2013). In such cases, the steady-state pit lake elevation is lower than the surrounding groundwater aquifer, resulting in passive hydraulic containment. Alternatively, under *flowthrough conditions*, groundwater flows into and out of the pit lake. Under these conditions, passive containment ceases, and the pit lake water can interact with groundwater

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downgradient of the pit. This type of pit lake is common in humid areas, but can also form when the bottom of a pit is above the water table and is filled with surface water. In such cases, outflows consist of vertical leakage and evaporation. Moreover, the hydrologic status of a pit lake may fluctuate between terminal and flowthrough in response to seasonal or long term climatic changes.

There are many modeling approaches for the solution of groundwater-related questions in mining operations, with differing levels of complexity (Gammons et al. 2009). Both analytical and numerical methods can be applied, depending on the size and site-specific conditions of the question. Marinelli and Niccoli (2000) state that numerical modeling may be required at advanced stages of mine planning, while simple analytical equations for estimating pit inflow rates can be informative during the initial stages of mine development. Fontaine et al. (2003) provides a brief but substantive summary on the applicability of numerical and analytical methods: numerical modeling is commonly used to estimate recovery time and groundwater inflows, which by necessity requires extensive hydraulic data, time, and resources that are usually unavailable at the preliminary stages of mine planning. Analytical methods, which are reliable and easy to use, can provide preliminary estimates for mine feasibility studies and to determine potential environmental impacts (Fontaine et al. 2003).

There are several numerical models that have successfully been used to simulate open pit dewatering and pit lake formation processes, depending the site-specific nature of each problem. MODFLOW (Harbaugh et al. 2000) is the most commonly used code. Several well-known applications of MODFLOW for mining operations include: the Canisteo mine pit in Minnesota (Jones 2002), Sleeper open pit gold mine in Nevada (Dowling et al. 2004), Collie Basin in southwest Australia (Müller and Eulitz 2010), and the Rosemont pit in Arizona (Myers 2008). The LAK2 (Council 1997) and LAK3 (Merritt and Konikow 2000) packages for MODFLOW are widely used to simulate lake-groundwater interactions and there are some examples where this package was also tested for pit lake simulations. However, as mentioned above, the site-specific nature of each problem allows or restrains the applicability of a package to a pit lake. For instance, the LAK2 package was applied for an open pit located in Central Nevada, where runoff from the pit walls was neglectable for pit lake simulations (Stone and Fontaine 1998) and the LAK3 package was used (Gabora et al. 2006) to simulate shallow ephemeral ponding in an open pit. Hence, both the size and geometry of the open pit, together with the hydrometeorological site conditions that contribute to pit lake formation in the post-closure phase, are important factors in model selection. Apart from MODFLOW's finite difference approach, Ardejani et al. (2003) obtained a two-dimensional finite element solution using SEEP/W software that is capable of simulating groundwater rebound process under both saturated and unsaturated conditions.

When selecting the model to be applied during the operational and post-closure phases of the mines and the methodology to be followed for any groundwater-related problem, it should be noted that each problem is site-specific; hence, there is no single and correct way to set up a solution. Maest et al. (2005) addresses this issue by stating that individual codes have slight advantages and disadvantages, depending on the application, but the experience of the modeler, the choice of input parameters and data, and the interpretation of the model output are more important than the choice of the code itself.

This paper assesses: (1) the dewatering requirements at Kışladağ gold mine in Uşak Province in Western Turkey (Fig. 1) during the operational period using analytical and numerical methods, (2) post-closure pit lake formation using a combination of numerical and volumetric budget models, and (3) the impacts of the ultimate pit lake on groundwater resources. The Kışladağ gold mine has been operated since 2006 by the TÜPRAG Metal Mining Company, a subsidiary of Eldorado Gold Corporation and is projected to end by 2030, leaving a large open pit. Main facilities of the mine consist of a leach pad, a waste rock storage area, and an open pit, with the planned expansion of the leach pad and waste rock storage area (Fig. 2). With its current design, the Kışladağ open pit will be one of the largest of its kind when it reaches its ultimate pit geometry. The pit will measure almost 2000 m by 1600 m at its crest and will be approximately 700 m deep.

By the end of 2012, the pit bottom elevation was $\approx$872 masl, which is just above the groundwater level ($\approx$870 masl). The groundwater level was to be reached around the end of 2013, but excavation will continue until the pit bottom reaches its ultimate elevation of 300 masl (by the end of 2029). Therefore, a dewatering program had to begin in 2012 to reduce groundwater levels by about 570 m in order to provide slope safety and dry excavation conditions. Consequently, the rate of groundwater inflow into the pit, which is expected to increase as the pit bottom is lowered, had to be quantified and dewatering systems had to be designed based on this rate. Once mining ends, the dewatering program will cease; hence, a lake is expected to form in the open pit area. It was important to understand the dynamics of the lake (lake levels, time required to reach equilibrium conditions, groundwater-pit lake interactions, etc.) in order to assess the impact of the lake on groundwater resources. This study, therefore, focuses on the dewatering requirements of the Kışladağ gold mine during its operation phase, post-closure pit lake formation process, and finally, the characteristics of the ultimate pit lake.

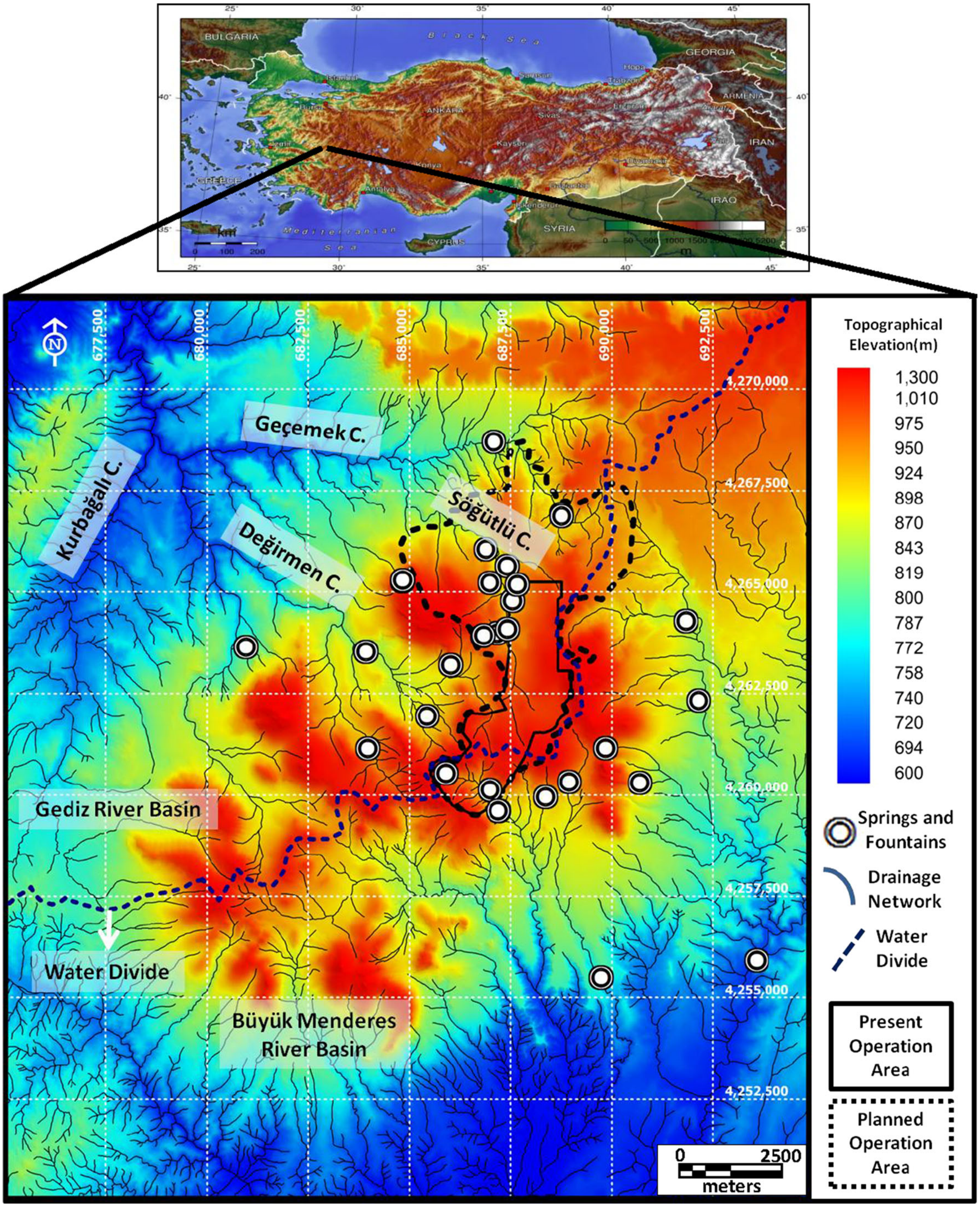


Fig. 1 Location of the study area

Physiography, Climate, and Geology of the Study Area

Studies were conducted over an area of around 440 km^2 around the mine site. Elevations in the study area range from approximately 1300 masl in the hilly areas to 600 masl at the base of the valleys, which are draining these hills (Fig. 1). The Kışladağ gold mine is located between the Aegean and Central Anatolian regions, where the Mediterranean transition climate, with relatively wet winters and springs, are dominant (Türkeş 1996). Wet and dry periods were determined and the average annual precipitation was calculated as 493 mm for the mine site using long-term (1975–2012) precipitation data series (Yazicigil

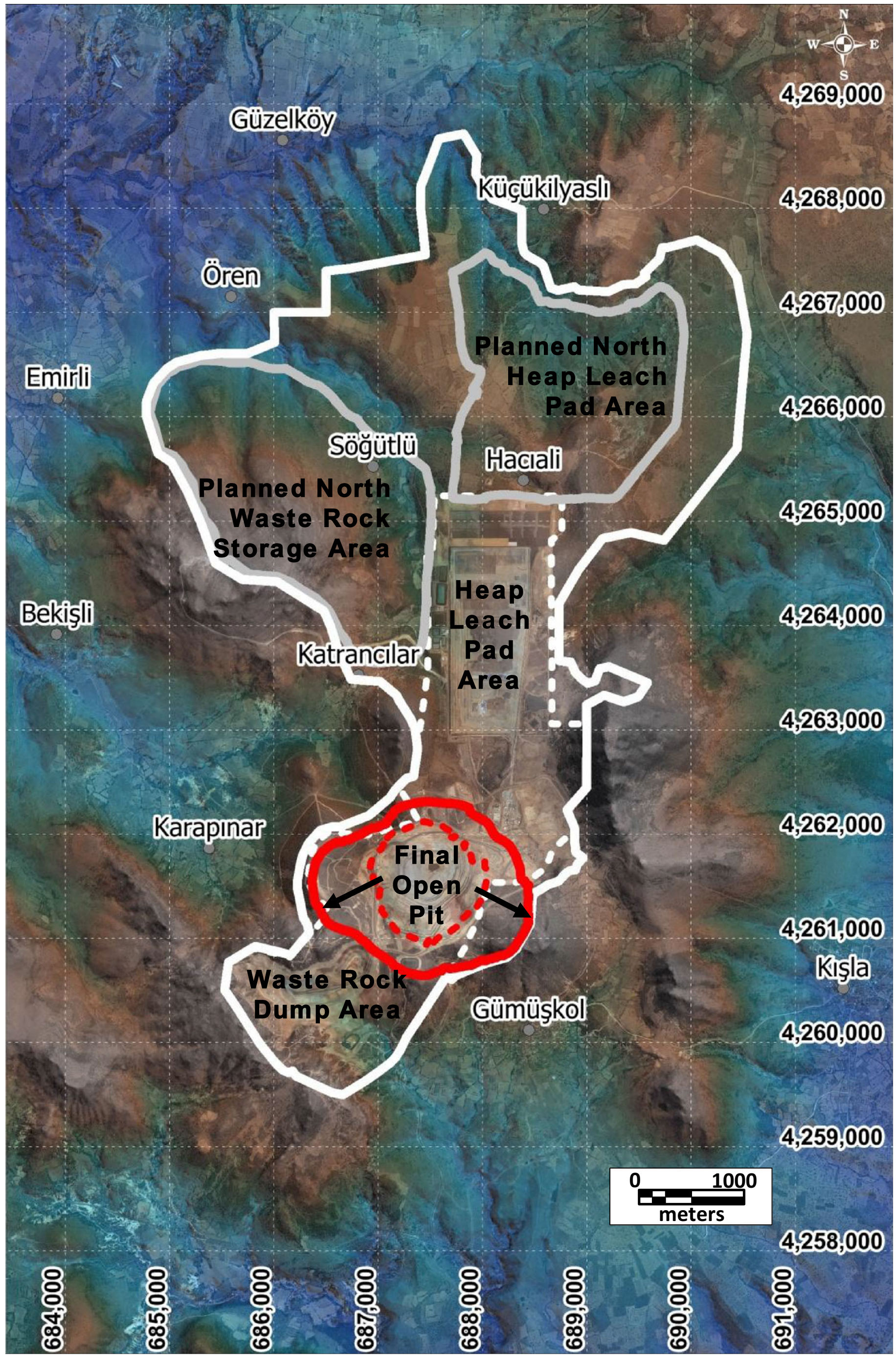


Fig. 2 Planned mine site layout by the end of 2029

et al. 2011, 2013). Monthly temperatures vary between 25.2 °C (August) and 2.23 °C (January). The average annual temperature is calculated as 13.3 °C. Relative humidity is relatively low in summer (between 38 and 50 %) at the mine site, indicating hot and arid summers, while it is about 75 % during the site's wet and cold winters. Long term annual evaporation for Kışladağ averages 1198 mm. Thus, the study area is subject to net evaporative losses due to its semi-arid nature.

Regional geology of the study area was examined by Yazicigil et al. (2000, 2008, 2013) and also mapped by MTA (2002). All the lithological units outcropping in the area are shown on the geological map (Fig. 3). The Eşme Formation, which is made up of schists and gneisses, comprises the crystalline basement rocks. Above this, the Ahmetler Formation is observed unconformably, forming a fining upward sequence made up of conglomerates, sandstone, tuffite, claystone, and marl. The Beydağı volcanic formation, which is made up of andesitic volcanics (lava flow, agglomerates, and tuffites) has extensive outcrops within the study area and provides sediment input for the lower layers of the Ahmetler and Ulubey Formations. Overlying the Ahmetler Formation conformably is the Ulubey Formation, which is made up of intercalating siltstone, claystone, marl, and clayey limestones at the bottom and lacustrine limestone at the top. This formation has extensive outcrops, especially in the eastern and the northern parts of the study area. The Asartepe Formation overlies the older units unconformably, and consists of alternating weakly cemented conglomerates, sandstones, and siltstones with local lenses of marl and claystone. Alluvial fan deposits, colluviums, and alluvium are the Quaternary units.

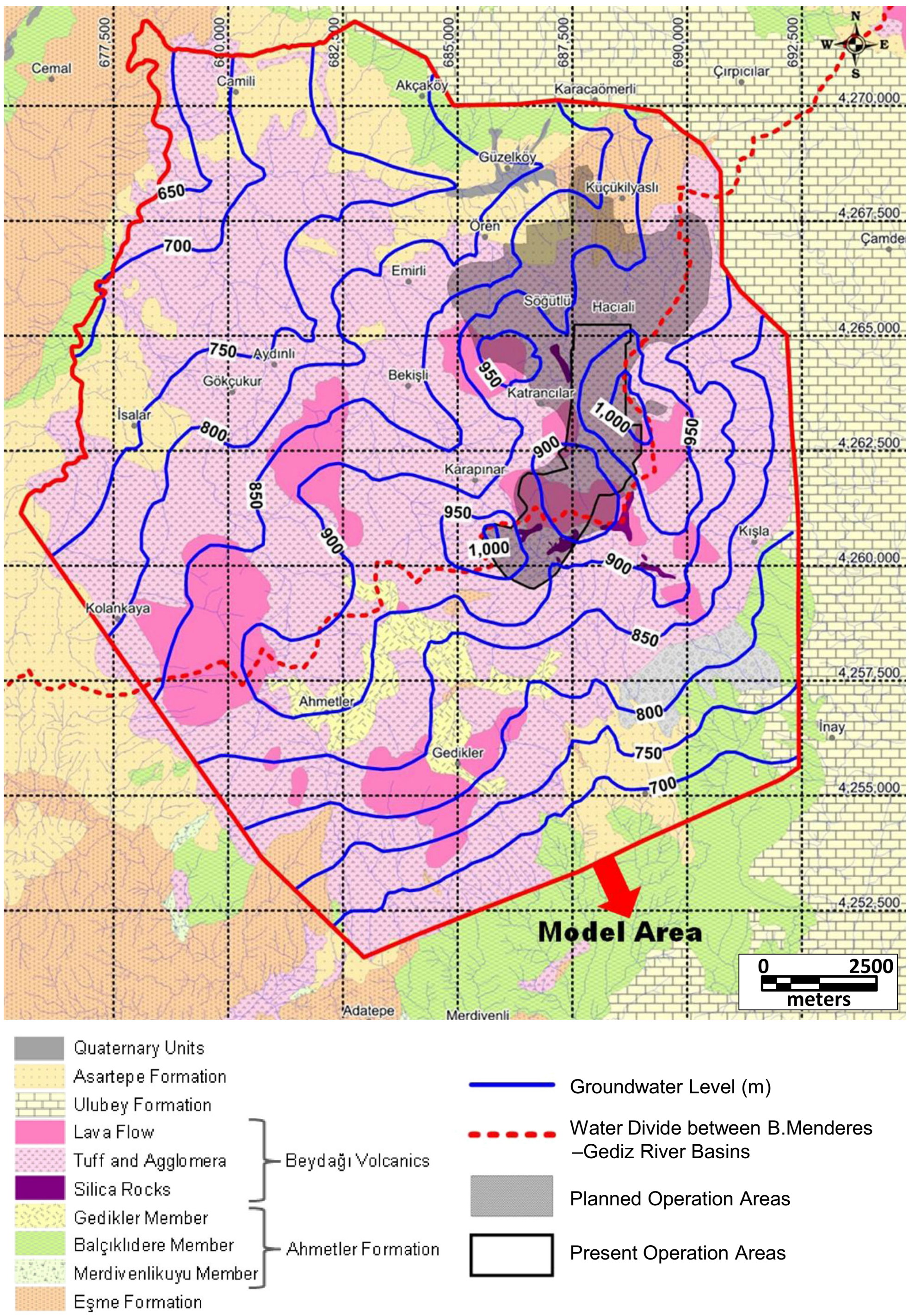


Fig. 3 Groundwater levels and geological map of the study area

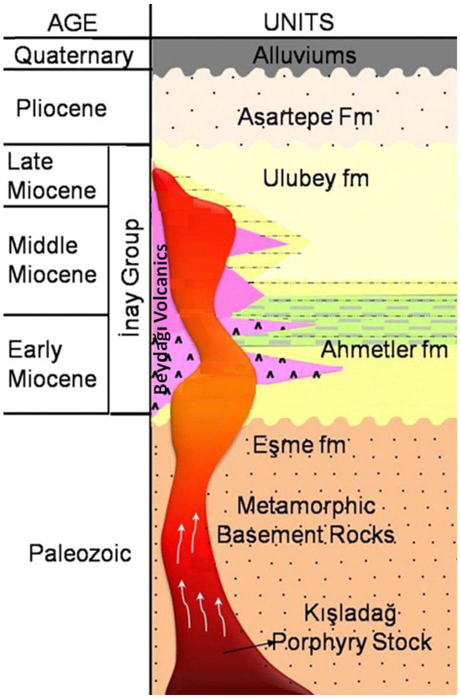


Fig. 4 Generalized columnar section of the study area

Figure 4 demonstrates a generalized columnar section, conceptualized for the mine site. According to this, the main rock units in the vicinity of the mine site are the Asartepe Formation and Quaternary units, locally overlying extrusives and intrusives of the Beydağı Volcanics and the volcanoclastics formed by the erosion of these, together with the underlying metamorphic units of the Eşme Formation. Intrusives, where gold mineralization is observed, are emplaced within the basement rocks. Although overlain by a thick sequence of volcanic rocks, these basement rocks can be observed at the surface as a result of erosion. Further away from the mine site, these rocks partially interfinger with and grade into clastic sedimentary rocks of the Ahmetler Formation and lacustrine limestones of the Ulubey Formation.

The Kışladağ mine site is defined as almost not deformed at all in the previous structural studies (Çolakoğlu 2011; Hudson 2009; Lewis Geoscience Inc. 2002), since a significant fault system of regional importance was neither observed during the field studies nor determined with logging.

Hydrology and Hydrogeology of the Study Area

The mine site is located on the water divide separating the Gediz and Büyük Menderes River Basins (Fig. 1). Only ephemeral creeks are present in the study area, as it is located on the water divide. Radial drainage of these surface waters is caused by the presence of the volcanic cones within the study area. The major creeks within and around the mine site are the Kurbağalı Creek flowing west of the mine site and the Geçemek Creek, flowing north of the mine site, with its tributaries, namely Söğütlü Creek (draining the mine area) and Değirmen Creek (Fig. 1). These two major drainages combine northwest of the project area and discharge to the Gediz River.

Within the boundaries of the study area, there are only very low-yield (<0.25 L/s) springs and seeps (Fig. 1), except for İnay Spring, which has a relatively high discharge rate (8.5 L/s) and drains the Ulubey aquifer. There are a total of 34 wells near that spring, drilled for several purposes (exploration, irrigation, domestic water supply, and water supply to the mine), which are all pumping water from the Ulubey aquifer.

On the other hand, at the mine site, there are 82 wells that have been drilled to determine hydrogeological conditions as well as hydraulic parameters, some of which are used to monitor groundwater levels and quality. After an assessment of all the available data gathered from the above mentioned water points, rock units within and around the study area were classified according to their lithologies and water-bearing capacities.

Finally, among all of the units of regional importance, the ones located in the vicinity of the mine site were determined as Eşme Formation, Beydağı Volcanics, Intrusives (Open Pit), and Asartepe Formation. Accordingly, hydraulic tests were conducted to characterize these lithologies. Minimum and maximum hydraulic conductivity values were determined for each lithological group tested, together with the corresponding geometric mean value (Fig. 5). As demonstrated in Fig. 5, hydraulic conductivity calculated for different units within the study area ranged between 2.50×10^{-9} m/s (for the Asartepe Formation) and 2.61×10^{-6} m/s (for the Eşme Formation); the geometric mean is 1.08×10^{-7} m/s for this range of values. The geometric mean values calculated for different lithologic units within the study area show that all the units have similar geometric mean values except the Asartepe Formation. The marls and claystones in this unit are dominant within the study area, rendering a lower hydraulic conductivity. It should be noted that the pit, which is located within the intrusive units, includes a zone of higher permeability relative to the adjacent intrusives (called the friable zone). Test results performed at this zone indicated a hydraulic conductivity of 1.4×10^{-6} m/s and specific storage value of 1.2×10^{-6} 1/m (SRK 2012).

Temporal Changes and Areal Distribution of Groundwater Levels

When groundwater levels recorded at the monitoring wells were examined together with the precipitation measurements, it was observed that there was no significant change

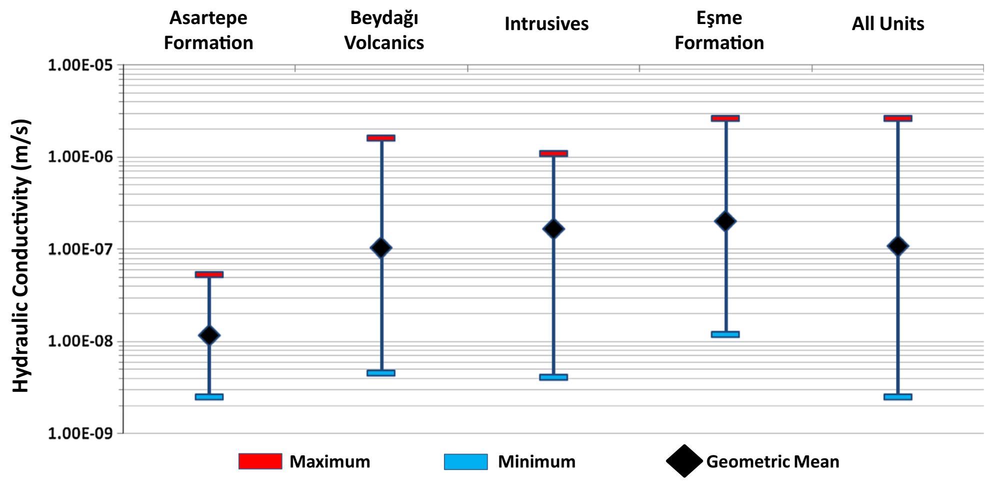


Fig. 5 Maximum, minimum and geometric mean of hydraulic conductivity values

in water levels, except for seasonal fluctuations. A different trend occurs at wells in the immediate vicinity of the open pit area, where groundwater levels have increased by about 8–10 m since 2009. This increasing trend is a consequence of induced groundwater recharge caused by the following factors: (1) reduced thickness of the vadose zone and enlargement of the catchment due to excavation in the open pit area; and (2) a wet period, observed since 2009. Vertical interactions between the different lithologic units were also checked by comparing the groundwater levels recorded at clustured wells that are screened at different lithologies. Detailed analysis revealed that groundwater levels monitored at clustered wells representing different lithological units are very close to each other all around the mine site. Moreover, all these different units show similar responses to changes in precipitation.

Since all the units within the study area have similar hydraulic properties and groundwater levels, they can be conceptualized as a single system that can be represented by a single regional groundwater elevation map (Fig. 3). The consistency of the generated groundwater levels was also checked with the groundwater levels of the Ulubey aquifer (Unsal and Yazicigil 2014). The resulting map (Fig. 3) indicates that the mine site is located on the groundwater divide and that the highest groundwater elevations are observed along the surface water divide. The groundwater level of the open pit, situated just between the heap leach pad and waste rock storage area, is very low (around 870 masl) compared to that observed at these two locations (around 1000 masl). Low groundwater levels in the open pit area can be explained by (1) increased hydraulic conductivity at this locality due to the formation of joint and fracture systems developed during and after mineralization at the contact and intrusion zone and (2) formation of new fractures and extension of existing ones as a result of stress relief as excavation advances. In other words, a lower groundwater level at the open pit location is a consequence of the hydraulic conductivity difference between the host rock, and intrusive units emplaced within them (Yazicigil et al. 2013). Moreover, a study conducted by Lewis (2002) suggests that joint and fracture systems are dominantly oriented NNW. Anisotropy developed in this direction controls groundwater flow as well.

Methodology

A conceptual model was developed for the site with the available data in order to comprehend the current system. Then, based on this, a numerical groundwater flow model was constructed and calibrated to site conditions in order to simulate the operational period and to quantify the dewatering requirements. An analytical model was also used to calculate pit dewatering rates and the results obtained were compared with those obtained from the numerical model. Furthermore, for the post-closure period, a spreadsheet model, which is integrated with the numerical model predicting groundwater inflow rates to the pit, was used to determine the steady-state pit lake level. In the final stage, this steady-state pit lake level was introduced into the numerical model in order to predict the hydrologic status of the pit lake at steady-state conditions and its impact on groundwater resources.

Conceptual Model of the Study Area

A conceptual (hydrogeological) model is a descriptive representation of a groundwater system that incorporates an interpretation of the geological and hydrological conditions (Anderson and Woessner 1992). It consolidates current understanding of the key processes of the groundwater system, including the influence of stresses, and assists in the understanding of possible future changes (Barnett et al. 2012). In that sense, the conceptual model, reflecting the hydrogeological characterization of the site, is the basis for the numerical groundwater flow model.

In the study area, the Eşme Formation and Beydağı Volcanics are the two units having the broadest extensions. Moreover these two units have very similar hydraulic characteristics, consistent groundwater levels with parallel seasonal fluctuations. It was also observed that results for all the other lithological units that were tested indicated very similar hydraulic properties. The ones that could not be tested (alluvium and the Ahmetler Formation) were assumed to have similar hydraulic properties with the units that dominate the study area.

Examining the regional groundwater elevation map (Fig. 3), it can be seen that groundwater is recharged from the mountainous area located along the water divide separating the Gediz and Büyük Menderes River Basins. Groundwater levels reaching elevations around 1000 masl within the mine site, decrease to 650–700 m levels, at the northwestern parts of the mine where schists outcrop and at the southeastern parts where the Ahmetler Formation crops out (Fig. 3). According to this trend, groundwater discharge occurs to: (1) Kurbağalı Creek, along the northwestern boundary; (2) Geçemek Creek, north of the mine site; (3) Ulubey Formation at the eastern boundary; and (4) the Ahmetler Formation, along the southeastern boundary.

In previous studies, different groundwater recharge rates were calculated for the site as 22 mm/year (SRK 2007) and 44 mm/year (SRK 2005), using different methods. To determine the areal distribution of recharge, Yazicigil et al. (2013) used the soil water balance (SWB; Westenbroek et al. 2010) model. With this model, a set of calculations are completed and different methods are tested for calculation of evapotranspiration including; Thornthwaite and Mather (1957), Jensen and Haise (1963), Turc (1961), and Hargreaves and Samani (1985). The model, which is calibrated by comparing simulated discharges with the site measurements, calculated average recharge to groundwater as 37.82 mm/year together with its areal distribution ranging from 0 mm/yr (at the leach pad and waste rock storage areas) to about 220 mm/yr at some highly porous locations.

Groundwater Flow Model

A groundwater flow model was developed for the study area (Unsal 2013; Yazicigil and Unsal 2013), using the Visual MODFLOW 2011.1 Premium software package developed by Schlumberger Water Services. Using this software, groundwater flow equations were solved by the MODFLOW-2000 code known as "3-D modular finite-difference groundwater flow model" developed by the US Geological Survey (Harbaugh et al. 2000).

Model Domain and Finite Difference Grid

The model domain covers an area of 245 km^2 (Figs. 3, 6) and is discretized into cells of variable size (Fig. 6). The grid is coarsest (100 × 100 m) along the model boundaries; at the open pit area where higher accuracy is required, grid size was refined to 25 × 25 m. The resulting grid is rotated 45°, so that it is aligned with the regional groundwater flow direction (NW–SE). The topographical surface was introduced in the model with elevations ranging between 600 and 1300 masl within the model domain. At the bottom, the model is confined with a no flow boundary at 0 m, corresponding to an elevation that is 300 m below the ultimate pit bottom. The thickness between these surfaces was divided into 15 layers in a vertical direction to enable a better simulation of dewatering activities during the operational phase of the mine.

Boundary Conditions

Next, the boundary conditions were defined in the numerical groundwater flow model. The northwest boundary of the model domain, which is aligned with the ephemeral Kurbağalı Creek, was simulated with a drain boundary condition so that groundwater is allowed to drain freely whenever groundwater level is above the assigned drain elevation (2 m below the topographical surface). Lithological boundaries southwest and north–northeast of the model were assumed to be no flow boundaries, according to the groundwater elevation map generated in the conceptual aquifer model (Fig. 3). Along the eastern boundary of the model domain, a general head boundary condition was used to simulate groundwater flow between the Ulubey Aquifer and the modeled units. As there is no physical boundary southeast of the model domain, this boundary was aligned with contours of the regional groundwater elevation map (Fig. 3) and simulated using a general head boundary condition, with a hydraulic head of 650 masl (Fig. 6). Perennial and seasonal drainage were simulated using drain boundary conditions. However, due to the lack of detailed hydrologic data for surface waters, all drain cells were assigned elevations 2 m below the topographical surface so that simulated groundwater levels were close to the topographical surface along the drainages.

Model Parameters

Recharge

Located along the water divide separating the Gediz and Büyük Menderes River Basins, the mine site is situated on a regional recharge area. Areal distribution of the recharge, determined by the SWB model, was assigned to the

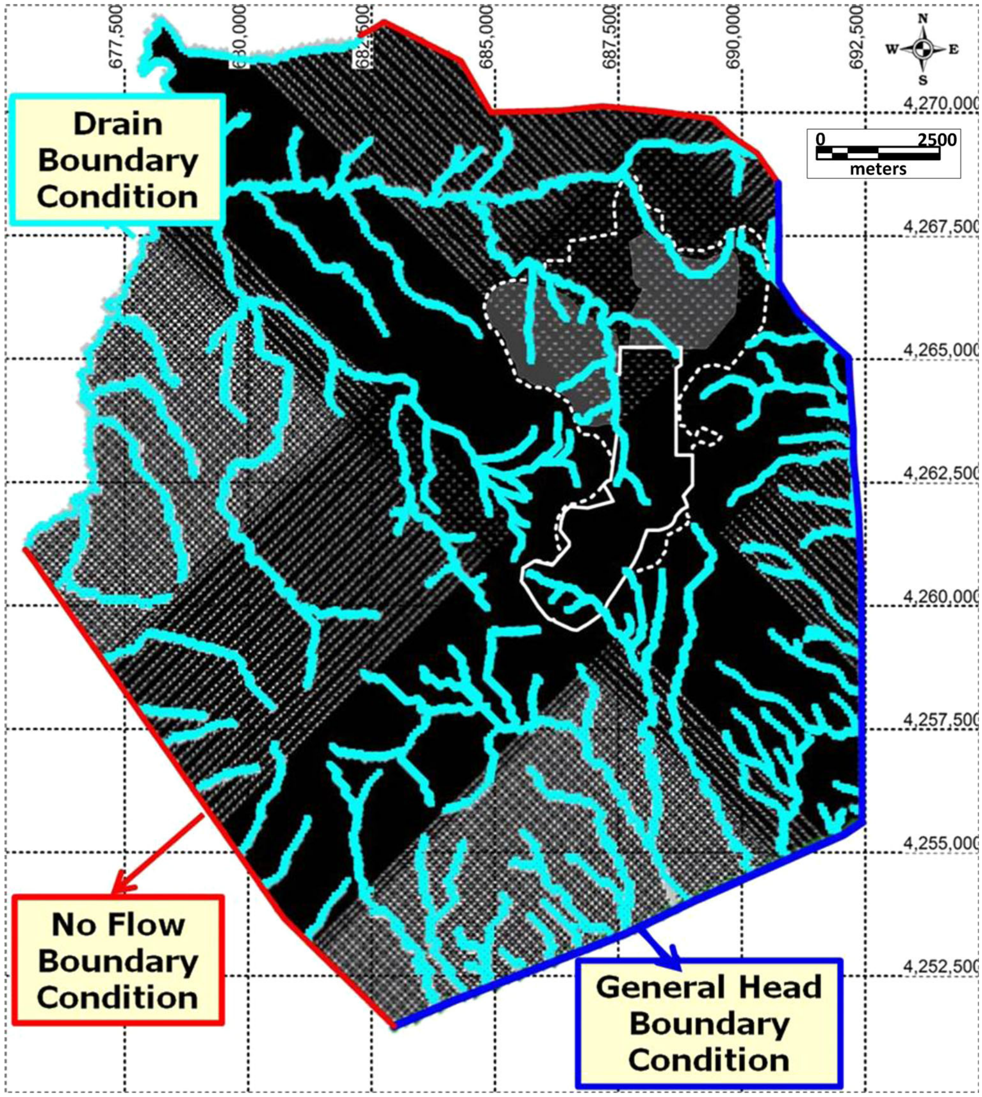


Fig. 6 Model grid and boundary conditions

groundwater flow model and calibrated considering the hydrological and hydrogeological characteristics of the site, as well as the changes in these characteristics induced by the presence of mining facilities (such as open pit, waste rock storage and leach pad areas). Finally, recharge from precipitation, determined by the SWB model as 37.82 mm/year for the whole study area (440 km^2), was calibrated to 29.6 mm/year for the model domain (245 km^2).

Hydraulic Conductivity

Hydraulic conductivity values obtained by the hydraulic tests were changed within the ranges obtained from the field tests to reflect the hydraulic characteristics of the lithologic units. Based on the results of the study conducted by Lewis Geoscience Inc. (2002), indicating a NW–SE regional trend for the fracture system, an anisotropy ratio of (K_y/K_x) of 5 was applied in the model. Besides, RQD (rock quality designation) values obtained from the wells drilled at the mine site and packer test results performed at different depths indicates that fracture frequency and apertures decrease with depth. Hence, it was concluded that hydraulic conductivity of the materials decrease with depth and therefore, lateral hydraulic conductivity values were assigned to the model layers in a downwards decreasing manner. The vertical hydraulic conductivity values of the units were determined by calibration as there was no field test data for this parameter. During calibration, the ratio of lateral to vertical hydraulic conductivity (K_x/K_z) was set to be 10:1 for all the units, except the intrusives located at the open pit area, where this ratio was set to 2:1. In the pit area, owing to its lithological characteristics, the friable zone is known to have higher conductivity and storage properties than the surrounding units. Therefore, this unit was assigned a relatively higher hydraulic conductivity value of 1.0×10^{-6} m/s.

Storage Coefficient

There is not much data regarding the storage coefficient of the units within the study area, but a pumping test was conducted in the open pit area, within the friable zone. Based on the results of this test, specific storage of the intrusive units at the open pit area was assigned as 1.2×10^{-6} 1/m, and the rest of the model domain was assigned a smaller value (1.0×10^{-7} 1/m).

Calibration and Sensitivity Analysis

Calibration

The numerical model was calibrated to the field conditions using the above mentioned input parameters. As the calibration was conducted under steady-state conditions, storativity could not be calibrated. So, during the dewatering simulations, which were conducted under transient conditions, several values were tested to determine the effect of this parameter on the model results. At the end, a good match between the observed and calculated groundwater levels was achieved based on the values of the error statistics and areal distribution of the water levels. The root mean square error (RMSE), correlation coefficient, and normalized RMSE were 13.9 m, 0.942, and 6.3 %, respectively. Therefore, it was concluded that this calibrated model was capable of simulating the possible responses of the system to the imposed stresses during the following stages.

Sensitivity Analysis

A series of simulations were performed to test the sensitivity of the model to changes in the model parameters. For sensitivity analysis, RMSE value was used to determine the sensitivity of the model to the changes imposed on the input parameters. Moreover, due to the fact that this calibrated model will be used to determine the groundwater flow rates at the open pit area, the model results have to be very precise at this location. Therefore, in addition to RMSE, sensitivity of the model was also assessed with respect to the open pit groundwater levels at the end of each sensitivity run. Finally, it was observed that among all the parameters tested, the model was most sensitive to a decrease in hydraulic conductivity defined over the whole model domain, which was followed by changes in anisotropy and recharge from precipitation. On the other hand, the response of groundwater levels at the open pit showed the greatest sensitivity to the changes in anisotropy and increases in the hydraulic conductivity defined over the whole model domain, such that doubling the hydraulic conductivity over the whole model domain caused an almost 40 m decrease in the open pit groundwater levels.

Open Pit Dewatering

Topographical elevation of the pit bottom of the Kışladağ gold mine, which was initially around 1080 masl in 2006 when mining began, has been lowered ever since, reaching ≈872 masl level by the end of 2012. The corresponding groundwater elevation was ≈870 masl. Plans are to lower the pit bottom elevation to 300 masl level by the end of 2029. This implies that during the next 17 years, the groundwater level will have to be lowered by about 570 m via proper dewatering systems. In order to design such a system, the groundwater inflow rate has to be quantified. At this stage, a calibrated numerical groundwater flow model was used to predict the amount of groundwater that will flow into the pit, as the pit bottom is lowered. Furthermore, the analytical model developed by Marinelli and Niccoli (2000) was also used in a stage-wise manner as the pit bottom was lowered and results were compared with those obtained from the numerical model. The two different modeling approaches that were tested are summarized below.

The numerical groundwater flow model, which was calibrated under steady-state conditions, was revised to account for the time-dependent components and was run in monthly stress periods to simulate the next 17 years of operation. Apart from the boundary conditions, specific storage and specific yield parameters had to be defined before the model could be run under transient conditions. For the specific storage, result of the test conducted at the friable zone was assigned to that area (1.2×10^{-6} 1/m). For the rest of the model domain, a smaller value (1.0×10^{-7} 1/m) was assigned. On the other hand, due to the absence of data on specific yield, its value was assumed to be 0.010 and a range of values (between 0.005 and 0.020) were also tested to analyze the sensitivity of the model results to changes in the value of this parameter. The assigned specific yield values are of the same order of magnitude as were observed in tests conducted on the Tertiary volcanic rocks in Death Valley in California (Belcher et al. 2002).

Furthermore, progression of the excavation had to be defined using boundary conditions. For this purpose, a drain boundary condition was used to simulate the time-wise progression of the pit by assigning time dependent head values to the drain cells. Head values were assigned in accordance with the mine layouts, interpolated for the monthly periods. The numerical groundwater flow model modified in this manner was run under transient conditions for 17 years, with monthly stress periods. Four sets of dewatering simulations were conducted using different specific yield values (0.020, 0.015, 0.010, and 0.005). At the end of these simulations, the amount of groundwater that will flow into the pit was determined on a monthly basis.

The analytical model developed by Marinelli and Niccoli (2000) was applied in a similar stage-wise manner. This model was used to calculate groundwater inflow rate into the mine pit for each 50 m incremental decrease of the bottom elevation of the pit, throughout the operational phase. Although the analytical model is not capable of estimating transient inflows, by assuming that groundwater will be lowered below the bottom of excavation, it is possible to estimate groundwater inflow rate to the pit incrementally. The stage-wise computation of the pit inflow rates with the analytical model shows that inflow rate ranges from 4 to 86 L/s, corresponding to pit bottom elevations of 840 and 300 m, respectively. The average pit inflow rate over the 17 years of operations is 36 L/s.

Figure 7a shows the results of the analytical model for the incremental change of the pit bottom elevation, compared to the results of the numerical model run for different specific yield values. Despite the inability of the analytical model to simulate the water released from storage, hence underestimating the groundwater flow rate into the pit, it provides a rough estimate for the lower limit of required dewatering. It can also be inferred from the graph

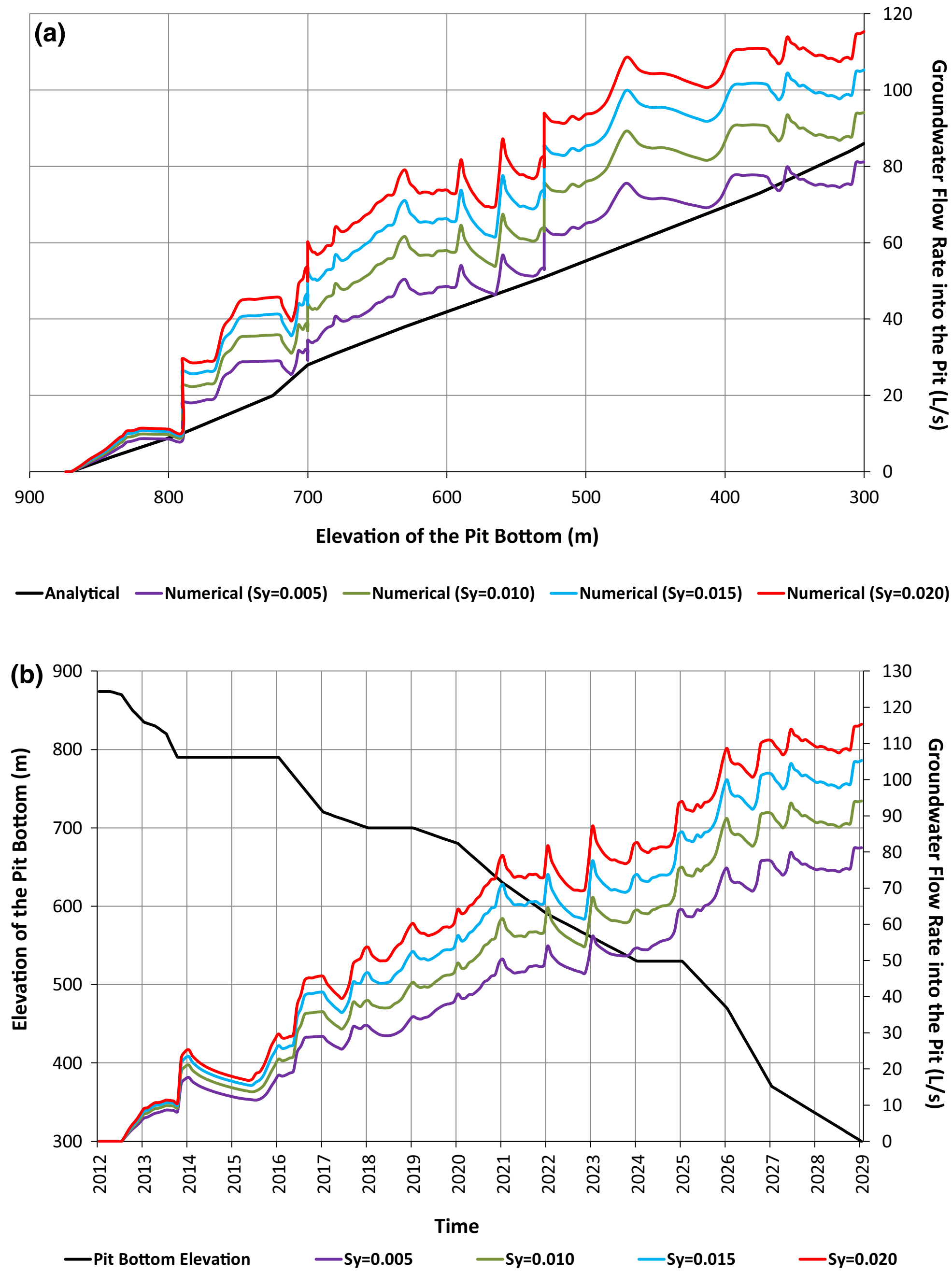


Fig. 7 **a** Comparison of groundwater flow rates into the pit calculated by analytical and numerical models. **b** Groundwater flow rate into the pit and elevation of the pit bottom versus time

presented in Fig. 7a that the consistency of the results provided by analytical and numerical models diminishes as the specific yield of the system increases. Therefore, for the transient simulations, it is more convenient to use the numerical model, which is capable of simulating the dynamic responses of the system to the imposed changes. Numerical models can handle not only the time-wise changes in input (seasonality of the recharge) and state (progression of excavation) variables of the system, but also the complexity of the excavation geometry, all of which would otherwise have had to be compromised with simplifying assumptions of the analytical model. This effect is reflected in the shape of the curves calculated by the numerical model, given in Fig. 7a, such that amount of groundwater expected to flow into the pit shows both seasonal fluctuations in accordance with the recharge and also irregular jumps owing to the non-uniform geometry of the pit. All these effects, on the other hand, are smoothed out when the analytical model is used.

Figure 7b demonstrates the time-wise progression of the pit bottom together with the corresponding groundwater inflow rates for a set of specific yield values calculated by the numerical model. As it can be seen from this figure, as a consequence of lowering the pit bottom from 870 to 300 masl level, groundwater inflow rate will increase continuously, reaching 81–115 L/s (corresponding to different storage values) at the end of the 17 years.

Annual groundwater budgets were also calculated by the numerical model for each storage value during the 17 year dewatering period. The results show an average annual groundwater flow rate into the pit of 41–62 L/s or 1.29–1.96 Mm^3/year.

Figure 8 represents the lateral and vertical hydraulic head distribution at the end of the 17 year dewatering period for the different storage values, when the pit bottom reaches 300 masl levels, on a cross-section passing through the open pit. As demonstrated in this figure, the pit is successfully dewatered at the end of each simulation. Moreover, the vertical hydraulic gradient induced by lowering the water table from 870 to 300 masl results in groundwater flowing into the pit from the pit bottom as well.

The hydraulic head distribution in a lateral direction at the end of each simulation was also checked. Due to the anisotropic characteristics of the aquifer, cones of depression having elliptical shapes with their long axis extending in a NW–SE direction are formed (apparently, smaller storage values result in cones of depression with wider extensions). Results also indicated that these depression cones reached the boundary formed by the Ulubey aquifer. Hence in order to assess the magnitude of influence, model budgets were checked and changes in the interactions between the modeled units and the Ulubey aquifer, were quantified. Accordingly, it was concluded that recharge from the Ulubey Aquifer into the model domain was barely affected at the end of 17 years. On the other hand, the amount of groundwater discharging from the model area to the Ulubey Aquifer will decrease by about 0.13–0.18 Mm^3/year, which is negligible compared to the natural annual recharge (190 Mm^3/year) of the Ulubey Aquifer (Yazicigil et al. 2008).

Pit Lake Formation

By the end of 2029, the pit bottom will be lowered to its ultimate level (300 masl) and operational phase will be completed; therefore, dewatering activities will cease. The water table that is lowered by about 570 m during last 17 years, will tend to rebound. A lake is expected to form in the open pit, with the water that will flow into the excavation area. The water level in the lake will rise and it will stabilize at an elevation when equilibrium is reached in terms of the following hydrogeological and hydrological components of the lake system: In general, inflow components of this budget can be classified as direct precipitation falling onto the lake surface; runoff from the pit walls following a precipitation event and groundwater inflow. On the other hand, outflow components are evaporation from lake-surface and groundwater outflow to the downstream direction if the lake level is higher than the surrounding groundwater levels.

All relevant characteristics specific to this study area and to the ultimate pit design were considered in selecting the appropriate methodology to simulate the pit lake formation process. The enormous computational time that would arise with a numerical model highlight the advantages of a volumetric balance approach over a numerical model (for instance LAK Package of MODFLOW) for this specific problem. Therefore, a volumetric balance approach was adopted that is; (1) flexible enough to allow a daily simulation until the water level of the pit lake stabilizes and also (2) capable of calculating a significant component of the lake water budget for this specific case, namely runoff from pitwalls, which will dynamically change with the lake level throughout the simulation period.

Hereby, a pit lake budget was formed to calculate the volumetric changes of all components on daily basis. Further, it was used to predict the time-wise change in lake levels, final pit lake level, and the time required to reach this level. As the calculations are based on the "volumes" of each component, geometry of the ultimate pit was used to convert the flow rates into volumetric flows. For this purpose, surface area and volume of the pit lake had to be determined for the different pit lake water levels. The relations of pit lake level—lake surface area—lake volume

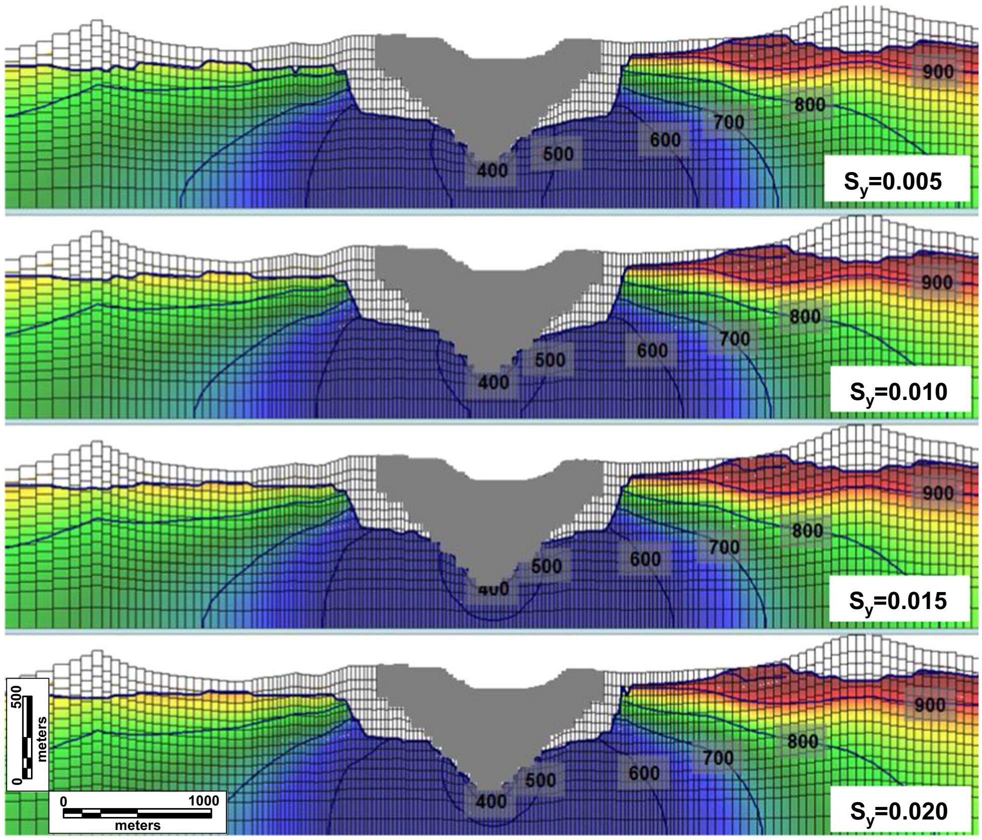


Fig. 8 Hydraulic head distribution at the end of 17 years

were introduced into the spreadsheet model together with the daily meteorological inputs obtained by the long-term daily measurements for the 1975–2012 period, for the entire simulation time.

Finally, volumetric balance of the pit lake was calculated by the equation given below:

$$\text{Inflow} - \text{Outflow} = \text{Net Change in Storage}$$
$$(V_{GWI} + V_{DP} + V_{PWR}) - (V_E + V_{GWO}) = V$$

where; V: net change in storage, V_{GWI}: groundwater inflow, V_{DP}: direct precipitation, V_{PWR}: pit wall runoff, V_E: evaporation from pit lake and V_{GWO}: groundwater outflow. Calculation of each component is discussed below in detail:

Groundwater Inflow (V_{GWI}) and Groundwater Outflow (V_{GWO})

The rate of groundwater inflow and/or groundwater outflow will be controlled by the lake level and groundwater level surrounding the pit. These two components were calculated numerically, by running the groundwater flow model under steady-state conditions, for each 50 m incremental increase in lake level from the bottom of the pit. Then a regression analyses was completed on the data and it was observed that a polynomial regression curve of order four is capable of representing the data perfectly (Fig. 9). Therefore, instead of running the numerical model for smaller increments, a regression curve, representing the discharge versus elevation data produced by the model for each 50 m incremental increase, was used to convert the groundwater inflow and outflow rates for each 1 m increments. Figure 9 shows the groundwater flow rates into the pit; note that the negative rates indicate an outflow from the pit lake. As it can be seen from this graph, groundwater inflow rate increases at the very early periods of lake filling, reaches a peak, and then decreases continuously. As mentioned by Castendyk and Eary (2009), in theory, the rate of inflow is initially rapid because the hydraulic gradient is at maximum and decreases over time as the gradient becomes smaller. At the same time, the rising water table increases the area where groundwater discharges into the lake and in some cases; this increase can offset the decrease in hydraulic gradient, resulting in a constant filling rate for a period of time (Castendyk and Eary 2009). In this case, the first increase in the flow rate could be explained by the rising water table, hence increasing the discharge area. However, after a short time, the effect of the decreasing gradient dominates over this effect and results in a continuous decline in the groundwater flow rates into the pit.

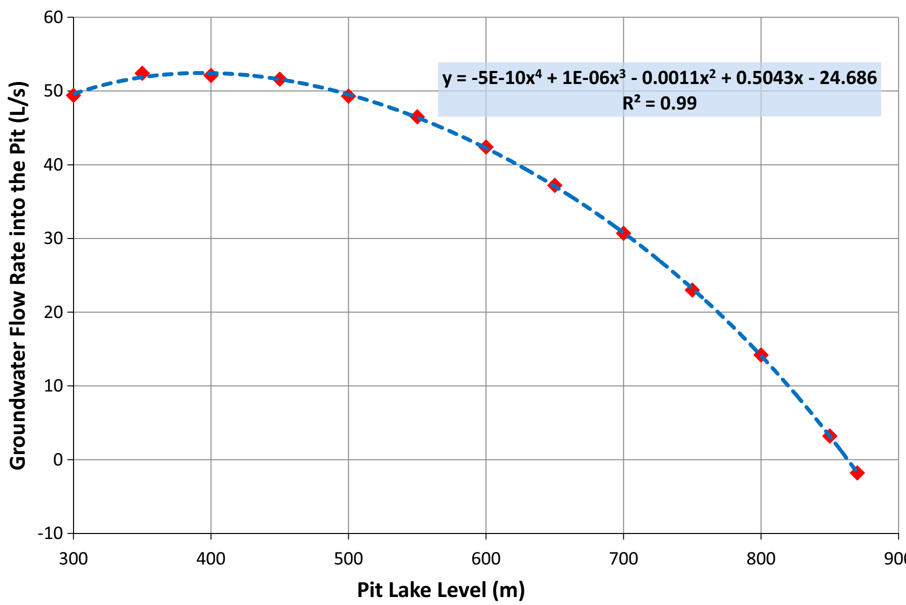


Fig. 9 Net inflow rate to pit at different elevations

Direct Precipitation (V_{DP})

Repetition of the long term (1975–2012) daily precipitation series was used to calculate this budget component. This data set covers three wet (1978–1981, 1997–2002, and 2009–2012) and two dry periods (1984–1996, 2003–2008); hence, it is capable of representing long-term precipitation patterns expected in the area. The volumetric inflow to the lake from direct precipitation was calculated by multiplying the daily precipitation with the pit lake surface area of the corresponding day.

Pit Wall Runoff (V_{PWR})

An analytical model was used to predict the runoff rate that will originate from precipitation flowing to the pit walls. This analytical model is based on U.S. Soil Conservation Service's flow curve number (CN) method (USDA 1986) which is well known for determining the runoff rate. Considering the hydrogeological and hydrological conditions, together with the geometry of the Kışladağ open pit; the curve number (CN) was determined as 95. However, a series of additional simulations were also completed with CN values of 96, 97, and 98, to assess the effects of this parameter on the pit lake water budget and on the equilibrium conditions of the system. Volumetric runoff was calculated by multiplying the daily precipitation with the pit wall area that is given by the difference between the pit crest area and the lake surface area for the same day.

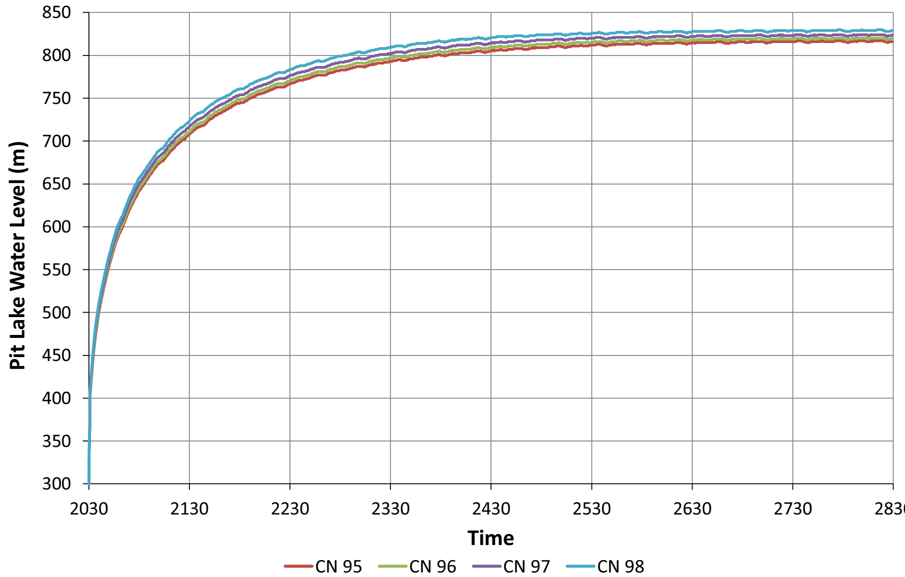
Evaporation (V_E)

A long term (1975–2012) daily evaporation data set generated by Yazicigil et al. (2011) for the mine site was updated and used to calculate evaporation from the pit lake surface. In the above mentioned research, data obtained from two currently active meteorological stations were used for the derivation of daily time series representing the meteorological conditions of the study area. One of these was installed by Turkish Meteorological General Directorate near Uşak city center in 1929 and the second one was installed at the mine site in 2000.

Daily evaporation measured at Kışladağ had some missing measurements and consequently, a correlation set was developed by Yazicigil et al. (2011) to estimate the missing data. Yazicigil et al. (2011) conducted a statistical analysis for the Kışladağ and Uşak Meteorological Stations evaporation data for the period between 2000 and 2012 (where the collected data overlapped). Using these analyses, long term daily evaporation data was generated for the period between 1975 and 2000 for Kışladağ and this was used repetitively to calculate losses from the lake surface. Daily evaporation values (pan evaporation values) were multiplied with the pan coefficient (taken as 0.75) to calculate the lake evaporation values. Then, on a daily basis, lake surface area and daily lake evaporation value were multiplied to calculate the total volume evaporating from the pit lake.

As described above, each component of the lake budget was calculated on a daily basis and included in the lake water budget to calculate the volume of the lake at that day.

Fig. 10 Pit lake level changes within time



These steps were repeated throughout the simulation until the lake level stabilizes. Moreover, as mentioned above, the spreadsheet model was run with different CN values, and resulting steady-state pit lake levels were determined. Figure 10 shows the pit lake level changes for a period of 800 years for different CN values. According to these runs, the pit lake level will stabilize $\approx$585 years after closure of the mine (at year 2615). Furthermore, other than climatic fluctuations, equilibrium pit lake level is noted as 816 masl for a CN value of 95, and 829 masl for a CN value of 98.

The components of the annual lake water budget for CN 95 over the 800 year period are given in Fig. 11. Groundwater inflow to the lake will be the most significant component of the pit lake water budget for the first 200 years because of the high hydraulic gradient caused by the dewatering. Later, as the hydraulic gradient decreases, its significance will decrease. Meanwhile, as a result of increasing surface area, inflow from direct precipitation will be the dominant inflow component of the lake budget. Similarly, the increase in the surface area of the pit lake will drastically increase the outflow by evaporation. On the other hand, runoff from the pit walls will normally decrease with time as the pit lake level increases. Even so, after groundwater inflow, the pit wall runoff constitutes the second-most important inflow to the pit lake for the first 100 years period. Another important outcome of Fig. 11 is that components of pit lake water budget, except for the groundwater inflow, are quite sensitive to climatic changes in precipitation and evaporation. Consequently, budget components depending directly on meteorological data show significant fluctuations in response to wet and dry periods in the long term climate.

Results indicated that for a CN value of 95, the pit lake level will fluctuate around 816 masl in response to the changing climatic conditions, and could reach a maximum level of 818 masl. On the other hand, equilibrium and maximum pit lake levels for a CN value of 98 were determined to be 829 m and 830 masl, respectively. These maximum lake levels were used to assess the hydraulic relationship between the ultimate pit lake and surrounding groundwater system. For this purpose, the calibrated numerical groundwater model was run under steady-state conditions after a few modifications to represent the post-closure phase of the mine. Several approaches were tested to simulate the pit lake. In each approach, lake level was simulated by the constant head boundary condition assigned to the final surface area of the pit. The approaches differ in the sense they were used to simulate the flow conditions within the open pit. The cells within the open pit were simulated: (1) as if having the same hydraulic properties as the surrounding cells, without any modification, (2) as inactive cells, and (3) as very high hydraulic conductivity cells (2000 m/d). A set of simulations were performed and their results were compared. Although computational time differed due to the convergence difficulties, in the end, all the methods produced very similar results. The results presented below were obtained from the model where the open pit was simulated as high hydraulic conductivity cells.

As mentioned above, maximum lake levels to be tested (818 and 830 masl), were introduced to the numerical groundwater model as the elevation of the constant head boundary cells. In this manner, it was possible to determine the hydraulic head distribution and interactions of the ultimate pit lake and surrounding groundwater system at the highest possible lake levels. Figure 12 represents the hydraulic head distributions corresponding to lake levels at

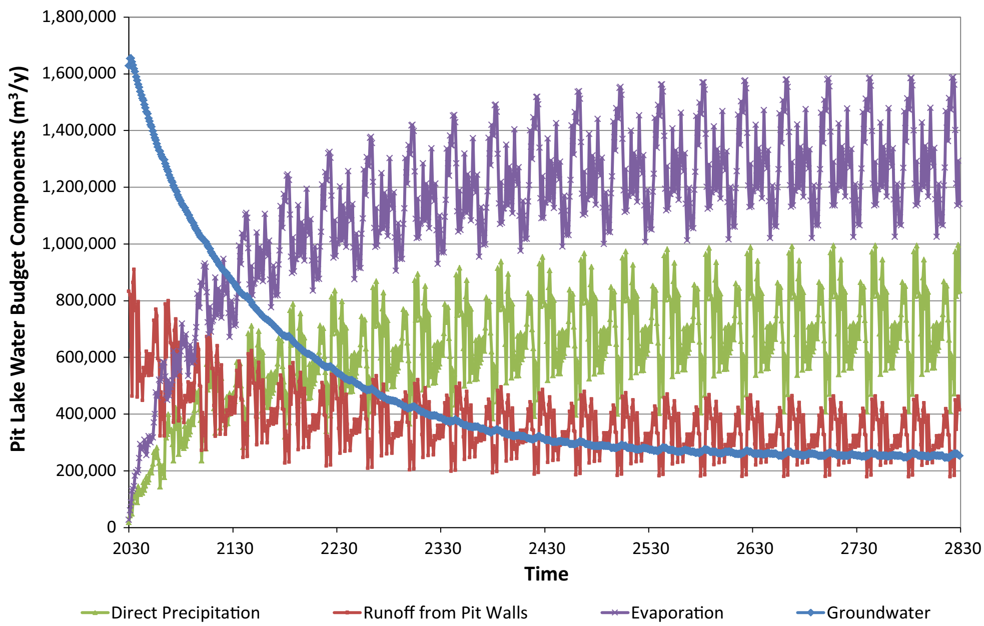


Fig. 11 Components of the annual lake water budget for CN 95

830 and 818 masl under the steady state conditions. As a result of these simulations, it is observed that at a level of 818 m, the lake behaves as a sink; in other words, it becomes a terminal pit lake. However, as the level increases to 830 m, the hydraulic status of the lake will change from terminal to flowthrough. Although the groundwater outflow component of the lake at 830 masl level is negligible, it could affect the downstream groundwater quality at levels above 830 masl.

Conclusions and Recommendations

Analytical and numerical models were used to predict groundwater inflow into the Kışladağ gold mine open pit over 17 years of mining, during which the pit bottom will be lowered from 870 to 300 masl. The analytical model, run in a stage-wise manner for each 50 m incremental decrease in the pit bottom, predicted that the groundwater inflow rate will increase from 4 to 86 L/s as the pit bottom is lowered from 840 to 300 masl. The average groundwater inflow rate for the 17 years was estimated at 36 L/s. On the other hand, simulations conducted using the numerical model under transient conditions show that pit inflow rates will increase from 5–8 to 81–115 L/s as the pit bottom is lowered. Averaged over 17 years, the anticipated average groundwater inflow rates were calculated as 41–62 L/s, depending on the storage values used in the simulations. The greater the storativity, the greater the inflow rate. The analytical model obviously yielded lower inflow rates than the numerical model since it does not account for groundwater released from storage. However, even though the analytical model underestimated the groundwater inflow rate, it provided a rough estimate for the lower limit of the dewatering requirement, especially for systems having low storage values. As the specific yield of the system increases, the difference between the two approaches becomes significant. This shows that knowledge on the storativity parameter of the system being simulated is crucial in transient dewatering simulations.

For the transient pit dewatering simulations, it is more convenient to use the numerical model, which can simulate the dynamic responses of the system to the imposed changes. The numerical model can handle not only the time-wise changes in input (seasonality of the recharge) and state (progression of excavation) variables of the system; but also the complexity of the excavation geometry. The pit bottom reached elevations below the groundwater level by the end of 2013. Hence, water flowing into the pit has been collected in a sump and pumped away from the open pit area, ever since. The pumped water amount was recorded and used for the verification of the calculated groundwater inflow rates by the numerical model. Results showed that progression of the pit was in compliance with the proposed plan and the pit bottom reached 790 masl by the end of 2014, as proposed. For January 2015, transient model calculated pit inflow rates in the range of 16.5–23.6 L/s, for different storage values. The values recorded at the mine site indicated that the amount of water pumped reached to 23.0 L/s in January 2015. It should be noted that for wet seasons, the actual amount of water pumped includes also direct precipitation falling on the pit bottom and runoff coming from the pit walls. On the other hand, the amount of water pumped in dry summer months

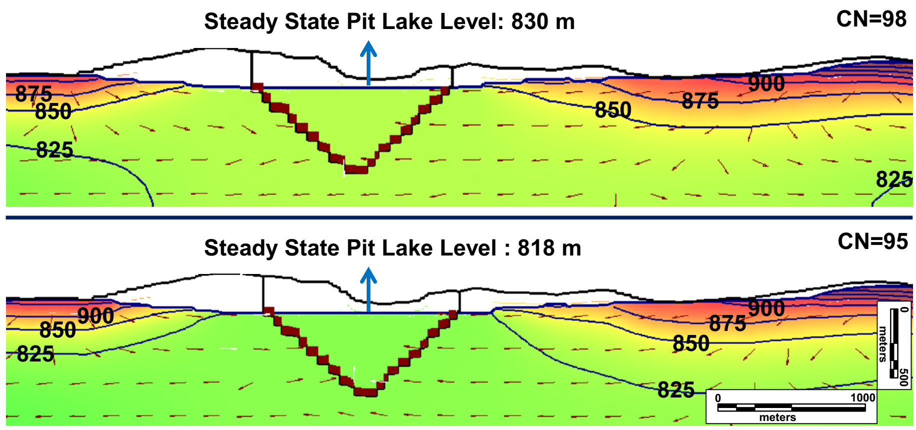


Fig. 12 Hydraulic head distributions corresponding to pit lake levels of 830 and 818 m

of 2014, which mostly reflects the groundwater inflow rate, was recorded as 16 L/s. As a result, it can be concluded that the actual pit inflow rates are well within the range predicted by the transient numerical model. Moreover, in spite of the uncertainities and assumptions associated with modeling approaches, developed model is capable of providing reliable and informative results for pit dewatering rates.

The annual amount of groundwater that has to be pumped during dewatering (1.29–1.96 Mm^3/year) was compared with the safe yield of the system (5.89 Mm^3/year, according to Yazicigil et al. 2013). It is noteworthy that the amount of pumping required for the dewatering lies within the limits of safe pumping.

For the post-operational period, volumetric pit lake water balance calculations were conducted for a period of 800 years, with different CN values. According to the results of these runs, the pit lake filling period will be completed after approximately 585 years (at year 2615) when lake levels stabilize at 816–829 m, depending on the CN value used. Seasonal fluctuations were also determined, with corresponding maximum lake levels of about 818–830 m. These maximum levels were further simulated in the numerical model in order to assess the status of the ultimate pit lake. Simulation results indicated that 830 masl is a transition elevation, below which the lake will behave as a sink, and above which, its status will change from terminal to flowthrough.

Based on the results of this research, it should be emphasized that the lack of data regarding the storage values of the water-bearing units imposes some uncertainty on our results. Hence, rather than using a single storage value, a range of values were tested with the simulations and the results are given as ranges. Future studies should determine this parameter and then re-run the model if the field value is not within the range tested.

On the other hand, the lake water budget was calculated using a spreadsheet model. The runoff rate that will originate from precipitation was predicted using the CN analytical method (USDA 1986). A CN value for the Kışladağ open pit was determined as 95, considering the hydrogeological and hydrological conditions, together with the pit geometry. However, using different CN values affects the model results so precisely determining the CN is crucial.

Moreover, the results indicated that climatic variations will significantly affect components of the water budget and the lake levels. The pit lake water budget calculations were conducted based on long term meteorological data, assuming that the past 38 years represents the next 800 years relatively well. However, based on past climatic trends (Durdu 2013; Tayanç et al. 2009) and future predictions (National Climate Change Action Plan 2011), an increasing trend in temperature and a more arid climate with less precipitation is predicted, both of which will definitely affect the pit lake water budget. Considering the combined effects of these changes, it is likely that the pit lake level will stabilize at a lower elevation than predicted in this study; consequently, a terminal pit lake will form, which will not affect the downgradient groundwater system.

Finally, it should be noted that the results presented in this paper were obtained by coupling different modeling approaches, which are based on several assumptions and hence, have uncertainties. All the models used in this study should be revised as new data becomes available during operations.

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