ASSESSMENT OF OPEN PIT DEWATERING REQUIREMENTS AND PIT LAKE FORMATION FOR KIŞLADAĞ GOLD MINE, UŞAK-TURKEY

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ASSESSMENT OF OPEN PIT DEWATERING REQUIREMENTS AND PIT LAKE FORMATION FOR KIŞLADAĞ GOLD MINE, UŞAK-TURKEY

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ABSTRACT

ASSESSMENT OF OPEN PIT DEWATERING REQUIREMENTS AND PIT LAKE FORMATION FOR KIŞLADAĞ GOLD MINE, UŞAK-TURKEY

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The main purposes of this research are (1) to quantify the dewatering requirements for Kışladağ gold mine (Uşak–Turkey) in order to provide stable and dry conditions for mining during the operational period, (2) to assess the pit lake formation in post-closure period, and (3) to assess the impacts of these effects on groundwater resources. Following the development of the site conceptual model, a numerical groundwater flow model is set up and calibrated under steady state conditions and sensitivity analyses are conducted. The calibrated model is used as a tool for the determination of groundwater flow rates into the pit, applying two different simulation approaches: steady state and transient. The results show that steady state simulated pit-inflow rate was almost half of the maximum rates calculated by the transient simulations. The average pit-inflow rates however are very close to each other indicating the reliability of the model results. Following the cessation of dewatering activities during the post-closure period, a pit lake is expected to form. Pit lake water balance calculations are conducted to predict the lake levels with time until the equilibrium conditions are reached. The results show that pit lake levels stabilize at 816 m, 585 years after dewatering ceases. The results also show that 829 m is a critical level, below which pit will behave as a sink and for the higher levels, it will be a flowthrough system which may adversely affect the quality of downstream groundwater resources.

Keywords: groundwater, dewatering, pit lake, numerical modeling, Kışladağ

ÖZ

KIŞLADAĞ ALTIN MADENİ AÇIK OCAK SUSUZLAŞTIRILMASI VE OCAK GÖLÜ OLUŞUMUNUN DEĞERLENDİRİLMESİ, UŞAK-TÜRKİYE

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Bu araştırmanın temel amaçları (1) Kışladağ Altın Madeni (Uşak – Türkiye) açık ocağında işletme dönemi boyunca, madencilik açısından güvenli ve kuru kazı şartlarının sağlanabilmesi için gerekli olan susuzlaştırma miktarının belirlenmesi, (2) kapama döneminde ocak gölü oluşumunun değerlendirilmesi ve (3) bütün bu süreçlerin yeraltısuyu sisteminde yaratacağı etkilerin ortaya koyulmasıdır. Sahayı temsil eden kavramsal modelin oluşturulmasının ardından, sayısal bir yeraltısuyu akım modeli kurulmuş ve kararlı akım koşulları altında kalibre edilerek, duyarlılık analizleri yapılmıştır. Kalibre edilen model aracılığıyla, iki farklı yaklaşım uygulanarak (kararlı ve kararsız akım koşulları), açık ocağa gelecek yeraltısuyu miktarı belirlenmiştir. Sonuç olarak, kararlı akım koşulları altında hesaplanan yeraltısuyu akım miktarının, kararsız akım koşullarında hesaplanan maksimum yeraltısuyu akım miktarının neredeyse yarısına eşit olduğu görülmüştür. Ancak, kararsız akım koşulları altında hesaplanan ortalama miktarın, kararlı akım koşulları altında hesaplanan akım miktarına oldukça yakın olması model sonuçlarının güvenilirliğini ortaya koymaktadır. Kapama döneminde ise, susuzlaştırma faaliyetlerinin son bulması ile birlikte açık ocakta bir ocak gölü oluşumu beklenmektedir. Ocak gölü su bütçesi oluşturularak, sistem denge şartlarına ulaşıncaya kadar geçen sürede, göl su seviyelerindeki zamansal değişim belirlenmiştir. Sonuçlar, ocak gölünün susuzlaştırma faaliyetlerinin sona ermesinden 585 yıl sonra 816 m seviyesinde dengeye ulaşacağını göstermektedir. Bunun yanı sıra, yapılan simülasyonların sonucunda, 829 m'nin kritik bir seviye olduğu, bu seviyenin altında alıcı bir ortam oluşturan ocak gölünün, daha yüksek seviyelerde akışı ileten bir ortam gibi davranacağı ve dolayısıyla akış aşağısındaki yeraltısuyu sistemini olumsuz yönde etkileyebileceği ortaya konulmuştur.

Anahtar Kelimeler: yeraltısuyu, susuzlaştırma, ocak gölü, sayısal modelleme, Kışladağ

TO MY BELOVED FAMILY

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My final words are for Uygar Duru, knowing that neither a couple of words, nor the longest sentences are enough to express the love, the joy, the peace, the trust, the bliss you brought to my life… I thank you by heart for every single moment of being yourself and being by my side. I know we owe each other nothing in return, but the next 45 years...

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CHAPTER 1

INTRODUCTION

One of the most significant environmental issues of bulk mining is the impact on groundwater resources. Bulk mining, by means of which low grade ore is extracted, generally requires deep excavations that shall be completed under the static groundwater level. In order to provide safe and stable conditions for mining during the operational period, it is required to dewater the excavation area and attain relatively dry operating conditions. Once dewatering ceases after the closure of such operations, groundwater and surface water flows into the pit together with the rainfall, contribute to the formation of a pit lake. Depending on the components of the pit lake water budget, it may take many years until an equilibrium state is reached and water level of the lake is stabilized. Determination of this equilibrium conditions is very crucial in the sense they reflect the interactions of the pit lake and surrounding groundwater system. Therefore, this permanent modification on the groundwater system has to be investigated in detail.

This study presents the dewatering scheme of Kışladağ Gold Mine during its 17 years of operation phase, pit lake formation process in the post-closure period and finally characteristics of the ultimate pit lake.

1.1 Purpose and Scope

The purpose of this study is to;

- Quantify the dewatering requirements by predicting the discharge rates (groundwater inflow to pit) during the operational period as the excavation advances to final operational depth;
- Assess the impact of dewatering operations on the surrounding groundwater system,
- Predict the future pit lake level after closure and filling period for long term daily meteorological conditions and
- Characterize the hydraulic relation between the ultimate pit lake and surrounding groundwater system.

In order to meet the purposes given above, a numerical three dimensional groundwater model is constructed and used as a tool to simulate the operational and the post-closure groundwater system. The modeling process, simulating the operational phase of the mine, is completed within three stages. Initially a conceptual groundwater model is constructed with the data provided by TÜPRAG and the data collected from the site. Then a numerical groundwater flow model is constructed in accordance with the conceptual model and calibrated to site conditions (with the observed groundwater levels). Finally, dewatering simulations are completed using the calibrated model and applying two different approaches: steady state and transient. The aim of these simulations is to quantify the groundwater inflows to pit as a consequence of dewatering actions throughout the operational period and to predict the potential impact on the groundwater resources in the close vicinity of the area. As the mining operations will be finalized in 2030, the dewatering program will be ceased. Thus, a lake is expected to form in Kışladağ open pit during the post-closure period. At this point a spreadsheet model is integrated with the numerical groundwater flow model, which is used to determine the groundwater inflow rates to the pit. Pit lake water balance calculations are conducted to simulate the lake levels with time until the equilibrium conditions are reached and to predict the steady pit lake level. The pit lake water balance calculations are completed for a 800-year period with the spreadsheet model with the daily evaporation and precipitation data set, prepared by the repetition of the long term daily meteorological data. Finally, the resulting steady pit lake level is introduced to the numerical groundwater model in order to predict the hydrologic status of the ultimate pit lake at its steady state conditions.

1.2 Location and Extent of the Study Area

Kışladağ Gold Mine is located in west-central Turkey between the major centers of İzmir, lying 180 km to the west on the Aegean coast, and the capital city Ankara, 350 km to the northeast. The Mine site is located 35 km southwest of the city of Uşak (population 170,000) near the village of Gümüşkol. The studies are conducted within a frame covering an area of around 440 km^2 (Figure 1.1).

The mine site is located on the water divide between the Gediz and Büyük Menderes River Basins. Open pit and present heap leach pad facility is located in the Gediz River basin and the present waste rock storage area is located in the Büyük Menderes River basin. All of the planned expansion facilities (proposed leach pad and waste rock storage areas) are within the Gediz River Basin. The elevations in the area range from approximately 1300 masl in the hilly areas to 600 masl at the base of the valleys which are draining these hills.

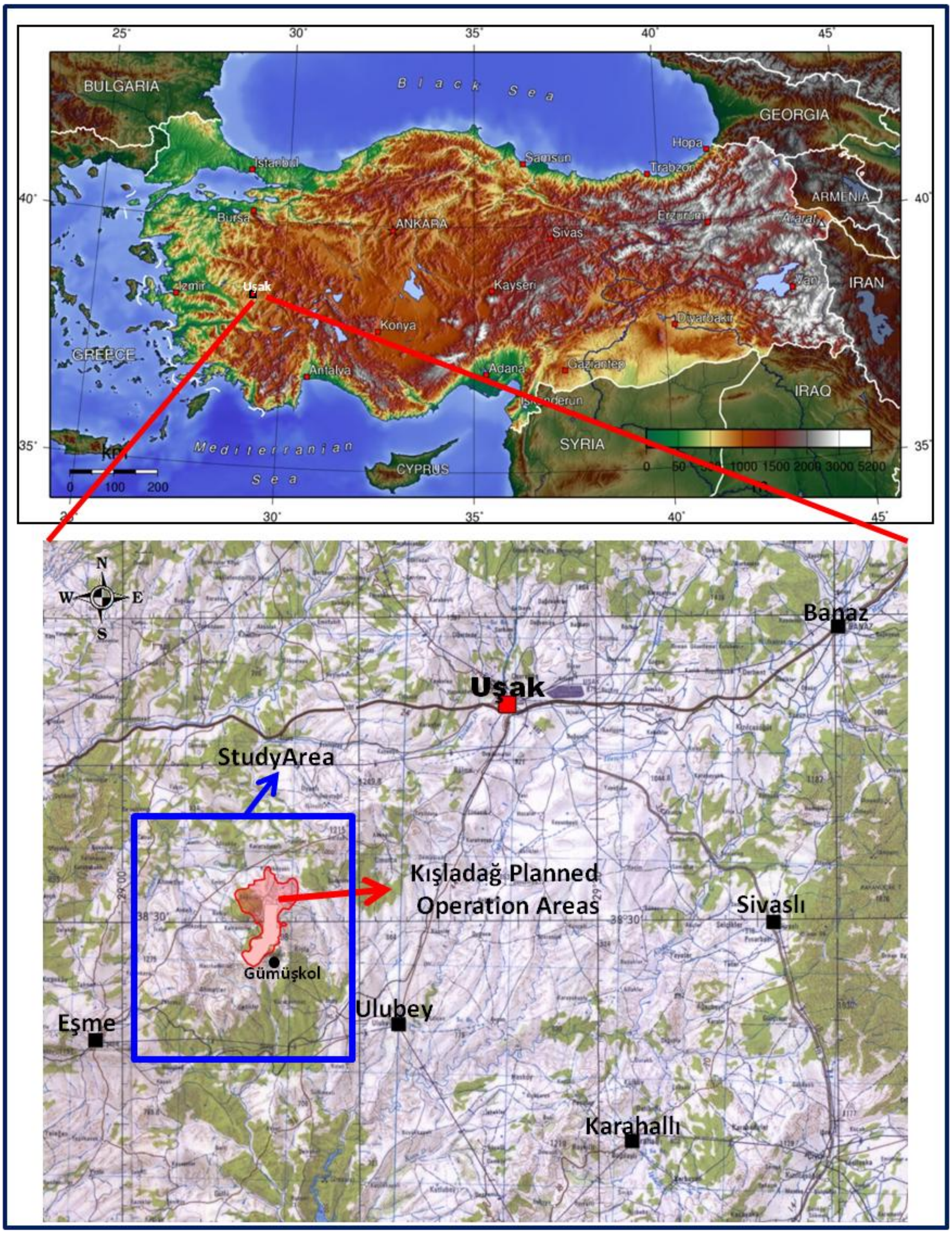

Figure 1.1. Location of the study area

1.3 Mining Activities at Kışladağ

Kışladağ open pit gold mine has been operating since 2006 with surface facilities consisting of heap leach pad, waste rock storage area, ADR plant, crushing plant and ancillary buildings Current fenced area of the mine is around 8.5 km^2. The mine operation is a standard drill and blast truck and shovel open pit operation. The mine operates 24 hours a day seven days a week.

The ore is processed in a standard heap leach facility containing a three stage crushing plant, conveyors, a stacker for placing the ore and also a carbon adsorption facility (ADR plant) for recovering the gold. The carbon is treated on site in a refinery and the final product is a gold doré bar. The heap leach pad is a permanent facility employing a two part liner system of a compacted layer of low permeability clay soil, with a 2 mm thick HPDE/LLDPE synthetic liner.

Kışladağ Gold Project received its EIA Positive certificate in 2003 (ENCON, 2003) and completed the construction of the mine in 2005. The initial plan of TÜPRAG was to produce 180 million tons of ore for a period of 17 years. Then within time, with the exploration of new resources and positive change in the gold mining economy, a capacity increase is planned to produce 600 million tons of ore (for the whole life of mine) by 2029. In addition to ore, over 1 billion tons of waste rock will be moved to waste rock storage areas.

The excavation will end up with a giant pit having almost 2000 m by 1600 m of crest dimensions and more than 700 m total depth from the original topography. The ultimate pit will cover 268ha area. Figure 1.2 shows the mine layout by the end of 2012, while final mine layout is given in Figure 1.3. Kışladağ open pit will be one of the greatest when it reaches to its ultimate geometry with the current design. In order to give an insight on how big the Kışladağ open pit will be, its dimensions can be compared to that of the greatest man-made excavation which is the Bingham Canyon Mine. Bingham Canyon Mine, also known as the Kennecott Copper Mine, is an open-pit mining operation extracting a large porphyry copper deposit southwest of Salt Lake City, Utah. The mine has been in production since 1906, and has resulted in the creation of a pit over 970 m deep, 4 km wide and covering 770 ha (http://en.wikipedia.org/wiki/Bingham_Canyon_Mine).

Figure 1.4 shows the cross-sections passing through the open pit in E-W and N-S directions. On these cross-sections present (by the end of 2012) and final (by the end of 2029) pit layouts are shown, together with the present groundwater table. The excavations at the open pit will continue under the static groundwater level after the pit bottom reaches the groundwater level which is around 870 m elevation (by the end of 2013). Thus, further operations in the pit will include a dewatering program until the end of production in 2029. After 2029 once the mining ceases, a pit lake is expected to form in the pit.

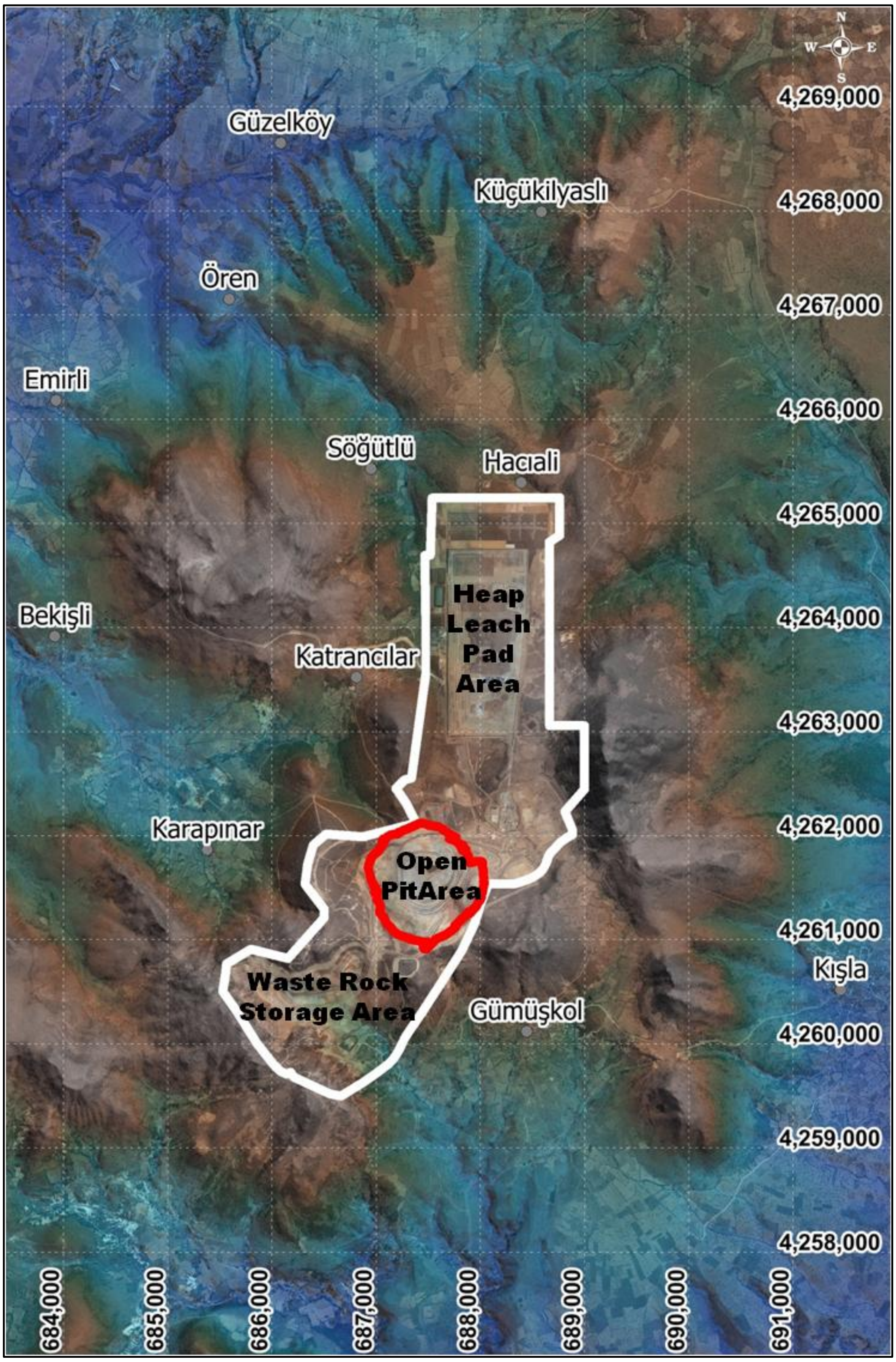

Figure 1.2. Mine site layout by the end of 2012

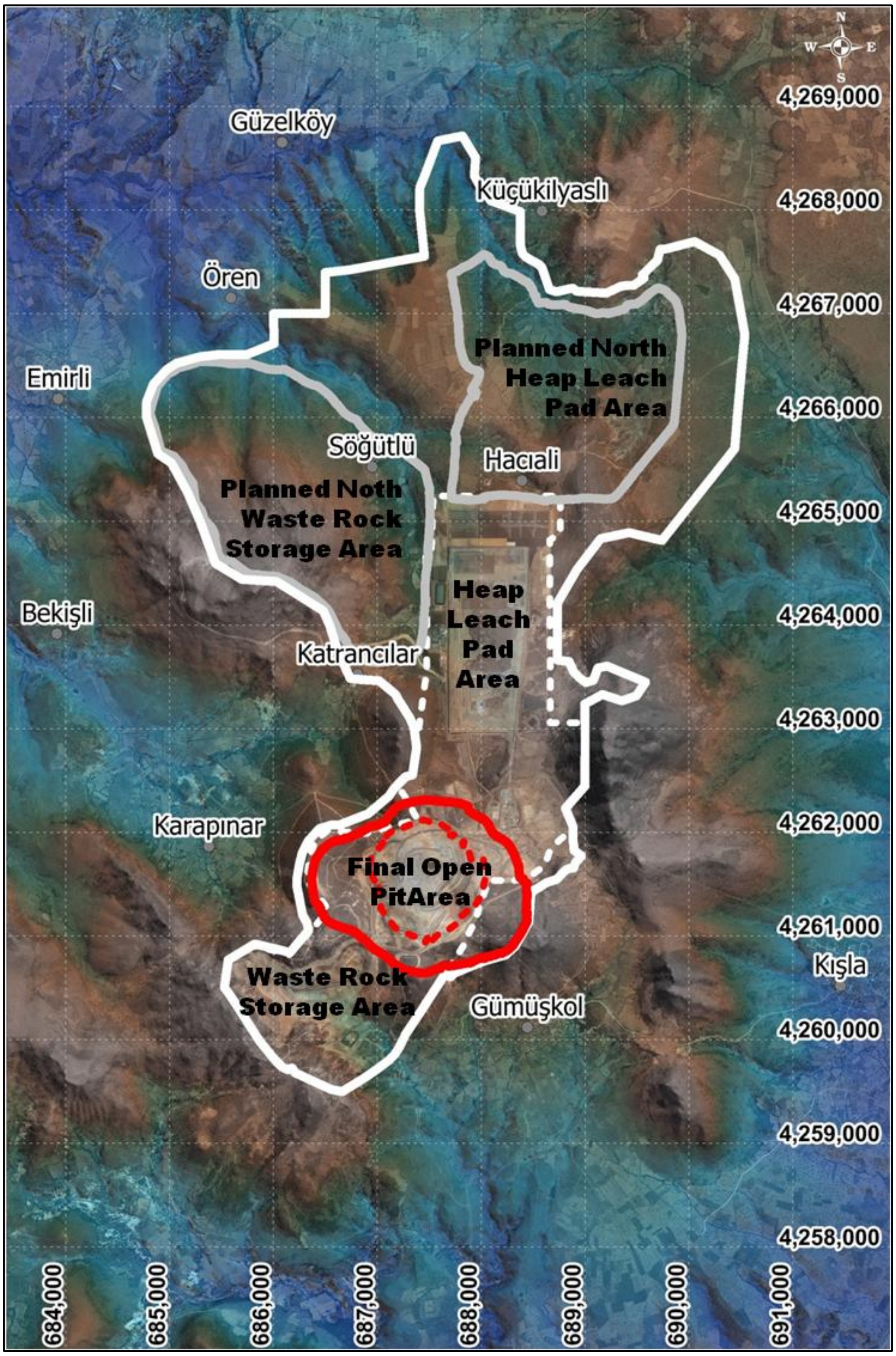

Figure 1.3. Planned mine site layout by the end of 2029

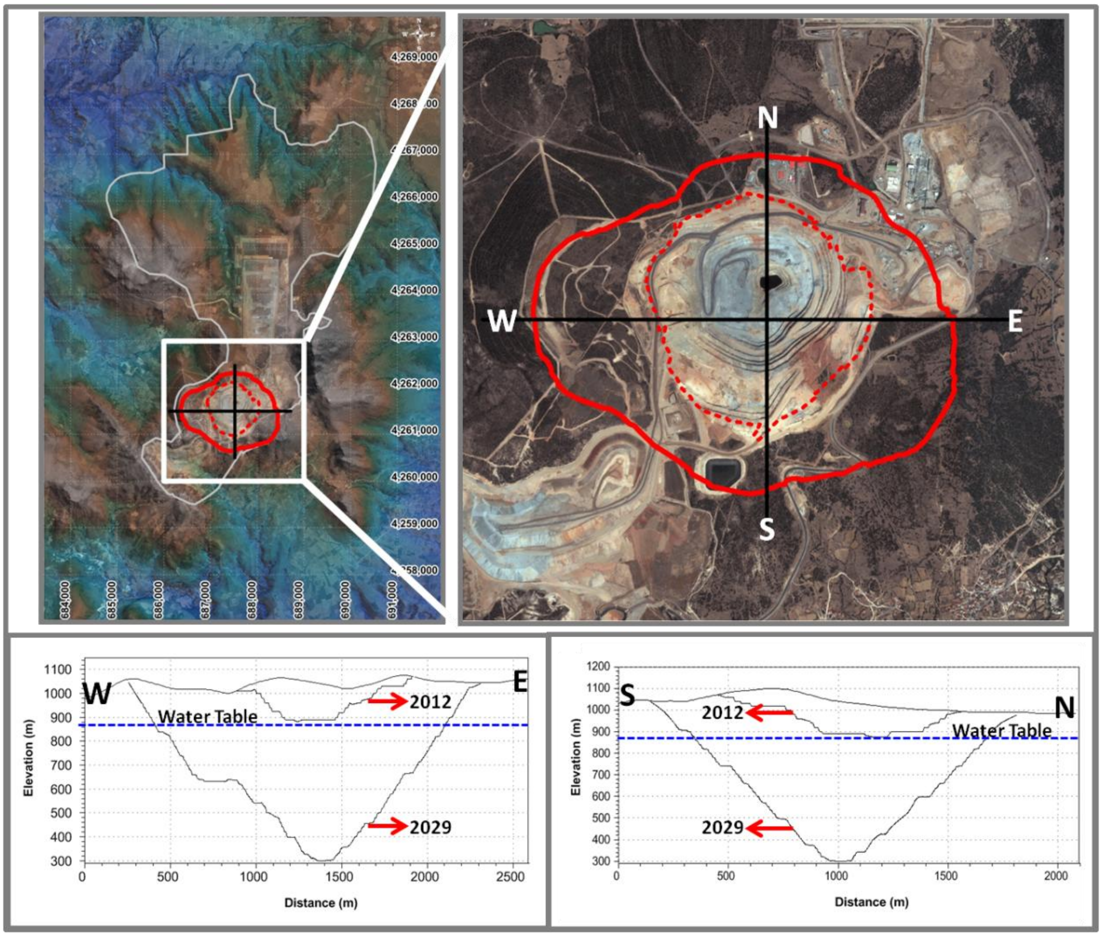

Figure 1.4. Cross-sections showing open pit layout in 2012 and 2029

1.4 Previous Studies

Many studies have been completed on the geology, hydrology, hydrogeology and water resources for the Kışladağ Gold Mine. Some of these studies have been completed for the mine site while others covered the region. These studies are summarized below.

1.4.1 Previous Studies on Geology

- General Directorate of Mineral Research and Exploration have completed 1/50,000 and 1/25,000 scaled geological maps for the area covering Uşak, Eşme, Ulubey, Banaz, Güre and Sivaslı.
- TÜPRAG's exploration group completed detailed geological studies in the close vicinity of the mine site. Other than TÜPRAG, many researchers (academics and

consultants) completed several studies, especially on the structural geology of the area. These studies are given below:

- A report on geological map and structural geology of Kışladağ Gold Mine (Lewis Geoscience Services Inc., 2002)
- Structural interpretation for 179/33 coded Landsat ETM+ satellite image (Murphy Geological Services, 2004)
- Structural Mapping of Kışladağ Gold Mine Open Pit (Kuşçu, 2008).
- Geology of Kışladağ-Sayacık Area (Hudson, 2009)
- Kışladağ Structural Geology (Herod ve Hodkiewicz, 2010)
- Geology of North of Kışladağ (ARC, 2011)

1.4.2 Previous Studies on Hydrology

- Detailed hydrologic studies have been completed for Kışladağ by Yazıcıgil et al. (2011) for the evaluation of the surface water potential. During this study, data on surface water discharge rates have been evaluated to obtain the run off coefficients.

1.4.3 Previous Studies on Hydrogeology

- Initial regional hydrogeological study was completed by State Hydraulic Works (DSI) for the water supply of the villages of Karahallı and Ulubey districts in 1955. Then in 1960, DSI completed a hydrogeological study on Uşak, Banaz and Sivaslı Plains and completed 13 investigation wells. A report on this study was published in 1976 by Koç et al.
- In 1979, DSI II. District completed the report “Hydrogeological Investigation Report on Water Resources of Uşak” (Aysan, 1979). Later in 1985, in an extensive region, covering Banaz Plain (Uşak-Banaz-Sivaslı-Ulubey-Karahallı Sub-plains), DSI II. District completed another hydrogeological investigation study. This study has been published in 1986 by Bilgisu and Çil. As a follow up study, DSI completed nine investigation wells between 1987 and 1990.
- After 1990, an additional drilling program was completed to the south and 6 more investigation wells were completed. Then these studies have been compiled by Kadıoğlu in 1993 and the report on hydrogeological investigation on Uşak-Banaz-Ulubey-Sivaslı and Karahallı Plains have been published.
- Most recent study was completed in 2006 by Vaytaş Sondaj İnşaat Turizm San. ve Tic. Ltd. Şti. on the drinking water resources of Uşak and “Hydrogeological Investigation on Uşak Centeral District-Susuzören Area” report was prepared.
- Ulubey aquifer is the most important aquifer in regional sense. Therefore, Yazıcıgil et al. (2008) completed a study for the characterization of Banaz Stream Basin and development of groundwater management plan for the Ulubey aquifer system in an area covering 3972 km^2. During this study, hydrogeological characterization of the Ulubey and Asartepe Formations have been completed and a numerical groundwater

model was utilized to develop and test groundwater management plans for the future water supply for irrigation cooperatives and the districts for the next 20 year period.

- Initial hydrogeological study in the vicinity of Kışladağ Gold Mine was completed by Yazıcıgil et al. (2000) for the water supply alternatives of the proposed gold mine. Following Yazıcıgil et al. (2000), SRK Consulting completed a series of studies for Kışladağ Gold Mine. These studies can be summarized as;
  - Surface and Groundwater Monitoring Plan for Kışladağ Gold Mine (SRK, 2002)
  - Groundwater Sampling and Analyses Report (SRK, 2003)
  - Water Supply Studies – Aquifer Test (SRK, 2003)
  - Groundwater Exploration Studies (SRK, 2005)
  - Conceptual Model Studies for Kışladağ Gold Mine (SRK, 2005)
  - Potential Impact of Waste Rock Dump on Groundwater Resources (SRK, 2007)
  - Pit Lake Formation and Potential Impact on Groundwater Resources (SRK, 2007)
  - Kışladağ Open Pit Dewatering / Depressurizing Study (SRK, 2012)
  - Evaluation of Dewatering Performance with Vertical Wells (SRK, 2013)

Among all, a recent study that compiled and analyzed all the previous data, as well as new site characterization for the planned expansion activities, was completed by Yazıcıgil et al. (2013). Within the scope of this study a very detailed "Hydrogeological Survey Report for Kışladağ Gold Mine Site" was accomplished.

Another recent study, which is in fact a continuation of the one conducted by Yazıcıgil et al. (2013), was completed by Yazıcıgil and Ünsal (2013). This final project titled "Assessment of Dewatering of Open Pit, Pit Lake Formation and Potential Impacts on Groundwater at Kışladağ Gold Mine", focused on the open pit. It should be noted that the study conducted by Yazıcıgil and Ünsal (2013) formed the basis of the thesis.

CHAPTER 2

LITERATURE SURVEY

2.1 Literature Survey on Theory of the Pit Lake Formation

Pit lakes occur at the end of open pit mining activities that are conducted below the pre-mining groundwater levels. In such situations, where dewatering is performed during the mining activities; water table tends to recover to its original position, as soon as the dewatering operations ceases. 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 water after closure, and also influences the final steady state water budget of the lake that is formed (Gammons et al., 2009).

Time for a pit lake to reach steady state and hydrologic status of the pit lake and surrounding groundwater regime at the steady state depend on many physical processes controlling pit lake hydrodynamics. These include the shape, orientation of the lake, and climatic conditions at the site (Miller et al., 1996; Huber et al., 2008). Under natural filling conditions, large open pit lakes can take a very long time (decades to centuries) to fill with water. This is particularly true in arid or semi-arid areas where precipitation and surface water inflow components are minimal. The rate of groundwater input varies quite a bit from mine to mine, and depends on the site geology, topography, and climate. A rough estimate of groundwater inflow can be obtained by noting the amount of water that was pumped during active mining operations, at least during the early stages of flooding. However, this rate will change as the pit fills with water, depending on the cross-sectional area of the flooded portion of the lake, and hydraulic gradient, in the zone of groundwater capture surrounding the lake. As the pit floods and the surface of the lake rises, the hydraulic gradient will decrease. However, this effect is offset by the fact that the value of cross-sectional area increases with time as the volume of the lake increases. The net result of these offsetting factors is that the filling rate of a pit lake may actually increase with time during the initial period of flooding, but will eventually level off and then slowly decrease to zero as the lake surface approaches its final equilibrium elevation. Once a pit lake has filled to its ultimate surface elevation, input and output components of the lake water budget will be equalized and lake level is stabilized except seasonal changes (Gammons et al., 2009).

There are two types of systems can form when the system reaches steady state: flowthrough conditions and terminal conditions. These final states of the system, and also the transitions in between are defined by Niccoli (2009) as follows:

i. **Flowthrough conditions:** surface and/or groundwater flows into and out of this type of lake (Figure 2.1). This type of pit lakes is common in humid areas. They may also form where the bottom of the pit is above the water table and is filled by surface water. In such cases, outflows consist of vertical leakage and evaporation as shown in Figure 2.2.
ii. **Terminal conditions:** groundwater flows into the pit and outflow occurs only as evaporation as shown on Figure 2.3. This type of pit lakes is common in arid areas.
iii. Moreover, with seasonal or long term climatic changes, the hydrologic status of a pit lake may fluctuate between terminal and flowthrough.

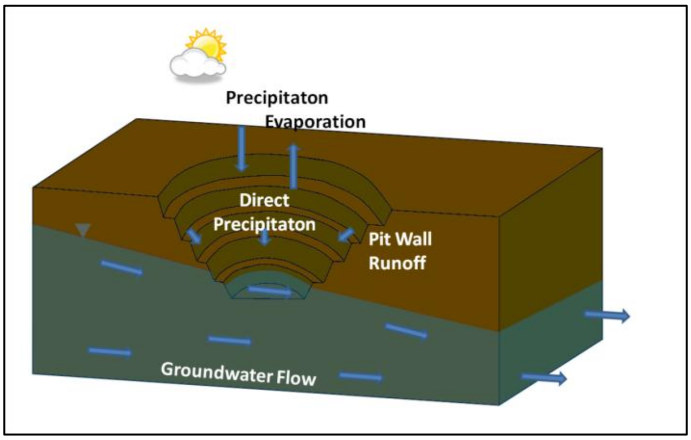

Figure 2.1. Flowthrough pit lake below the groundwater table (modified after Niccoli, 2009)

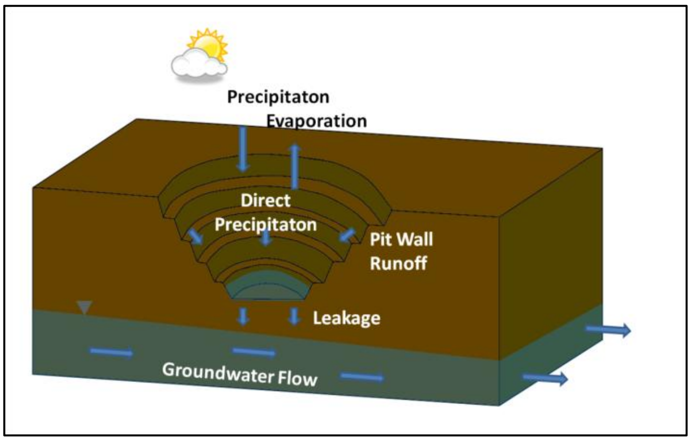

Figure 2.2. Flowthrough pit lake above the groundwater table (modified after Niccoli, 2009)

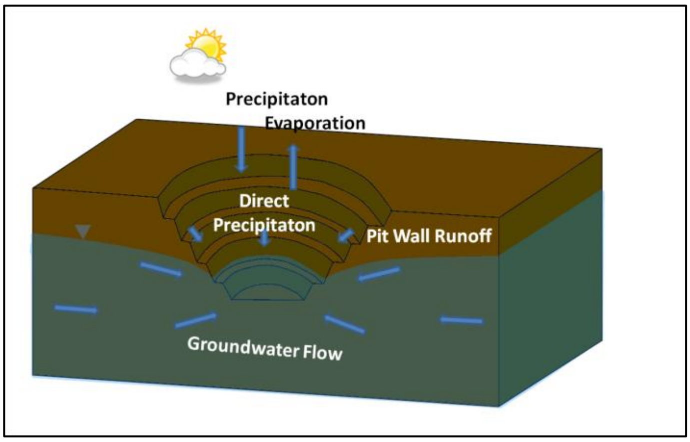

Figure 2.3. Terminal pit lake (modified after Niccoli, 2009)

Müller et al. (2010) states that pit lakes are both potential water resources and potential environmental risks and, as such, raise significant environmental issues for the mining industry. Increased social expectation, such as legislation and regulation and desired end uses by local communities, are increasingly requiring higher standards of environmental assessment and management for pit lakes (Müller et al., 2010). Therefore, determination of the final characteristics of a pit lake is very crucial in terms of environmental and social concerns. For this purpose, for every pit lake a water budget has to be set up and time-wise changes in each component of the lake water budget has to be determined until a steady state equilibrium is reached. Moreover, the level at which the lake will stabilize at steady state conditions is also very important. As stated by Braun (2002), depending on the magnitude of net evaporation, the steady state pit lake elevation can be lower than the surrounding groundwater aquifer, resulting in passive hydraulic containment. Under this scenario, the lake acts as a solute sink and the only outflow is by evaporation. Alternatively, groundwater outflow occurs, passive containment is lost, and the pit lake water can interact with groundwater down gradient of the pit.

Hence, it is critical to have a good idea of how fast the pit lake will fill; if the pit lake is part of the final plan for a closed mine states Naugle and Atkinson (1993). There are many modeling approaches for the solution of this problem, with differing levels of complexity (Gammons et al., 2009). Below is a summary of the models that could be applied for the solution of such problems, together with the fundamentals of the modeling theory.

2.2 Literature Survey on the Use of Groundwater Models

2.2.1 Description of the Model

Models are the tools that are used to comprehend the mechanisms of the real world systems and to predict the responses of these systems under different pressures. In order to represent a real world system using a model, proper simplifications and assumptions should be made. A groundwater model, in this sense, is any computational method that represents an approximation of an underground water system (Anderson and Woessner 1992).

There are basically three types of groundwater models: physical, analog and mathematical models. A physical model is the replication of the real world systems in a different scale, for instance sand tank models are miniature aquifer systems demonstrating flow and transport mechanisms as shown in Figure 2.4. An analog model is based on the similar characteristics and processes of different systems, even if they are physically irrelevant; for example flow of water can be associated with electrical current, where flow rate, hydraulic gradient, hydraulic conductivity are represented by electrical current, potential difference and resistance, respectively. A mathematical model differs from other models in its attempt to simulate the actual behavior of a system through the solution of mathematical equations (Schwartz et al., 1990). Two different approaches are used to solve the governing equations that represent groundwater flow and transport processes in mathematical models.

Figure 2.4. Sand tank model (www.envisionenviroed.net)

These equations can either be solved by analytical methods, which provide exact solutions to equations that describe very simple conditions, or by numerical methods, which utilize approximations of equations (finite differences, or finite elements) that describe very complex conditions (Mandle, 2002). An analytical model makes simplifying assumptions to enable solution, such that properties of the aquifer are considered to be constant in space and time. On the contrary, a numerical model uses space and/or time discretization so that features of the governing equations and boundary conditions can be specified as varying over space and time. This enables more complex, and potentially more realistic, representation of a groundwater system than could be achieved with an analytical model (Barnett et al, 2012).

Both groundwater flow and transport mechanisms can be modeled numerically. Groundwater flow models are capable of simulating the hydraulic head distribution and groundwater flow rates within and across the boundaries, as well as providing estimates of water balance of the systems under consideration. On the other hand, solute transport models, which are based on the groundwater flow models are used to simulate the concentration distribution for the substances dissolved in groundwater.

While groundwater models are, by definition, a simplification of a more complex reality, they have proven to be useful tools over several decades for addressing a range of groundwater problems and supporting the decision-making process (Barnett et al, 2012). Mandle (2002) lists, widely used applications of groundwater flow and transport models, as follows:

- Evaluation of regional groundwater resources
- Prediction of the effect of future groundwater withdrawals on groundwater levels
- Prediction of the possible fate and migration of contaminants for risk evaluation
- Tracking the possible migration pathway of groundwater contamination
- Evaluation of design of hydraulic containment and pump-and-treat systems
- Design of groundwater monitoring networks
- Wellhead protection area delineation

2.2.2 Use of Models in Mining Applications

Besides the above mentioned applications, groundwater models are widely and efficiently utilized in the solution of groundwater related problems associated with mining industry. Groundwater is a major issue that has to be taken into account during all the stages of mining, form the operation to the closure phases. Rapantova, et. al (2007) groups applications of the groundwater models for mining operations according to the development stage of the mine, namely active or closed. For the active mines, groundwater models can be used as tools in development of dewatering strategies and determination of discharge water quality/quantity. At closed mines, numerical modeling can be used to predict the future responses of the system under the pressures exerted by the changes in both the groundwater flow pattern and the natural drainage base due to geomorphologic changes (Rapantova, et. al, 2007). For modeling at mine sites, among a variety of hydrologic and geochemical codes, the most commonly used numerical groundwater flow code is MODFLOW (Harbaugh et al., 2000), while the most widely used code for modeling water quality (including geochemical speciation and reaction path) is PHREEQC (Parkhurst, 1995).

2.2.3 Use of Models for Simulating Dewatering Operations and Pit Lake Formation

Models are widely used to quantify the dewatering requirements, to design dewatering systems and to test the effectiveness of such systems. Moreover, many research have been conducted so far in order to determine the pit lake filling process and the steady state characteristics of the final pit lake by means of models.

Several analytical and numerical methods are applied depending on the size and site-specific conditions of the problem. For instance, if the pit lake is planned to be filled rapidly by diverted surface water or rapidly pumped groundwater; then the dominant component of the lake budget is quantitatively very well known and the contribution of natural groundwater inflow rate is negligible. In such cases, a simple spreadsheet model could suffice. It is also possible to estimate the initial rate of groundwater flow into an open pit using relatively simple analytical equations. For more sophisticated modeling, especially for long-range predictions or in cases where the lake is expected to fill slowly, a 3-D numerical groundwater flow model will be needed to predict the rate of groundwater seepage into or out of a pit lake (Gammons et al., 2009). As also stated by Marinelli and Niccoli (2000), 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 substantial summary on the applicability of numerical and analytical methods: Numerical modeling is commonly used to estimate the time of recovery and groundwater inflows, which by necessity requires extensive hydraulic data, time, and resources that are usually unavailable at the preliminary stages of mine planning. As an alternative, analytical methods, which are easily applicable and reliable, can be used as tools to provide preliminary estimates for mine feasibility studies and to determine potential environmental impacts.

2.2.4 Types of Models Used to Simulate Dewatering Operations and Pit Lake Formation

Analytical Models:

Many analytical models can be found in the literature for prediction of groundwater flow into the mine excavations. These models often are developed based on some very specific assumptions and boundary conditions that restrict their applicability in many mining situations. Among those analytical models, most widely known model used to calculate groundwater inflow rate to a mine pit, is that suggested by Marinelli and Niccoli (2000). As this model is also based on several simplifying assumptions, the applicability of the solution to a real mine site is directly related to the consistency of these assumptions with the actual site conditions. However, Marinelli and Niccoli (2000) states that the solution is capable of representing the hydrogeological conditions that may be encountered at many mine sites. Applicability of the solution is proven by a case study where this analytical model is applied to an actual pit lake existing at a non-operating gold mine in Nevada. The groundwater flow rate into the pit that is calculated by the analytical method is compared to that calculated by a detailed pit lake water balance considering all components (such as groundwater inflows, piped inflows from other areas of the mine site, direct precipitation onto the pit lake, surface water inflows, evaporation and changes in pit lake storage volume). Finally, it is stated that both methods result in similar groundwater flow rates. Marinelli and Niccoli (2000) mentioned that this method assumes steady state flow conditions, which is reasonable for moderate to high permeability materials and mine pits that are excavated over a period of years.

Fontaine et al. (2003) also states that the solution recommended by Marinelli and Niccoli (2000) cannot be used to estimate transient inflows during pit lake recovery, and/or require that the final pit lake elevation be known a priori. In contrast, the Jacob-Lohman equation (Jacob and Lohman, 1952) can be used to estimate the time required to fill the pit lake and estimate transient inflow rates without a priori knowledge of the final pit lake level. It is a well-accepted, easily-evaluated equation that provides reliable estimates of inflow into a large diameter void based on the head difference between static ground water levels and the water level in the void space. It should be noted that the Jacob-Lohman equation is based on the assumption that the aquifer is homogeneous, isotropic, and laterally extensive, that transmissivity and storativity are constant, and that inflow enters the pit horizontally. These are reasonable assumptions for many open-pit mines because vertical conductivity is typically much lower than horizontal. Moreover, Hanna et al. (1994) demonstrated that the Jacob-Lohman equation could be used for estimates of groundwater inflow for pit dewatering, and modified the equation to account for partial penetration of the pit and for possible effects of vertical flow (Fontaine et al., 2003).
A recent analytical model is the CRYPTIC (Comprehensive Realistic Yearly Pit Transient Infilling Code) suggested by Fontaine et al. (2003). This model is based on the Jacob-Lohman equation; however, it is modified to include the pit geometry and effects of precipitation and evaporation from the pit lake surface, as well as the input/output of external flows. It assumes that the aquifer is homogeneous and isotropic with laterally extensive horizontal flow but differs from other methods in that it includes transient inflows.

- CRYPTIC was used to successfully model the Berkeley Pit Lake (Butte, Montana) recovery data, which is one of the best documented pit lakes (post-recovery) in the world. Underground mining began in the area during 1870's, and groundwater encountered at depths of 6-122 m by the earliest shafts. In 1955, development of the Berkeley Pit, was initiated. The water levels in the area were drawn down to about 600 m below the bottom of the Berkeley Pit, as underground mining was performed in conjunction with open pit mining. The pumps were turned off in 1982 and a pit lake was allowed to form. Recovery curve calculated by CRYPTIC model is compared with the lake stages measured during the 15 years period between 1982 and 1997; and it is observed an excellent agreement is attained with 0.3% of error.

- Moreover, the predictions made by CRYPTIC are also compared favorably with results from the Pipeline Pit (north-central Nevada) numerical model. Numerical model developed for Pipeline pit is selected because of its good calibration and excellent post-model agreement with measured dewatering rates over a 53 month period between April 1996 and August 2000. The mine plan requires dewatering to continue for another nine years, at which point the pumps will be turned off and a pit lake will be allowed to form. It is a useful case study because the model structure has undergone numerous reviews and is well validated with over four years of data and also, it is well documented that 97% of the flow to the pit during filling inflows horizontally compared to only 3% vertically (Geomega, 1999), hence meeting the lateral flow condition of the analytical solution. The numerical model also includes a number of faults that act as partial barriers to flow; these were simulated using the horizontal-flow barrier (HFB) package for MODFLOW. Pit lake filling was simulated using the LAK2 package (Council, 1997) and MODFLOW-SURFACT (HydroGeologic 1999). CRYPTIC is observed to be in excellent agreement with the numerical model in estimating the correct pit level and transient inflow rates (Fontaine et al., 2003).

However, as stated by Fontaine et al. (2003), while this analytical approach provides useful hydraulic insights at the feasibility stage of mine planning, more detailed analysis is required to determine critical mine permitting requirements. For example, the lateral extent of the drawdown cone, time to maximum extent of dewatering, and temporal effects on springs and seeps require deployment of a full numerical code and substantially more data (Fontaine et al., 2003).

Numerical Models:

Bair and O'Donnell (1983), criticize the application of the analytical models in designing the dewatering systems, stating that these analytical models are based on restrictive assumptions which may result in oversimplification of the groundwater flow system, excavation geometry and construction sequence and necessitate the use of large safety factors, resulting in overdesigned dewatering systems. Numerical models, on the other hand, are not restricted by many of the assumptions required by analytical models, and therefore, can provide more accurate solutions to problems involving complex geologic and hydrologic conditions. As stated by Bair and O'Donnell (1983), numerical models offer the capability to solve hydrogeological problems involving complex boundary conditions, heterogeneous and anisotropic aquifers, irregularly shaped aquifers, steady state and transient flow conditions, leakage from confining beds, non uniform recharge and evapotranspiration, variable pumping rates, partially penetrating wells, infiltration, confined-unconfined transitions and other hydrologic phenomena. Therefore, numerical models can be used to aid in the design of dewatering and depressurization systems (Bair and O'Donnell, 1983).

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. As it is mentioned above, MODFLOW (Harbaugh et al., 2000) is the most commonly used numerical groundwater flow code used to simulate mine sites. MODFLOW requires a large amount of site-specific information including climate, topography, sources of groundwater recharge and discharge, and information on the hydrogeologic properties of geologic units in the sub-surface, including both the vadose zone and zone of saturation. Below is a short list of the widely used versions used in mining applications, together with the included package and/or coupled model.

Application of MODFLOW-96 Model for Simulating Canisteo Mine Pit:

Jones (2002) reports a study conducted by the U.S. Geological Survey, in cooperation with the Minnesota Department of Natural Resources, to characterize groundwater flow conditions between the Canisteo Mine Pit and surrounding aquifers in Minnesota. Since mine abandonment in 1985, water level in the pit has been continuously rising. The lake level reached to 397 m elevation, while the lowest pit wall altitude is 404 m. Therefore, concern exists that as the lake level continues to rise, mine water may eventually discharge from the pit over land surface, resulting in undesirable downgradient erosion and localized flooding. Hence, the objective of the study was to estimate the amount of steady-state, ground-water flow between the mine and surrounding aquifers at pit water-level altitudes below the level at which surface-water discharge from the pit may occur. Groundwater flow rates into and out of the pit were estimated using a calibrated steady state groundwater flow model developed using MODFLOW-96 code (Harbaugh and McDonald, 1996). A series of steady state simulations at constant pit lake level altitudes between 396 and 404 m was completed to assess the effect of current and potential future pit lake levels on groundwater inflow and outflow from the pit. It is noted that when the pit lake level is at 396 m, the model calculated the groundwater inflow to the pit as 39.6 L/s, while groundwater discharge to local aquifers as 1.7 L/s. On the other hand, when the pit lake level rises to 404 m, groundwater inflow to the pit decreases to 28.3 L/s and groundwater discharge to local aquifers increases to 25.8 L/s. This study is important in the sense that it presents the changing behavior of the pit lake from terminal (where the groundwater outflow is almost negligible) to flowthrough while the lake level rises by 8 m. Although, the change in the lake level does not seem too much (8 m), changing behavior of the pit lake is very critical in terms of environmental concerns as it has potential to affect the downgradient groundwater system.

Application of MODFLOW Model and Manual Pit Lake Water Budget Calculations for Simulating Sleeper Mine:

An important example of numerical modeling applications in mine dewatering and pit lake formation is documented by Dowling et al. (2004), which is applied at the Sleeper open pit gold mine in Nevada, USA that was operated from mid-1980s to the mid-1990s. Mining operations were mostly conducted below groundwater level. The final open pit was approximately 1675 m in length, 760 m in width, and had a maximum depth of about 177 m below the original ground surface. Groundwater was originally 4.5-9.0 m below the surface and at the end of the dewatering activities; it was lowered by about 180m. Major dewatering operations commenced in 1986 and peaked at a flow rate of approximately 930 L/s in 1993. At the time, this represented one of the largest mine dewatering operations worldwide. Predictive assessments of water level recovery in the pit and dewatered groundwater system were made using the MODFLOW code and manual water budget estimations. Evaluations were made of natural recovery and alternative rapid filling scenarios. Because of the environmental concerns, rapid filling option is applied during the post-closure period and it is observed that actual filling time closely matched the predictions made by coupling numerical groundwater flow model and manual pit lake water budget calculations (Dowling et al., 2004).

Application of MODGLUE and MODFLOW Models for Simulating Collie Basin:

In a recent study, by Müller et al. (2010) numerical modeling is applied to simulate pit lakes that have formed within the Collie Basin, which is a small sedimentary basin in the south-west of Western Australia. There are an estimated 1,330 Mt of coal resource in the basin of which extractable reserves account for 480 Mt (Varma, 2002). Underground and open cut coal mining has taken place in the Collie basin since 1898. There are more than 15 mine lakes in Collie, with surface area between 1–10 ha, depth between 10–70 m and age between 1–50 years. The numerical modeling software used in this project aims to reflect the physical, chemical, and biological processes of these pit lakes. In order to model this pit lake system, modeling knowledge from different scientific domains such as groundwater, lake circulation, hydrochemistry, and limnology needs to be combined. The pit lake system is simulated by MODGLUE (MODel for Prediction of Groundwater and Erosion influenced Lake Water Quality Using Existing Models) model (Müller, 2004), which is capable of coupling three models;

- PCGEOFIM (Sames et al. 2005, Müller et al. 2003) is a finite volume groundwater flow and transport model that is specifically designed for mining and post-mining areas. It allows the subsurface parameters to be specified as time-dependent, allowing for modeling the excavation of mine pits, filling with overburden and creation of lakes all in one model run. While working with a regular grid, multiple nested grid refinements that may overlap can be used to get higher resolution in areas of special interest. Groundwater recharge may be specified as constant in time or depending on groundwater level below surface. This model provides a simple but very useful mechanism to account for the interactions between lakes and groundwater. The lake is represented as a water level-volume relationship. Inflows and outflows (such as groundwater and rivers) are budgeted. Precipitation and evaporation yield a new lake water volume and hence a new water level. This water level is used as head for Cauchy boundary conditions that act jointly as "the lake" (Blankenburg et al., 2012).

- CE-QUAL-W2 (Cole and Buchak, 1995) is a 2-D finite difference lake circulation water quality and hydrodynamic model.
- PHREEQC (Parkhurst, 1995) is the most commonly used geochemical speciation and reaction path code (Maest et al., 2005), designed to perform a wide variety of aqueous geochemical calculations.

MODGLUE has been successfully applied to several lakes in Germany for prediction of water quality and evaluation of effects of lake treatments. It can work without feedback to a groundwater model taking only specified inflows and outflows as input data. Therefore, MODGLUE can work with results input from other groundwater models using this off-line approach. Furthermore, the online coupling with PCGEOFIM is designed as a loose coupling: only spatially distributed inflow and outflow fluxes are exchanged at every time step. These fluxes can be provided by a different groundwater model than PCEGOFIM.

In this application, groundwater inflow rates are calculated by the MODFLOW models, where the lakes were modeled as constant head boundary conditions by specifying the lake stage. Furthermore, the development of lake water levels could be computed with MODGLUE and used for the groundwater model as input for the boundary conditions representing the lakes in MODFLOW model. In turn, the resulting groundwater inflows could be used by the lake models as data inputs. This feedback loop would allow for more accurate groundwater inflow calculations.

Another model, is the The Pit Lake Model (Müller 2004), which is created such that established models were engaged, coupled, and extended, rather than developing a totally new model. It is based on the coupling of the three codes mentioned above (CE-QUAL-W2, PHREEQC and PCGEOFIM) and also MODMST (Boy et al. 2001), which is a groundwater flow and transport model for density-driven flow. Therefore, it can be used as an alternative groundwater model instead of PCGEOFIM when density effects are of importance. This flexible model allows adaption to site-specific needs (Müller and Eulitz, 2010).

<u>Application of MODFLOW SURFACT Model and LAK2 Package for Simulating Rosemont Pit:</u>

Rosemont Copper Company (Rosemont) is planning the development of an open pit mine southeast of Tucson, Arizona. Operations will occur for approximately 22 years, during which the open pit will be incrementally expanded and dewatered.

Three numerical models were developed to simulate the different stages of the project: pre-mining, mining-phase, and post-closure. The pre-mining model was calibrated based on existing water-level measurements and stream flows under steady state conditions and it formed the basis for the subsequent transient flow models. Results of the calibrated pre-mining model were subsequently used as the start of the transient mining-phase model simulating the step-wise deepening of the open pit during the 22-year operational period. Dewatering of the open pit was simulated with drain cells, which removed water from the model when water levels reached a specified elevation below the bottom of the pit. Conditions simulated at the end of the mining-phase model were used as the input to the post-closure model, in which the LAK2 package (Council, 1999) is used to simulate the refilling of the pit following the end of dewatering. All three models used the finite-difference model code MODFLOW-SURFACT (HydroGeologic 1999).

MODFLOW SURFACT is a finite difference code applicable in mine dewatering projects. As stated by Ugorets (2012), this code goes beyond the standard MODFLOW code to simulate saturated/unsaturated conditions (multiple water tables), open pit excavation (using seepage face cells and collapsing model grid), and dewatering wells using the fractured well package. This model is widely used (1) to evaluate the most efficient dewatering option and to reduce residual passive inflow to the mine where active dewatering is required, (2) to define the optimal pumping rates and well spacings for the dewatering system (3) to reduce both pumping costs and hydrogeological risks to the project, optimising the mine plan, where hydrogeological conditions are complex (Ugorets, 2012).

Following is a brief summary of the planned mining process and simulation results obtained from the consecutive three stages of numerical modeling work: Dewatering of the proposed open pit will result in groundwater levels being lowered to approximately 920 m elevation, which is about 670 m below the pre-mining water level. The projected bottom of the pit is at 930 m elevation. Following the cessation of dewatering, the pit will naturally refill with water. The post-closure numerical groundwater flow model predicts the refilling process will take 700 to 1000 years to reach an equilibrium or steady-state condition. At this point, the equilibrium lake stage is predicted to be around 1300 m elevation. Due to the high evaporation rate in the area, the pit lake is predicted to be a hydraulic sink. A capture zone will exist around the pit, perpetually drawing groundwater into the pit or pit-lake. Flowthrough conditions, or a non-terminal pit-lake, would exist should the lake stage reach an elevation of 1430 m elevation. Sensitivity analyses were run on various model scenarios and model input parameters, such as changes in the evaporation rate and in groundwater recharge contributions from meteoric precipitation. None of the sensitivity model runs, however, caused the lake stage to reach the elevation of this groundwater divide.

Application of MODFLOW-SURFACT Model and LAK3 Package for Simulating an Ephemeral Pit Lake:

Gabora et al. (2006) integrated LAK3 package (Merritt and Konikow, 2000) into MODFLOW-SURFACT in order to solve an ephemeral pit lake problem associated with a proposed hard rock quarry in northern California. As a result of the climate and low permeability of the bedrock in the vicinity of the quarry, an ephemeral pit lake was expected to form upon cessation of mining activities. Utilization of MODFLOW-SURFACT permitted free movement of the steeply dipping water table in unconfined layers adjacent to the dewatered quarry. While, the LAK3 package was required because it allows for efficient drying and rewetting of lake cells. The rewetting procedure in the LAK3 package uses the average hydraulic head in the cells underlying the lake cells, which, due to steep hydraulic gradients associated with the pit, created unrealistic starting heads during rewetting. A modified rewetting procedure was implemented in the LAK3 package to accurately simulate shallow ephemeral ponding in the reclaimed quarry whereby the lake stage was set to the quarry bottom plus a nominal head of 1.5 cm (Gabora et al., 2006).

Lake (LAK3) Package documented by Merritt and Konikow (2000) is widely used to simulate lake-groundwater interactions. Hunt (2003) states that this package is a very effective replacement of the previous approach of simulating lake as either specified head boundary, or by general head boundary; or even as high-K (Anderson et al., 2002) nodes for the simulation of lake-groundwater interactions. Each of these approaches has some weaknesses such that the first two requires that lake levels to be known a priori, while the latter one may introduce some convergence difficulties. With the Lake package, the stage in the lake is computed by MODFLOW based on the water budget. The water budget is a function of inflow/outflow resulting from head differences between the aquifer and the lake. The flow budget also includes the effect recharge, evaporation, and anthropogenic inflow and discharge. The storage capacity of the lake is determined automatically based on the lake geometry. The Lake Package can be used for either steady state or transient simulations. Moreover, as it is mentioned by Hunt (2003), LAK3 package is superior to other lake simulation techniques. Its ability to simulate lake stage is an improvement over lake simulations using constant heads or head dependent flux boundaries because changes in lake stage can have appreciable effects on the groundwater system. Although High-K simulations and LAK3 results reported to compare well both at steady state and transient stages, it is known that LAK3 simulations are more stable and require less computational time.

However, like all the other models Lake Package is also based on many assumptions and limitations documented by Merritt and Konikow (2000), several of which are listed below:

- In some cases, a finer horizontal discretization in the vicinity of the lake and a finer vertical discretization than would be necessary to simulate heads in the aquifer, may be required to define the lake volume.
- When the option of rewetting dry cells is not implemented, the model user must use the lakebed leakance specification to represent the combined leakance of the lakebed and the aquifer in the vertical direction.

- Lake-aquifer simulations may experience stability problems if inappropriate parameter values are specified in the input data for the setup of the wet-dry option.
- If the head in the aquifer drops below the bottom of a lake still containing water, the seepage rate from the lake is limited to that which would occur if the aquifer head were the same as the elevation of the bottom of the lake.
- In using the explicit method of updating lake stages, the time step length should be small enough that lake stages from the previous time step provide good estimates of lakebed seepage in the current time step. While using the explicit method of updating lake stages, there will be a limitation on time step size that must be observed to prevent time-wise oscillations in lake stage. Therefore, compared to the explicit method of updating lake stage, the semi-implicit and fully-implicit methods require more iterations, more run time, and tighter convergence criteria to minimize the percent discrepancy in the aquifer water budget. However, it should be noted that only explicit method of updating lake stage can be used when the Lake Package is used as part of a MODFLOW steady-state simulation.
- The method used for computing lake stages as part of a MODFLOW steady state solution can fail if the initial estimate is substantially different from the solution value, so the user should choose an initial value that is as close as possible to the anticipated solution value.
- When the Lake Package is used as part of a MODFLOW steady state solution, the option for simulating coalescing and dividing lakes will not work, and its use should not be attempted.
- The Lake Package is not suitable for simulating tilted aquifer systems having a tilted grid because the package assumes that lake stage is uniform across the entire surface area of the lake.

<u>Application of MODFLOW and MINEDW Codes for Simulating an Open Pit in western US:</u>

Ding and Hodge, (2013) simulated the groundwater flow into an open pit mine in the western United States using a finite-difference code, MODFLOW and a finite-element code, MINEDW. MINEDW is a 3-D Finite Element groundwater flow model designed specifically for mining applications, developed from FEMFLOW 3D by USGS (Durbin and Bond). It is used at more than 50 mines throughout the world for mining-related issues in diverse hydrogeological and climatic conditions. It is capable of simulating open pit and underground mining operations for dewatering design and input to slope stability analysis. It is also capable of simulating excavation and subsequent pit lake infilling to represent different mining schedules, as well as the interaction between groundwater and surface water (Ding and Hodge, 2013).

Ding and Hodge (2013) compared the relative time and facility of using the above mentioned two codes to simulate mine dewatering and pit-lake formation. Groundwater flow models are developed to simulate mining and pit lake formations, pumping to dewater a pit lake, and current and future dewatering requirements to maintain 'dry' working conditions. To simulate these mining sequences, four separate model simulations were needed when using MODFLOW and only two model simulations were needed when using MINEDW. Moreover, they encountered convergence issues using MODFLOW due to the gradients that resulted from complex geologic conditions and using the LAK3 package. However, it is noted that the MINEDW model generally had no convergence issue. Thus, using MINEDW can save considerable time on a modeling project. Additionally, MINEDW is able to represent pit geometry using a collapsing mesh, while MODFLOW is limited by discretization and the use of the LAK3 package. This study shows the ability of both groundwater models to simulate open pit mining and pit lake infilling. The comparison suggests, however, that MINEDW has the advantage of simulating complex geology and groundwater systems without convergence problems and can simulate mine sequences with one single model.

Up to now, several examples where MODFLOW code is used to simulate the dewatering and pit lake formation processes in mining applications. Apart from MODFLOW, another code, of which applicability has recently been expanded, is FEFLOW. Rapantová et al. (2007), describes the applicability of FEFLOW and advantages over MODFLOW code in the simulation of mining operations as follows: the FEFLOW (Diersch, 2006), overcomes the problems in conceptualization and modeling of the mining environment with its ability to describe and quantify the hydraulic properties of preferential pathways (by simulating double porosity flow as well as preferential flow along mine workings). Moreover, the flexibility of finite elements mesh design enables the geometrization of the deposits on an acceptable level of simplification. In addition to 3-D elements it is possible to work with combination of planar and linear elements applicable for simulation of fractures and vertical and horizontal mine workings. Within these elements there is a choice of hydraulic calculations after either Darcy law for porous media or Hagen-Poiseuille law for fracture flow or Manning-Strickler law for channel flow.

Above, a list of the widely used models (both analytical and numerical, and sometimes coupled) is presented. It is obvious that there are many modeling applications to simulate open pit dewatering and pit lake formation processes, depending the site-specific nature of each problem. Examining the applications listed above, it is possible to conclude that the site-specific nature of each problem, reveals the advantages of a model over the others. Consequently, a model that is advantageous for any problem cannot be applicable to another. Therefore, when selecting the model to be applied and the methodology to be followed for any groundwater related problem during the operational and post-closure phases of the mines, it should be noted that each problem is site-specific and there is no single and correct way to set up a solution.

Wels et al. (2012) states that the selected model should meet the modeling objectives, include relevant aspects of the conceptual model, and should be consistent with data available for model calibration. Furthermore, selection of the code that will solve the flow equations will depend, for example, on the level of assessment required (simple or complex; analytical or numerical), dimensionality (2-D plan, 2-D cross-section, axisymmetric or 3-D) and the required outputs (Wels et al., 2012). If the groundwater inflow to an open pit is to be modeled specifically, it is noted that excavation of the pit and associated dewatering tend to create a significant drawdown in the surrounding aquifer somewhat analogous to a pumping well. In most mining projects, open pits reach significant depths and a representation of the vertical flow field is important. If the pit geometry is regular and the surrounding groundwater flow field is relatively uniform, a cross-sectional model may be adequate to simulate flow to the pit. However, in a more complex setting, a fully 3-D representation of the open pit and the surrounding aquifer may be required (Wels et al., 2012).

Maest et al. (2005) approaches the above discussed issues 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 modeling output are more important than the choice of the code itself. Moreover, it should also be noted that all these models can be coupled depending on the needs and the site-specific nature of the problem. Moreover, several models may also be used to cross-check the solutions.

CHAPTER 3

DESCRIPTION OF THE STUDY AREA

3.1 Topography

The study area, specifically the mine site, is located on the water divide between the Gediz and Büyük Menderes River Basins (Figure 3.1). At the mine site, open pit and the present heap leach pad area lies within the Gediz River Basin and waste rock storage area lies within the Büyük Menderes River Basin. All of the planned expansion facilities (proposed leach pad and waste rock storage areas) are within Gediz River Basin.

Since the mine site is located on the water divide, only ephemeral creeks are present in the area. The surface water features that are draining the mine site to the north are discharging to the branches of the Gediz River, while southerly ones discharge to the branches of the Büyük Menderes River.

The elevations in the whole study area range from approximately 1300 masl in the mountainous areas to 600 masl at the base of the valleys which are draining these mountains. The terrain in the vicinity of the mine site is rolling hills from approximately 950 m in the leach pad area to 1300 m to the top of the Kışladağ Mountain (Figure 3.1).

Digital Elevation Model (DEM) of the project site is initially produced from the digitized 10 m interval contours from the 1/25000 scaled maps. For the mine site and very close vicinity, this DEM is refined with the 1 m interval contours obtained from a more detailed topographical mapping study. Resulting DEM with a grid size of 10m is presented in Figure 3.1.

3.2 Morphology

The morphology of the region is characterized by the peneplains situated on the metamorphic basement rocks on the west and flat to nearly flat plateaus originated by Neogene-aged sedimentary rocks on the east. Between these features of the west and the east sides of the area, there are a number of young volcanic cones forming typical dome-like morphological features. On the other hand, the physiographic features of the mine site are mainly characterized by the presence of two volcanic cones on the SW-NE direction measuring 10 km in length by 9 km in width (Beydağı on southwest and Kışla on northeast). The Kışladağ gold deposit is associated with the northeastern stratovolcano, namely Kışla.

As it is mentioned above, topography of the study area is formed by the valleys having base elevations down to 600 masl, mountains having top elevations upto 1300 masl and gentle slopes in between. This topography is formed by the erosion of the plateau of metamorphic basement rocks overlain by laterally intercalating lacustrine limestones and volcanic rocks. Topographical highs are generally represented by the volcanic rock formations.

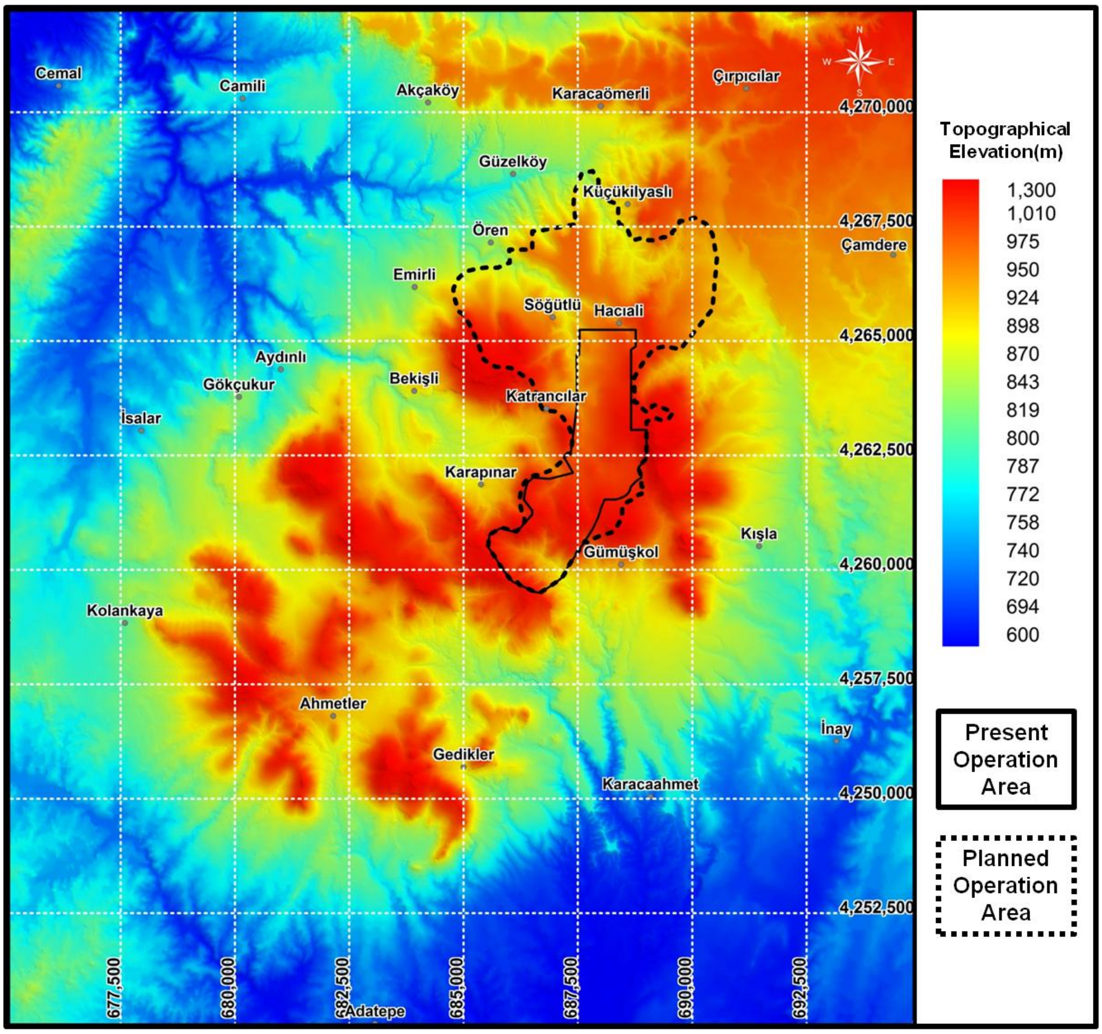

Figure 3.1. Digital Elevation Model of the study area

3.3 Geology

3.3.1 Regional Geology

Regional geology of the study area has been described by Yazıcıgil et al. (2000). The following description of the regional geology is a brief summary from this study.

- The oldest rocks forming the basement in the study area are those of the permo-triassic aged Menderes Metamorphic Complex, consisting of granitic gneisses and aplites of the Güneyköyü Formation overlain by calcareous schists, crystalline gneisses and augen gneisses of the Eşme Formation and, finally, the Musadağı marbles (Yazıcıgil et al., 2008).
- The basement rocks are overlain by the Tertiary aged Hacıbey Group, comprised of a series of conglomerates, sandstones, claystones, and limestones. The Hacıbey Group consists of three formations, namely Kürtköyü, Küçükderbent and Yeniköy Formations.
- The Hacıbey Group is overlain by the İnay Group, comprised of an assemblage of sedimentary rocks known as the Ahmetler Formation, the Beydağı Volcanics and the Ulubey Formation, a widely distributed sequence of lacustrine limestones.
- Asartepe Formation, of Pliocene age, unconformably overlies the İnay Group. It consists of conglomerates, sandstones and siltstones of various compositions with minor lenses of marl and claystone occurring in some locations.
- The alluvium consisting of gravels, sands, silts, and clays deposited along river courses, alluvial fan deposits, and colluvium represent unconsolidated Quaternary sediments on a regional scale.

Figure 3.2 represents the generalized columnar section and Figure 3.3 shows the geological map of the study area.

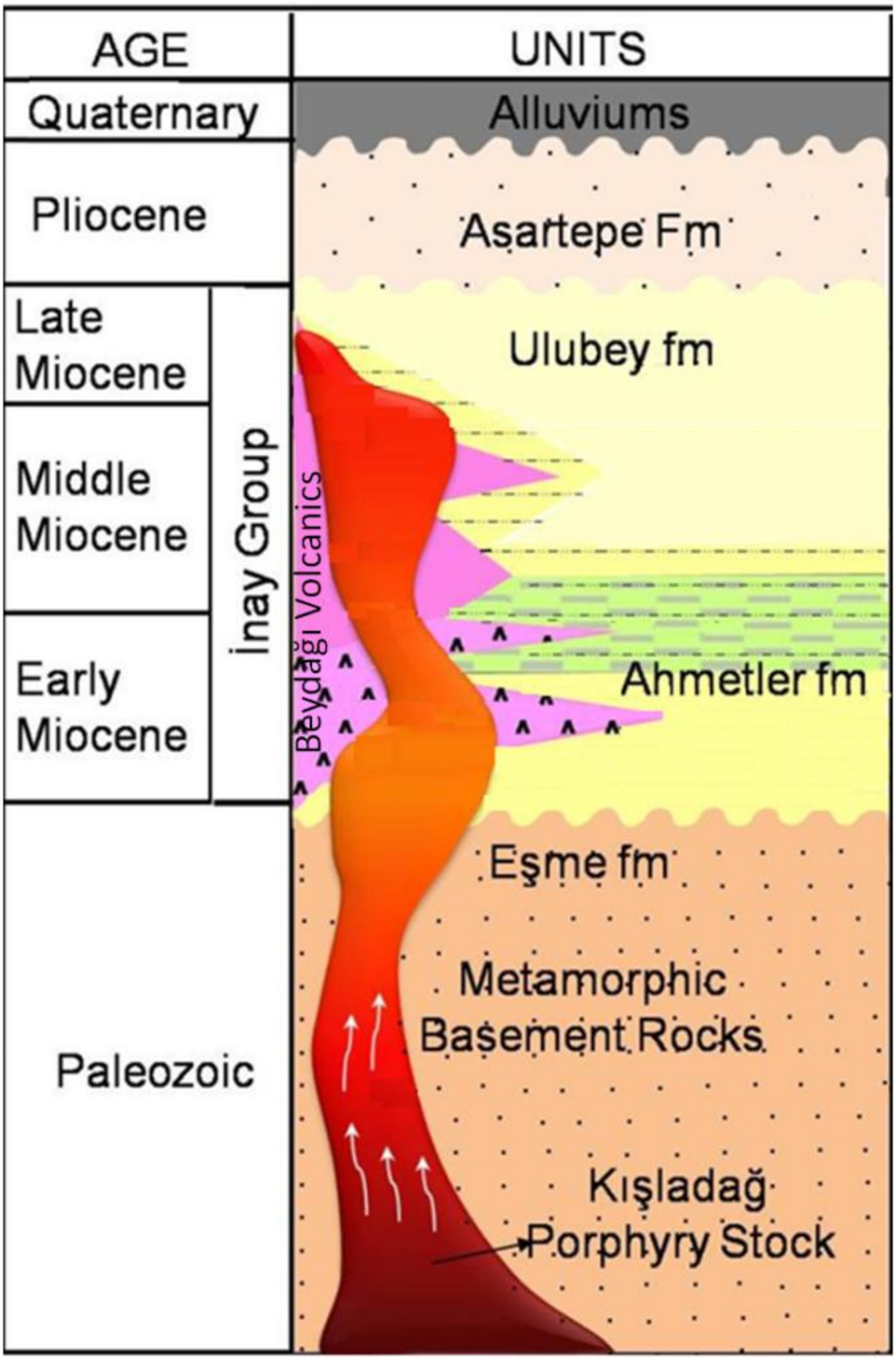

Figure 3.2. Generalized columnar section of the study area

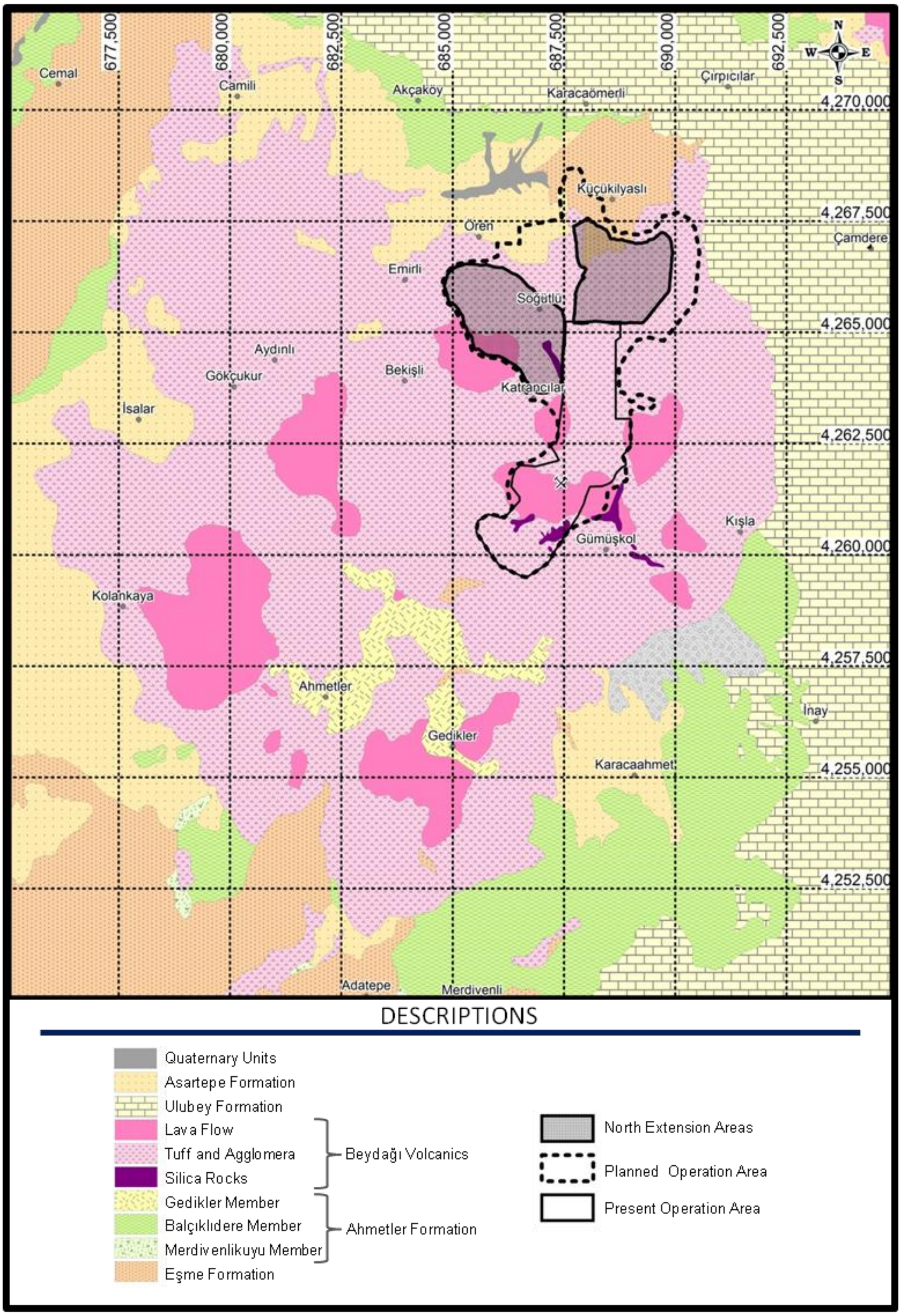

Figure 3.3. Geological map of the study area

After this brief description of regional geology, the units observed in the study are, which can be seen in the generalized columnar section (Figure 3.2), are given below in detail:

- **Eşme Formation:** Outcrops of this formation is observed in the vicinity of Takmak, Eşme and Kayalı. Schists and gneisses of Eşme Formation form the crystalline basement (Yazıcıgil et al., 2008). Formation is made up of schists and gneisses such that schists cover the gneiss core.
- **Ahmetler Formation:** Within the study area, Ahmetler Formation is observed unconformably above the basement rocks. In general, it forms a fining upward sequence made up of conglomerates, sandstone, tuffite, claystone and marl (Yazıcıgil et al., 2008). This formation is made up of the following three members (Ercan et al., 1978):
    - <u>Merdivenlikuyu Member:</u> This unit is made up of the angular blocks forming an old alluvial fan of un-distinct layers, originating from the metamorphic basement rocks. Outcrops of this unit having thicknesses of about 60 m, have very limited extension within the study area.
    - <u>Balçıklıdere Member:</u> This unit, overlying the Merdivenlikuyu Member conformably, is made up of alternating fluvial conglomerate, sandstone tuffite, claystones, marl and limestones. Tuffites of the units are originated from Beydağı Volcanics. Extensive outcrops of this unit are observed southwest of the Inay village, while smaller outcrops are also observed north and northwest of the mine site, especially along the valley bottoms. Thickness of the unit is less than 200 m, with almost horizontal layers of fining upward sequence.
    - <u>Gedikler Member:</u> This unit is made up of siltstone, claystone and tuffite alternations, which conformably overlies the Balçıklıdere Member. Volcanic sediments of the unit are originated from the Beydağı Volcanics. Presence of the volcanic bombs and blocks of the same origin indicate that the age of the unit is the same as Beydağı Volcanics. Thickness of the unit is around 60 m. Outcrops are observed in the vicinity of Ahmetler and Gedikler villages.
- **Beydağı Volcanics:** This andesitic volcanics of Miocene age are known to provide sediment input for the lower layers of Ahmetler and Ulubey Formations. This formation is made up of lava flow, agglomerates and tuffites. Extensive outcrops are observed at the study area.
- **Ulubey Formation:** This formation, overlying Ahmetler Formation conformably, is made up of intercalating siltstone, claystone, marl and clayey limestones at the bottom and lacustrine limestones at the top. Thin layers of sandstone and conglomerates are also observed within the limestone. Limestones of middle to thick layers, having irregular cracks and karstic features are locally silicified. Age of the formation is determined as Miocene. Deposits of this formation have extensive outcrops especially east of the study area within the Banaz Stream Basin, in the vicinity of Uşak, Ulubey and İnay. It is also observed in the northern parts of the study area. Typical outcrops of the unit can be observed along the canyon formed by

Yavu Creek, east of the study area, where continuous outcrops of alternating limestone and clayey limestone and/or marl can be observed.

- **Asartepe Formation:** This formation, overlying the older units unconformably, consists of alternating weakly cemented conglomerates, sandstones and siltstones with local lenses of marl and claystone. Conglomerates are generally of metamorphic origin, grains are well-rounded to sub-angular and matrix is made up of sand, silt and clay sized grains. Middle-thick layers are gently dipping to horizontal. Thickness of the formation is about 200 m. Asartepe Formation is formed in a fluvial environment in Pliocene. The most extensive outcrops of this unit are observed in the vicinity of Eşme and also in the northern parts of the mine site.
- **Quaternary Units:** alluvial fan deposits, colluviums and alluvium are the Quaternary units of the study area. They are observed along the river beds and made up of conglomerate, sand and silt sized sediments.

3.3.2 Site Geology

The volcanic stratigraphy in the mine site is very complex partially as a result of several successive phases of volcanic activity forming overlapping stratovolcanoes. Locally, the mine site occurs within intrusive, extrusive, and volcanoclastic rocks of an eroded stratovolcano, which is emplaced within and overlies the schists and gneisses of the Menderes Metamorphic Complex. Therefore, main rock units in the vicinity of the mine site can be listed as extrusives and intrusives of the Beydağı Volcanics and the volcanoclastics formed by the erosion of these, together with the underlying metamorphic units forming the basement. Intrusives of Miocene age are emplaced within the Paleozoic basement rocks made up of schists and gneisses. Although overlain by a thick sequence of volcanic rocks, these basement rocks can be observed at the surface as a result of erosion. Extrusive and intrusive rocks of Beydağı Volcanics have broad extension within the mine site and in the close vicinity. Most of the volcanic sequence consists of coarse fragmental rocks, flows, and porphyritic intrusions, representing lithofacies proximal to the volcanic center. 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.

Volcanic units at the mine site (Figure 3.4) are classified into six primary units by Lewis Geoscience Inc. (2002), as follows:

i. monolithologic volcanic breccias (PBb);
ii. massive flow-banded latite flows (PBf);
iii. stratified tuffaceous and epiclastic rocks (PBvc);
iv. quartz-phyric latite flows (PBq);
v. monolithologic volcanic conglomerate (PBcg); and
vi. porphyritic hypabyssal intrusions (PBi), which are locally further divided into three sub-units (PBi1, PBi2 and PBi3)

A cross-section in N-S direction passing through the ore within the open pit area is given in Figure 3.5.

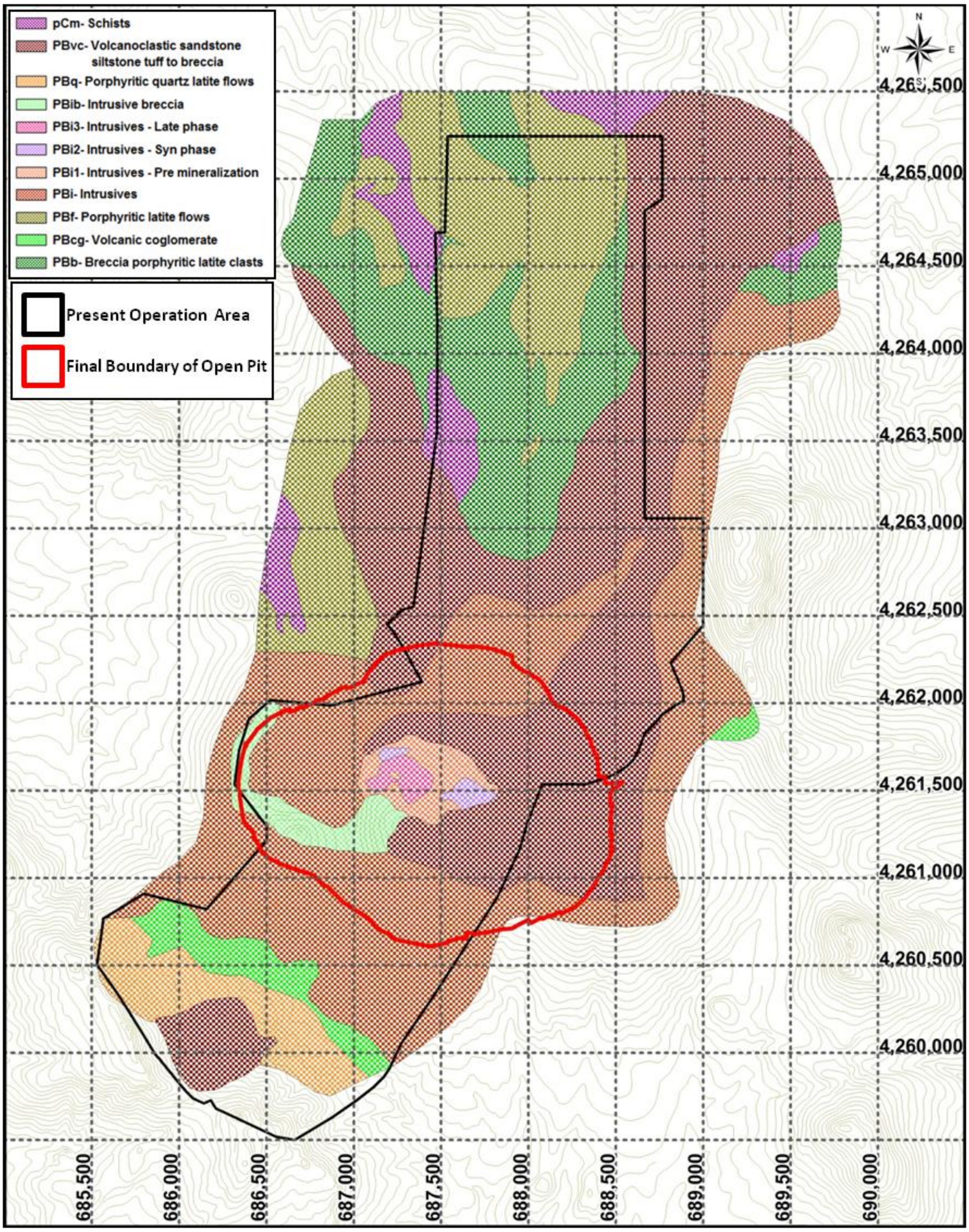

Figure 3.4. Geological map of the mine site (SRK, 2005)

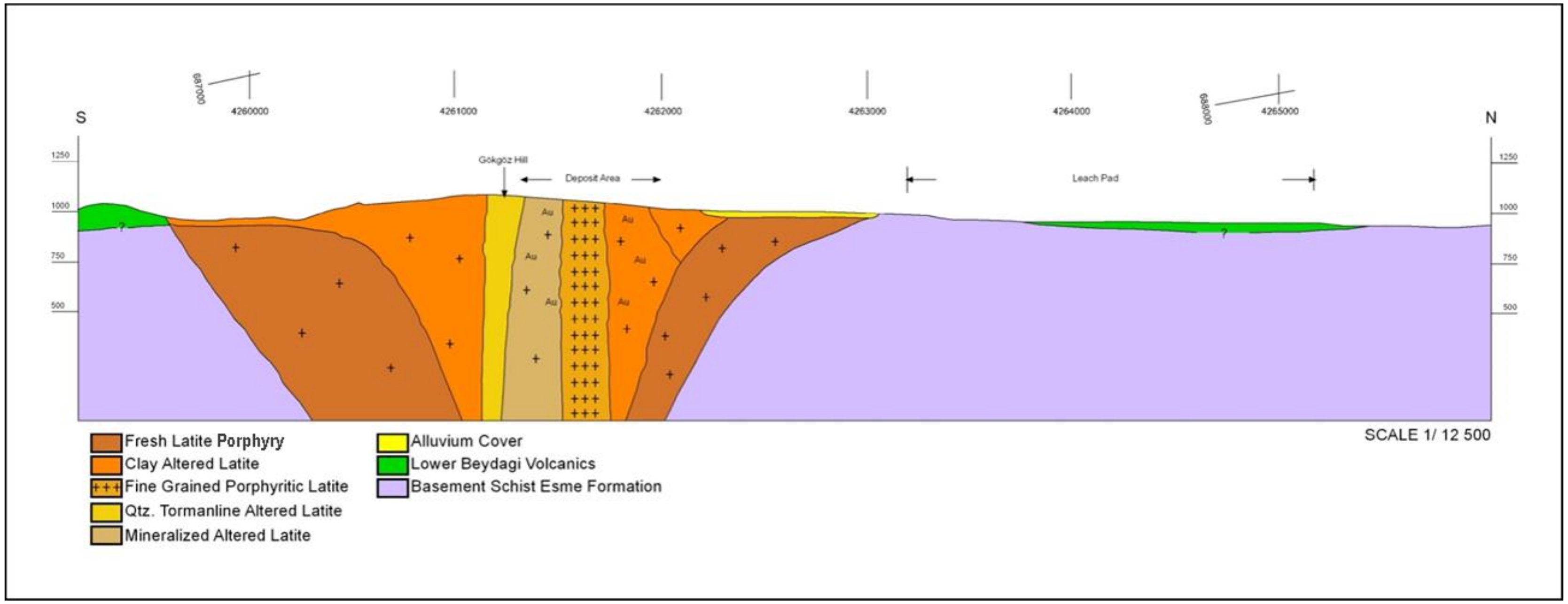

Figure 3.5. N-S geological cross-section passing through the ore within the open pit area (SRK, 2005)

Geology of the mine site and close vicinity is studied in 2008 in 1:5000 scale (Hudson, 2009). Later on concurrent with the planned capacity increase, this mapping study is extended to the north of the mine site (ARC, 2011). The detailed geological map of the mine site and its close vicinity, comprising these two studies, are given in Figure 3.6. The combined boundary of these two studies covers almost all planned expansion areas (Figure 3.6). Geological cross-sections are also provided along the lines shown on the map given in Figure 3.6. Among these, cross-sections passing through the lines A-A'', B-B''', C-C', D-D' and E-E', prepared by Hudson (2009) are given in Figure 3.7, while those passing through the lines F-F' and G-G', prepared by ARC (2011) are given in Figure 3.8.

These two studies, providing more precise boundaries of the geological units compared to the regional geological map, is very beneficial for hydrogeological site characterization. However, on the other hand, both of these studies include description of the units in too much detail, which is not required for the purpose of hydrogeological characterization and for the scope of this study. Therefore, within the content of this study, in order to make hydrogeological classification, detailed units determined with the two above mentioned studies are classified so that they are consistent with those provided in the regional geological map as follows:

- Quaternary units
- Asartepe Formation
- Ulubey Formation
- Beydağı Volcanics (further grouped into three units, as intrusives, lava flow, finally tuffs and agglomerates)
- Eşme Formation

Resulting geological map showing these major groups are presented in Figure 3.9.

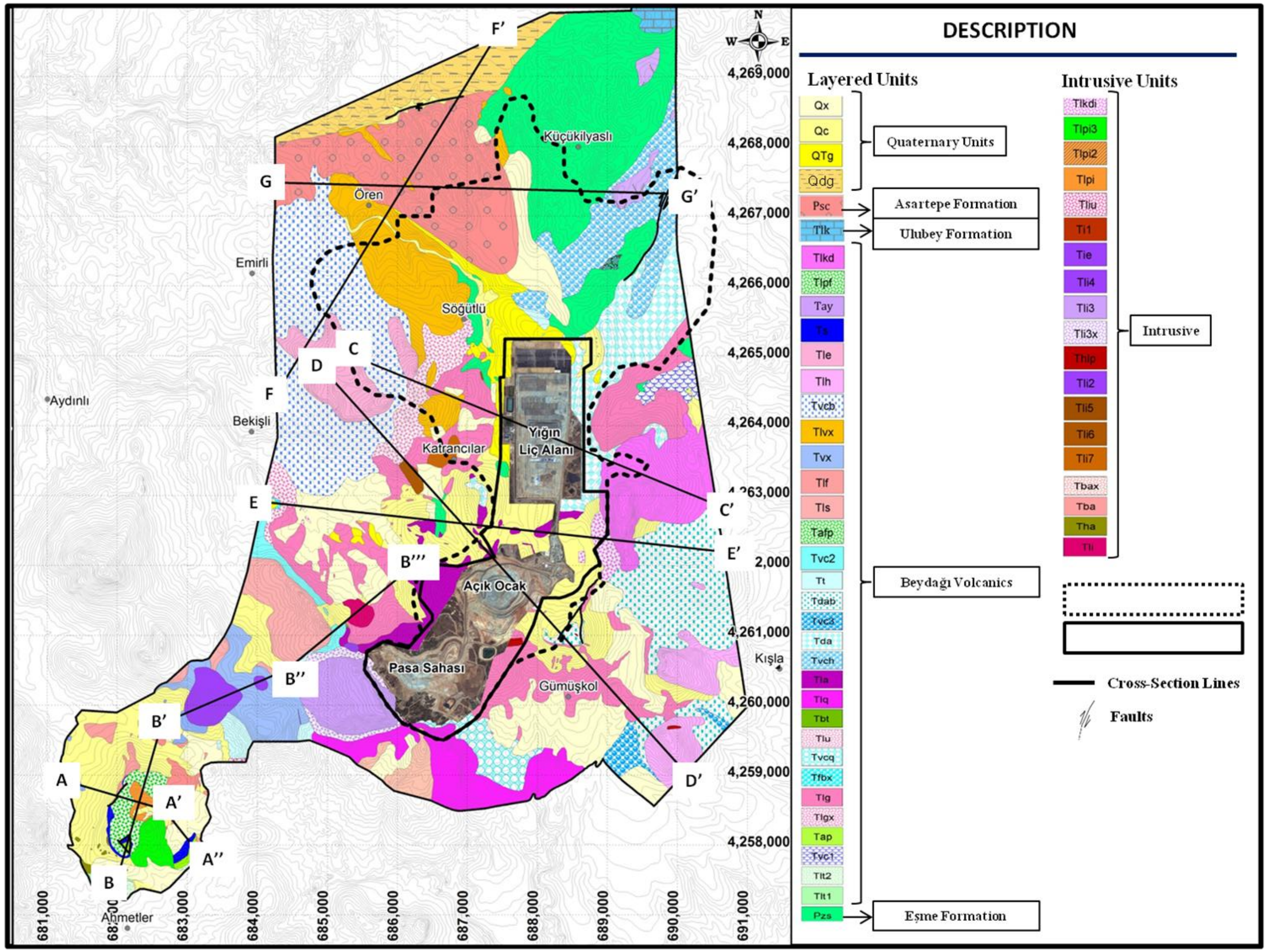

Figure 3.6. Detailed geological map of the mine site and close vicinity (Hudson, 2009 and ARC, 2011)

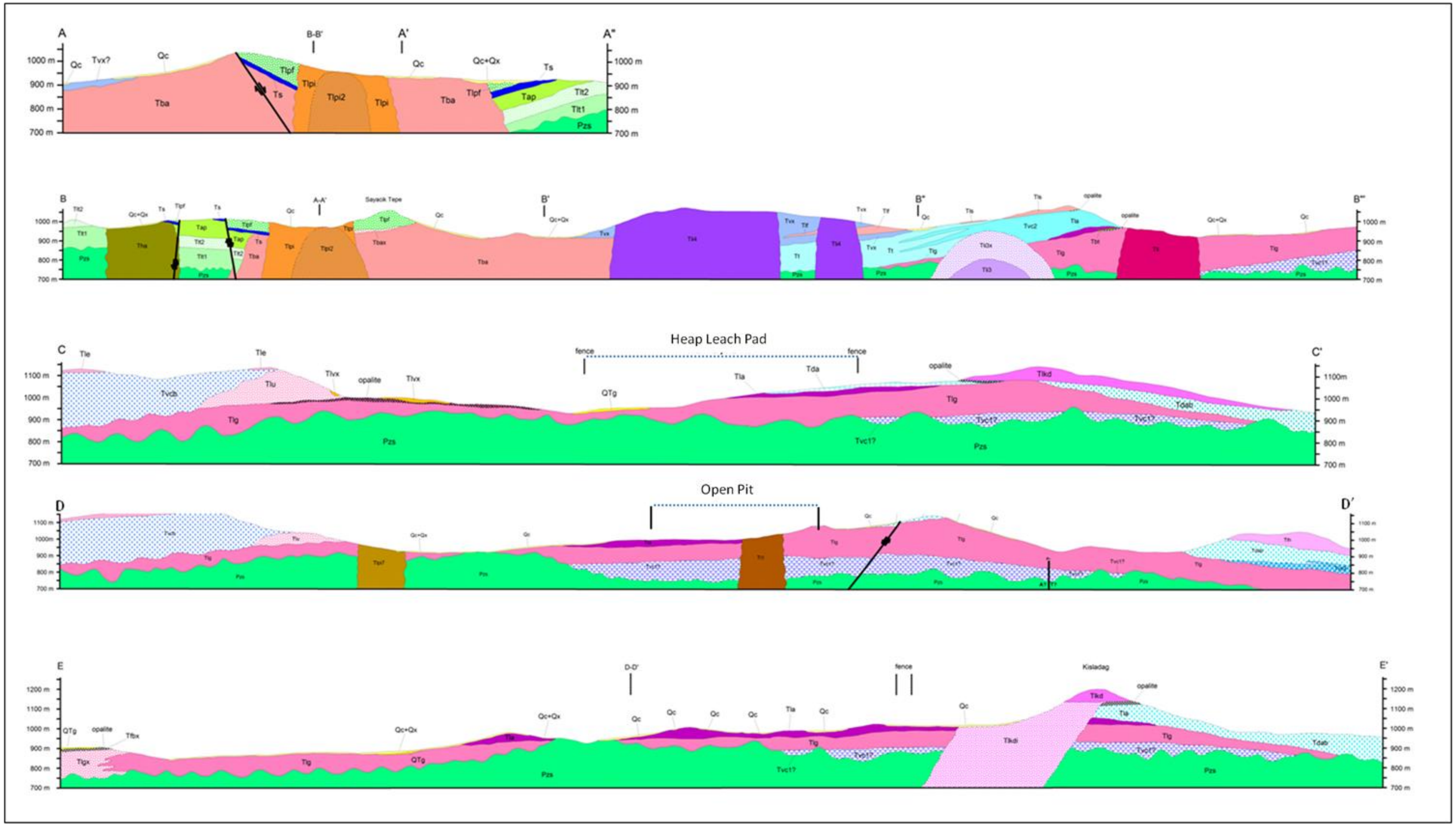

Figure 3.7. Geological cross-sections A-A’’, B-B’’’, C-C’, D-D’ and E-E’ (Hudson, 2009)

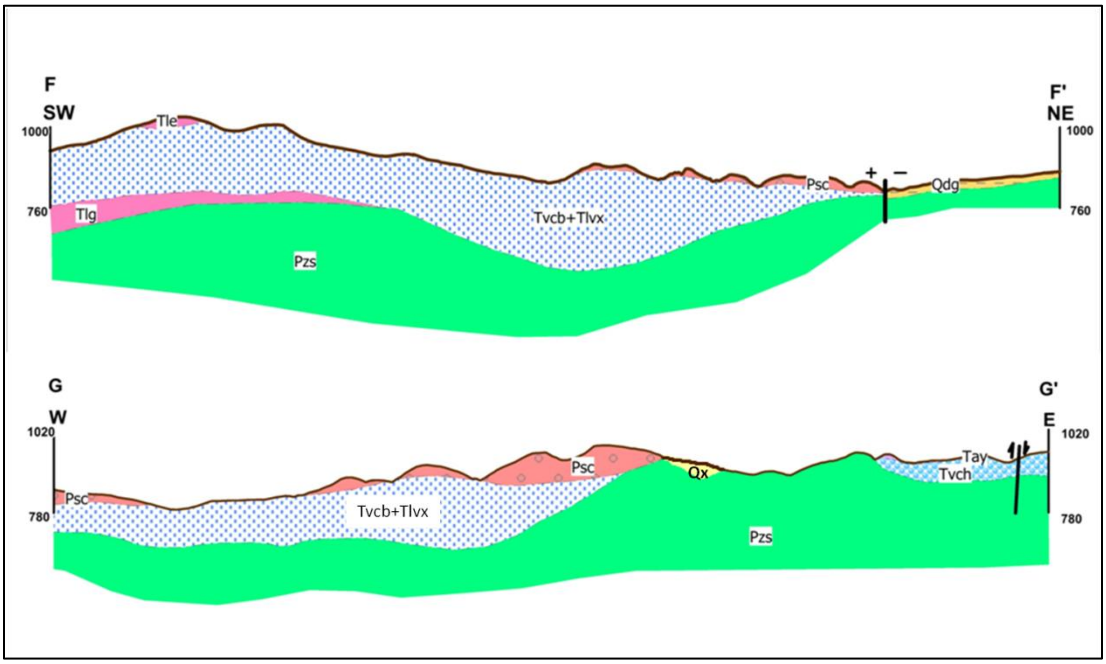

Figure 3.8. Geological cross-sections FF’ and GG’ (ARC,2011)

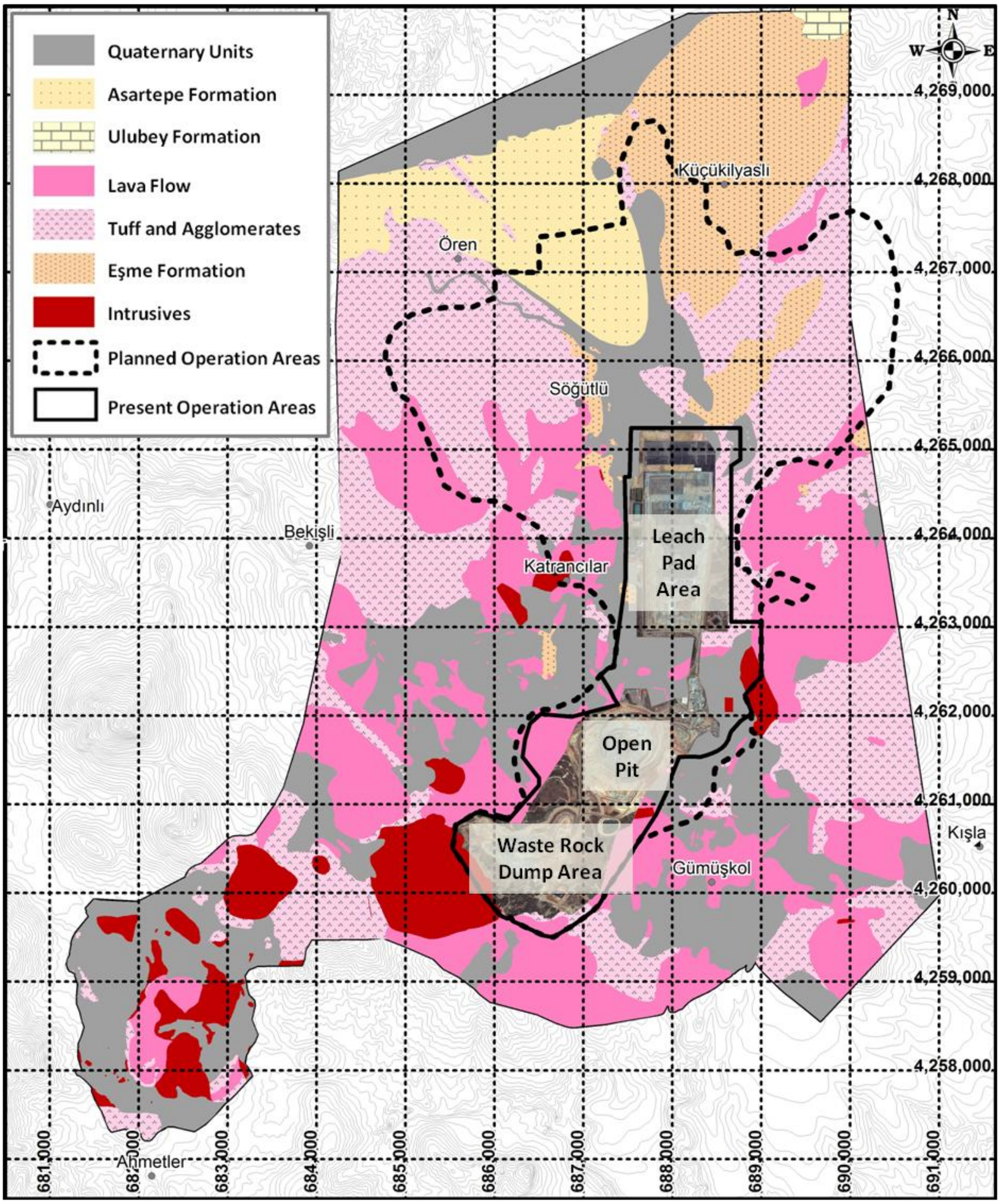

Figure 3.9. Generalized geological map of the mine site and close vicinity (modified after Hudson, 2009 and ARC, 2011)

3.3.3 Structural Geology

With the two studies conducted at 1:5000 scale (Hudson, 2009 and ARC, 2011), only small local faults are determined which do not have a unique trend and continuation within the study area. In the study conducted by Lewis Geoscience Inc. (2002) no major fault offsets of lithologic units was recognized. On the other hand, a couple of fault/fracture zones were identified. However these faults were not confirmed by the drilling data. The strikes of main fracture-joint directions from the oriented core data are N10-20E, N68-75E and N27W. Dips of these features range between vertical and approximately 55 degrees.

These, together with generally gently dipping stratigraphic layering and limited development of outcrop-scale fractures and faults indicated the low intensity of deformation of the units within the study area. As a result, it can be concluded that a significant fault system of regional importance is neither observed during the field studies nor determined with logging. Therefore, as in the previous studies, Kışladağ mine site could be defined as almost not deformed at all.

3.4 Climate and Meteorology

Detailed research on the climate and meteorology of the study area is completed in a previous study conducted by Yazıcıgil (2013). Below is a brief summary compiled from the previous studies.

Kışladağ Gold Mine is located in the border between Aegean and Central Anatolian regions, where Mediterranean Transition Climate characteristics are dominant (Türkeş, 1996). Mediterranean Transition Climate's distinct character is its relatively wet winters and springs.

Turkish Meteorological General Directorate (MGM) installed a meteorological station near Uşak city center in 1929 and this station is still operating. According to the data collected from this station, long term annual average precipitation for Uşak is determined as 531.7 mm. The hottest months are noted as July and August, where the coldest month is noted as January. Figure 3.10 shows the location of the Uşak Meteorological Station in comparison with the mine site together with the elevation profile between this station and the mine site.

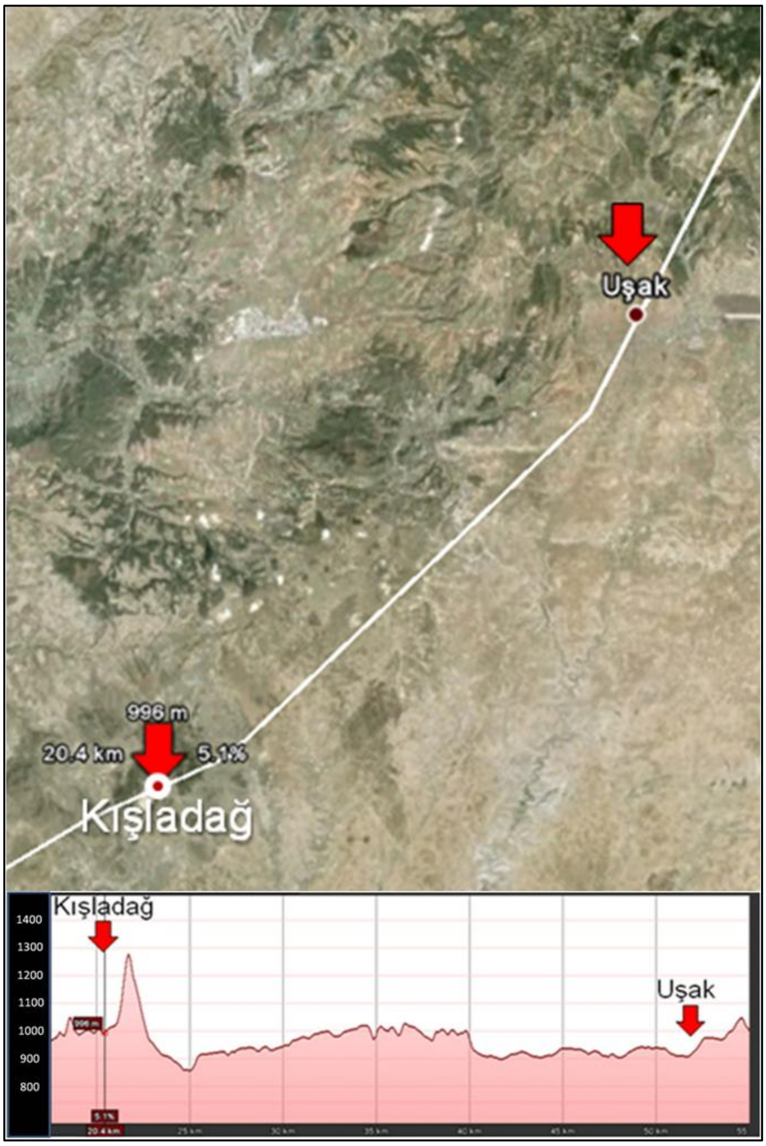

Figure 3.10. Location of Uşak Meteorological Station (modified after Yazıcıgil et al., 2011)

On April 2000, TÜPRAG started to operate a meteorological station at mine site and since then site-specific meteorological data has been collected for Kışladağ (Table 3.1, Figure 3.11). Initially temperature, wet/dry bulb temperatures, wind speed and direction, precipitation and evaporation data was being recorded manually (three times a day, at 7:00, 14:00 and 21:00) at this station. Later in August 2005, an automatic meteorological station (AWOS) was installed at the same location, to collect barometric pressure, temperature, relative humidity, wind speed and direction, solar radiation and precipitation data, on five minute intervals. At the same time, TÜPRAG continued to operate the manual station to collect precipitation and evaporation data. Furthermore, a second automatic meteorological station was installed in the open pit, in April 2010. However operational period of this station was not long enough to use its data in this study.

The precipitation and evaporation data collected from Kışladağ between 2000 and 2012 are evaluated during this study. Furthermore, a statistical analyses was conducted on daily data of precipitation and evaporation for the period between 1975 and 2000 from Uşak station to generate long term daily precipitation and evaporation data set for Kışladağ mine site for 1975-2012 period. In addition to this, temperature and relative humidity data collected by Kışladağ AWOS is analyzed for the period between 2006 and 2012.

Table 3.1. Information on the meteorological stations

Station	**Operator**	**UTM-X**	**UTM-Y**	**Elevation (m)**	**Operational Period**
Kışladağ Manuel	TÜPRAG	687692	4262462	997	04/2000-to date
Kışladağ AWOS	TÜPRAG	687692	4262462	997	08/2005-to date
Kışladağ Open Pit AWOS	TÜPRAG	687130	4260476	1026	04/2010-to date
Uşak	MGM	708760	4284370	930	1929-to date

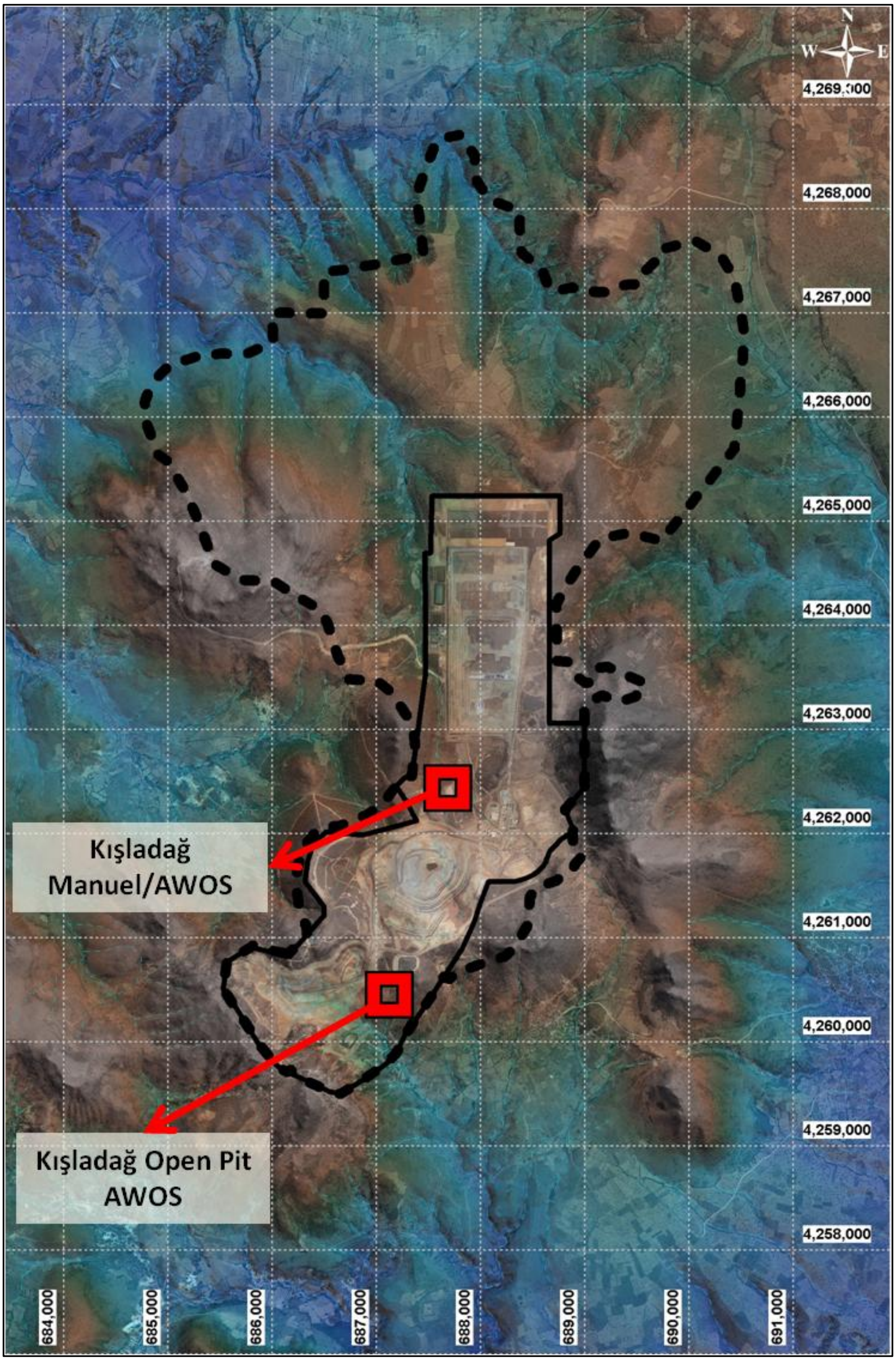

Figure 3.11. Meteorological stations at the mine site

3.4.1 Precipitaton

Since the meteorological station for Kışladağ is in operation for a relatively shorter period (2000-2012), long term precipitation data for Kışladağ is calculated by Yazıcıgil et al. (2011) with correlating the long term data collected at Uşak meteorological station (1975-2000) (Yazıcıgil et al., 2011).

Uşak meteorological station is located 29 km northeast of the mine site. The precipitation data collected from Kışladağ and Uşak Meteorological Stations are correlated for the period between 2000 and 2012 (where the collected data overlaps). Using this correlation, long term precipitation data is extrapolated for the period between 1975 and 2000 for Kışladağ. As a result, long term (1975-2012) meteorological data is obtained for the mine site. Figure 3.12 shows the obtained long term precipitation data and cumulative deviation from the average annual precipitation for Kışladağ. As can be noted from Figure 3.12, long term average annual precipitation for Kışladağ is calculated as 493 mm. Similarly the average annual precipitation for Kışladağ is noted as 491 mm between 2001 and 2012 (actual collected data).

According to Kışladağ long term precipitation data, the driest year is 2004 (283 mm) and the wettest year is 2012 (693 mm). Furthermore, periodic wet and dry periods can be determined from the cumulative deviation graph given in Figure 3.12. According to this figure, 1978-1981, 1997-2002 and 2009-2012 covers the wet periods, while 1984-1996, 2003-2008 covers the dry periods. When the operational period for Kışladağ Gold Mine is considered, a significant dry period is noted until 2008, followed by a wet period starting from 2009.

Calculated long term (1975-2012) and measured short term (2001-2012) average monthly precipitation data is given in Figure 3.13 and Figure 3.14, respectively. Both data indicate significant seasonality, where winter is wettest and summer is driest seasons.

When the monthly distribution of the average precipitation is examined (Figure 3.14), it is determined that 42% of the annual precipitation occurs during winter, followed by 26% in spring, 9% in summer and 23% in fall. Moreover, as shown on Figure 3.14, the wettest month is December (71.5 mm) and driest month is August (9.14 mm).

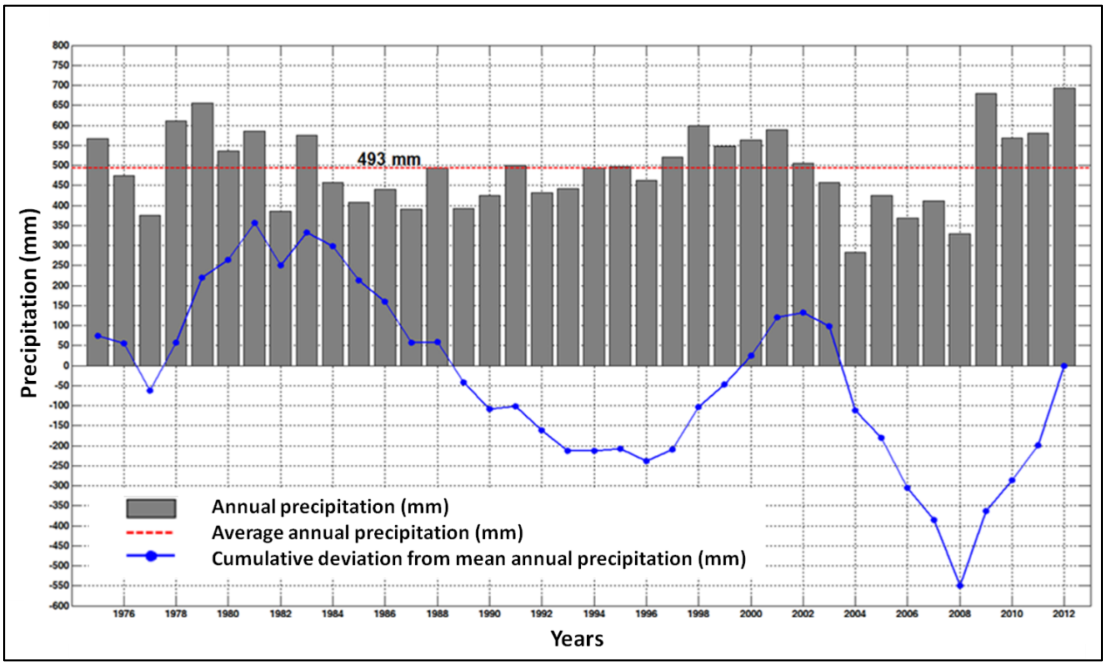

Figure 3.12. Annual Precipitation (mm) and cumulative deviation from the average annual precipitation (mm) graph for Kışladağ (1975-2012)

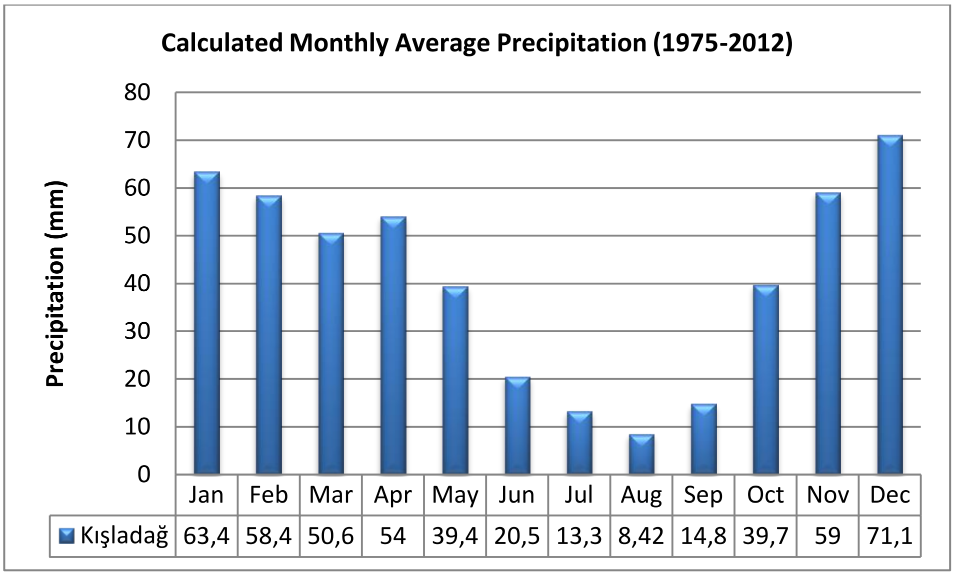

Figure 3.13. Monthly Average Precipitation Data for Kışladağ Long Term (1975-2012)

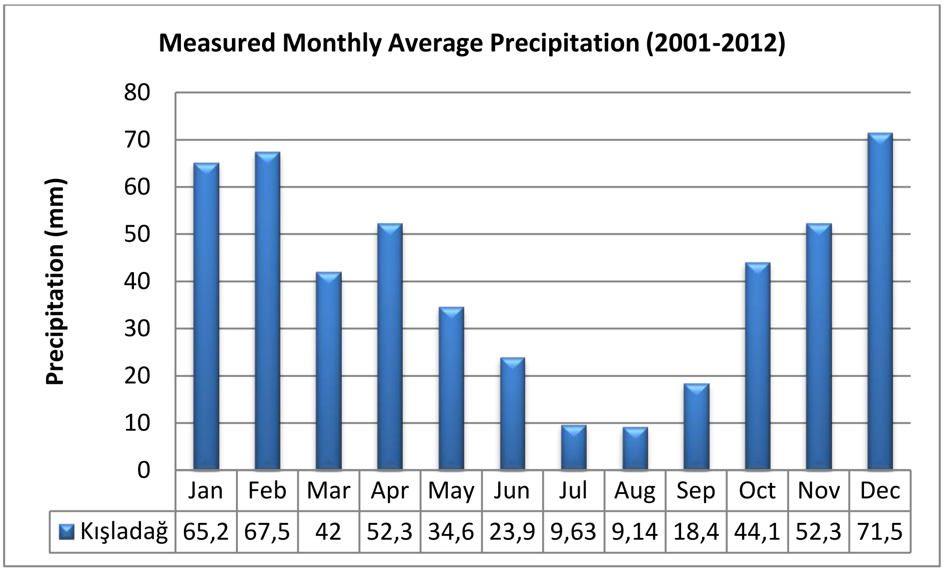

Figure 3.14. Monthly Average Precipitation Data for Kışladağ Short Term (2001-2012)

3.4.2 Temperature

The monthly average temperature for Kışladağ AWOS (2006-2012) is given in Figure 3.15. The hottest and coldest months in the mine site are August (25.2^{o}C) and January (2.23^{o}C), respectively. Kışladağ's average annual temperature is calculated as 13.3 ^{o}C. According to average annual minimum temperature data, coldest months are January (-9.4 ^{o}C) and February (-9.6 ^{o}C) which indicates icing and snow cover for winter and early spring (Figure 3.16). According to average annual maximum temperature data, July (37.1 ^{o}C) is the hottest month for Kışladağ (Figure 3.17).

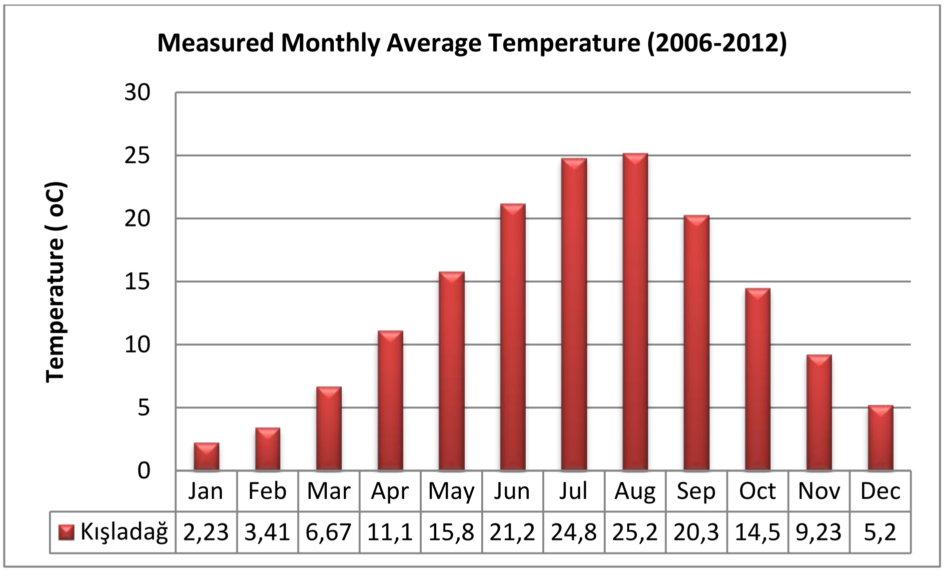

Figure 3.15. Monthly Average Temperature, Kışladağ Station (2006-2012)

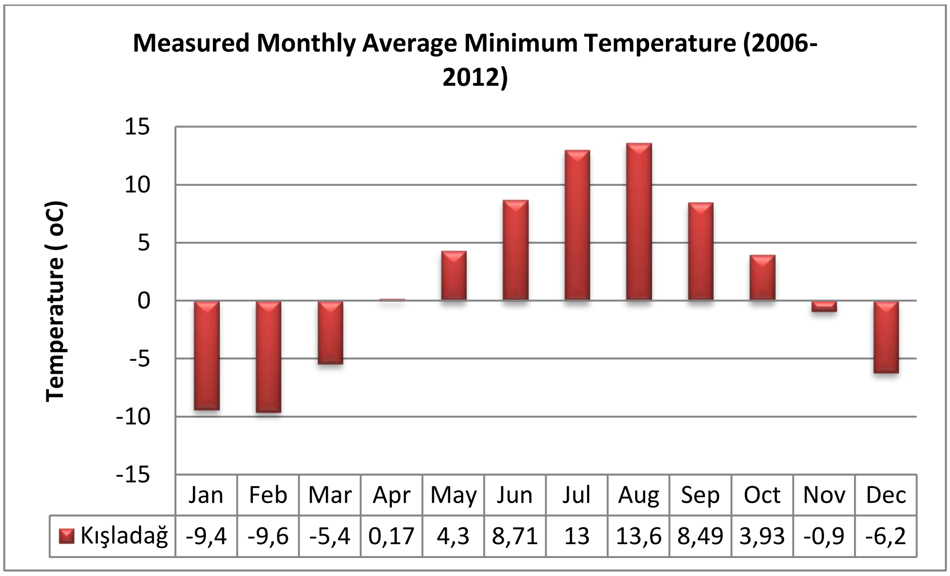

Figure 3.16. Monthly Average Minimum Temperature, Kışladağ Station (2006-2012)

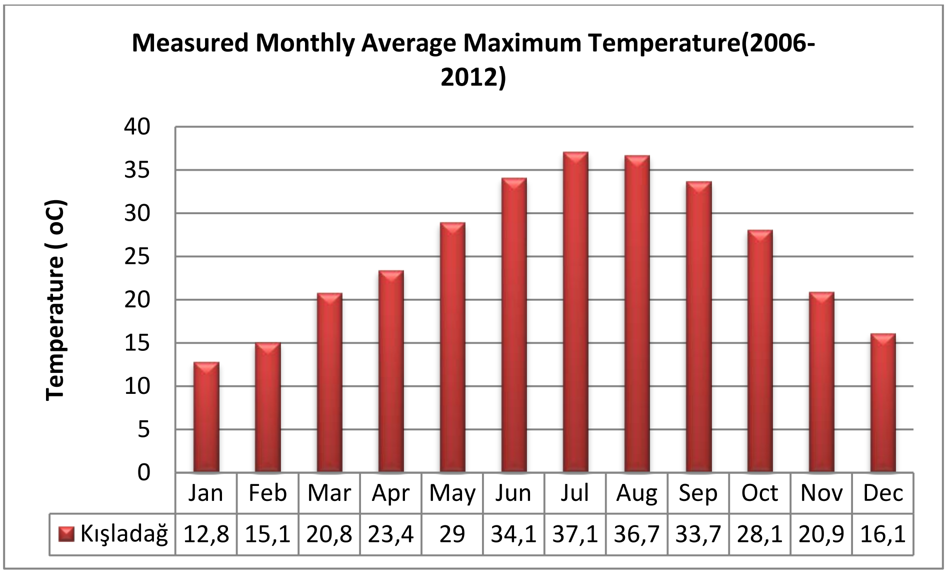

Figure 3.17. Monthly Average Maximum Temperature, Kışladağ Station (2006-2012)

3.4.3 Relative Humidity

The monthly average relative humidity values observed in Kışladağ AWOS is given in Figure 3.18 for the period 2006-2012. According to this figure, relative humidity is considerably low for summer (between 38% and 50%), indicating hot and arid summers. On the other hand, relative humidity is noted as 75% for the wet and cold winters.

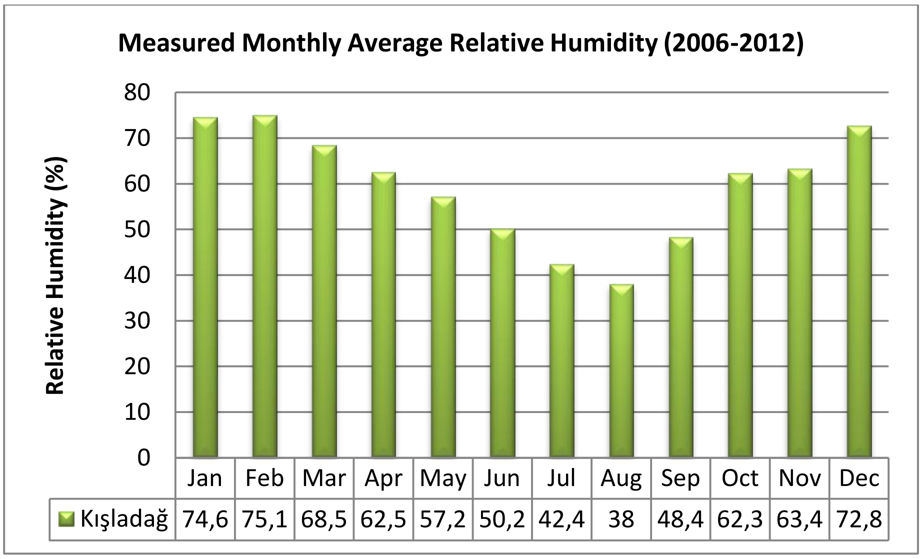

Figure 3.18. Monthly Average Relative Humidity, Kışladağ Station (2006-2012)

3.4.4 Evaporation

Daily evaporation at Kışladağ is measured generally between April and October, for 2000 and 2012 period. This data set has some missing measurements and consequently, a set of correlation is conducted by Yazıcıgil et al. (2011) to estimate the missing data.

First estimation is completed for the period where the evaporation measurements are missing for seven consecutive days or less. For this condition, if Uşak Meteorological Station's data is present, the data is introduced to Kışladağ data set, with a correlation factor calculated by Yazıcıgil et al. (2011). If not, it is estimated with calculating the average evaporation rate for four days before and after the missing days' data. Second estimation is completed for the period where the evaporation measurements are missing for more than seven consecutive days. For this condition, if Uşak Meteorological Stations data is present, the data is introduced to Kışladağ data set, also with a correlation factor calculated by Yazıcıgil et al. (2011). Otherwise, as estimated by Yazıcıgil et al. (2011), the missing data is estimated utilizing Penmann Equation (Dalgün, 1988). Furthermore, for winter months where the evaporation data is missing, the evaporation rates calculated by Dalgün (1988) are introduced to the data set.

Similar estimations are completed for the missing evaporation rates of Uşak Meteorological Stations data, as described above. In order to generate the long term daily evaporation data, by Yazıcıgil et al. (2011) conducted a statistical analyses, similar to precipitation analyses, for Kışladağ and Uşak Meteorological Stations evaporation data for the period between 2000 and 2012 (where the collected data overlaps). Using this analyses, long term daily evaporation data is generated for the period between 1975 and 2000 for Kışladağ. As a result, long term (1975-2012) daily evaporation data set is generated for the mine site.

Monthly average evaporation rates measured at Kışladağ Meteorological Station (2001-2012) are given in Figure 3.19. Calculated monthly average evaporation rates for Kışladağ Meteorological Station for long term (1975-2012) is given in Figure 3.20. According to these figures, it can be noted that short and long term data show similarity. The short-term (2000-2012) data indicates that the highest evaporation is observed in July and August, as 233 mm and 226 mm, respectively. The long- term data indicates that the lowest evaporation is observed in December as 15.7 mm.

A comparison is given in Figure 3.21 for the calculated annual precipitation and evaporation data. From this figure, it can be noted that the evaporation rate is considerably high between April and October. For the winter period, precipitation rate is higher than the evaporation, due to low temperatures. Thus, it can be noted that the highest recharge to groundwater is expected for the winter period.

Calculated long term (1975-2012) annual evaporation data is given in Figure 3.22. This data set indicates that the long term average annual evaporation for Kışladağ is 1198 mm.

Between years 1990 and 1999 the annual evaporation rate is below the long-term average, while it is above the average after 2000.

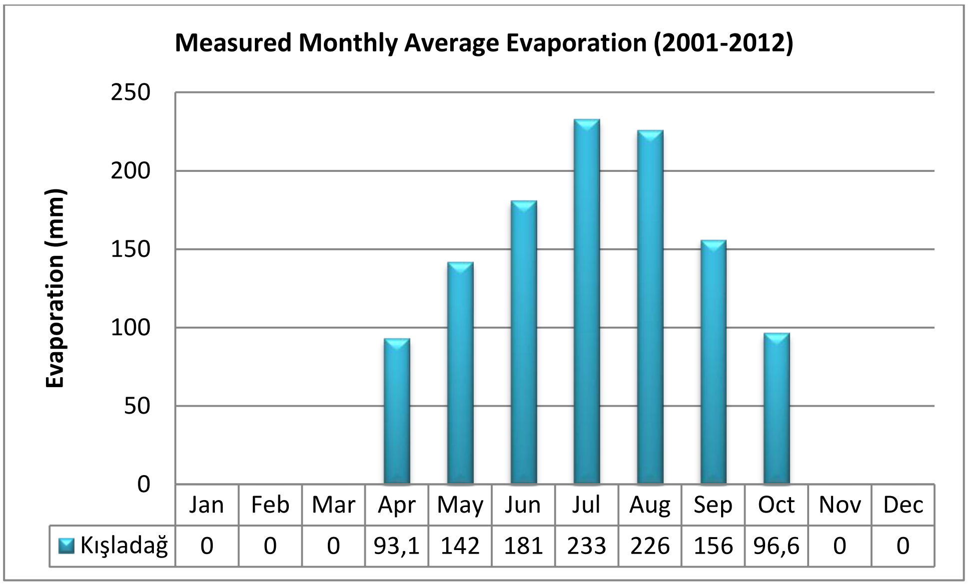

Figure 3.19. Calculated Monthly Average Evaporation for Kışladağ Short Term (2001-2012)

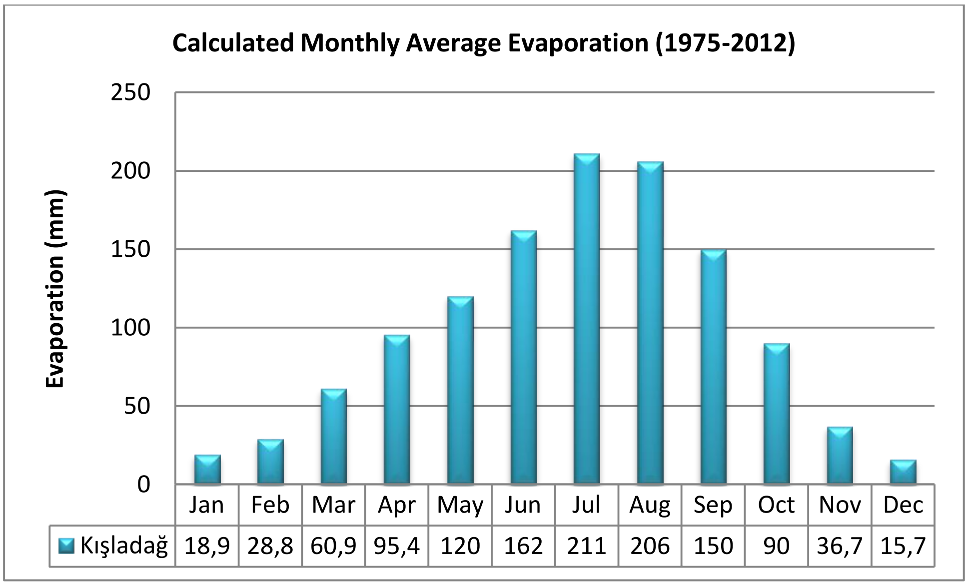

Figure 3.20. Calculated Monthly Average Evaporation for Kışladağ Long Term (1975-2012)

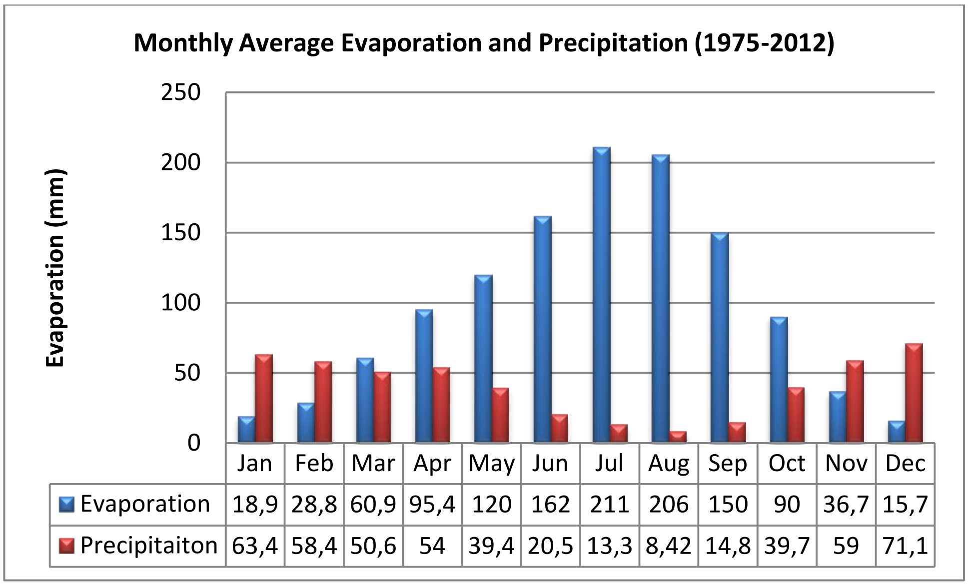

Figure 3.21. Calculated Monthly Average Evaporation and Precipitation Data for Kışladağ (1975-2012)

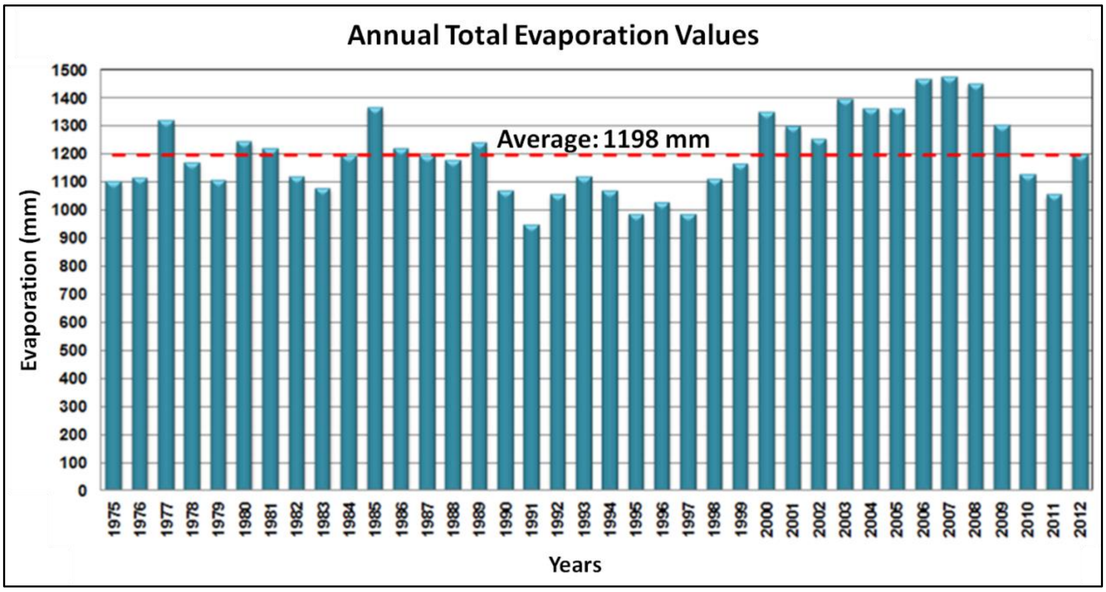

Figure 3.22. Calculated Long Term Annual Evaporation Rates for Kışladağ (1975-2012)

CHAPTER 4

HYDROGEOLOGY

4.1 Water Resources

4.1.1 Surface Water Resources

The study area and specifically the mine site are located on the water divide between the Gediz and Büyük Menderes River Basins (Figure 4.1). Since the mine site is located on the water divide, only ephemeral creeks are present in the area. Although only seasonal flow is generally observed along these creeks, heavy rainfall may result in sudden runoff. The surface water features that are draining the mine site to the north are discharging to the branches of the Gediz River, while southerly ones discharge to the branches of the Büyük Menderes River.

In the whole study area, on the other hand, there are both perennial and ephemeral creeks (Geçemek, Değirmen, Kurbağalı Deresi etc.). The major creeks within and around the mine site are Kurbağalı Creek flowing west of the mine site and Geçemek Creek, flowing north of the mine site, with its tributaries, namely Söğütlü Creek (draining the mine area) and Değirmen Creek (Figure 4.1). These two major drainages combine at the northwest of the project area and discharges to the Gediz River. Radial drainage network of these surface waters is caused by the presence of the volcanic cones within the study area.

Six weirs were installed at different dates in order to monitor the surface flow along the major creeks draining the mine site. Weirs 1 through 4 were installed in June 2005; while Weir-5 was installed in March 2008. The last one, Weir-6 was installed in October 2011 in order to monitor the flow discharging from the planned expansion areas in the north. Locations and drainage basins of the weirs are shown in Figure 4.2, while data regarding these weirs, such as drainage areas and operational periods are given in Table 4.1. As it can be seen from this figure drainage areas of the first five weirs, (Weir 1 to 5), cover all the surface flow occurring at the present mine site and the last one (Weir-6) covers most of the drainage from the planned leach pad area north of the present mine site.

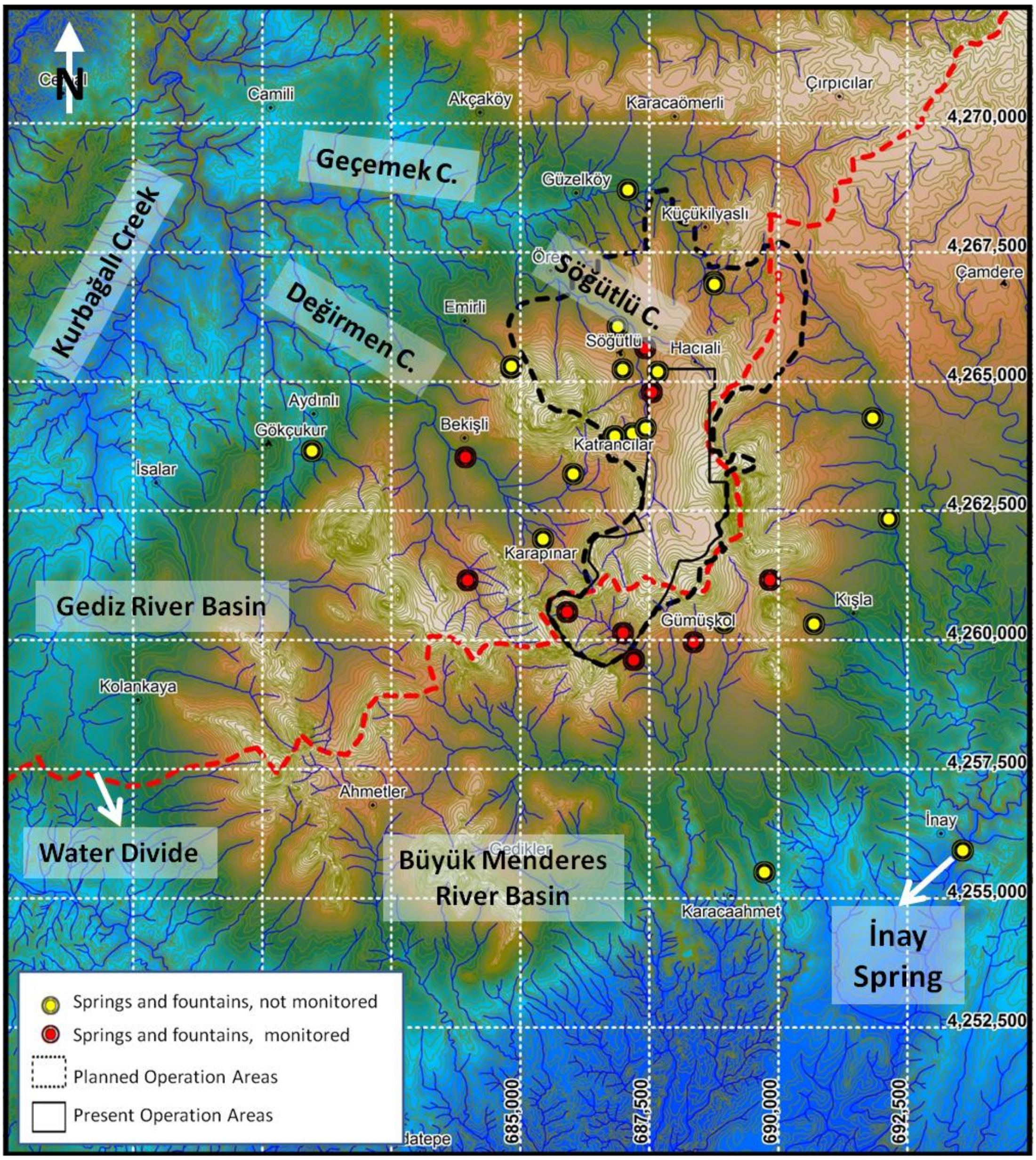

Figure 4.1. Surface water resources (drainage, springs, seeps and fountains)

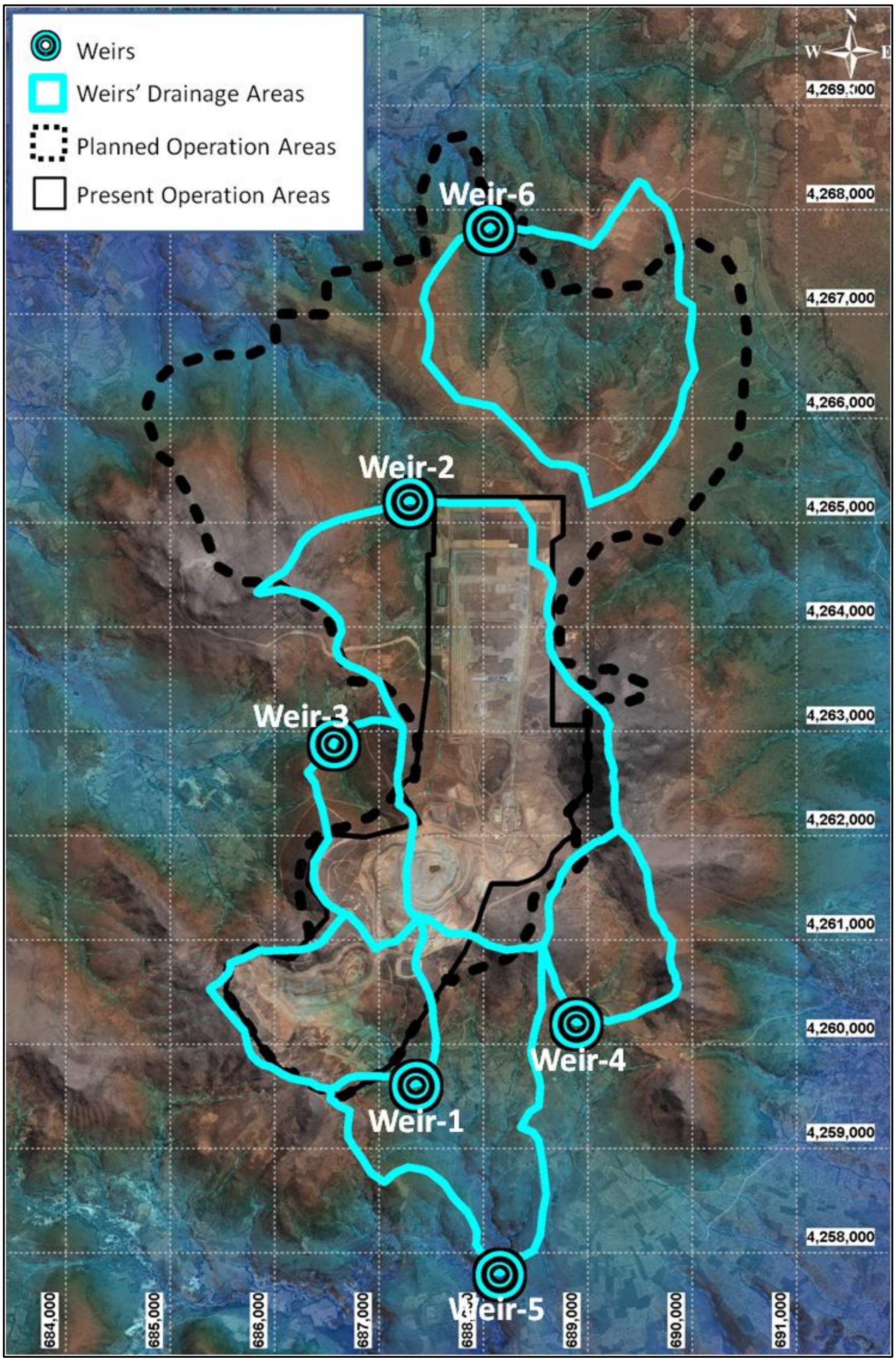

Figure 4.2. Location of the weirs and their drainage areas

Table 4.1. Drainage area and operational period of the weirs

Weir ID	Drainage Area (ha)	Measurement Period
Weir-1	234.98	1/6/2005 – present
Weir-2	761.13	1/6/2005 – present
Weir -3	161.88	1/6/2005 – present
Weir -4	164.58	1/6/2005 – present
Weir -5	610.04	1/3/2008 – present
Weir -6	506.29	1/11/2011- present

Figure 4.3 shows the average daily flow measurements (in log-scale) together with the precipitation values plotted against time. According to this graph, flows start to increase by November and start to cease after March. Maximum flows are generally observed in December, January, February and March, while almost no flow is observed during July, August and September. Moreover, it is noted that average daily flow seldom exceeds 200 L/s and only for a couple of times and only for a very short duration reaches to 1000 L/s.

4.1.2 Springs and Fountains

The springs having high yields (Karabol, Avgan, Sarıkız, Cabar, İnay, Kocapınar, Uyuz, Hasköy and Sivaslı Springs) discharge from the Ulubey aquifer, which has a broad extension at eastern and northern parts of the study area. Among these high-yield springs, only İnay Spring is located within the boundaries of the study area. This spring located approximately 7 km away from the mine site (Figure 4.1), is the drinking and domestic water supply of İnay Village. Discharge of this spring is measured by DSI (State Hydraulic Works) during the period between the years 1986 and 1988. During this period lowest discharge is observed as 2 L/s (in January 1988) and highest discharge is observed as 13 L/s (in July 1986) while average discharge is calculated as 8.5 L/s (Yazıcıgil et al., 2008).

Apart from high-yield springs, there are several low-yield (<0.25 L/s) springs, seeps and fountains in the vicinity of the mine site. Eleven of these are included in the monitoring program, which was initiated in 2000 by TÜPRAG. At these locations, monthly sampling is conducted for water quality. Locations of these monitoring points are shown in Figure 4.4 and data regarding these points are given in Table 4.2.

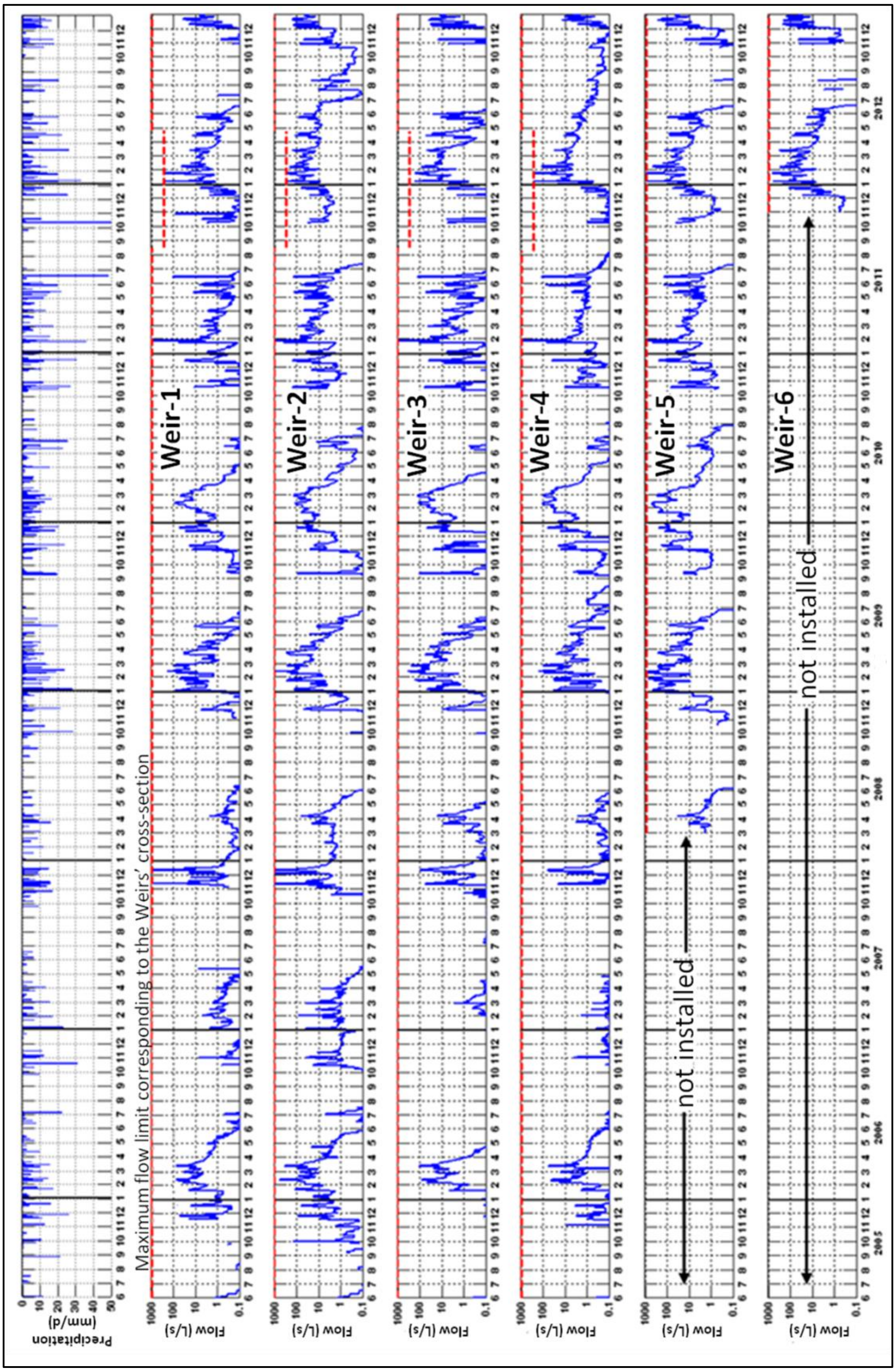

Figure 4.3. Flow measurements (in log scale) and precipitation versus time

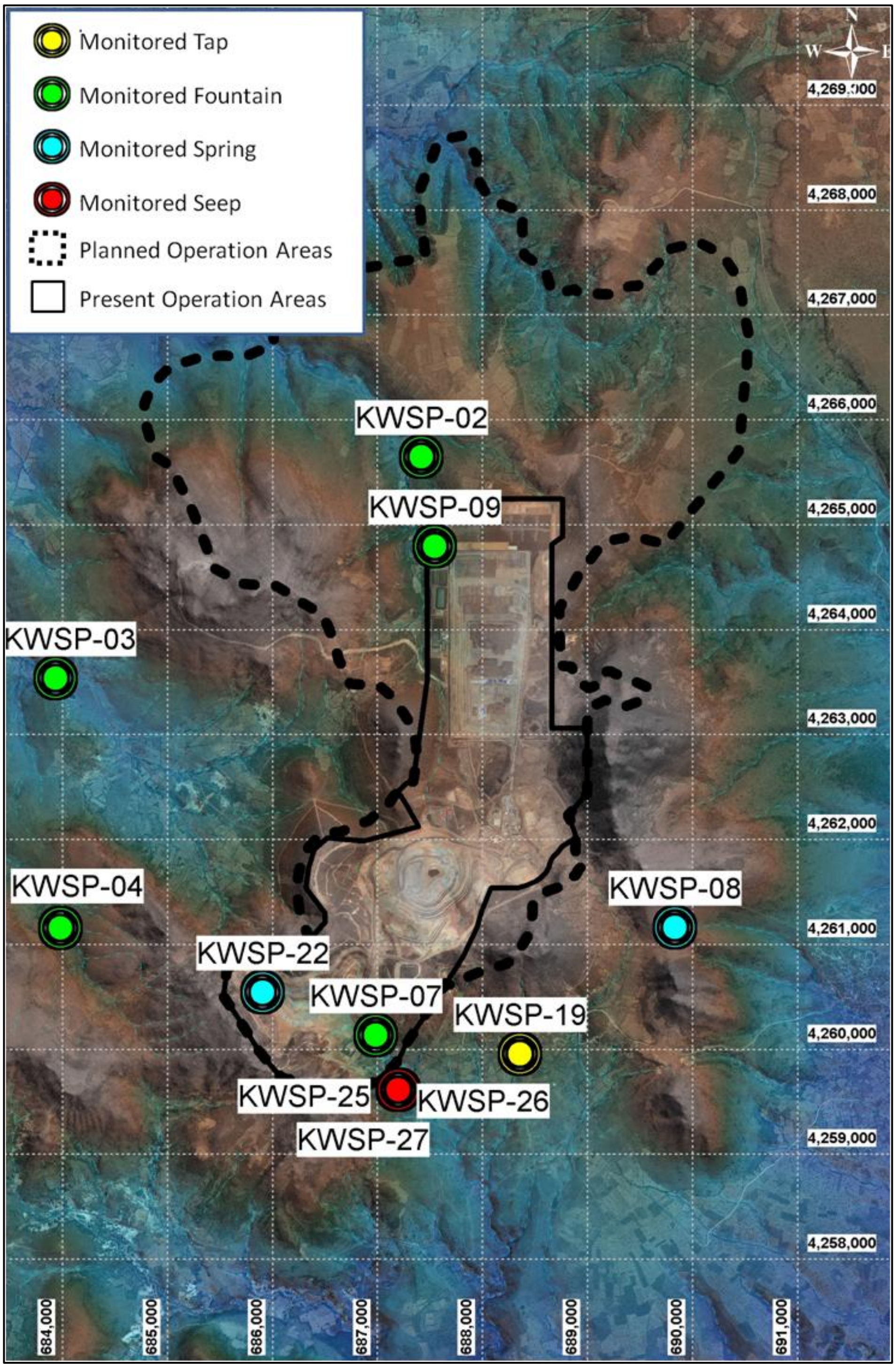

Figure 4.4. Monitored springs, fountains and seeps

Table 4.2. Monitored springs, seeps and fountains within the study area

Monitoring Point	Coordinates		Monitoring Period	Type	Location	Formation
	Easting	Northing				
KWSP-02	687424	4265662	2000-2004	Fountain	Heap Leach Pad Area	Beydağı Volcanics
KWSP-03	683940	4263554	2000-2006	Fountain	Out of Mine Site	Beydağı Volcanics
KWSP-04	683983	4261171	2000-present	Fountain	Out of Mine Site	Alluvium
KWSP-07	686989	4260150	2000-2005	Fountain	Waste Rock Dump Area	Beydağı Volcanics
KWSP-08	689840	4261177	2001-present	Spring	Out of Mine Site	Beydağı Volcanics
KWSP-09	687550	4264809	2001-present	Fountain	Heap Leach Pad Area	Beydağı Volcanics
KWSP-19	688361	4259974	2003-present	Tap	Out of Mine Site	Ulubey Formation
KWSP-22	685909	4260559	2004-present	Spring	Waste Rock Dump Area	Beydağı Volcanics
KWSP-25	687207	4259632	2005-present	Fountain	Waste Rock Dump Area	Beydağı Volcanics
KWSP-26	687199	4259630	2005-present	Fountain	Waste Rock Dump Area	Beydağı Volcanics
KWSP-27	687203	4259628	2005-present	Seep	Waste Rock Dump Area	Beydağı Volcanics

4.1.3 Wells

Wells within and in the vicinity of the mine site are shown on the hydrogeological map presented in Figure 4.5. These wells are grouped into three as follows:

- **Wells drilled by the governmental agencies** (DSİ, Bank of Provinces, Rural Services): There are 16 wells within the study area, of which two of them are drilled by DSI, three by the Bank of Provinces and the rest are drilled by the Rural Services. The ones drilled by DSI are for the purpose of exploration and the rest are drilled for drinking purposes and domestic water supply. Wells drilled by the Rural Services, supply water to the neighboring villages, while the ones drilled by the Bank of Provinces supply water to the municipalities.
- **Wells drilled by individuals:** within the study area apart from the five water supply wells of TÜPRAG, there are 18 wells drilled by individuals. They are all drilled in order to supply irrigational water, except the one drilled south of Çamdere village, which is drilled to supply drinking and domestic water.

As it may be seen from the map given in Figure 4.5, most of the wells drilled by the governmental agencies and by the individuals are located on the Ulubey Formation and the rest are located along the boundary. Therefore, it can be concluded that nearly all the wells within these two groups are pumping water from Ulubey aquifer.

- **Wells drilled by TÜPRAG:** These wells are drilled for the determination of hydrogeological conditions and hydraulic parameters of the mine site and also for the monitoring of groundwater levels and quality. There are a total of 82 wells, 33 of which were drilled before 2007 and 49 of them were drilled after 2011 within the scope of capacity expansion studies. Locations of these wells are shown on the map given in Figure 4.5. Data regarding these wells (name, coordinate, elevation, monitoring period, location with respect to the mining facilities, screened formation, screen interval, depth and hydraulic conductivity values) are presented in the Table 4.3.

- Monitoring activity, which was initiated in 2000, is still continued at 41 wells on monthly basis and groundwater level/pressure is recorded. 28 of them are also monitored for groundwater quality. In order to determine the hydraulic conductivity and storage parameters of the groundwater bearing formations, aquifer tests (namely packer, pumping, recovery and slug tests) are also conducted at several wells. With all this data gathered from the monitoring wells, site characterization is performed.

- Below is a brief description of all these wells grouped according to the well ID's:
    - WR Wells: These wells are located at the vicinity of the present waste rock storage area. So far a total of six wells are drilled for the monitoring of the waste rock storage area. One of these is a replacement well, therefore, at the moment there are six active monitoring wells in this locality.

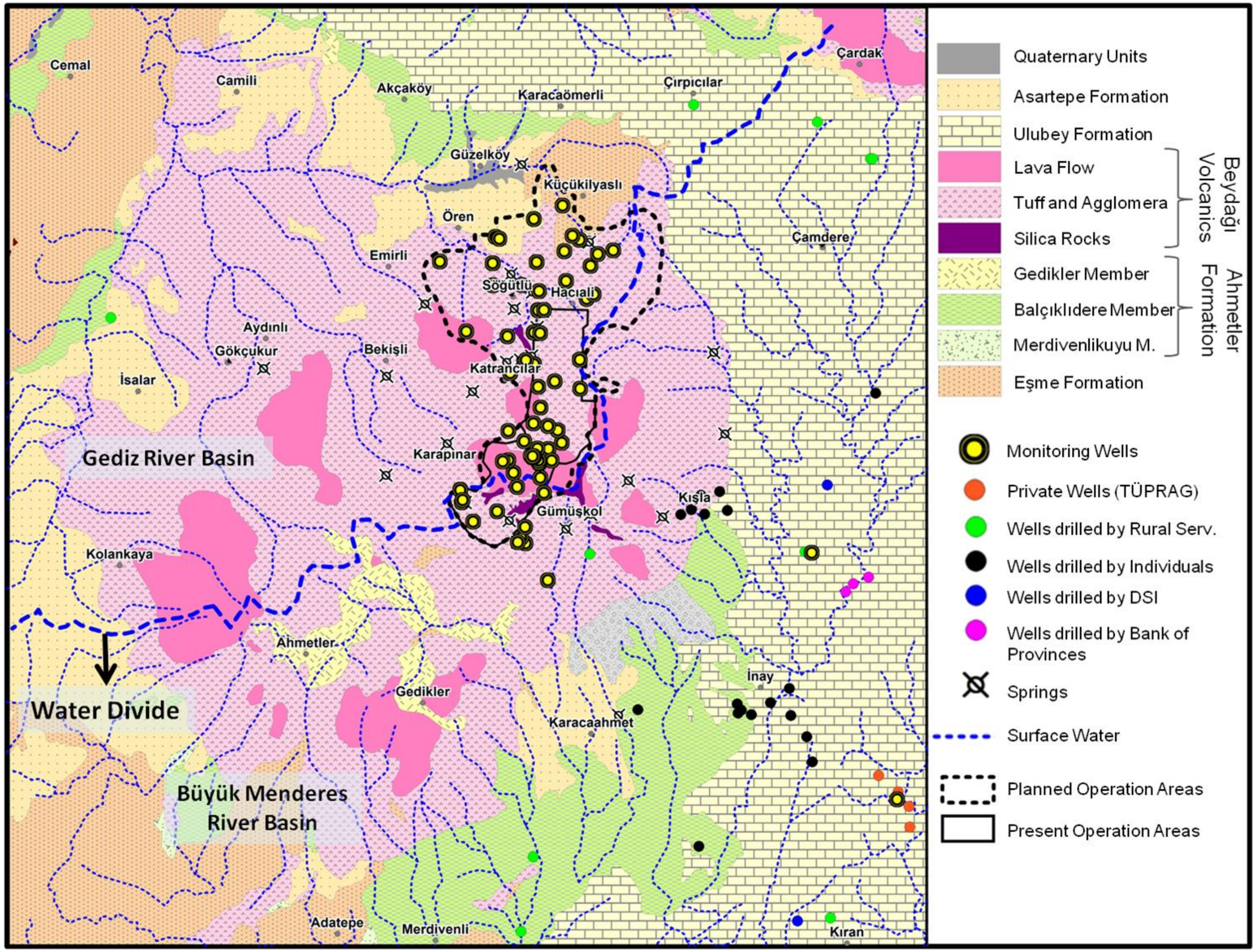

Figure 4.5. Regional hydrogeological map

Table 4.3. Information on the wells drilled within and around the mine site

Monitoring Point ID	Coordinates		Elevation (m)	Monitoring Period	Type of Monitoring Point	Mining Facility	Formation Monitored	Depth (m)	Screen Interval	Hydraulic Conductivity
	Easting	Northing								K (m/s)
KWSP-1	688211	4262054	1000.000	2000-2005	Dug Well	Open Pit	Volcanics	10	-	
KWSP-10	687158	4265822	886.000	2002-present	Water Well	North Waste Rock Storage Area	Schists		-	
KWSP-11	694314	4259546	820.000	2002-2005	Water Well	Outside the mine site	Ulubey Formation (lst)		-	
KWSP-15	688008	4263524	998.283	2002-2005	Monitoring Well	Heap Leach Pad Area	Volcanics - Schists		32.7-45.7	
KWSP-16	688109	4262350	1002.651	2002-2011	Monitoring Well	Open Pit	Intrusives	100	-	
KWSP-17	687473	4261725	1013.780	2002-2005	Exploration Well	Open Pit	Ore Zone	250	180-240	4.07E-09
KWSP-18	686694	4260361	922.848	2003-2006	Exploration Well	Waste Rock Storage Area	Volcanic Conglomerate		0-70	2.00E-08
KWSP-20	696527	4253663	690.000	2003-2004	Water Well	Outside the mine site	Ulubey Formation (lst)		-	
KWSP-21	685832	4260561	1009.782	2003-2004	Monitoring Well	Waste Rock Storage Area	Volcanic Conglomerate	40	-	
KWSP-23	685848	4260617	1009.841	2004-2005	Monitoring Well	Waste Rock Storage Area	Volcanic Conglomerate	20	-	
KWSP-24	686115	4260100	992.151	2004-2009	Monitoring Well	Waste Rock Storage Area	Volcanic Conglomerate	20	-	
WR-1	685785	4260862	1056.500	2005- present	Monitoring Well	Waste Rock Storage Area	Volcanics	32		
WR-1A	685787	4260851	1056.670	2012-present	Monitoring Well	Waste Rock Storage Area	Volcanics	61		
WR-2	687283	4259743	881.660	2005- present	Monitoring Well	Waste Rock Storage Area	Volcanic Conglomerate	52.5	16-52	3.66E-07
WR-3	687396	4259609	876.910	2005- present	Monitoring Well	Waste Rock Storage Area	Volcanic Conglomerate	51	14-50	2.55E-07
WR-4	687375	4260004	920.060	2005- present	Monitoring Well	Waste Rock Storage Area	Volcanics	40.5	16-40	1.61E-06
WR-5	687204	4259630	890.000	2005- present	Monitoring Well	Waste Rock Storage Area	Porphyry Latite Lava	40.5	16-40	5.02E-07
WR-6	687953	4258737	844.740	2005- present	Monitoring Well	Waste Rock Storage Area	Volcanic Conglomerate	32	11658	2.17E-07
LP-1	687679	4262887	975.560	2005- present	Monitoring Well	Heap Leach Pad Area	Volcanoclastics	51	14-50	2.39E-07
LP-2	687501	4263932	938.150	2005- present	Monitoring Well	Heap Leach Pad Area	Volcanic Breccia	51	28-50	2.00E-07
LP-3	687499	4263927	937.990	2005- present	Monitoring Well	Heap Leach Pad Area	Volcanic Breccia	21	43983	1.70E-07
LP-4A	687473	4264687	924.800	2012-present	Monitoring Well	Heap Leach Pad Area	Schists	90	50-86	9.54E-08
LP-4	687550	4264670	930.830	2011-2012	Monitoring Well	Heap Leach Pad Area	Volcanic Breccia - Schists	54	16-48	1.18E-07
LP-5A	687481	4264689	925.430	2012-present	Monitoring Well	Heap Leach Pad Area	Volcanic Breccia	34	14-30	9.01E-07
LP-5	687630	4264678	941.822	2011-2012	Monitoring Well	Heap Leach Pad Area	Volcanic Breccia	34	13.5-33.5	8.65E-09
LP-6	687561	4265227	939.250	2011-present	Monitoring Well	Heap Leach Pad Area	Schists	180	148-176	2.61E-06
LP-7	687568	4265225	939.680	2011-present	Monitoring Well	Heap Leach Pad Area	Asartepe Formation	62	24-56	
LP-8	688602	4264058	1033.120	2005- present	Monitoring Well	Heap Leach Pad Area	Volcanics - Schists	150	130-150	1.80E-07
LP-9	688599	4264061	1032.990	2005- present	Monitoring Well	Heap Leach Pad Area	Volcanoclastics	85	20-80	1.45E-07

Table 4.3. Information on the wells drilled within and around the mine site (continued)

Monitoring Point ID	Coordinates		Elevation (m)	Monitoring Period	Type of Monitoring Point	Mining Facility	Formation Monitored	Depth (m)	Screen Interval	Hydraulic Conductivity
	Easting	Northing								K (m/s)
LP-10	688629	4263363	1085.610	2005- present	Monitoring Well	Heap Leach Pad Area	Volcanoclastics	80	20-80	1.49E-07
LP-11	687609	4263388	953.550	2005- present	Monitoring Well	Heap Leach Pad Area	Schists	51	14-50	5.85E-07
PZ-2	687981	4261617	1051.660	2007-2012	Monitoring Well	Open Pit	Pyroclastics	310	145-305	
PZ-3	687895	4261897	1013.560	2007-present	Monitoring Well	Open Pit	Pyroclastics	286	136-280	
PZ-4	687303	4262066	1003.290	2007-2011	Monitoring Well	Open Pit	Pyroclastics - Schists	312	103-307	
PZ-5	687064	4261303	1039.470	2007-2009	Monitoring Well	Open Pit	Pyroclastics	340	139-335	
PZ-6	686930	4261600	995.530	2007-2010	Monitoring Well	Open Pit	Pyroclastics - Ore Zone	288	94-282	
PZ-7	687715	4261196	1056.830	2007-2010	Monitoring Well	Open Pit	Pyroclastics - Ore Zone	336	153-329	
WS-1	687501	4263932	938.431	-	Water Well	Heap Leach Pad Area	Volcanics-Schists	200	12-196	1.09E-07
WS-2	687708	4265237	933.954	-	Water Well	Heap Leach Pad Area	Schists	200	40-196	1.02E-07
WS-3	686916	4262303	946.130	2007-present	Monitoring Well	Outside the mine site	Volcanics- Schists	200	56-196	2.24E-09
HY-1	687504	4266387	968.390	2012-present	Monitoring Well	North Extension Areas	Asartepe Formation	86	48-80	5.34E-08
HY-2	686495	4266971	957.850	2012-present	Monitoring Well	North Extension Areas	Asartepe Formation	68	32-64	kuru
HY-3	688528	4266947	894.510	2012-present	Monitoring Well	North Heap Leach Pad Area	Schists	51	22-42	9.55E-08
HY-4	687415	4267418	971.550	2012-present	Monitoring Well	North Extension Areas	Asartepe Formation	102	51-95	2.50E-09
HY-5	686448	4266335	893.880	2012-present	Monitoring Well	North Waste Rock Storage Area	Volcanoclastics	64	28-60	6.99E-08
HY-6	686463	4265801	935.950	2012-present	Monitoring Well	North Waste Rock Storage Area	Volcanoclastics	100	28-96	9.22E-08
HY-7	689347	4266714	911.260	2012-2012	Monitoring Well	North Heap Leach Pad Area	Schists	55.3	23.3-51.3	1.19E-08
HY-8	688809	4266330	917.350	2012-present	Monitoring Well	North Heap Leach Pad Area	Schists	51	27-47	3.79E-07
HY-9	685169	4266344	888.215	2012-present	Monitoring Well	North Waste Rock Storage Area	Porphyry Latite - Volcanic Breccia	181	52-168	4.56E-09
HY-10	686841	4264583	973.305	2012-present	Monitoring Well	North Waste Rock Storage Area	Pyroclastics	101.7	37.7-93.7	6.44E-08
HY-11	685847	4264679	1128.835	2012-present	Monitoring Well	North Waste Rock Storage Area	Volcanic Breccia	200	52-192	7.84E-08
GC-445	687520	4262499	984.690	2011-present	Monitoring Well	Open Pit	Pyroclastics	292.9	140.5-190.5	
GC-446	687631	4261897	979.558	2011	Geotechnical Borehole	Open Pit		461.5	-	
GC-447	687874	4262449	986.010	2011-present	Monitoring Well	Open Pit	Pyroclastics	848.5	310-360	
GC-448	687159	4260961	1046.401	2011	Monitoring Well	Open Pit	Pyroclastics	500.5	251-301	
GC-449	686797	4261567	1006.340	2011-present	Monitoring Well	Open Pit	Intrusives	419.5	128-178	
GC-450	687659	4261617	925.615	2011	Geotechnical Borehole	Open Pit		500	-	
GC-451	687506	4266384	968.460	2011-present	Monitoring Well	North Extension Areas	Schists	300.6	110-130	

Table 4.3. Information on the wells drilled within and around the mine site (continued)

Monitoring Point ID	Coordinates		Elevation (m)	Monitoring Period	Type of Monitoring Point	Mining Facility	Formation Monitored	Depth (m)	Screen Interval	Hydraulic Conductivity
	Easting	Northing								K (m/s)
GC-452	686592	4266929	955.841	2011	Geotechnical Borehole	North Extension Areas		350.5	-	
GC-453	688733	4265528	1005.330	2011-present	Monitoring Well	North Heap Leach Pad Area	Schists	300.1	100-120	
GC-454	686445	4266336	893.920	2011-present	Monitoring Well	North Waste Rock Storage Area	Schists	301	210-242	
GC-455	686461	4265803	935.380	2011-present	Monitoring Well	North Waste Rock Storage Area	Schists	287.7	230-280	
GC-456	686931	4263701	974.681	2011-present	Exploration Well	North Waste Rock Storage Area		302	-	
GC-457	687299	4264017	938.530	2011-present	Monitoring Well	North Waste Rock Storage Area	Schists	302.5	114-142	
KPT-1	687809	4260836	1039.050	2012-present	Monitoring Well	Open Pit	Pyroclastics	498	94-498	2.10E-08
KPT-2	687677	4261558	940.010	2012-2012	Monitoring Well	Open Pit	Intrusives	262	54-262	1.10E-06
KPT-3	687679	4261541	940.110	2012-2012	Monitoring Well	Open Pit	Intrusives	316	60-280	7.83E-07
KPT-4	687667	4261564	939.900	2012-2012	Monitoring Well	Open Pit	Intrusives	153	0-153	1.07E-06
PBPW-01	687538	4261699	869.939	2012	Monitoring Well	Open Pit	Intrusives	35.45	13.45-35.45	
PBMW-01	687551	4261699	870.001	2012	Monitoring Well	Open Pit	Intrusives	33.07	21.07-33.07	
PBMW-02	687527	4261700	870.016	2012	Monitoring Well	Open Pit	Intrusives	26.79	6.79-26.79	
PBMW-03	687539	4261687	869.883	2012	Monitoring Well	Open Pit	Intrusives	28.75	6.75-28.75	
PBMW-04	687534	4261714	870.109	2012	Monitoring Well	Open Pit	Intrusives	37.02	15.02-37.02	
PBMW-05	687518	4261711	870.149	2012	Monitoring Well	Open Pit	Intrusives	32.74	10.74-32.74	
PBMW-06	687518	4261681	869.639	2012	Monitoring Well	Open Pit	Intrusives	35.57	23.57-35.57	
DH-2	688100	4267760	864.961	2012	Geotechnical Borehole	North Extension Areas	Schists	22	not screened	
DH-3	688353	4267039	911.150	2012	Geotechnical Borehole	North Heap Leach Pad Area	Schists	29	not screened	
DH-4	688168	4266665	944.320	2012	Geotechnical Borehole	North Heap Leach Pad Area	Schists	28	not screened	
DH-7A	687577	4265687	934.700	2012	Geotechnical Borehole	North Extension Areas	Alluvium - Volcanic Breccia	30	not screened	
DH-8A	688902	4265645	1007.830	2012	Geotechnical Borehole	North Heap Leach Pad Area	Schists	20	not screened	
DH-9	688975	4266616	910.986	2012	Geotechnical Borehole	North Heap Leach Pad Area	Volcanic Conglomerate	30	not screened	
DH-10A	688227	4265948	967.880	2012	Geotechnical Borehole	North Heap Leach Pad Area	Volcanic Breccia	22	not screened	

- LP Wells: These wells are located around the present heap leach pad area. 13 wells are drilled at this location, two of which are for replacement and 11 of them are active monitoring wells.
- PZ Wells: They are seven deep wells drilled for geotechnical purposes. They are all located at the perimeter of the open pit. They are screened and used to monitor the groundwater levels around the open pit. However, as a consequence of the excavations and progression of the pit, they are all cancelled except one.
- WS Wells: These wells are drilled for water supply purposes; however they are then converted to monitoring wells. There are three WS wells, two of which are located in the vicinity of the present heap leach pad area and the third one is out of the mine site. At the moment, only one of them is used for monitoring purposes.
- KWSP Wells: There are a total of 11 KWSP wells, which have been used for monitoring. Only one of these wells is currently used for monitoring, which is located near Söğütlü Creek. The rest, previously drilled at several locations either as monitoring and exploration wells or as shallow wells for water supply, is all inactive at the moment.
- HY Wells: These 11 wells are drilled for the characterization of the planned expansion areas in the north. Except two of them (one is dry and the other one is closed because of the artesian conditions), the rest are currently being monitored twice a month for the determination of the groundwater levels and monthly for water quality.
- GC Wells: There are 13 GC wells, drilled for geotechnical and exploration purposes. Three of them are inclined and one has collapsed during completion, but the remaining nine wells are available for groundwater level monitoring only.
- DH Wells: These seven wells are drilled at the planned expansion areas for geotechnical purpose. They are shallow wells of depths around 30 m. They are not included within the monitoring program.
- KPT Wells: These four wells are drilled at and just around the open pit in order to conduct pumping tests and to determine the hydraulic parameters in this area.
- PBM Wells (and PBPW): These seven shallow wells (around 30 m depth) are drilled at the bottom of the open pit in order to conduct a pumping test and to determine the hydraulic parameters just below the pit bottom. Furthermore, the aim of drilling these wells was also to test dewatering performance with vertical wells.

4.2 Regional Hydrogeology

Upon the assessment of all the available data gathered from the above mentioned water points, rock units outcropping within and around the study area are classified according to their lithologies and water-bearing capacities. Hydrogeological map given in Figure 4.5, shows these hydrogeologically classified units, together with water wells, springs and drainage network. A brief description of the hydrogeological units presented in this figure is summarized below:

Schists and Gneisses (Eşme Formation)

This unit, made up of schists and gneisses, forms the crystalline basement rocks. These metamorphic rocks crop out in the west and southwest parts of the study area around Kayalı, Eşme, Takmak and west of Örencik. They are locally overlain by Ahmetler and Asartepe Formations in the west and volcanic rocks in the mine site. These rocks are classified as poor aquifers, with very low yielding wells and springs. The yields of the wells drilled in this formation at the mine site and in the vicinity of Eşme are around 2.5–3.0 L/s. These rocks, however, are important because of their regional extent and generally good quality of water. According to the results of the aquifer tests conducted at the mine site, average hydraulic conductivity of this unit changes between 1.19×10^{-8} m/s and 2.61×10^{-6} m/s, while geometric mean is calculated as 2.02×10^{-7} m/s.

Volcanics (Beydağı Volcanics)

These rocks, consisting of lava flows, agglomerates, and tuffs; cover extensive areas at the central part of the study area (Figure 4.5). These rocks intrude within and overlie the schists and gneisses at the mine site. Toward east they interfinger and grade into the clastic sedimentary rocks and lacustrine limestones of the Ulubey and Ahmetler Formations. Groundwater bearing potential of these volcanic units is very low. Within the mine site, especially in the leach pad and waste rock storage areas, they form local perched aquifer systems over the schists and gneisses. Pump and slug test results show that hydraulic conductivity of the unit ranges between 4.56×10^{-9} m/s and 1.61×10^{-6} m/s, while geometric mean is calculated as 1.05×10^{-7} m/s. Hydraulic conductivity of the intrusive rocks of this unit, which are observed at and around the open pit, is almost the same; ranging between 4.07×10^{-9} m/s and 1.10×10^{-6} m/s, with the geometric mean of 1.67×10^{-7} m/s.

Ahmetler Formation

Merdivenlikuyu, Balçıklıdere and Gedikler are the members of the Ahmetler Formation. This formation made up of pebblestone, sandstone, siltstone, tuffite, mudstone, marl and limestone. Fine grained clastics are more common. It is known that limited number of wells drilled in this formation have very low yields (Yazıcıgil, et al., 2008); therefore, this formation is classified as impermeable. Moreover, it should be noted that forming the lower boundary of Ulubey aquifer, it is of regional importance. Ahmetler Formation overlies schists and gneisses at northern and southeastern parts of the study area.

Ulubey Formation

Even though it is not located within the study area, having a broad extension at the eastern parts (around 1700 km^2), this sedimentary unit is the major aquifer in the regional scale. It is made up of thick, very thick and locally massive lacustrine limestones and alternating marl units. Thickness of the unit is around 250 m. Bedding is horizontal to sub-horizontal. Formation has fractured, jointed and karstic nature. Karstic cavities and solution cracks are common. Wells having highest yields (15-30 L/s) and springs having highest discharge rates (250-500 L/s) are located within the Ulubey Formation. Among the 41 wells drilled in this formation, yields change between dry and 30 L/s, with average yields of 11 L/s; while specific capacity values range between 0 and 17.46 L/s/m, with average 2.78 L/s/m. According to the pumping test results conducted at wells drilled by DSI and the Bank of Provinces, transmissivity of this unit is determined to range between 6 and 5158 m^2/day and hydraulic conductivity is determined in the range between 1.04×10^{-6} m/s and 1.45×10^{-3} m/s. While geometric mean of the hydraulic conductivity is calculated as 3.58×10^{-5} m/s using the results of 20 pumping tests. Storage coefficient of the unit having unconfined flow conditions is determined as 0.059, with the pumping test conducted at the well field of TÜPRAG (SRK, 2003). As stated by Yazıcıgil (2000), Ulubey Formation includes all the classes having poor, middle and good aquifer properties. Local good aquifer properties of the formation are believed to derive from the fracture, crack and fault induced karstification. Impermeable lower boundary of the unconfined Ulubey aquifer is formed by the Ahmetler Formation. Groundwater level of the Ulubey aquifer is given in Figure 4.6. According to this graph, groundwater level is around 900 m in the center of Uşak and decreases southwards, reaching 600 m levels around Ulubey town and decreases to 410 m at Adıgüzel Dam, in the southern boundary of the basin.

Asartepe Formation

Major outcrops of this formation are observed in northern and southeastern parts of the study area, where it overlies schists and gneisses. Its most extensive outcrops, on the other hand, are observed outside the boundaries of the study area, in the northeast around Sivaslı and Banaz (Yazıcıgil et al., 2008). It is made up of alternations of pebblestone, sandstone, siltstone, claystone and marl. Fine grained units are very common. At the field, they can be distinguished with their reddish brown color. This formation is classified as poor to middle aquifer, as the limited number of wells drilled in this formation has low yields. At the five wells drilled in Asartepe Formation, within and around the study area, yields range between 1.46 L/s and 26 L/s, while its average is 11.3 L/s. Specific capacity of these wells are calculated in the range 0.06 L/s/m and 17.54 L/s/m, with average of 4.7 L/s/m. Pumping test results conducted at four DSI wells, indicated that transmissivity of the unit ranges between 94 m^2/day and 796 m^2/day, while hydraulic conductivity ranges between 6.50×10^{-6} m/s and 1.00×10^{-4} m/s. Four wells are drilled in this formation in the northern parts of the mine site. One of these wells is dry, and two have very low yields, therefore only slug tests could be conducted. According to the results of these slug tests, hydraulic conductivity of the unit is calculated as 1.16×10^{-8} m/s indicating that at the mine site this formation is less permeable.

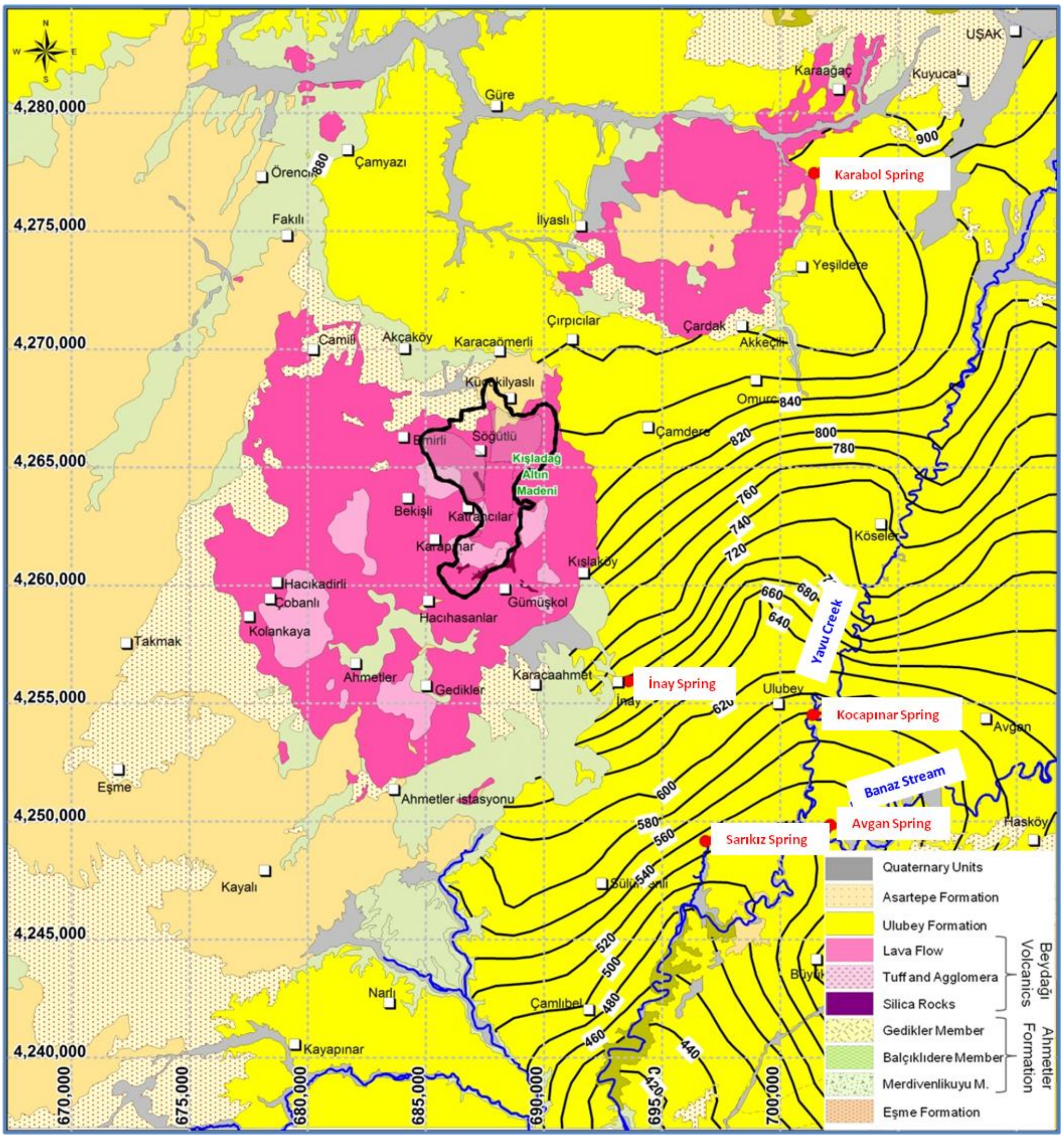

Figure 4.6. Groundwater elevation map of Ulubey Aquifer (Yazıcıgil et al., 2008)

Quaternary Deposits

This units is made up of alluvial fan deposits, terrace deposits and alluvium. Apart from these, there are some deposits previously used for agriculture and named as agricultural disturbance, which are also grouped in this unit. Within the study area, this unit is observed west and north parts of the open pit, generally along stream beds and along steep slopes. Outside the study area, especially to the northeast around Uşak, Banaz and Güre many shallow and caisson wells drilled in alluvial aquifers are used efficiently for irrigation. Pumping test results conducted at four DSI wells, indicated that transmissivity of the alluvium aquifer ranges between 67 m^2/day and 482 m^2/day, while hydraulic conductivity ranges between 3.93×10^{-5} m/s and 2.50×10^{-4} m/s.

4.3 Site Hydrogeology

In determination of the hydrogeological characteristics of the mine site and its close vicinity, the wells and springs, which are discussed above in detail, are used. The locations of these monitoring points are shown on Figure 4.7. Moreover, in order to give a better insight on the location of these wells and their position with respect to the main mining facilities (open pit, heap leach pad and waste rock storage facilities, and also planned north expansiomn areas), maps from Figure 4.8 to Figure 4.11 are presented, showing all the observation wells at the mine site.

Within the content of this study, groundwater elevation map generated by the previous studies is revised with the recently available data obtained from the new wells. Especially for the northern parts of the mine site, where there was no data, many new wells are drilled for the characterization of the planned expansion areas. All these groundwater level measurements are used to develop a groundwater elevation map at regional scale. Apart from the well data, topographical elevations of the springs in the study area, which have been determined during several field studies, and those of the perennial surface waters are also considered during map generation. After a groundwater elevation map is generated, its consistency with the topographical surface and the groundwater levels of the Ulubey Aquifer determined by Yazıcıgil et al. (2008) is checked. Resulting regional groundwater elevation map is shown in Figure 4.12.

The mine site is also located on the groundwater divide. As shown in Figure 4.12, highest groundwater elevations around 1000 m are observed along the surface water divide, at the present leach pad and waste rock storage areas, where higher recharge occurs due to higher elevations. Groundwater level at the open pit, situated just between these two locations, is very low (around 870 m) compared to that observed at leach pad and waste rock storage areas (around 1000 m). Low groundwater levels at the open pit area can be explained by the 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, as well as the formation of new fractures and development of the existing ones as a result of the stress relief as the excavation advances. In other words, 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 those (Yazıcıgil et al., 2013). Moreover, results of the study conducted by Lewis (2002) suggest that joint and fracture systems are dominantly oriented NNW. The anisotropy developed in this direction controls the groundwater flow as well. Groundwater levels reaching elevations around 1000 m within the mine site, decrease to 650-700 m levels, at the northwestern parts of the mine where schists are outcropping and at the southeastern parts where Ahmetler Formation crops out (Figure 4.12).

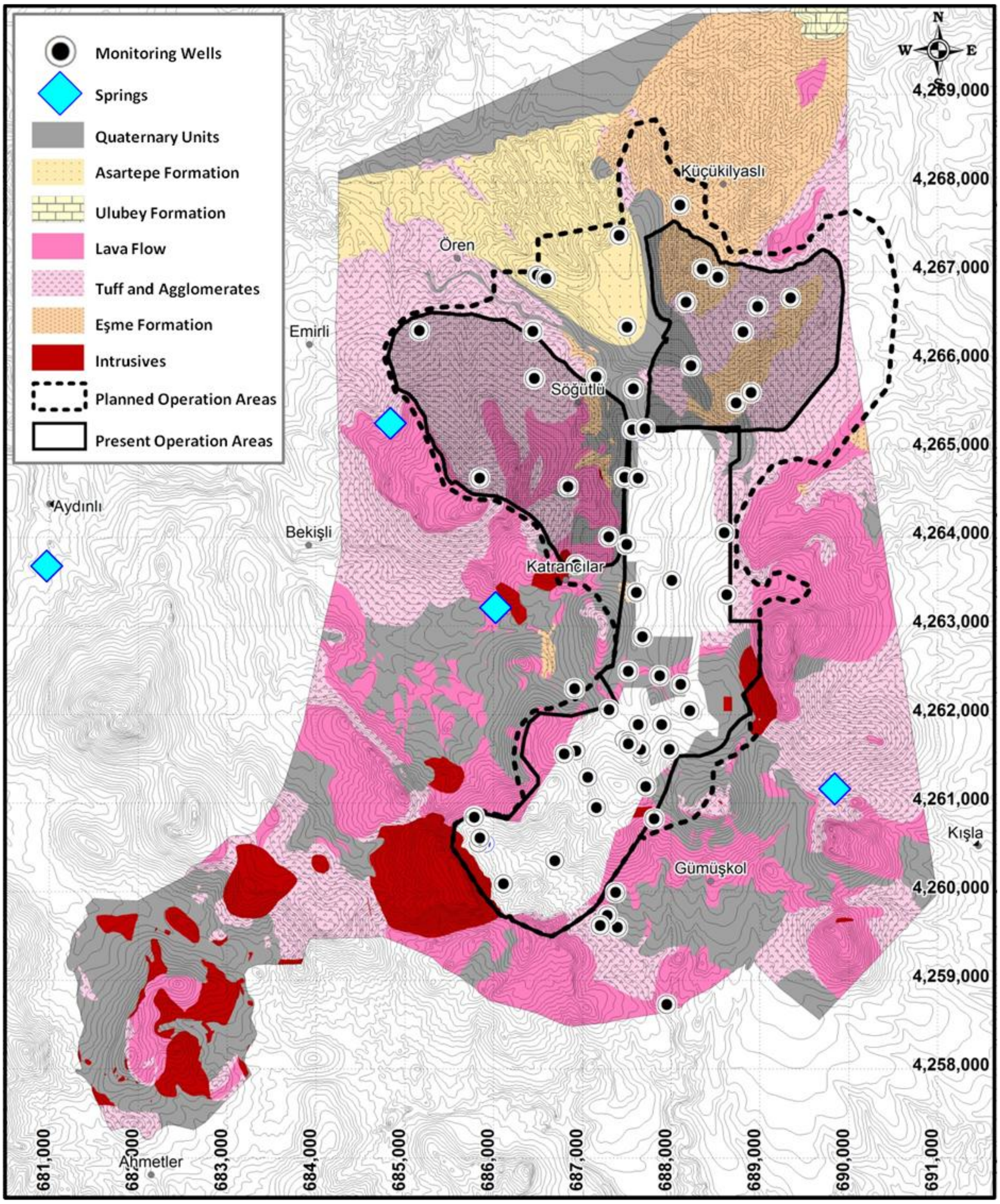

Figure 4.7. Monitoring wells and springs

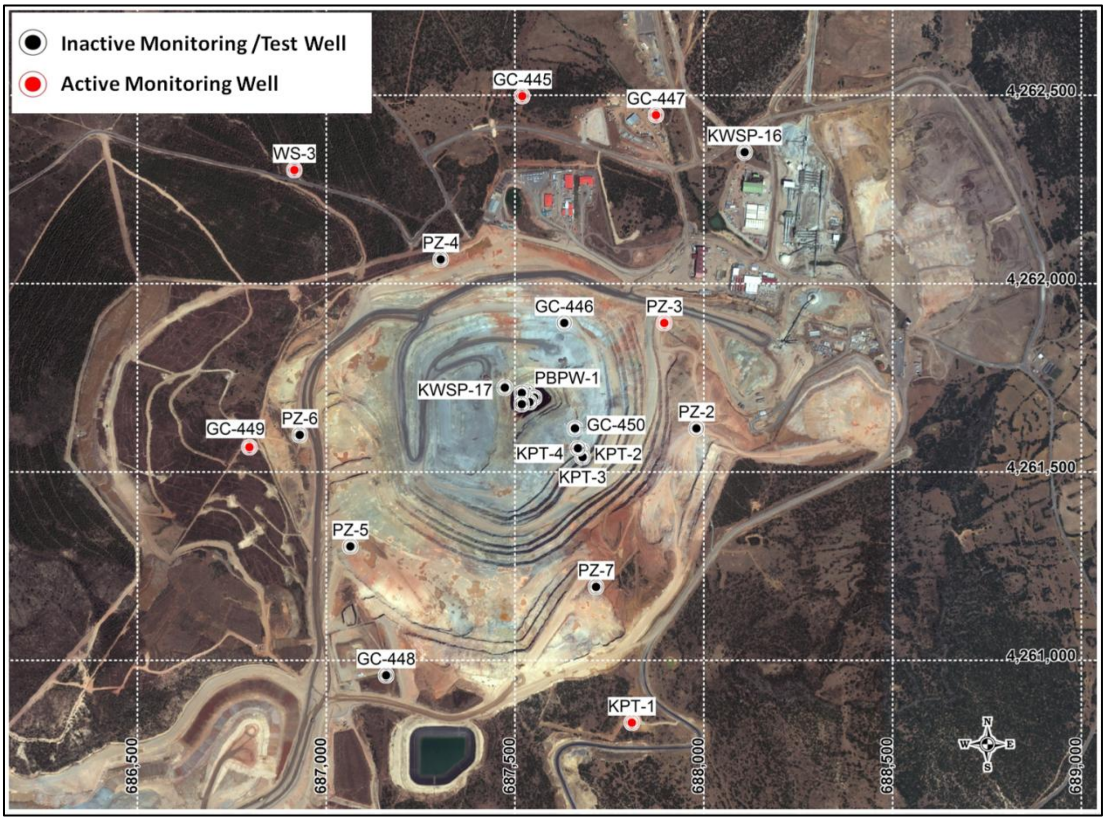

Figure 4.8. Wells within and around open pit area

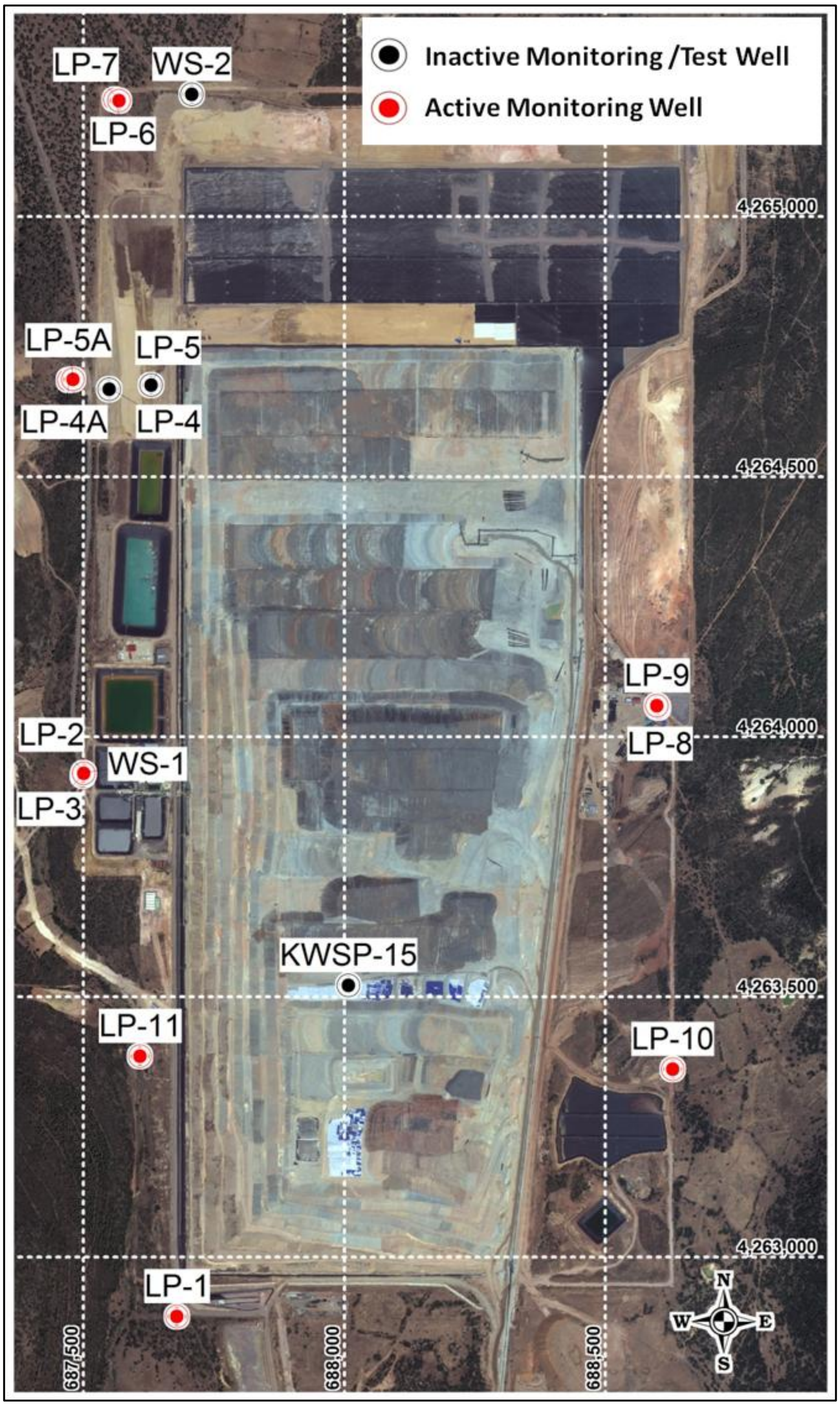

Figure 4.9. Wells within and around heap leach pad area

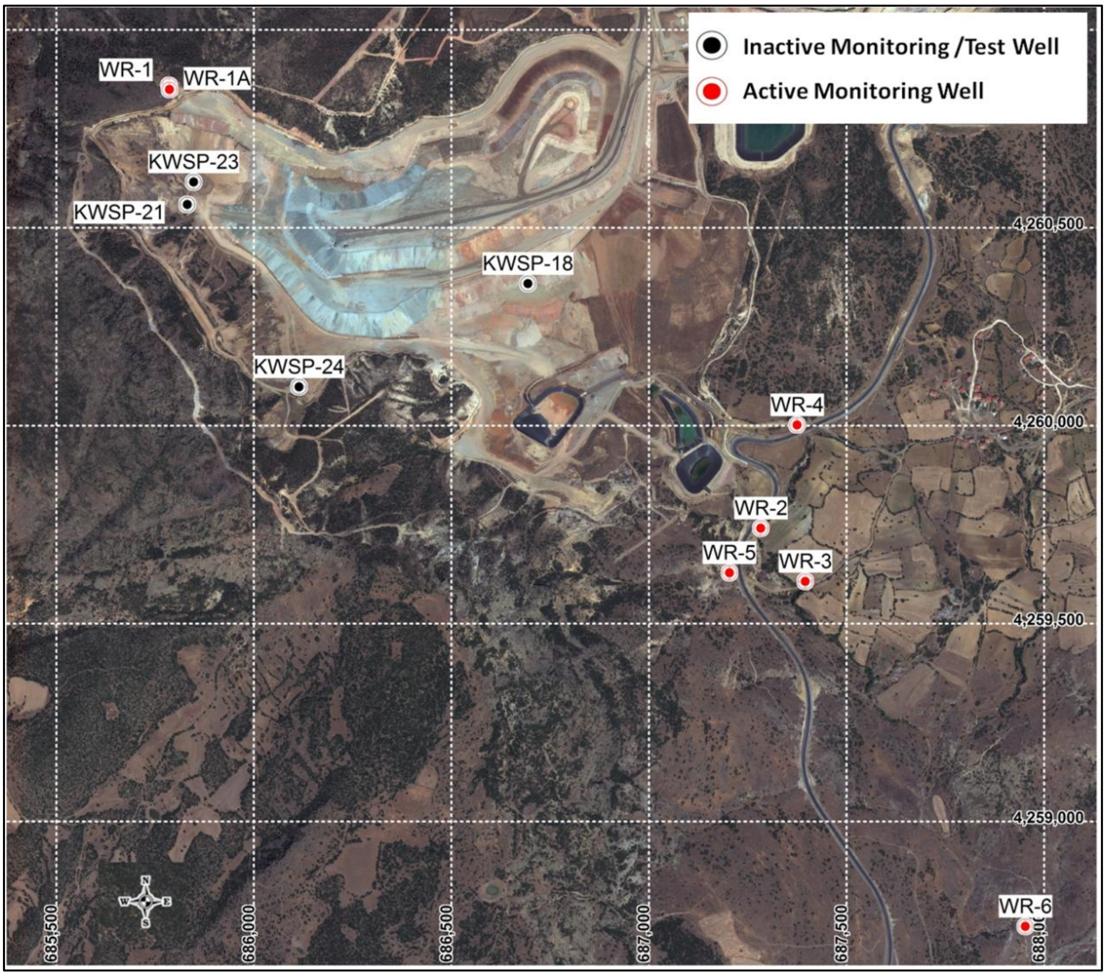

Figure 4.10. Wells within and around waste rock storage area

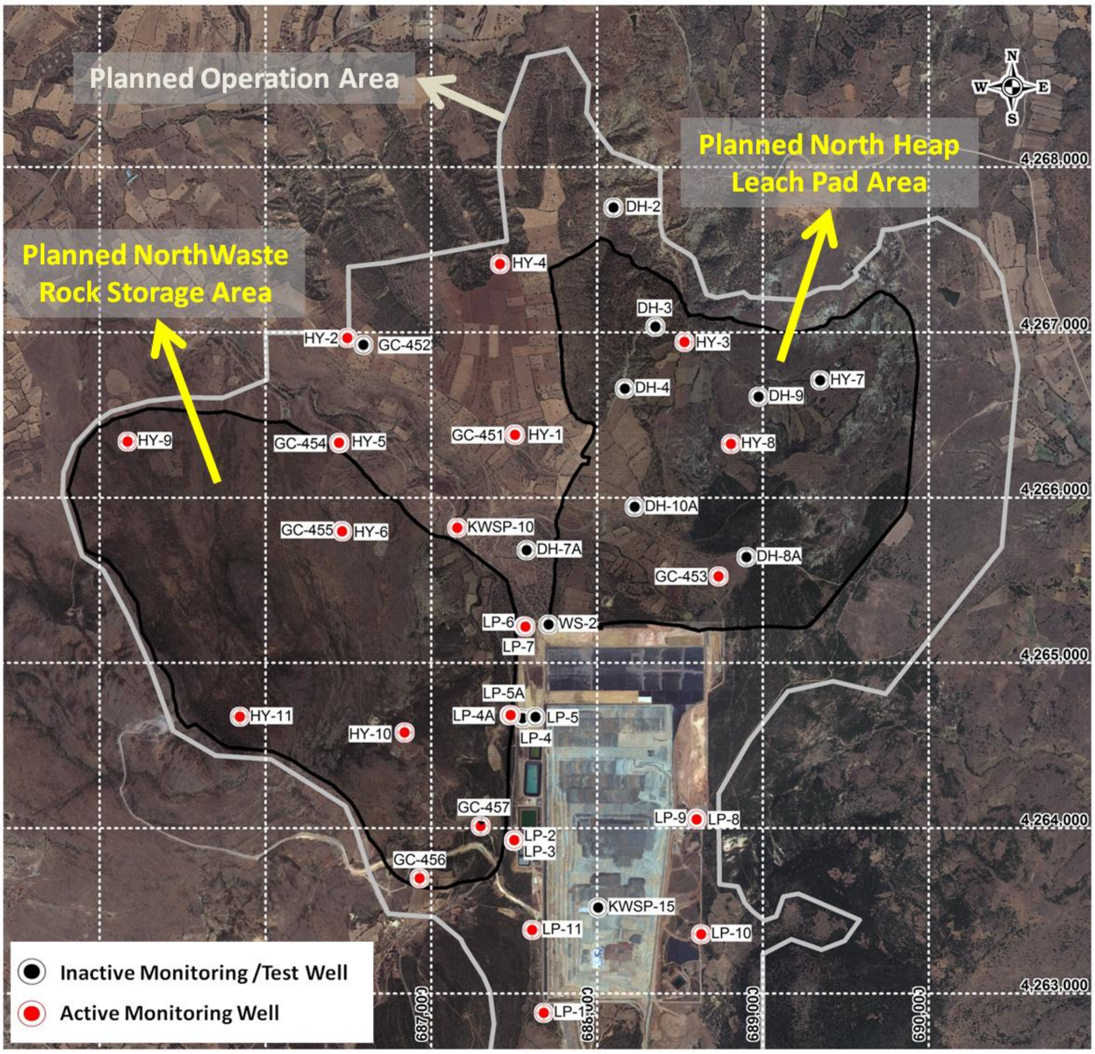

Figure 4.11. Wells within and around proposed expansion area

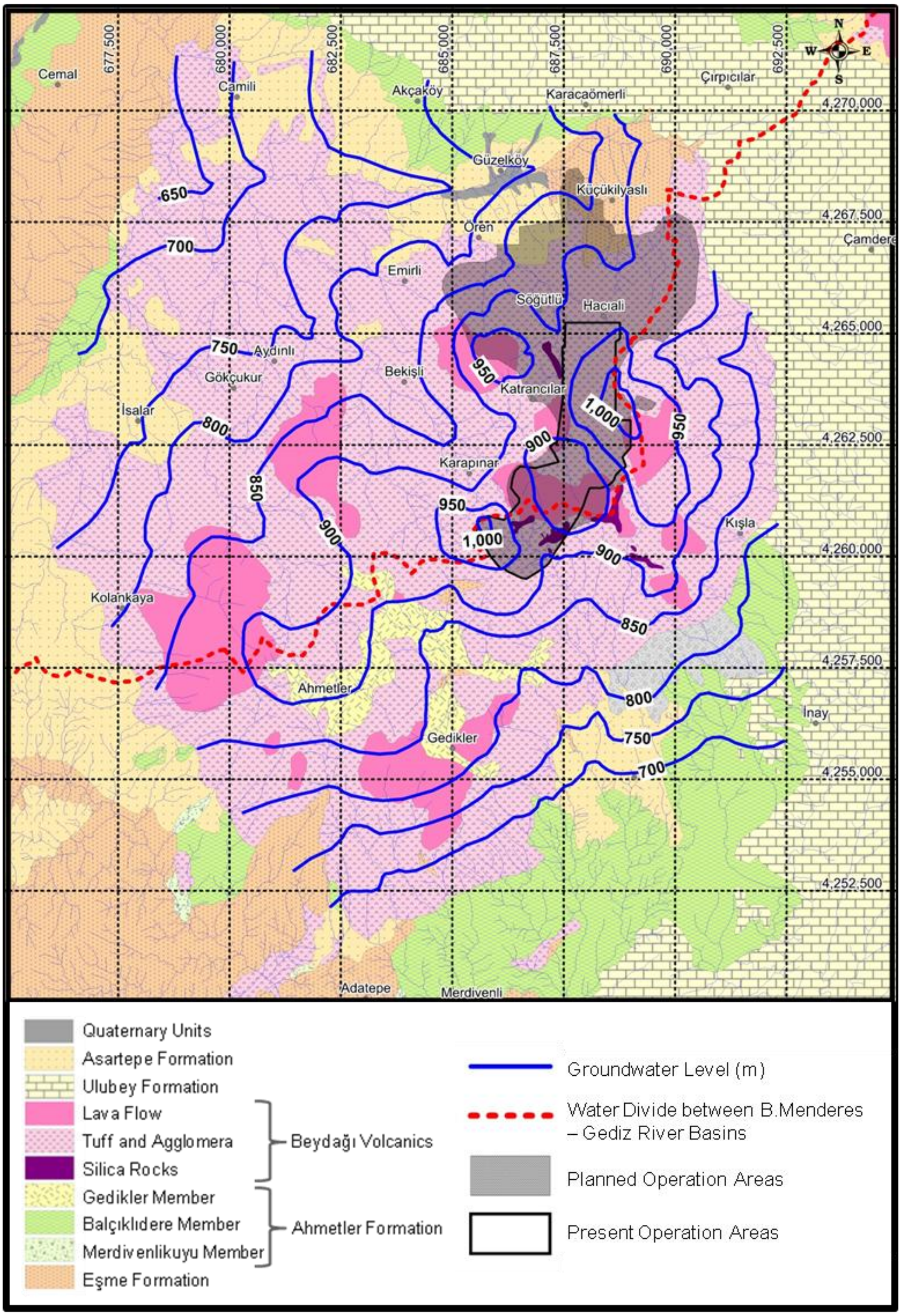

Figure 4.12. Regional groundwater elevation map

4.3.1 Detailed Hydrogeological Characterization of the Open Pit Area

As this research focuses on the processes that will occur in the open pit area during the operational phase of the mine (dewatering activities) and also in the post-closure phase (pit lake formation), in this section hydrogeology of the open pit will be discussed thoroughly. While for the rest of the study area, results of the detailed hydrogeological characterization completed by Yazıcıgil et al. (2013) will be summarized.

Open pit is located within the intrusive rocks (latite porphyry). In order to monitor the groundwater levels and to predict the hydraulic parameters of the units within and around the open pit, many monitoring and test wells are drilled. Locations of these wells are given in Figure 4.7, while detailed information is presented in Table 4.3.

Groundwater level monitoring activities at the open pit area has initiated in 2002. KWSP-17 (or its other name, GR-108) is an exploration well drilled in the ore zone and it is among the first wells included in the monitoring program. Besides, two slug tests are conducted at this well by SRK and Golder Associates, which resulted with hydraulic conductivity values of 5.13×10^{-9} m/s and 3×10^{-9} m/s, respectively. However, these values are obtained from a single point in the open pit; therefore, they do not reflect the areal hydraulic properties of the open pit area. Hence, many other wells are drilled and several kinds of hydraulic tests are performed for the hydrogeological characterization of this area, which is quite different from the units surrounding it.

SRK conducted several tests (packer, airlift and pumping tests) at the six wells which are originally drilled with geotechnical purposes and then converted to piezometers. Packer tests performed at these wells, at 78 different depth intervals, resulted in a hydraulic conductivity range between 1×10^{-9} m/s and 9×10^{-7} m/s, with a geometric mean of 7×10^{-8} m/s (SRK, 2012). Here it should be noted that packer tests can be performed in relatively strong and intact rocks. Hence, at a test well, at the elevations where the material to be tested is broken and weak (hence more porous), test interval is shifted to the closest zone having stronger material to allow testing. As a result, maximum hydraulic conductivity values obtained by the packer tests do not reflect the actual conductivity at the field.

Therefore, in order to determine the hydraulic properties of this highly permeable and loose material (especially the Friable Zone), air lift and pumping tests are conducted by SRK. Results of the air lift test performed at GC-450 well are evaluated by SRK using Leaky Aquifer Model and hydraulic conductivity of the aquifer is calculated as 5.6×10^{-9} m/s, while hydraulic conductivity of the underlying and overlying aquitards are calculated as 1×10^{-6} m/s and 1×10^{-4} m/s. When the results of the same test are evaluated using Gringarten Model for fractured aquifers, hydraulic conductivity is calculated as 6.85×10^{-6} m/s (SRK 2012).

In 2012, four wells are drilled at the open pit area by SRK in order to determine the groundwater levels and hydraulic parameters. One of the two tests performed using these wells, aims to test the Friable Zone and it is conducted by using one pumping well (KPT-2) and two observation wells (KPT-3 and KPT-4). Using the results of this test, hydraulic conductivity of the Friable Zone is calculated as $1.4x10^{-6}$ m/s and specific storage value is calculated as $1.2x10^{-6}$ 1/m. The other test is conducted at KPT-1 well which is drilled within the volcanoclastic units enclosing the intrusives of the open pit. According to the results of this test, hydraulic conductivity of the volcanoclastic units is calculated as $2.1x10^{-8}$ m/s (SRK, 2012).

Moreover, SRK conducted another pumping test at the bottom of the open pit, using one pumping well and 6 observation wells in order to predict the performance of the alternative systems that could be used to dewater the pit, in the progressive stages of the mining facilities.

When the regional groundwater elevation map given in Figure 4.12 is examined, as it is mentioned above, groundwater levels at the open pit (around 870 m) , are very low compared to those at the heap leach pad and waste rock storage areas (around 1000 m). The reasons for this difference are discussed in Section 4.3 in detail.

4.3.2 Temporal Changes in Groundwater Levels within the Mine Site

In order to assess the responses of groundwater levels to precipitation and to determine the seasonal fluctuation (if there is any), water level observations together with the precipitation measurements are plotted against time for all monitoring wells shown in Figure 4.7 (Yazıcıgil et al., 2013). However, as open pit area is the focus of interest of this study, plots of all the wells at this locality is given below. Moreover, in order to show the vertical interactions of different lithologic units, plots of the clustured wells drilled at the heap leach pad area and at the north expansion areas are also given below. These clustered wells are very important for the hydrogeological characterization and very useful in setting up the conceptual model of the site.

The long term groundwater levels measured at PZ wells are plotted against time and presented at the graphs given in figures from Figure 4.13 to Figure 4.18. These graphs also show the precipitation values measured at the mine site for the same time period. Examining those figures, it is noted that groundwater level at an approximate depth of around 150-200 m below ground surface, has risen by 8-10 m, since 2009. This increase is a natural consequence of the increased groundwater recharge caused by two factors: reduced thickness of the vadose zone and enlargement of the catchment due to excavations in the open pit area; and the wet period observed since 2009. Following the dry period during 2007 and 2008, 2009 is a very wet year with a precititation increase of 75-110% compared to 2008's precipitations.

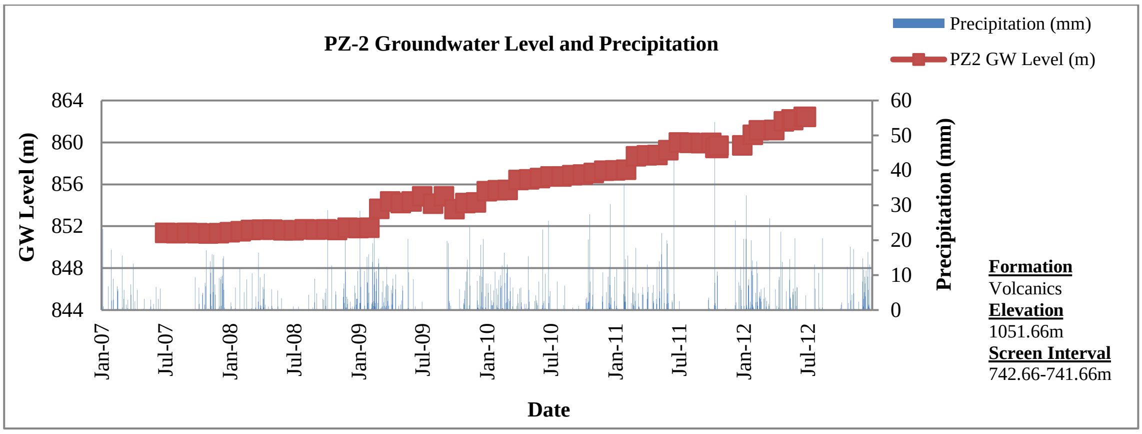

Figure 4.13. Temporal changes in groundwater levels measured at PZ-2

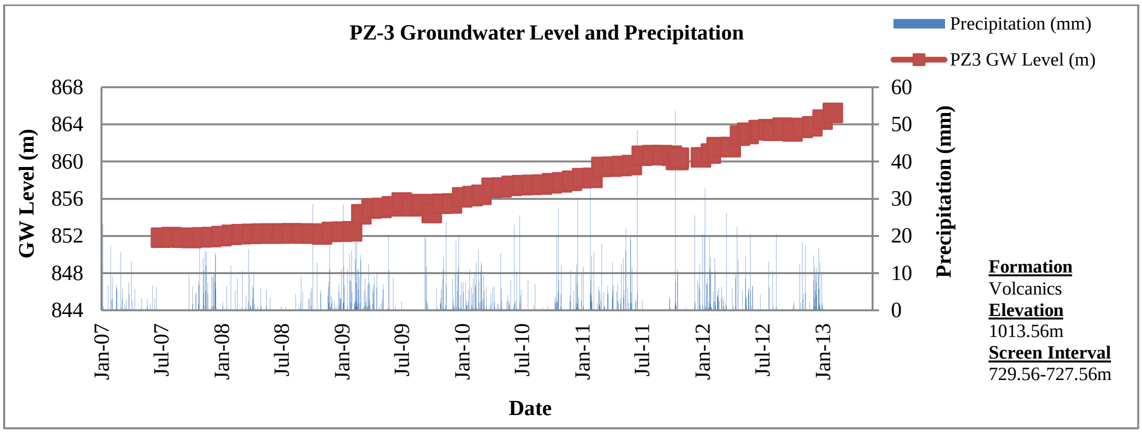

Figure 4.14. Temporal changes in groundwater levels measured at PZ-3

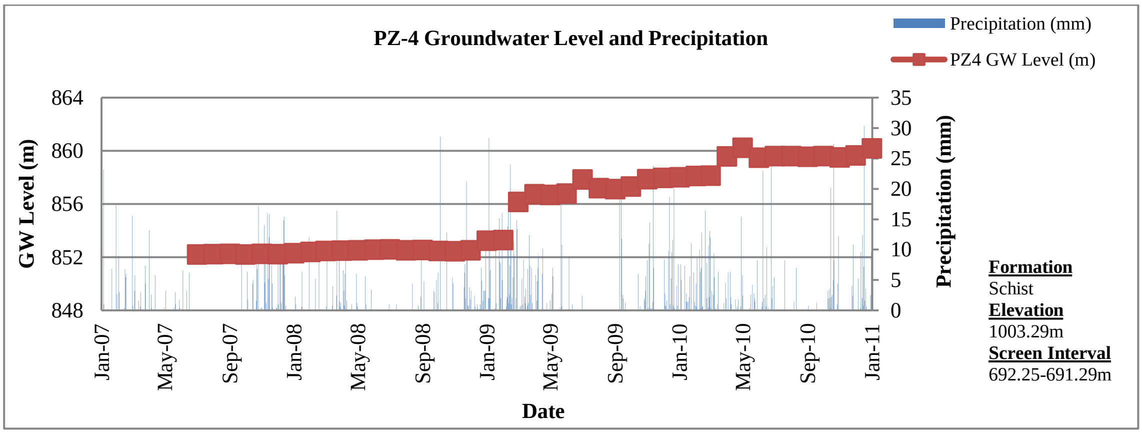

Figure 4.15. Temporal changes in groundwater levels measured at PZ-4

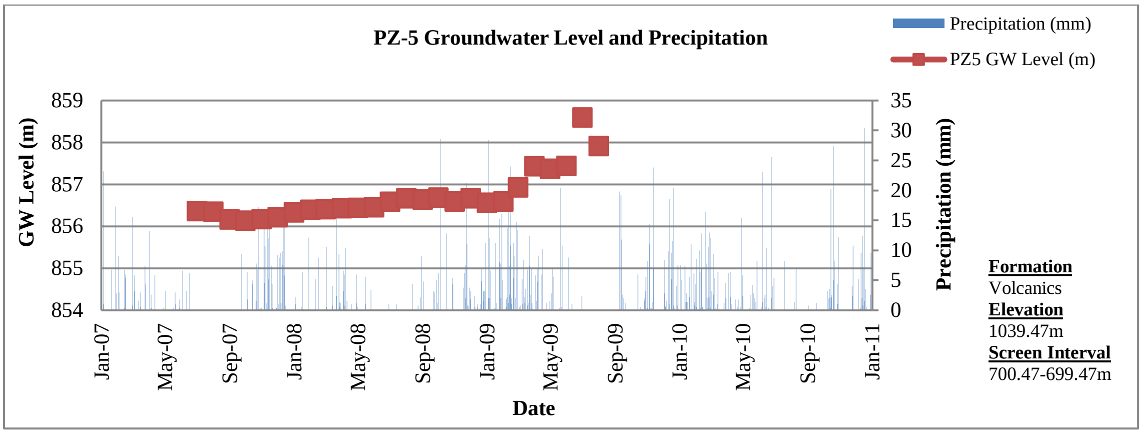

Figure 4.16. Temporal changes in groundwater levels measured at PZ-5

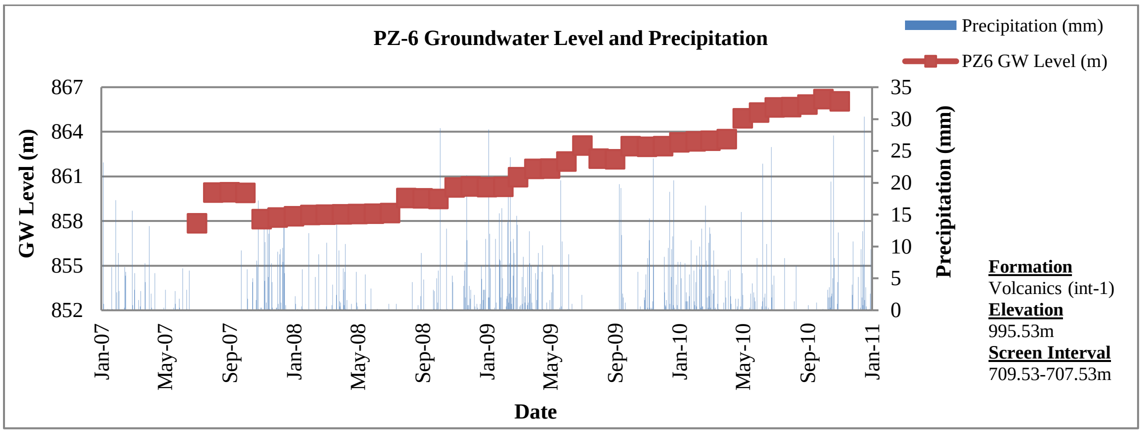

Figure 4.17. Temporal changes in groundwater levels measured at PZ-6

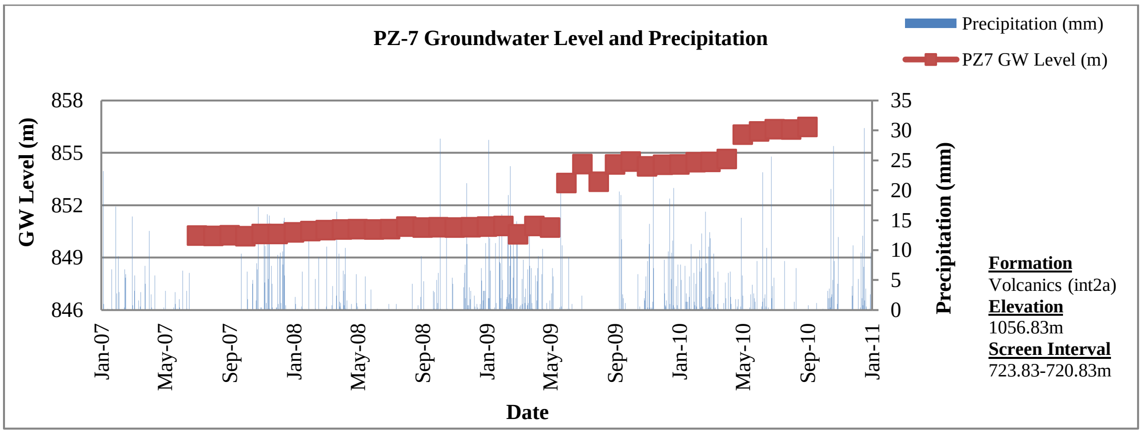

Figure 4.18. Temporal changes in groundwater levels measured at PZ-7

At the mine site, there are several clustered wells screened at different depths in order to determine the vertical interactions between different hydrogeological units (Asartepe Formation, Beydağı Volcanics and Eşme Formation). 2 pairs of them are located around the heap leach pad area (LP-4A and LP-5A, LP-6 and LP-7), while the new ones (HY-1 and GC-451) are also drilled at the north expansion area. Groundwater levels monitored at each clustered well pair are presented in the same graph together with the precipitation in order to investigate the responses of different lithological units to changes in precipitation and also to compare their groundwater levels.

According to the collected data from the individual and clustered wells;

- Figure 4.19 demonstrates the data from clustered well pair, LP-4A completed in schists and LP-5A completed in volcanics. Although data represents a relatively short term period, it is observed that the groundwater levels of the schists are slightly (0.5 m) above the volcanics. In Figure 4.20, data from clustered well pair, LP-6 completed in schists and LP-7 completed in Asartepe Formation, is given. According to this graph, groundwater levels of the schists are 4 m above the Asartepe Formation. These results indicate that the schists are showing a confined behavior in the current leach pad area.
- When groundwater levels of HY-1 (completed in Asartepe Formation) and GC-451 (completed in schists) are examined (Figure 4.21), it is observed that at the planned expansion area north of the mine site, groundwater level of the schists is almost 1 m lower than that of Asartepe Formation.
- When the two different behavior of the schist units is examined (confined at the present heap leach pad area, while unconfined at the north expansion area), it is observed that there is not enough evidence to confirm the confined behavior of this unit throughout the study area.
- Rather, it is concluded that groundwater levels monitored at different lithological units are very close to each other, all around the mine site. Moreover, different units show similar responses to the precipitation.

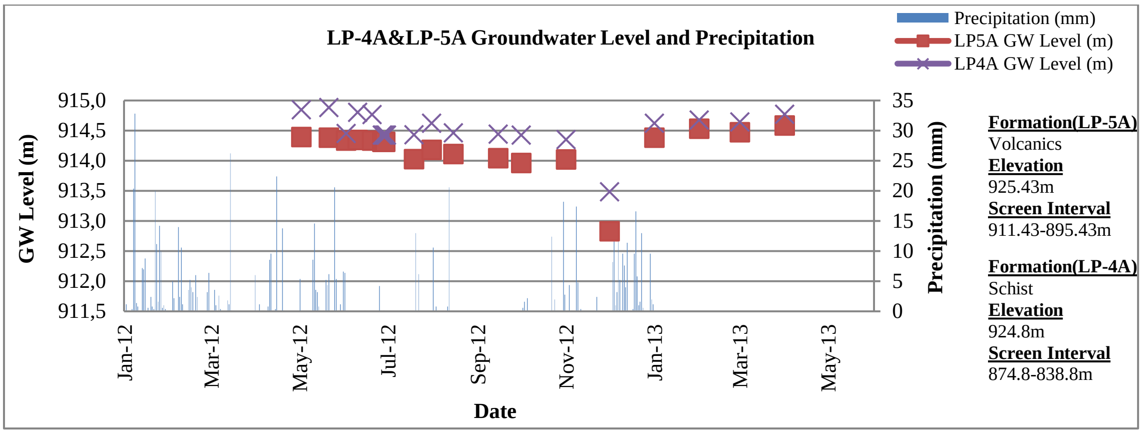

Figure 4.19. Temporal changes in groundwater levels measured at LP-4A and LP-5A

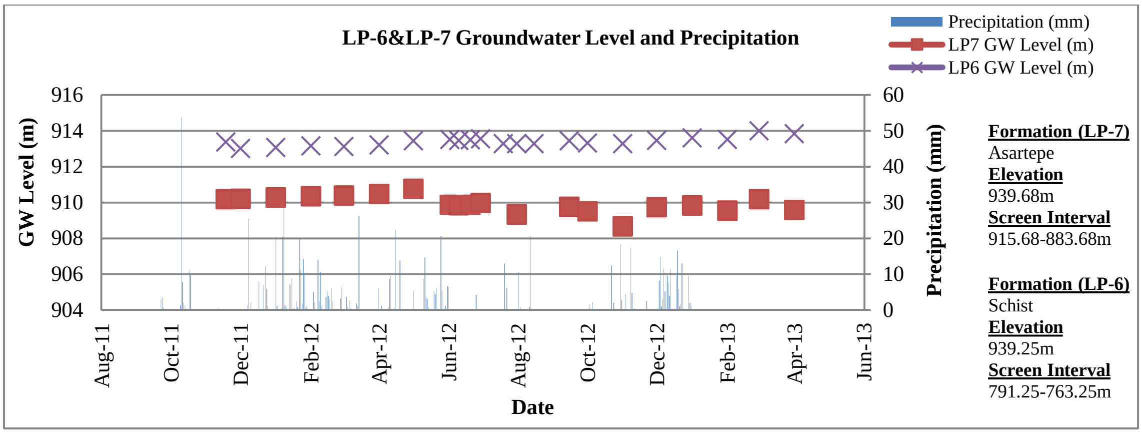

Figure 4.20. Temporal changes in groundwater levels measured at LP-6 and LP-7

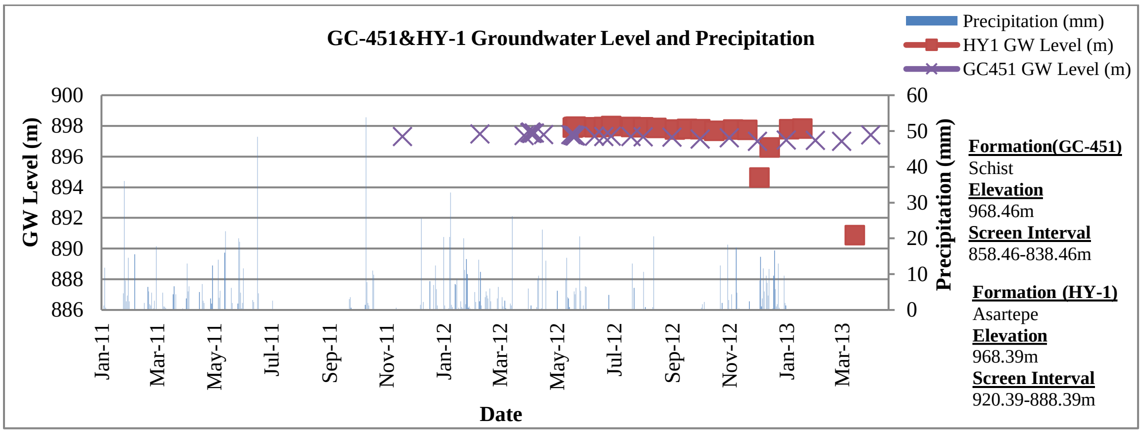

Figure 4.21. Temporal changes in groundwater levels measured at HY-1 and GC-451

4.3.3 Results of the Hydraulic Tests Conducted within the Mine Site

All hydraulic tests conducted within the study area so far are first grouped according to the lithologies tested (Asartepe Formation, Beydağı Volcanics, Eşme Formation and intrusive units within and around the open pit area). A total of 38 test results, which are grouped according to the lithologic units is then analyzed in order to determine the maximum, minimum and also the geometric mean of the hydraulic conductivity values of each lithological unit. Results are both tabulated (Table 4.4) and presented graphically (Figure 4.22).

Table 4.4. Maximum, minimum and geometric mean of hydraulic conductivity values (m/s)

	Number of Wells Tested	**Min K**	**Max K**	**Geo. Mean**
Asartepe Formation	2	2.50×10^{-9}	5.34×10^{-8}	1.16×10^{-8}
Beydağı Volcanics	25	4.56×10^{-9}	1.61×10^{-6}	1.02×10^{-7}
Intrusives (Open Pit)	5	4.07×10^{-9}	1.10×10^{-6}	1.67×10^{-7}
Eşme Formation	6	1.19×10^{-8}	2.61×10^{-6}	2.02×10^{-7}
All Units	38	$\mathbf{2.50 \times 10^{-9}}$	$\mathbf{2.61 \times 10^{-6}}$	$\mathbf{1.08 \times 10^{-7}}$

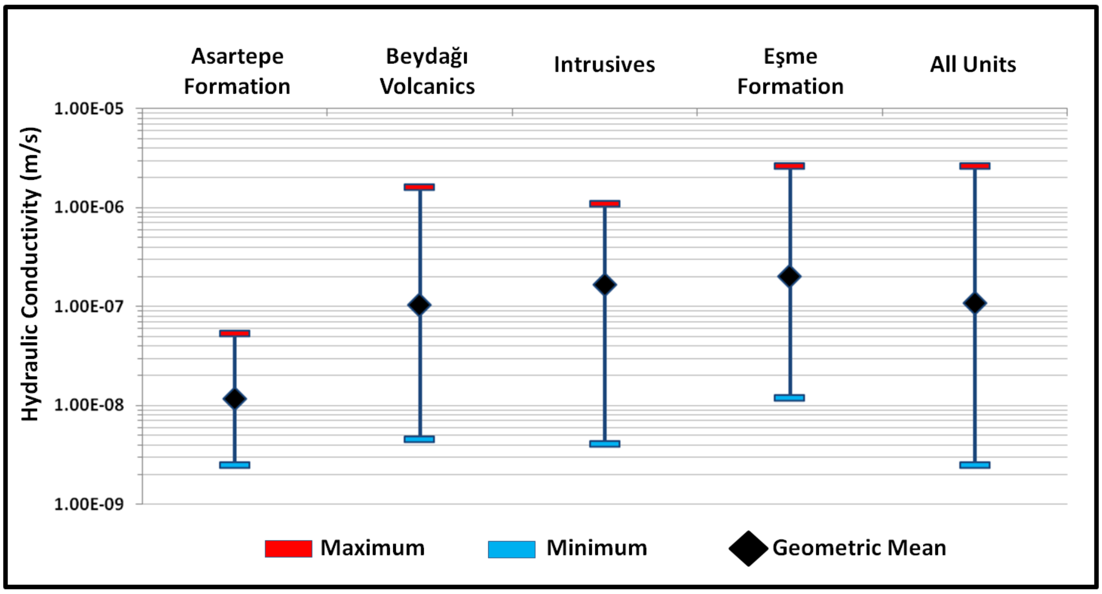

Figure 4.22. Maximum, minimum and geometric mean of hydraulic conductivity values

According to these results tabulated in Table 4.4 and presented in Figure 4.22, following conclusions are made:

- As it is mentioned before, Asartepe Formation, forms a local aquifer outside the study area within the Banaz Stream Basin having extensive outcrops and high hydraulic conductivity values (6.50×10^{-6} – 1.00×10^{-4} m/s). On the other hand, within the study area, it has lower hydraulic conductivity (2.50×10^{-9} – 5.34×10^{-8} m/s) owing to its clayey content.
- Moreover, within the study area, hydraulic properties of the volcanics and schists are very close. It can be concluded that in a regional point of view, hydraulic conductivity values of the units within the study area ranges between 2.50×10^{-9} and 2.61×10^{-6} m/s, with a geometic average of 1.08×10^{-7} m/s.

4.4 Hydrologic Budget of the Study Area and Groundwater Recharge

In the previous studies, recharge value for this site is determined by the analysis of the long term average monthly precipitation and temperature values recorded in Uşak Meteorological Station using different methods. It is observed that different recharge values are determined for the site in the previous studies as: 22 mm/year (SRK, 2007) by CN Method and 44 mm/year (SRK, 2005) by Thornthwaite Method. Moreover, these two recharge values calculated using different methods do not reflect the areal recharge distribution. Therefore, a different methodology is applied by Yazıcıgil et al. (2013) using the Soil-Water-Balance (SWB; Westenbroek et al. 2010) model developed by the United States Geological Services. Below is a very brief summary of the sophisticated approach applied by Yazıcıgil et al. (2013).

SWB model can be utilized to calculate the hydrologic parameters, as well as the aerial distribution of groundwater recharge (within a model domain discretized into cells and by assigning related parameters to each cell).

The main equation for SWB model to calculate the hydrologic water budget is as follows:

Change in Soil Moisture = Water inflow (to cell) – Water Outflow (from cell) – Groundwater Recharge

where; Water Inflow (to cell) = Rainfall + Snow + Runoff (to cell)
Water Outflow (from cell) = Interception (by vegetation) + Runoff (from cell) + Actual Evapotranspiration

- **Rainfall:** Daily precipitation data
- **Snow:** Snow is allowed to accumulate or melt in accordance with the daily maximum and minimum temperatures

- **Interception (by vegetation):** Specified amount of rainfall is trapped by the vegetation
- **Runoff:** An analytical model is utilized to predict the runoff rate that will originate from each cell. Then the excessive water is transferred to the downstream cell. This analytical model is based on U.S. Soil Conservation Service's runoff curve number (CN) method (USDA, 1986) which is well known for the determination of the runoff rate.
- **Evapotranspiration:** The rate of potential evapotranspiration can be calculated with different methodologies. These are; Thorntwaite-Mather (1957), Jensen-Haise (1963), Turc (1961) ve Hargreaves and Samani (1985).
- **Soil Moisture:** This parameter indicates the amount of water that is stored in a cell.

SWB model is constructed for an area covering more than 400 km^2 as shown in Figure 4.23, which is divided into cells having dimensions of 25 m x 25m. Then land use/vegetation cover (considering land slope and thickness) data is introduced to the model.
Prior to the introduction of the evapotranspiration rates, a set of calculations are completed with different methods such as; Thorntwaite-Mather (1957), Jensen-Haise (1963), Turc (1961) and Hargreaves and Samani (1985).

The calculated different evapotranspiration rates are introduced to the SWB model and the calculated runoff rates are compared with the site measured runoff rates for Weir-5. Then the curve numbers are iterated to reach a calibrated model. According to these calibrated models, following groundwater recharge rates are calculated by Yazıcıgil et al. (2013):

- Thorntwaite-Mather 63.80mm/year
- Jensen-Haise 49.94mm/year
- Hargreaves-Samani 33.43mm/year
- Turc 37.82mm/year

Hargreaves-Samani and Turc methods resulted similar groundwater recharge rates for the calibrated SWB models. Furthermore, the runoff values calculated with Turc method are similar with 2010's runoff values (here, it should be noted that the total precipitation in 2010 is similar to long term average). Thus, Turc method is utilized to calculate the evapotranspiration losses of the water budget component (Yazıcıgil et al., 2013).

According to the calculations, using this method, annual precipitation is distributed into its budget components as follows:

- 75.50% evapotranspiration
- 6.80% interception by vegetation
- 8.50% runoff
- 6.64% groundwater recharge
- 2.50 % change in soil moisture

To sum up, total annual groundwater recharge within the study area ranges between 0 (at the leach pad and waste rock storage areas) and 220 mm, while its average over the study area is calculated as 37.8 mm. The resulting areal distribution map for the groundwater recharge is given in Figure 4.23.

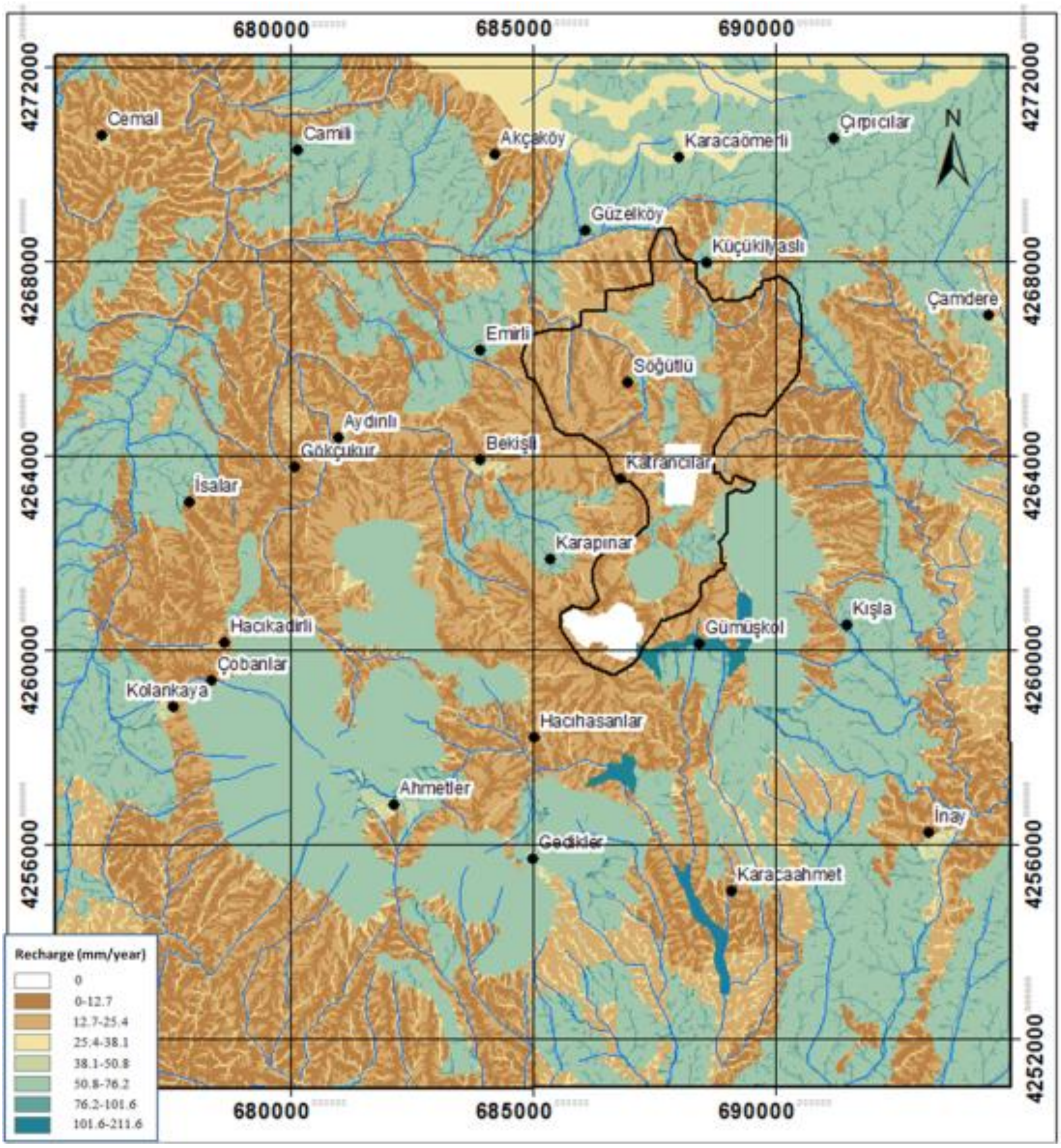

Figure 4.23. Areal distribution of recharge (Yazıcıgil et al., 2013)

CHAPTER 5

CONCEPTUAL AQUIFER MODEL

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 the 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, conceptual model, reflecting the hydrogeological characterization of the site, is the basis for numerical groundwater flow model.

Within the content of this study, the conceptual model created by SRK (2005) for the site, is revised and improved using the recently available data, tests and analysis. For the systematical examination, first major lithological units of the study area are determined as follows: Eşme Formation, Beydağı Volcanics, Ahmetler Formation, Asartepe Formation and alluvium (Figure 5.1). Hydrogeological characteristics of these units are summarized in section 4.2, where regional hydrogeology is described in detail.

According to this hydrogeological characterization, Eşme Formation and Beydağı Volcanics are the two units having the broadest extension within the study area. Here it should be noted that the results of the aquifer tests performed at the wells drilled in these two units, are very close; suggesting that these two units have very similar hydraulic characteristics (See Table 4.4 and Figure 4.22). This fact is also proven by the data obtained from the clustered wells at the mine site, which have very close groundwater levels and parallel seasonal fluctuations. As it can be noted from the Table 4.4, all the lithological units tested (Asartepe Formation, Beydağı Volcanics, Eşme Formation and intrusive units within and around the open pit area), resulted in very similar hydraulic properties. The units that could not be tested (alluvium and Ahmetler Formation) within the study area, due to lack of data that can reveal the hydraulic properties of the formation, they are assumed to have similar hydraulic properties with those of Beydağı Volcanics and schists within the model area. On the other hand, Ulubey Formation, even though not located within the study area, is the major aquifer in the regional scale and constituting the east and north boundary of the model area, this unit very important.

To sum up according to the hydrogeological characterization, all the lithological units tested resulted in very similar hydraulic properties. This is also proven by the close groundwater levels and parallel seasonal fluctuations. Therefore, all the units within the study area are assumed to have similar hydraulic properties and groundwater levels, consequently it is assumed that all units form a single system within the study area; hence, a single regional groundwater elevation map is generated representing all the units (Figure 5.1).

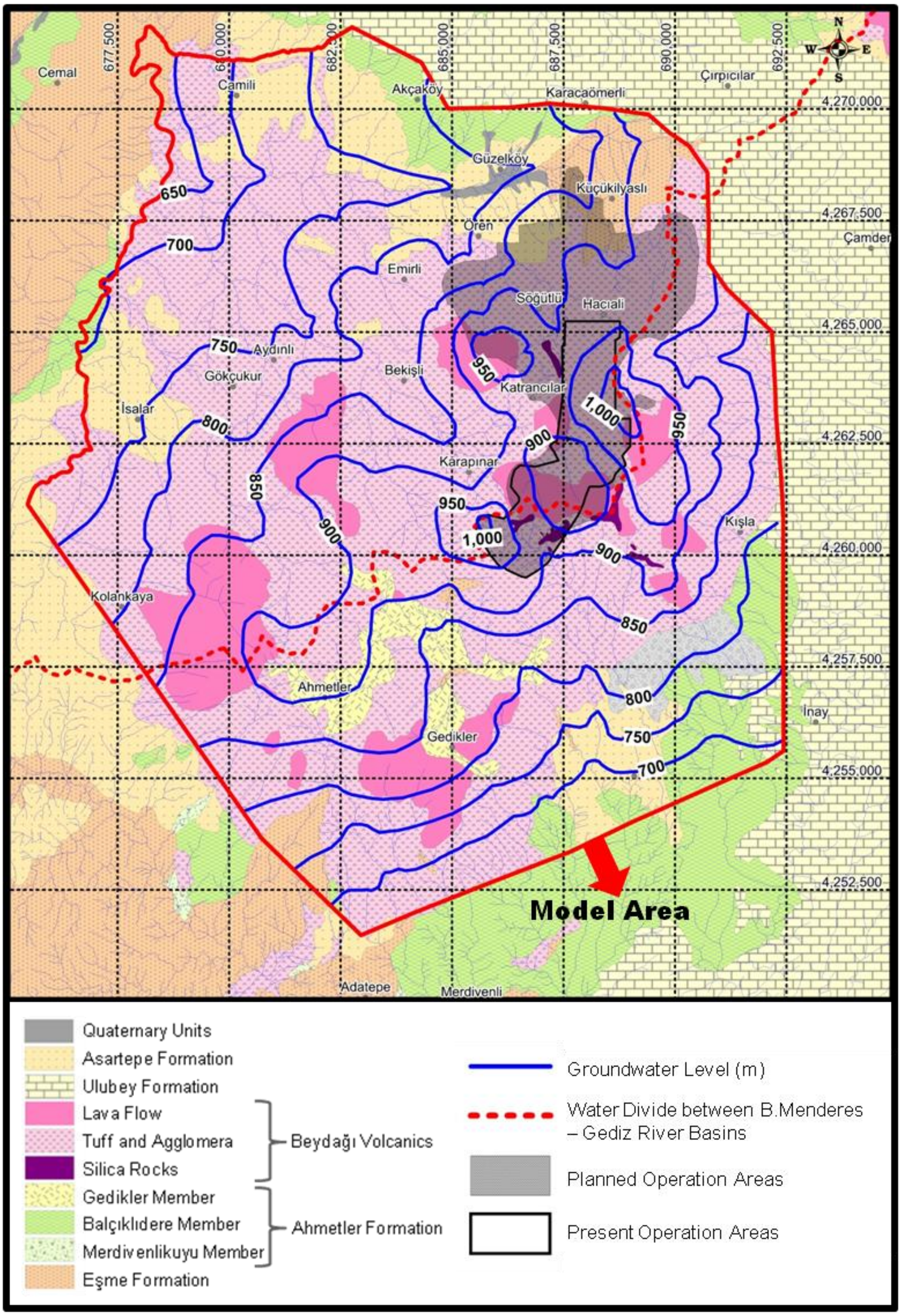

Figure 5.1. Hydrogeological map of the study area

Groundwater is recharged from the mountainous area located along the water divide separating Gediz and Büyük Menderes River Basins. For the study area, components of the water budget are calculated by Yazıcıgil et al. (2013), using Soil-Water-Balance (SWB; Westenbroek et al. 2010) model, developed by the United States Geological Services. According to the results of this model, average annual groundwater recharge from direct precipitation is calculated as 37.8 mm/year for the study area.

When groundwater levels recorded at the wells drilled in mine site are examined, it is observed that there is no significant change in water levels, except seasonal fluctuations. At the mine site, an increasing trend is observed only in groundwater levels recorded at PZ Wells, which were drilled in 2007 for geotechnical purposes and then converted to monitoring wells. Groundwater levels recorded at these wells show an increasing trend of about 8-10 m, since 2009. This increasing trend is a consequence of increased groundwater recharge caused by two factors: reduced thickness of the vadose zone and enlargement of the catchment due to excavations in the open pit area; and the wet period observed since 2009.

Within the content of this study, groundwater elevation map generated by the previous studies is revised with the recently available data obtained from the new wells. Especially for the northern parts of the mine site, where there was no data, many new wells are drilled for the characterization of the planned expansion areas. All these groundwater level measurements are used to create a groundwater elevation map at regional scale. Apart from the well data, topographical elevations of the springs in the study area, which have been determined during several field studies, and those of the perennial surface waters are also considered during map generation. After a groundwater elevation map is generated, its consistency with the topographical surface and with the groundwater levels of the Ulubey Aquifer, which are determined by Yazıcıgil et al. (2008), is checked. Resulting regional groundwater elevation map is demonstrated in Figure 5.1.

As shown in this figure, highest groundwater elevations around 1000 m are observed along the water divide, at the present leach pad area and waste rock storage areas, where higher recharge occurs due to higher elevations. Groundwater level at the open pit, situated just between these two locations, is very low (around 870 m) compared to that observed at leach pad area and waste rock storage areas (around 1000 m). Low groundwater levels at the open pit area can be explained by the 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. In other words, 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 those (Yazıcıgil et al., 2013).

In the previous studies, Kışladağ mine site is defined as almost not deformed as no significant fault system is observed. Moreover, results of the study conducted by Lewis (2002) suggest that joint and fracture systems are dominantly oriented NNW. The anisotropy developed in this direction controls the groundwater flow as well.

As shown in Figure 5.1, within the study area, groundwater is recharged from the mountainous areas located and around the mine site. Groundwater levels reaching elevations around 1000 m within the mine site, decrease to 650-700 m levels, at the northwestern parts of the mine where schists are outcropping and at the southeastern parts where Ahmetler Formation crops out (Figure 5.1). According to this trend, groundwater discharge occurs to:

- Kurbağalı Creek forming the northwestern boundary,
- Geçemek Creek at the north of the mine site,
- Ulubey Formation at the eastern boundary and
- Ahmetler Formation along the southeastern boundary.

CHAPTER 6

GROUNDWATER FLOW MODEL

6.1 Software Description

A 3-D groundwater flow model is developed for the study area using the Visual MODFLOW 2011.1 Premium software package developed by Schlumberger Water Services. Visual MODFLOW Premium is a 3-D groundwater flow and contaminant transport modeling application that integrates several packages including, MODFLOW-2000, SEAWAT, MODPATH, MT3DMS, etc.

Using this software, groundwater flow equations are solved by MODFLOW-2000 (Harbaugh et al., 2000) code, known as “3-D modular finite-difference groundwater flow model” developed by the U.S. Geological Survey (Harbaugh et al., 2000). The applications of MODFLOW started to grow up by 1980’s and since then MODFLOW has continuously evolved with additional packages and programs. Simulations performed by MODFLOW are verified worldwide by modeling studies performed in the universities, as well as the public and private sectors. Moreover, in many legal cases, MODFLOW has been accepted as a legitimate approach in the analysis of groundwater systems, all over the world.

6.2 Model Domain and Finite Difference Grid

The first stage in the development of a numerical groundwater flow model is the determination of the expansion area and corresponding boundaries of the aquifer to be modeled. Flow model developed for this site, covers an area of 245 km^2 surrounding the water divide separating Gediz and Büyük Menderes River Basins with a NE-SW trend (Figure 6.1).

Next stage is setting up the finite difference grid and splitting the aquifer system into cells in which hydrogeological parameters are assumed to be uniform. Normally, the smaller the cell size, the better simulated the aquifer characteristics. On the contrary, the smaller the cell size, the more time and computer memory required to solve the model. Therefore, minimum number of cells that are capable of representing the heterogeneity of the aquifer, distribution of available data and aquifer boundaries should be utilized. Therefore, variable cell size is selected depending on the position of the cell within the model domain. The aquifer area is first splitted into cells with uniform size of 100x100 m, and then the grid is refined at the vicinity of the present and planned mining facilities, especially around the open pit. Therefore, the coarsest cell size is 100x100m along the model boundaries and finer grid size is preferred at the present and planned mining facilities (50x50 m) and at the open pit area

(25x25 m), where higher accuracy is required (Figure 6.1). This grid design resulted in 86862 active cells in a single layer. The resulting grid is rotated 45°, so that it is aligned with the regional groundwater flow direction (NW-SE).

Top boundary of the model is the topographical surface that has an elevation ranging between 600 m and 1300 m, within the model domain. Bottom boundary of the model is defined as no flow boundary at 0 m elevation, where it is 300 m below the ultimate pit bottom elevation. The thickness between these top and bottom surfaces is divided into 15 layers in vertical direction, to enable the better simulation of dewatering activities during the next 17 years of mine operation. In the determination of the layer elevations, the thickness between the present pit bottom (870 m) and the ultimate pit bottom (300 m), is divided into 11 layers vertically, so that the top layer has a thickness of 70 m and the lower 10 layers have thicknesses of 50 m. Below the ultimate pit bottom elevation, layers 12 and 13 have thicknesses of 50 m, while layers 14 and 15 have thicknesses of 100 m. Layer elevations designed as such at the open pit area, are applied to the whole model domain so that the ratio of the layer thicknesses at the open pit area will remain constant. Resulting distribution of the layers in the vertical direction is presented in Figure 6.2, on a cross-section passing through the line AA’ line shown in Figure 6.1.

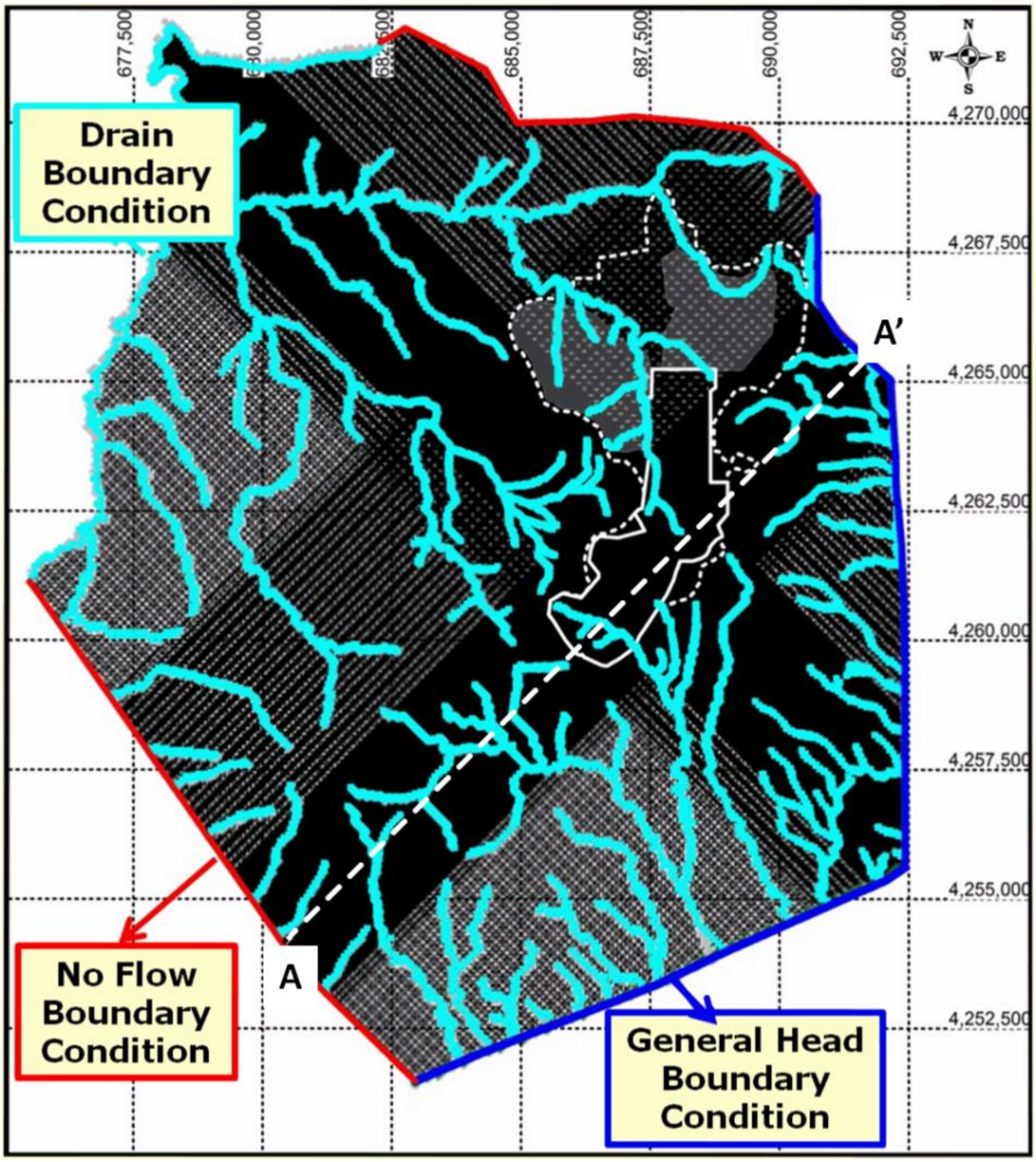

Figure 6.1. Model grid and boundary conditions

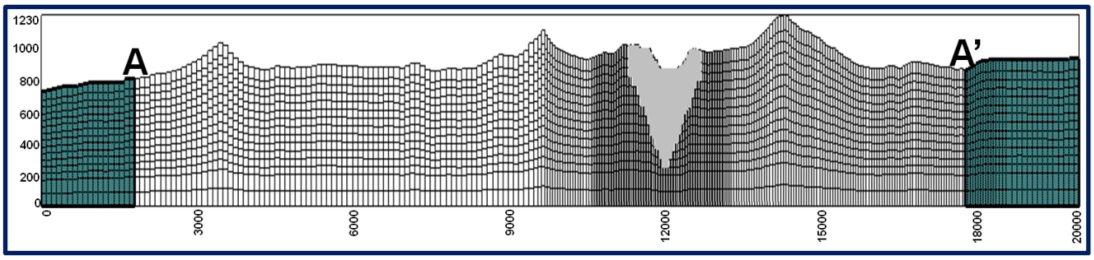

Figure 6.2. Vertical layout of the model layers

6.3 Boundary Conditions

Boundary conditions simulated in the model are given in Figure 6.1. As it is demonstrated in this figure, model domain extends from Kurbağalı Creek along northwest boundary, to the lithological boundary formed by the Ulubey Formation along north and east boundaries. Southwest boundary of the model follows the lithological boundary between Beydağı Volcanics and Eşme Formation outcropping and extending westwards, which is locally overlain by Asartepe Formation along this boundary. There is no physical boundary southeast of the model domain as confirmed by the southeasterly groundwater flow direction outward from this boundary.

In the next stage, these conceptual boundaries are defined in the numerical groundwater flow model. Groundwater flow towards the Kurbağalı Creek, which forms the northwest boundary of the model domain, is simulated with drain boundary condition assigned to the topmost model layer. Due to the absence of detailed hydrologic data regarding the Kurbağalı Creek, elevation of the drain cells located along this boundary are assigned to be 2 m below the topographical surface. Below this layer the contact between model area and the outcropping Eşme and Ahmetler Formations are simulated with no flow boundary condition.

Lithological boundaries along southwest and north-northeast of the model are assumed as no flow boundaries according to the groundwater elevation map generated in conceptual aquifer model given in Figure 6.1.

Along the eastern boundary of the model domain, general head boundary condition is used to simulate groundwater flow between Ulubey Formation extending eastwards of the study area and the modeled units. This boundary condition is assigned to the topmost three layers of the model, corresponding to the estimated thickness of Ulubey Formation at this locality (150 m). Elevations of the general head boundary cells along this boundary are assigned using the hydraulic heads form the groundwater elevation map of the Ulubey aquifer (Figure 4.6). The boundary condition assigned in this manner, allows the simulation of groundwater exchange between the two units.

As there is no physical boundary along the southeast of the model domain, this boundary is aligned with contours of the regional groundwater elevation map (Figure 6.1) and simulated using general head boundary condition. Along this boundary a uniform hydraulic head of 650 m is assigned according to this map.

Perennial and seasonal drainage within the model domain are simulated using drain boundary condition. However, due to the lack of detailed hydrologic data for these surface waters, the drain cells are assigned elevations, 2 m below the topographical surface so that simulated groundwater levels are close to the topographical surface.

6.4 Model Parameters

After the determination of model grid and boundary conditions, recharge and discharge mechanisms of the system and hydraulic parameters of the units are defined in the model. In the next stage, these parameters are calibrated until a good match between the groundwater levels measured at the field and calculated by the model is achieved. In the following sections, the calibrated values of these parameters are compared to those set up in the conceptual aquifer model and calculated by the field tests.

6.4.1 Recharge

Located along the water divide separating Gediz and Büyük Menderes River Basins, mine site is situated on the recharge area in the regional sense. In the previous studies, recharge value for this site is determined by the analysis of the long term average monthly precipitation and temperature values recorded in Uşak Meteorological Station, using different methods. It is observed that different recharge values are determined for the site, in the previous studies as: 22 mm/year (SRK, 2007) and 44 mm/year (SRK, 2005). Moreover, these two recharge values calculated using different methods do not reflect the areal recharge distribution. Therefore, a new methodology is applied by Yazıcıgil et al. (2013), using the Soil-Water-Balance (SWB; Westenbroek et al. 2010) model developed by the United States Geological Services. This model allows the determination of areal distribution for each component of the surface water balance, including the recharge from precipitation. According to the results of this model, annual average groundwater recharge from precipitation is calculated as 37.8 mm/year for the study area. Resulting areal recharge distribution is assigned to the groundwater flow model and calibrated considering the hydrological and hydrogeological characteristics of the site, as well as the groundwater levels measured at the field. At some localities, initial recharge values are revised during calibration.For instance, recharge value calculated by the Soil-Water-Balance model in Emirli Hill is determined to be lower than expected considering the field conditions. Hence, at this location, discharge from Emirli spring is used to estimate the recharge value (76 mm). Moreover, it is known that at the open pit area groundwater level is very close to the current excavation surface (almost at 1 m depth), where high evaporation is expected. At this locality it is assumed that high evaporation rates, are balanced by high recharge and due to the fact that evaporation is not simulated in the model (neglected), groundwater recharge at this area is also set to be zero. Apart from these two localities, minor modifications are made on the groundwater recharge rates calculated by the SWB Model so that calculated groundwater levels match those observed at the field. No major modification is made for the distribution of areal recharge and at the end of calibration, recharge from precipitation is determined as 29.6 mm/year for the model domain. Figure 6.3 shows the areal distribution of recharge within the model domain.

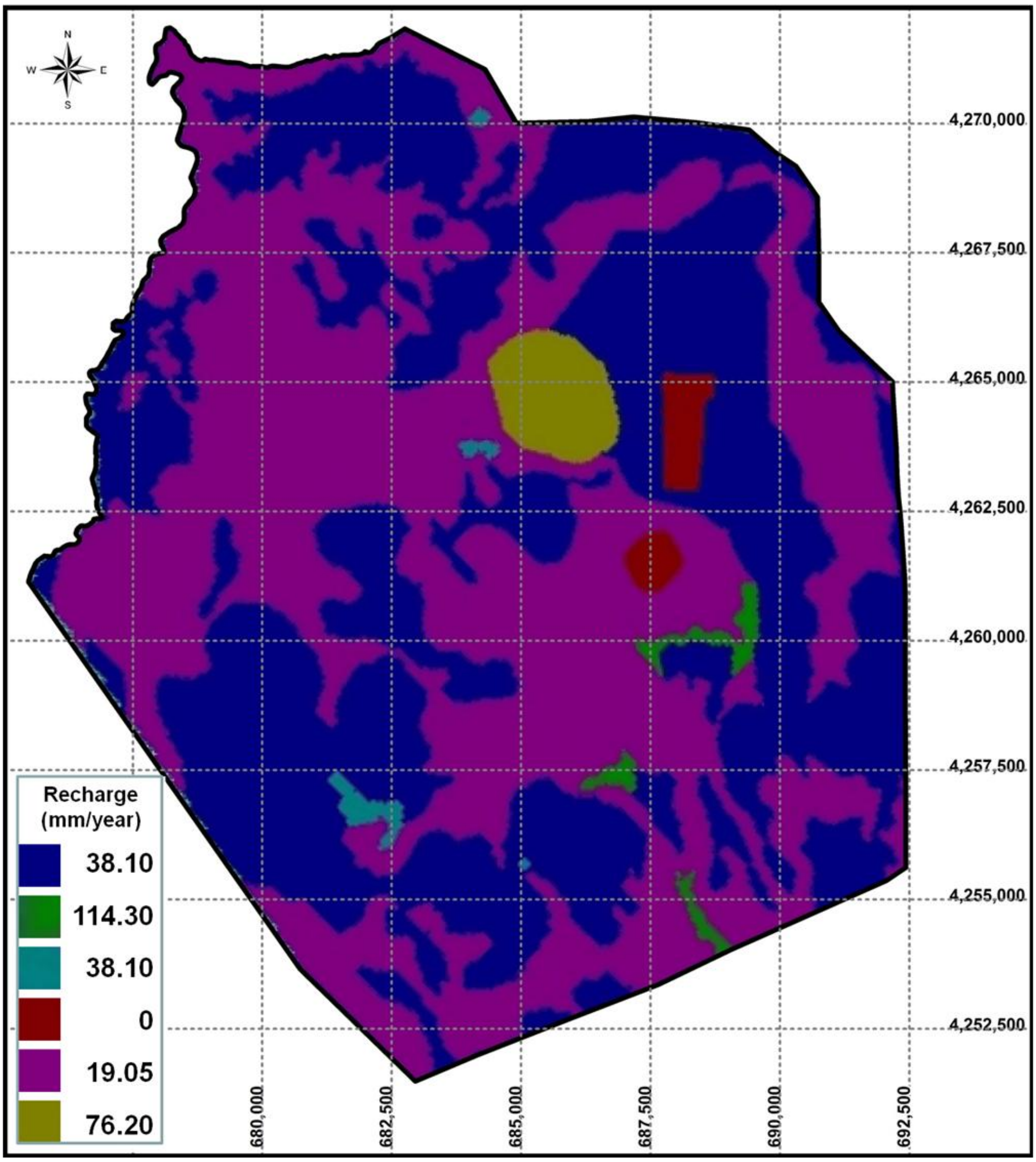

Figure 6.3. Areal recharge distribution used in the calibrated model

6.4.2 Hydraulic Conductivity

Hydraulic conductivity values obtained by the hydraulic tests conducted, are limited to the present mine site and the planned expansion area at north. On the other hand, all the lithological units present at the mine site, have continuity throughout the model domain. Therefore, hydraulic properties of these units, having extensions far from the mine site where there is no data, are assumed to be the same as those at the mine site. Hydraulic conductivity values assigned to these lithological units are changed within the ranges obtained from the field tests reflecting the hydraulic characteristics of the 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, is applied in the model. Besides, RQD values obtained from the wells drilled at the mine site as well as the packer test results, which are performed at different depths, indicates that fracture frequency and apertures reduces with depth. Hence, it is concluded that hydraulic conductivity of the materials decreases with increasing depth and during the model setup and calibration processes, lateral hydraulic conductivity values are assigned to the layers in a downwards decreasing manner. The vertical hydraulic conductivity values of the units are determined with calibration as there is no data obtained from the field testing regarding this parameter. During calibration, ratio of lateral to vertical hydraulic conductivity (K_x/K_z) is set to be 10/1 for all the units, except the intrusives located at the open pit area, where this ratio is set to 2:1. At the open pit area, owing to its lithological characteristics, Friable Zone is known to have higher conductivity and storage properties than the surrounding units. Therefore, this unit is assigned a relatively higher hydraulic conductivity value. Figure 6.4 shows the regional hydraulic conductivity distribution for the top model layer, as well as the vertical change in the values along the cross-section passing through the line A-A’, shown on the map.

6.4.3 Storage Coefficient

There is not much data regarding the storage coefficient of the units within the study area. However, in the open pit area, within the Friable Zone (having relatively higher conductivity and storage properties), a pumping test is performed using a pumping well (KPT-02) and two observation wells (KPT-03 and KPT-04). Based on the results of this test, specific storage of the intrusive units at the open pit area is assigned as $1.2\text{x}10^{-6}$ 1/m, and the rest of the model domain is assigned a smaller value ($1.0\text{x}10^{-7}$ 1/m).

In the model, storativity parameter for the unconfined aquifers is assigned to be 0.01 for the whole model domain, as there is no specific value determined for this parameter. Later on, during the dewatering simulations, which are conducted under transient conditions, several values are tested in order to determine the effect of this parameter on the model results.

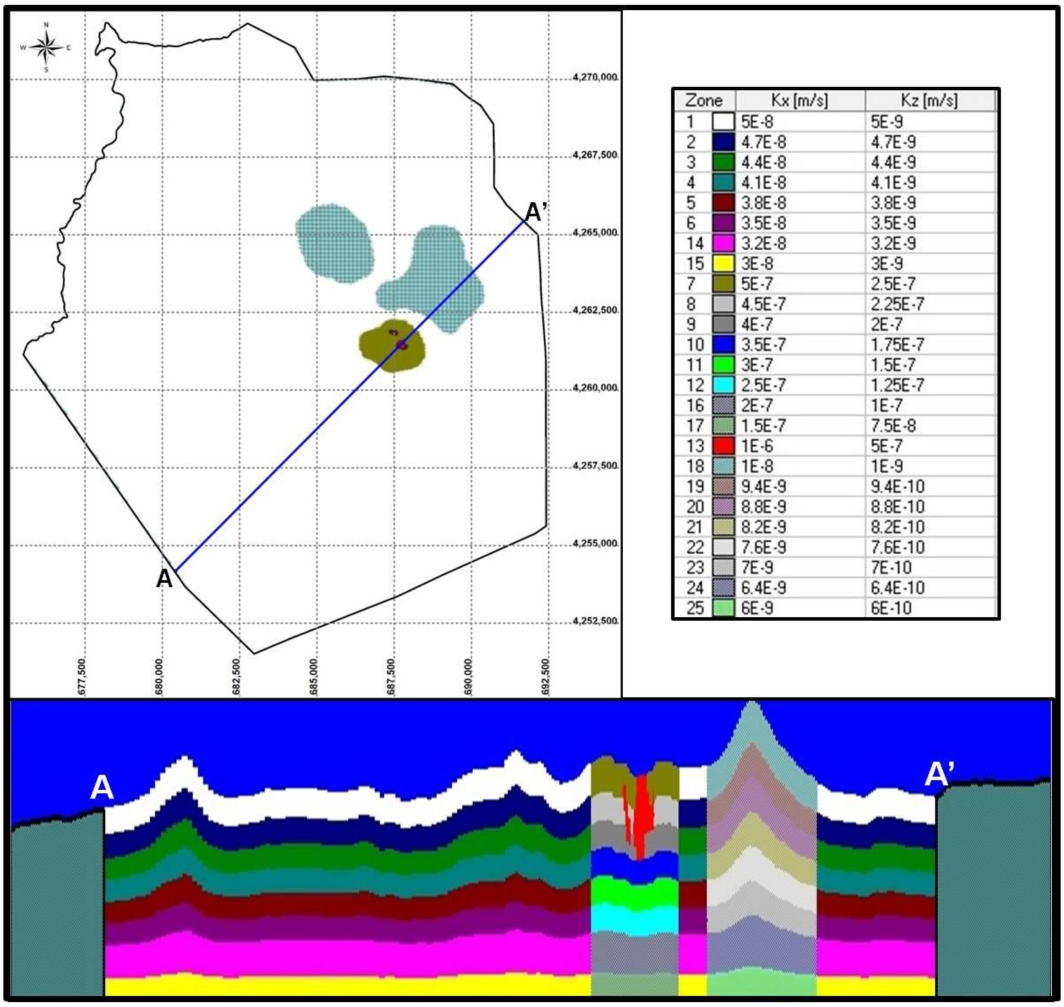

Figure 6.4. Hydraulic conductivity distribution used in the calibrated model

6.5 Calibration Results

After the groundwater flow model is set up with the meteorological, geological, hydrological and hydrogeological data collected at the field; it is calibrated to the field conditions by comparing the groundwater levels observed at the field and calculated by the model.

During calibration, above mentioned input parameters of the model (hydraulic conductivity, anisotropy and recharge from precipitation) are modified within the geological, hydrological and hydrogeological limits by trial and error, so that a good match between the groundwater levels observed at the field and calculated by the model is achieved. As the model calibration is conducted under steady-state conditions, storativity parameter could not be calibrated. Rather, as it is mentioned above, transient state dewatering simulations are performed with different storativityvalues for the unconfined conditions and effects of this parameter on the model results are determined.

Under steady-state conditions, model is calibrated to the average groundwater levels observed during the period 2002-2012 and to the groundwater levels measured at the observation wells recently drilled at the present mine site and the planned expansion area. The temporal variations in observed groundwater levels were minor, except those observed at the open pit area, reasons of which are discussed in Chapter 5 in detail.

Regarding the spatial distribution of groundwater levels, there is not much data except the present mine site and planned expansion area. Therefore, where there is no observation, results calculated by the model are compared to the regional groundwater levels and flow directions generated in the conceptual aquifer model during the calibration.

Consistency of the model calculated and field measured groundwater levels, is quantified using the two statistical parameters, equations of which are given below. During calibration, the aim is the minimization of both RMSE (Root Mean Square Error) and NRMS (Normalized Root Mean Square Error).

$$\boxed{RMSE = \sqrt{\frac{1}{n}\left[\sum_{i=1}^{n}\left(h_0 - h_h\right)_i^2\right]}}$$

$$\boxed{NRMS(\%) = \frac{RMSE}{(h_0)_{\max} - (h_0)_{\min}}}$$

where, n : total number of observation points,
h_0 : observed groundwater level,
h_h : calculated groundwater level,
$(h_0)_{max}$: maksimum value for observed groundwater level,
$(h_0)_{min}$: minimum value for observed groundwater level.

At the end of calibration, the graph presented in Figure 6.5 is obtained where groundwater levels observed at the field are plotted against groundwater levels calculated by the model. As it can be seen from this graph, a good match between the observed and calculated groundwater levels is achieved, with RMSE of 13.9 m and a correlation coefficient of 0.942.

Moreover, NRMSE value of the calibrated model is 6.3%, which is well below 10%, indicating that the calibration is successful.

Groundwater levels calculated by the calibrated model are presented together with the regional groundwater level map generated in the conceptual model as shown in Figure 6.6. The two maps given in this figure show that groundwater levels and flow patterns are consistent in regional scale as well.

As a result, it can be concluded that the model calibration under steady-state conditions is accomplished and hydraulic parameters assigned to the model efficiently represent the field conditions. Therefore, this calibrated model is capable of simulating the possible responses of the system to the imposed stresses. In other words, in the following stages, this model can be used as a tool to predict the amount of groundwater that has to be pumped during dewatering activities, theformation of the pit lake levels after the mine closure and the interaction of the pit lake with the surrounding groundwater regime.

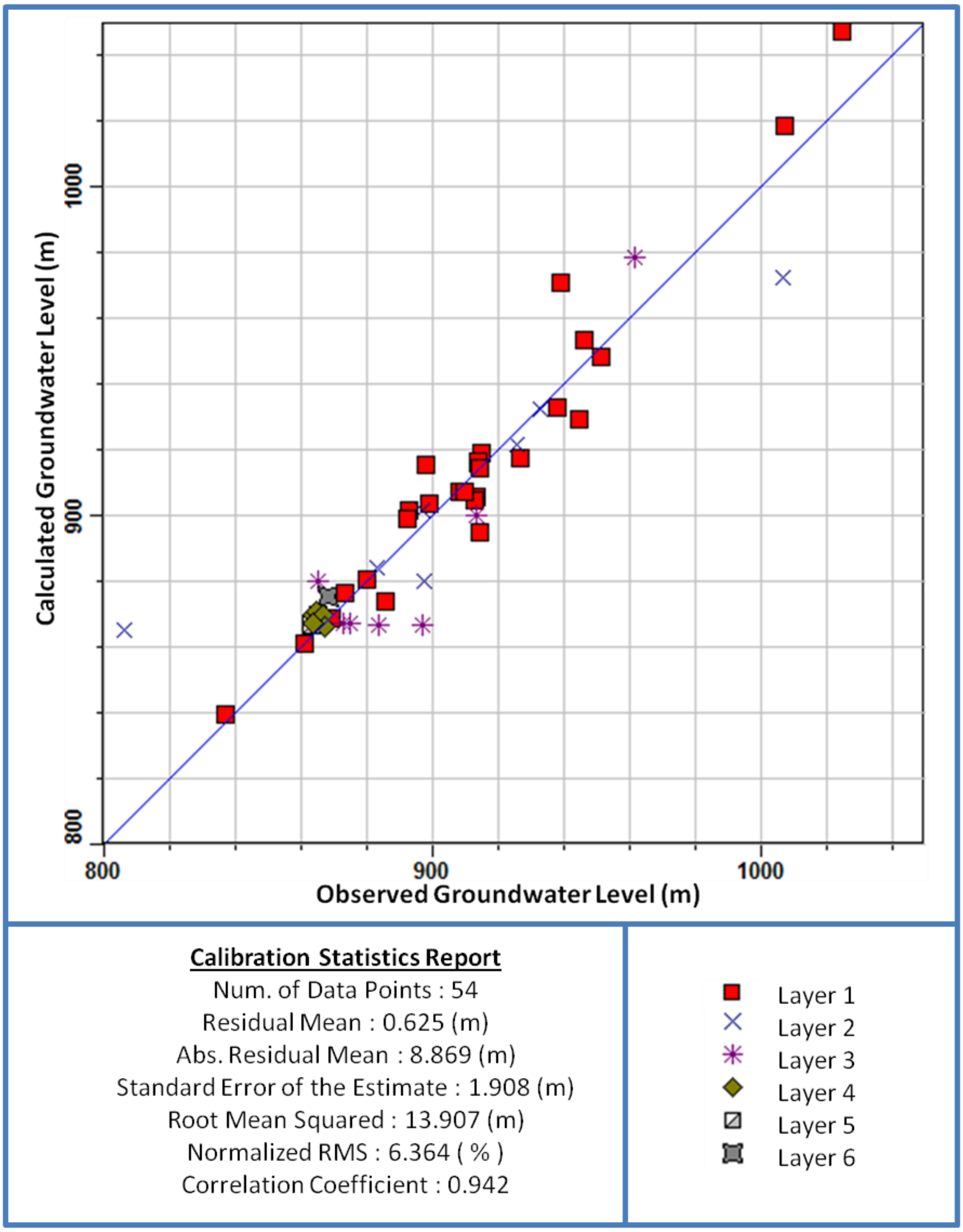

Figure 6.5. Observed vs calibrated groundwater levels

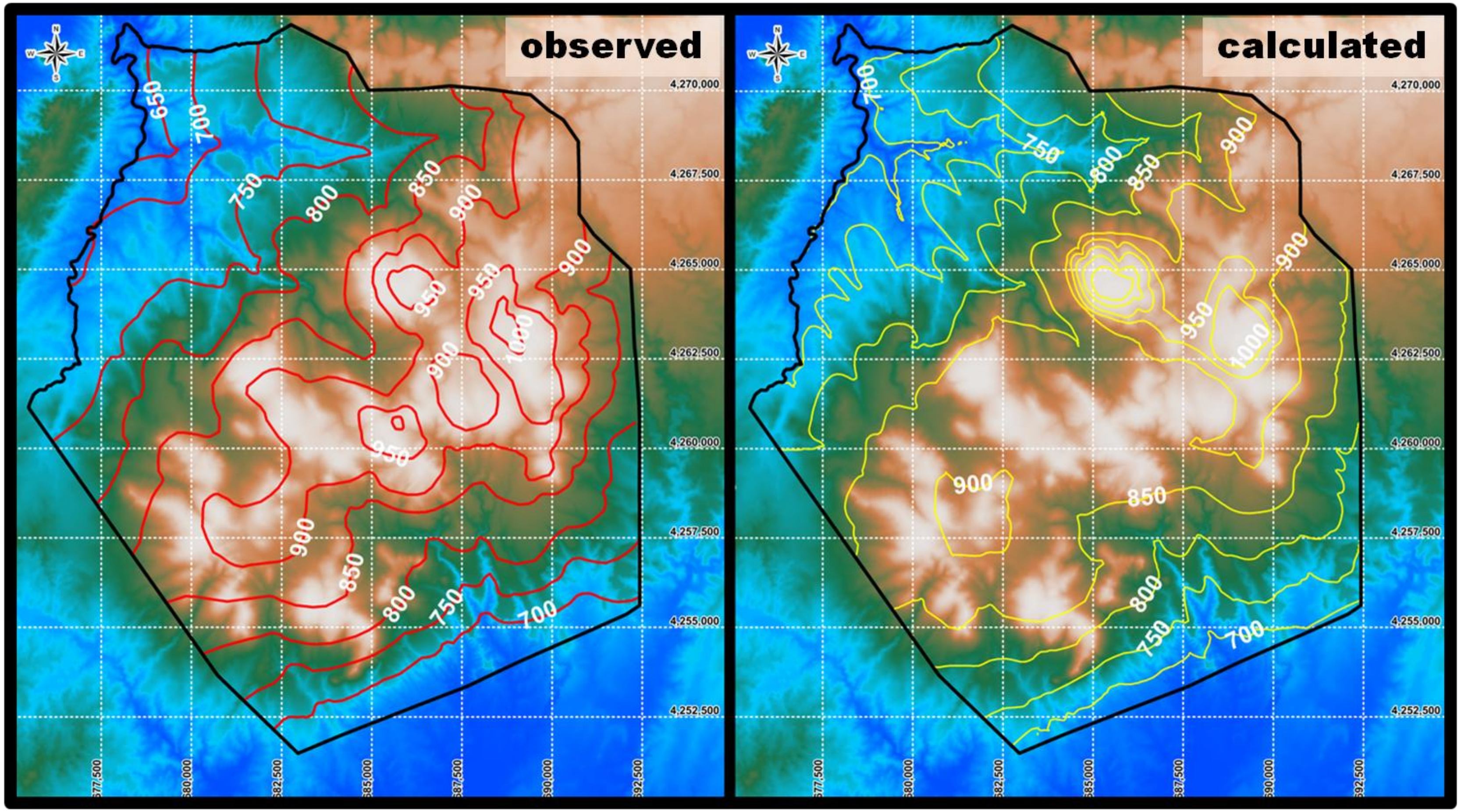

Figure 6.6. Observed and calculated groundwater levels

6.6 Calibrated Groundwater Budget

The best practice in the determination of the groundwater budget and its components for the study area is to use the groundwater budget calculated by the model. Therefore, depending on the results of the calibrated model, a groundwater budget is set up for the site at steady state conditions, where recharge and discharge components the system are separately determined (Table 6.1). According to these results, for the model domain, annual recharge is calculated as 7.36 Mm^3. Almost all of this recharge (99%), comes from direct precipitation, while only a small portion (1%) comes from Ulubey Aquifer as lateral inflow. Nearly, 62% of the total recharge discharges to the surface waters within and along the model boundaries, while 29% discharges laterally out of the model domain along the southeast boundary and remaining 9% discharges laterally to the Ulubey Aquifer (Figure 6.1).

Table 6.1. Groundwater budget for the calibrated model

RECHARGE	Mm^3/yıl	**DISCHARGE**	Mm^3/yıl
Recharge from precipitation	7.25	Discharge to surface waters	4.54
		Discharge by lateral flow	2.15
Recharge from Ulubey Aquifer	0.11	Discharge to Ulubey Aquifer	0.67
TOTAL	7.36	TOTAL	7.36

6.7 Sensitivity Analysis

Sensitivity analysis is very beneficial in determination of the parameter or parameters which are effective on the model results. The results of sensitivity analysis are not only useful in planning of possible data collection in the future, but also in the minimization of the model errors.
A series of simulations are performed in order to test the sensitivity of the model to changes in the following parameters:

- hydraulic conductivity in the whole model domain
- hydraulic conductivity in the open pit area
- ratio of lateral to vertical hydraulic conductivity in the open pit area
- anisotropy in the whole model domain
- recharge from precipitation

During sensitivity analysis, at each attempt one of the above-listed parameters is modified while keeping others constant. For sensitivity analysis, RMSE value is used as a criterion to determine the sensitivity of the model to the changes imposed on the input parameters. At the end of each sensitivity run, calculated RMSE value is compared to that of the calibrated model.

Moreover, due to the fact that this calibrated model will be used as a tool in the determination of the groundwater flow rates, during the dewatering and closure phases, model results has to be very precise especially at the open pit area. Therefore, in addition to RMSE, sensitivity of the model is also assessed with respect to the open pit groundwater levels at the end of each sensitivity run.

Results of the simulations from sensitivity analysis are summarized in the graphs presented in Figure 6.7. In these graphs, for each parameter, imposed change in the parameter is plotted against the calculated RMSE value and the simulated open pit groundwater level corresponding to that change.

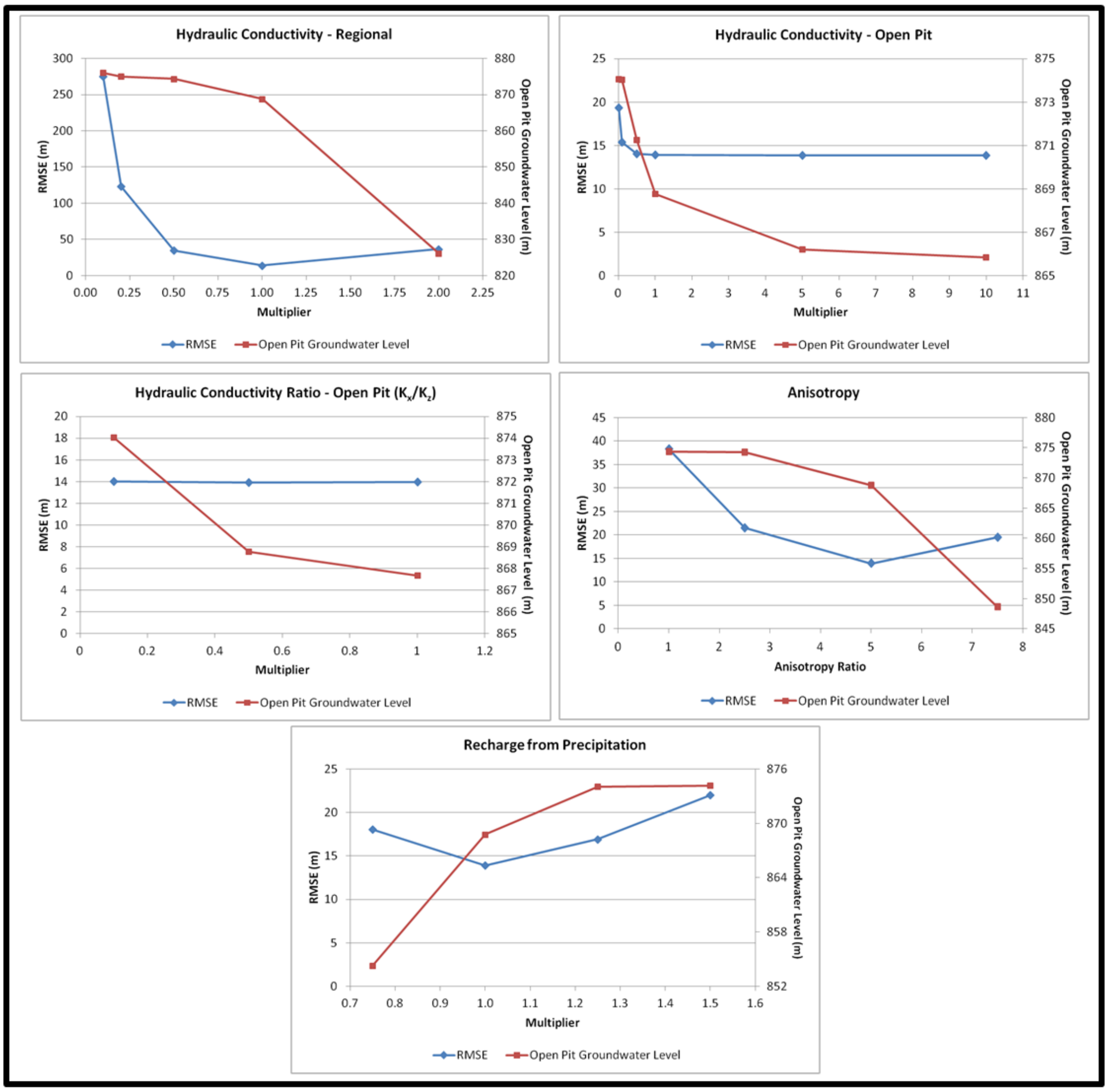

Figure 6.7. Results of sensitivity analysis

Examining the responses of RMSE in these graphs, it is observed that among all the parameters tested, the model is most sensitive to the decrease in the hydraulic conductivity defined over the whole model domain, which is followed by the changes in anisotropy and recharge from precipitation. Moreover, the model is more sensitive to the decrease in hydraulic conductivity in the open pit area rather than the increase in the same parameter. Finally, it is observed that the model is not sensitive to the changes in the ratio of lateral to vertical hydraulic conductivity in the open pit area.

The examination of the responses of open pit groundwater levels shows the highest sensitivity to the increases in the hydraulic conductivity defined over the whole model domain; such that doubling the hydraulic conductivity in the whole model domain, corresponds to an almost 40 m decrease in the open pit groundwater levels. Increasing anisotropy causes a similar response in the open pit groundwater levels. Recharge from precipitation, especially in the case of a decrease, is another important parameter determining the open pit groundwater levels. When the effects of the changes in hydraulic conductivity in the open pit area are examined, it is seen that groundwater levels at the open pit are more sensitive to the decreases compared to the increases in this parameter.

CHAPTER 7

OPEN PIT DEWATERING

At Kışladağ Gold Mine, open pit mining activities initiated by the year 2006. Topographical elevation of the pit bottom, which was initially around 1080 m, has been lowered ever since, reaching to 870 m level by the end of 2012. Corresponding groundwater elevation is measured as 869 m. Up to this level, dewatering actions were not required as the excavations were conducted above the groundwater level, where dry operating conditions was available. However, by the end of year 2013, pit bottom elevation is planned to be lowered below the groundwater level. Below this level groundwater inflow is expected into the pit. Therefore, after this level, groundwater level has to be kept below the excavation bottom in order to provide and sustain stable and dry conditions for the excavations.

By the end of 2029 when the mining operations ceases, elevation of the pit bottom is planned to be lowered to 300 m level. Considering the present groundwater level, which is around 870 m level, during the next 17 years of the mine operations, groundwater level should be lowered by about 570m. To achieve this dewatering target, groundwater inflow rate, which is expected to increase with decreasing bit bottom elevation, should be quantified. Based on this result, proper dewatering systems should be designed.

At this stage calibrated numerical groundwater flow model is used as a tool to predict the amount of groundwater that will flow into the pit, as the pit bottom is lowered. Different modeling approaches are tested during dewatering simulations and their results are compared. Following sections will summarize the results obtained by the simulations conducted under steady state and transient conditions.

7.1 Steady-State Dewatering

The first attempt in the determination of the amount of groundwater that has to be dewatered during the operational phase of the mine is simulating the system under steady state conditions. For this purpose, calibrated numerical groundwater flow model is used and new boundary conditions are imposed on this model in order to simulate the final layout of the open pit. To assign the new boundary condition, ultimate pit geometry of the pit, at the end of year 2029 is used and this geometry is simulated in the model with drain boundary condition. Drain elevations are assigned in such a way that they are equal to the ultimate elevation of the pit bottom at that cell, and groundwater is discharged from these drain cells. In this manner, groundwater elevation is equalized to the pit bottom elevation, at the final stage. Results of this steady-state simulation indicated that 57 L/s of groundwater is expected to discharge from the pit walls and the pit bottom, when the bottom elevation of the pit reaches to 300m level.

However, groundwater flow model running under steady-state conditions ignores the storage term. In other words, the calculated amount of groundwater discharge (57 L/s) does not include the amount of groundwater that would be released from storage, if the model were run under transient conditions. Therefore, the result of this simulation conducted under steady state conditions reflects the minimum amount of groundwater that is expected to flow into the pit. Consequently, it became compulsary to perform the dewatering simulations in transient state.

7.2 Transient Dewatering

The groundwater flow model calibrated under steady-state conditions is revised and it is run in monthly stress periods for the next 17 years of operation stage. In the transition from steady-state to transient state, time dependent components of the budget should be determined and transformed into time series. In this case, the recharge from precipitation is the only time dependent component of the steady state budget. To assign recharge as time series, it is assumed that average annual recharge distribution that is determined under steady state conditions is not changing throughout the years. However, time-wise distribution of recharge throughout the year is considered and steady state calibrated recharge values are converted into the monthly recharge series, in this manner.

Apart from the boundary conditions, specific storage and specific yield parameters have to be defined before the model is run under transient conditions. As it is mentioned in the Chapter 5, where the model parameters are discussed, there is not much data regarding the storage coefficient of the units within the study area. Therefore, based on the results of the test conducted in the open pit area, specific storage of the intrusive units at this location is assigned as $1.2x10^{-6}$ 1/m, and the rest of the model domain is assigned a smaller value ($1.0x10^{-7}$ 1/m). Due to the absence of a specific yield parameter (in other words storage coefficient for the unconfined conditions) defined for the study area; this value is assumed to be 0.01. Later on, dewatering simulations are performed using different specific yield values (0.020, 0.015, 0.010, 0.005) and the effects of this parameter on the model results are tested.

After the basic modifications are completed to transform the model from steady-state to transient state, progression of the pit in time has to be defined using boundary conditions. For this purpose, drain boundary condition is used to simulate the groundwater flow into the pit as the pit bottom is lowered, similar to the steady-state dewatering method described above. In addition to this, drain boundary condition is capable of simulating the time-wise progression of the pit by assigning time dependent head values to the drain cells. Head values are assigned in accordance with the mine development plan, which are available for different time periods during the 17 years of operational stage.

Within this time interval between the years 2012 and 2029, mine development plans designed for the following time schedules are utilized:

- for 2013 and 2014, quarterly
- for 2015 and 2016, biannually,

- for 2017 and 2027, annually and
- for 2029, corresponding to the final pit layout.

During this period, mine layouts are interpolated for the months having no plans, assuming that the elevation linearly changes in between the periods of known design.

Groundwater flow model modified in this manner is run under transient conditions for 17 years, divided into monthly stress periods and amount of groundwater flow that has to be dewatered during the operational phase of the mine is determined.

Four sets of dewatering simulations under transient state are conducted using different specific yield values (0.020, 0.015, 0.010, 0.005). At the end of these simulations, amount of groundwater that will flow into the pit is determined on monthly basis (for 204 months). Figure 7.1 shows the time-wise progression of the pit bottom together with the corresponding monthly groundwater inflow rates for different specific yield values. As it can be seen from this figure, as a consequence of lowering the pit bottom from 870 m to 300 m level, groundwater inflow rate will increase continuously and reach to 81-115 L/s (corresponding to simulations using different storage values) at the end of the 17 years.

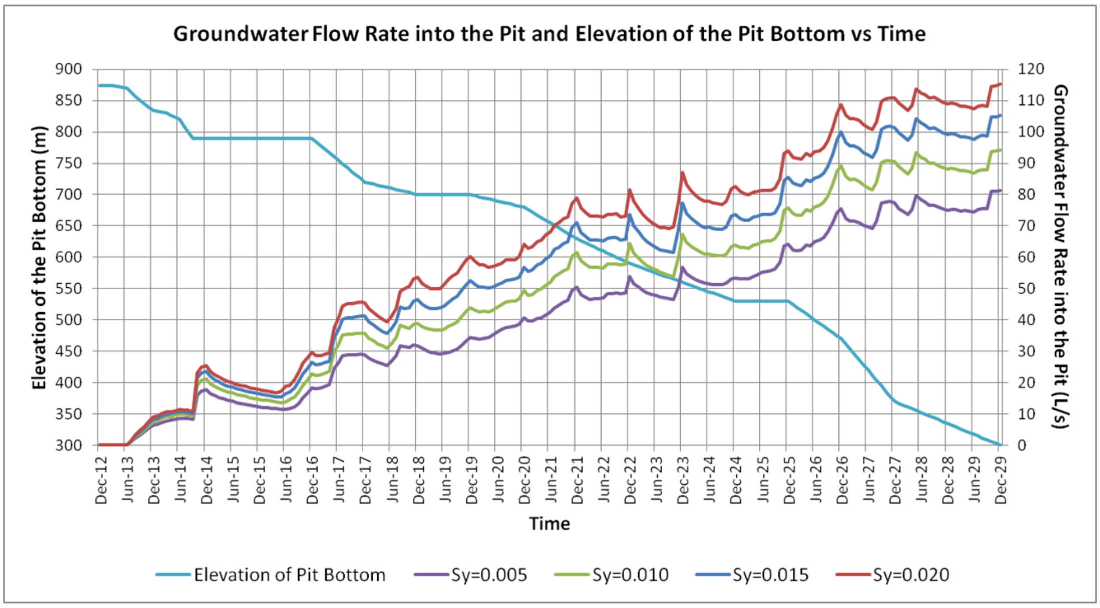

Figure 7.1. Groundwater flow rate into the pit and elevation of the pit bottom vs time

Tables 7.1-7.4 summarizes the annual groundwater budgets calculated by the model corresponding to the four set of simulations using different storage values, during the 17 years of dewatering period. Examining these annual budgets,

- average annual groundwater flow rate into the pit is calculated as 41-62 L/s or
- average annual amount of groundwater flow into the pit is calculated as 1.29-1.96 Mm^3/year

The safe yield of this system is determined by Yazıcıgil et al. (2013), as 5.89 Mm^3/year, which corresponds to 80% of the recharge (7.36 Mm^3/year) for this model are. When this amount is compared with amount of groundwater that has to be pumped during the dewatering activities (1.29-1.96 Mm^3/year), it is noted that the amount of groundwater that has to be pumped for satisfying the dewatering requirement, lie within the limits of safe pumping.

Table 7.1. Annual groundwater budget calculated by the model (Sy=0.005)

Time	RECHARGE (Mm³/year)				DISCHARGE (Mm³/year)					
	Total	Precipitation	Ulubey Form.	Storage	Total	Lateral Flow (SE)	Ulubey Form.	Surface Waters	Open Pit	Storage
2013	12.19	7.24	0.11	4.85	12.24	2.20	0.70	5.23	0.06	4.06
2014	12.30	7.24	0.11	4.95	12.33	2.18	0.68	4.89	0.32	4.26
2015	12.27	7.24	0.11	4.92	12.34	2.17	0.67	4.78	0.44	4.28
2016	12.16	7.24	0.11	4.82	12.24	2.16	0.67	4.71	0.42	4.28
2017	12.52	7.24	0.11	5.17	12.54	2.15	0.66	4.64	0.79	4.31
2018	12.53	7.24	0.11	5.18	12.56	2.14	0.65	4.56	0.91	4.30
2019	12.50	7.24	0.11	5.15	12.53	2.12	0.64	4.49	0.97	4.31
2020	12.59	7.24	0.11	5.24	12.63	2.12	0.63	4.43	1.15	4.30
2021	12.69	7.24	0.11	5.34	12.78	2.10	0.62	4.35	1.38	4.32
2022	12.72	7.24	0.11	5.37	12.83	2.08	0.61	4.29	1.52	4.32
2023	12.66	7.24	0.11	5.31	12.78	2.07	0.60	4.24	1.55	4.33
2024	12.71	7.24	0.12	5.36	12.81	2.06	0.59	4.19	1.66	4.31
2025	12.78	7.24	0.12	5.43	12.87	2.04	0.58	4.13	1.78	4.34
2026	13.00	7.24	0.12	5.65	13.12	2.02	0.57	4.08	2.10	4.35
2027	13.13	7.24	0.12	5.78	13.22	2.00	0.55	4.02	2.31	4.35
2028	13.11	7.24	0.12	5.75	13.23	1.99	0.54	3.96	2.41	4.33
2029	13.07	7.24	0.12	5.71	13.16	1.96	0.52	3.90	2.42	4.36

Table 7.2. Annual groundwater budget calculated by the model (S_y=0.010)

Time	RECHARGE (Mm^3/year)				DISCHARGE (Mm^3/year)					
	Total	Precipitation	Ulubey Form.	Storage	Total	Lateral Flow (SE)	Ulubey Form.	Surface Waters	Open Pit	Storage
2013	12.27	7.24	0.11	4.93	12.31	2.18	0.69	5.04	0.07	4.33
2014	12.49	7.24	0.11	5.14	12.50	2.17	0.68	4.81	0.38	4.47
2015	12.54	7.24	0.11	5.19	12.56	2.16	0.67	4.73	0.53	4.47
2016	12.46	7.24	0.11	5.12	12.49	2.16	0.67	4.69	0.51	4.46
2017	12.87	7.24	0.11	5.52	12.89	2.15	0.66	4.63	0.97	4.48
2018	12.92	7.24	0.11	5.57	12.94	2.14	0.66	4.58	1.10	4.46
2019	12.97	7.24	0.11	5.62	12.99	2.13	0.65	4.53	1.23	4.46
2020	13.07	7.24	0.11	5.72	13.09	2.12	0.64	4.48	1.41	4.43
2021	13.25	7.24	0.11	5.90	13.28	2.10	0.63	4.41	1.68	4.45
2022	13.32	7.24	0.11	5.97	13.34	2.09	0.62	4.36	1.83	4.44
2023	13.22	7.24	0.11	5.87	13.26	2.08	0.61	4.30	1.82	4.44
2024	13.30	7.24	0.11	5.95	13.32	2.07	0.61	4.26	1.96	4.42
2025	13.37	7.24	0.11	6.02	13.39	2.05	0.60	4.20	2.10	4.44
2026	13.68	7.24	0.12	6.33	13.70	2.04	0.59	4.16	2.47	4.44
2027	13.83	7.24	0.12	6.47	13.85	2.02	0.57	4.11	2.72	4.44
2028	13.86	7.24	0.12	6.51	13.88	2.01	0.56	4.06	2.83	4.41
2029	13.75	7.24	0.12	6.40	13.79	1.99	0.55	4.00	2.81	4.44

Table 7.3. Annual groundwater budget calculated by the model (S_y=0.015)

Time	RECHARGE (Mm^3/year)				DISCHARGE (Mm^3/year)					
	Total	Precipitation	Ulubey Form.	Storage	Total	Lateral Flow (SE)	Ulubey Form.	Surface Waters	Open Pit	Storage
2013	12.25	7.24	0.11	4.90	12.34	2.17	0.69	4.95	0.08	4.45
2014	12.50	7.24	0.11	5.15	12.59	2.17	0.68	4.76	0.42	4.56
2015	12.61	7.24	0.11	5.26	12.69	2.16	0.67	4.71	0.59	4.56
2016	12.60	7.24	0.11	5.25	12.65	2.16	0.67	4.68	0.59	4.54
2017	13.04	7.24	0.11	5.69	13.11	2.15	0.67	4.64	1.11	4.55
2018	13.16	7.24	0.11	5.81	13.21	2.14	0.66	4.60	1.28	4.54
2019	13.29	7.24	0.11	5.94	13.33	2.13	0.65	4.55	1.47	4.53
2020	13.40	7.24	0.11	6.05	13.43	2.13	0.65	4.52	1.65	4.49
2021	13.60	7.24	0.11	6.25	13.66	2.11	0.64	4.46	1.95	4.50
2022	13.68	7.24	0.11	6.33	13.73	2.10	0.63	4.41	2.10	4.49
2023	13.59	7.24	0.11	6.24	13.63	2.08	0.62	4.36	2.08	4.49
2024	13.67	7.24	0.11	6.32	13.72	2.08	0.61	4.32	2.24	4.46
2025	13.75	7.24	0.11	6.40	13.80	2.06	0.60	4.27	2.38	4.48
2026	14.07	7.24	0.11	6.72	14.12	2.05	0.60	4.22	2.77	4.48
2027	14.28	7.24	0.12	6.93	14.31	2.03	0.58	4.18	3.05	4.47
2028	14.31	7.24	0.12	6.95	14.36	2.02	0.57	4.14	3.18	4.44
2029	14.20	7.24	0.12	6.85	14.28	2.00	0.56	4.08	3.16	4.47

Table 7.4. Annual groundwater budget calculated by the model (S_y=0.020)

Time	RECHARGE (Mm^3/year)				DISCHARGE (Mm^3/year)					
	Total	Precipitation	Ulubey Form.	Storage	Total	Lateral Flow (SE)	Ulubey Form.	Surface Waters	Open Pit	Storage
2013	12.29	7.24	0.11	4.94	12.37	2.17	0.69	4.90	0.08	4.53
2014	12.60	7.24	0.11	5.25	12.65	2.17	0.68	4.73	0.45	4.62
2015	12.72	7.24	0.11	5.37	12.78	2.16	0.67	4.69	0.63	4.62
2016	12.72	7.24	0.11	5.37	12.76	2.16	0.67	4.67	0.66	4.59
2017	13.22	7.24	0.11	5.87	13.28	2.15	0.67	4.63	1.22	4.61
2018	13.38	7.24	0.11	6.03	13.43	2.14	0.66	4.60	1.44	4.59
2019	13.57	7.24	0.11	6.22	13.61	2.13	0.65	4.56	1.69	4.58
2020	13.66	7.24	0.11	6.31	13.71	2.13	0.65	4.53	1.86	4.54
2021	13.90	7.24	0.11	6.55	13.97	2.11	0.64	4.48	2.19	4.55
2022	13.94	7.24	0.11	6.59	14.04	2.10	0.63	4.44	2.34	4.53
2023	13.90	7.24	0.11	6.55	13.95	2.09	0.63	4.39	2.32	4.52
2024	14.00	7.24	0.11	6.65	14.06	2.08	0.62	4.36	2.51	4.49
2025	14.08	7.24	0.11	6.72	14.13	2.07	0.61	4.31	2.63	4.51
2026	14.41	7.24	0.11	7.06	14.47	2.05	0.60	4.27	3.04	4.50
2027	14.63	7.24	0.11	7.28	14.68	2.04	0.59	4.23	3.33	4.50
2028	14.69	7.24	0.12	7.34	14.75	2.03	0.58	4.19	3.48	4.46
2029	14.62	7.24	0.12	7.26	14.68	2.01	0.57	4.14	3.47	4.49

At the end of the dewatering period of 17 years, when pit bottom reaches 300 m level, hydraulic head distribution is inspected. Considering all the model thickness, which is divided into 15 vertical layers; at the open pit area 300 m elevation corresponds to the first 11 layers. In other words, at the end of the 17 years, first 11 layers of the model should be dried for successful dewatering. Figure 7.2 shows the results of the dewatering simulations performed using different storage values on a cross-section passing through the open pit. As demonstrated on this figure, at the end of each simulation, pit is successfully dewatered and changing aquifer characteristics, represented by different storage values, resulted in different hydraulic head distributions.

Another significant consequence of dewatering activities is that lowering the water table from 870 m to 300 m, results in hydraulic head differences not only in lateral direction but also in vertical direction. Due to this vertical hydraulic gradient, groundwater flows into the pit from the pit bottom as well. It should be noted that defining the time-wise progression and geometry of the pit using drains with time dependent head values allows the simulation of groundwater flow into the pit from both the walls and the bottom of the pit, which is the case in the real field conditions.

As it is shown on Figure 7.2, at the end of the dewatering period of 17 years when the pit bottom is lowered to 300 m level, different hydraulic head distributions are produced at each model layer. Areal distribution of the drawdowns at the end of 17 years are presented for the third model layer because this layer allows the best representation of the interaction between the modeled units and the Ulubey Aquifer. In the lateral extension, out of the model domain, below the elevations corresponding to the bottom of this layer, Ulubey Aquifer is underlain by the impermeable Ahmetler Formation. In Figure 7.3, areal extensions of the 20 m drawdown contours, produced as a result of simulations performed using different storage values, are shown. Due to the anisotropic characteristics of the aquifer, cone of depressions have elliptical shape, whose long axis extending 4.6-5.8 km from the center of the open pit, in NW-SE direction. As can be seen from this figure, showing the results of simulations conducted using different storage values, smaller storage values result in cone of depressions having wider extensions. However, examining the Tables 7.1-7.4, it can be seen that these drawdowns do not affect the interactions between the modeled units and the Ulubey Aquifer, significantly. Depending on the different storage values used in simulations, discharge from the model area to the Ulubey Aquifer decreases about 0.13-0.18 Mm^3/year, while the recharge from the Ulubey Aquifer into the model domain is almost not affected at all at the end of 17 years. Decrease in the amount of groundwater discharging to the Ulubey Aquifer is negligible when compared to the annual of recharge of the Ulubey Aquifer (190 Mm^3/year) calculated by Yazıcıgil et al. (2008).

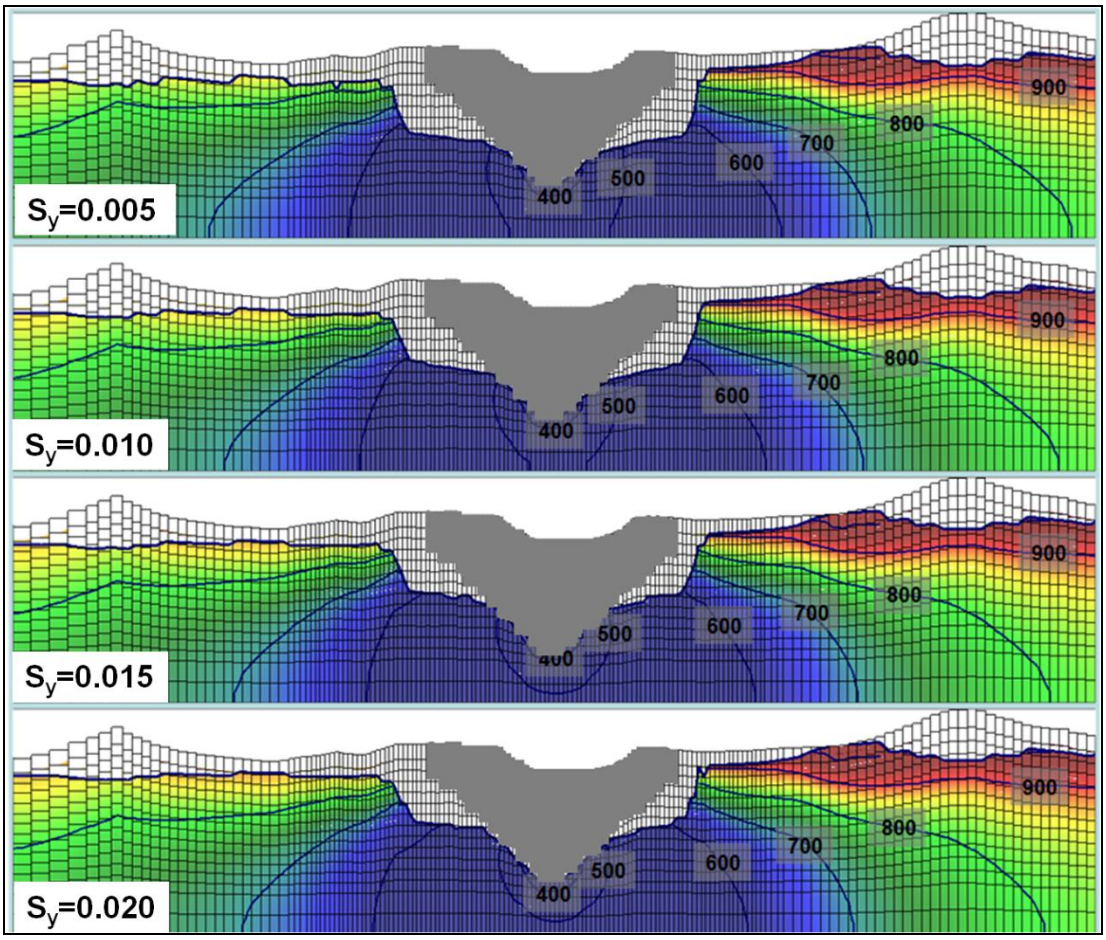

Figure 7.2. Groundwater level and hydraulic head distribution at the end of 17 years

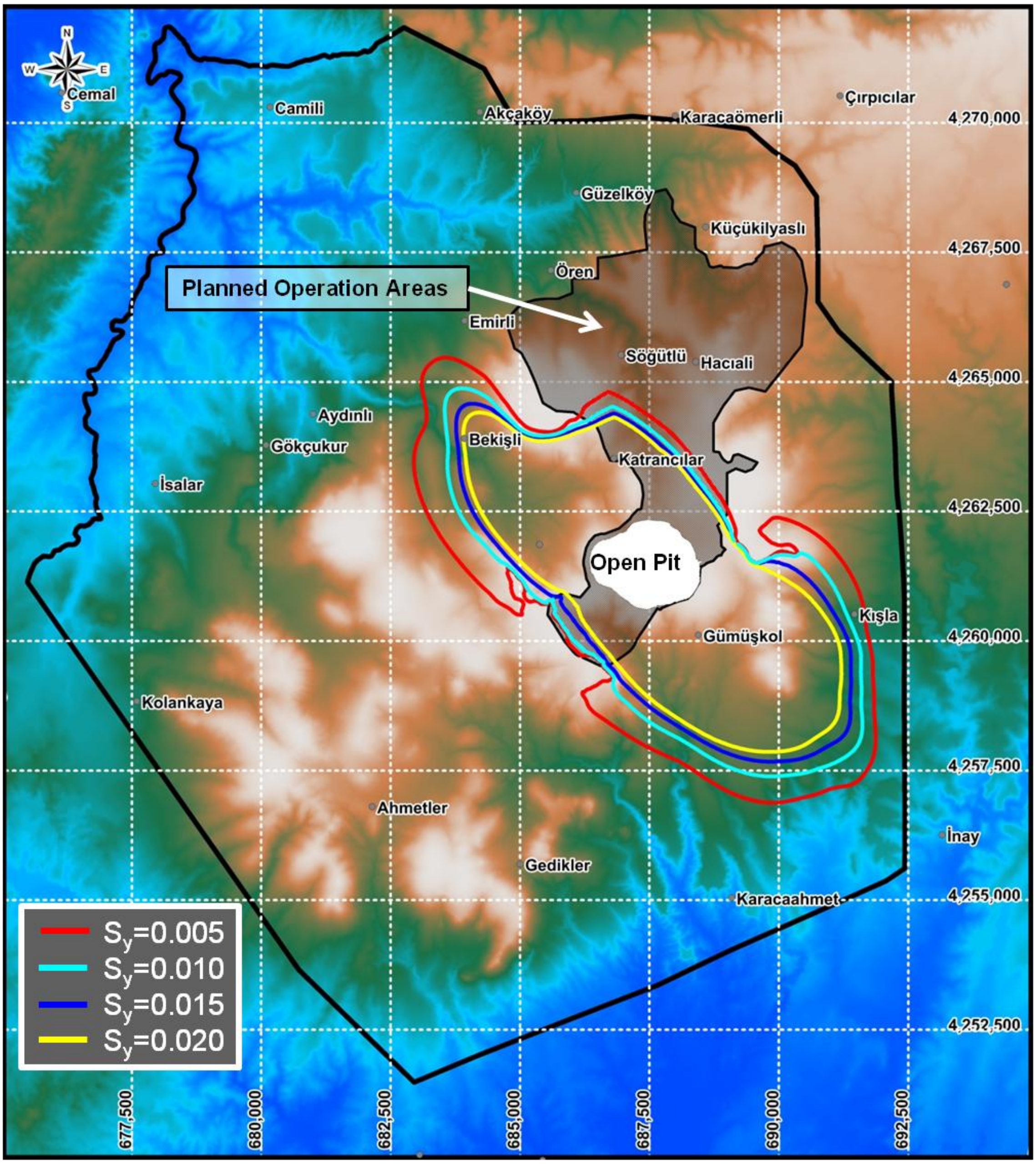

Figure 7.3. Distribution of the 20 m drawdown contour at the end of 17 years

CHAPTER 8

PIT LAKE FORMATION

Open pit mining activities at Kışladağ Gold Mine is initiated by the year 2006. Till the end of 2012, mining activities were pursued above the water table; hence, during this period dewatering actions were not required. However, by the end of year 2013, pit bottom elevation is planned to be lowered below the groundwater level. Therefore, dewatering activities has to commence and continue throughout the operational phase of the mine (17 years until the end of 2029) in order to provide and sustain stable and dry conditions for the excavations. The previous chapter gives detailed information on the simulations and calculations, which have been conducted for the operational phase, that will last 17 years, since 2013 till 2029. This chapter, on the other hand, focuses on the post-closure phase.

By the end of 2029, the pit bottom will be lowered to the ultimate level (300 m) 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 of the operational phase, will tend to rebound and groundwater will inflow to the pit. A lake is expected to form in the open pit, with the water that will flow into the excavation area. The water sources that will contribute to the formation of the pit lake are groundwater inflow, direct precipitation falling onto the lake surface and runoff from the pit walls following a precipitation event. The outflow mechanisms of the pit are in general, evaporation from the lake surface and groundwater outflow, depending on the hydraulic conditions. The lake level will stabilize at an elevation when equilibrium is reached in terms of hyrogeological and hydrological components of the lake system, under the given meteorological conditions.

In order to predict the final pit lake level, the time required to reach this level and the hydraulic status of the ultimate pit lake in the regional hydrogeological regime, water budget (total inflow and total outflow) calculations are formulated for the lake. In general, inflow components of this budget can be classified as (1) direct precipitation (2) runoff from the pit walls (3) groundwater inflow; while, the outflow components are (1) evaporation and (2) groundwater outflow to the downstream direction. A pit lake budget is formed, by which volumetric changes of all these components are calculated on daily basis.

As the calculations are based on the "volumes" of each inflow and outflow component, pit lake geometry is used to convert the flow rates into volumetric flows. For this purpose, surface area and volume of the pit lake have to be determined corresponding to different pit lake water levels. Therefore, the ultimate configuration of the pit lake that will be reached by the end of 2029 is used to calculate the relation between pit lake level – lake surface area – lake volume. These relations are demonstrated in Figure 8.1, which also shows the size of the final open pit. It can be noted from this figure that surface area of the pit walls at the final excavation level is about 3.75 km^2. These relations are introduced to the excel spreadsheet model together with the daily inflow and outflow components and time-wise change of the pit lake level is determined.

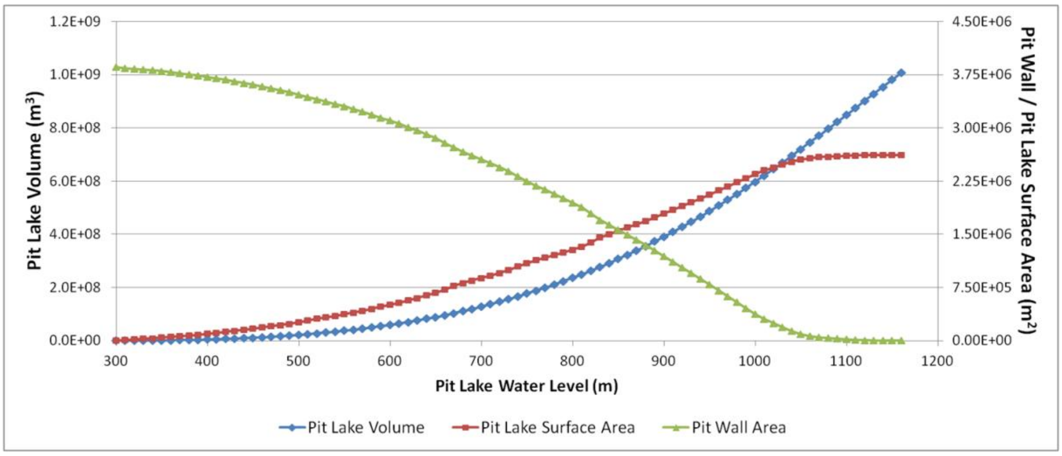

Figure 8.1. Pit lake level – lake surface area – lake volume relation

The equation to calculate the volumetric balance of the pit lake is given below:

Inflow – Outflow = Net Change in Storage

$$\mathbf{(V_{GWI} + V_{DP} + V_{PWR}) - (V_E + V_{GWO}) = V}$$

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.

The components of the conceptual lake water balance are schematically shown in Figure 8.2. Detailed description of each component and related assumptions are given below.

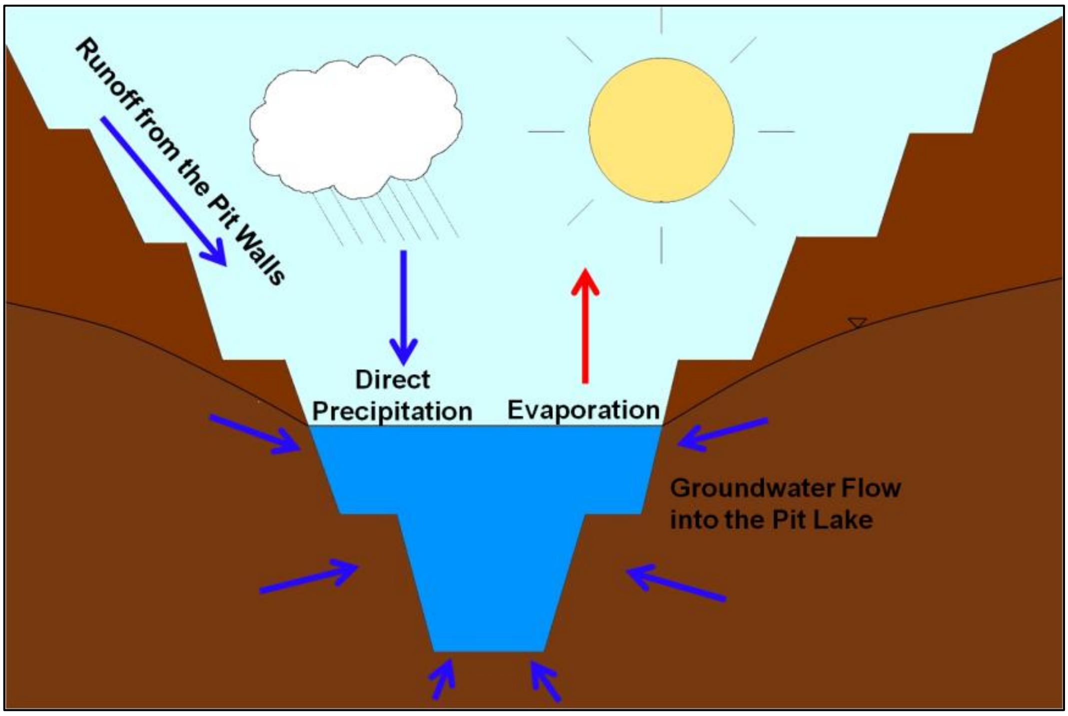

Figure 8.2. Components of the conceptual pit lake

- **Groundwater Inflow (V_{GWI}) and Groudwater Outflow (V_{GWO}):** As the dewatering operations are completed, groundwater will start to flow into the pit. The rate of groundwater inflow and/or groundwater outflow will be controlled by the lake level and groundwater level surrounding the pit. The groundwater inflow and/or outflow rates are calculated with the numerical groundwater flow modelby running the model under steady-state conditions assuming a lake-level for every 50 meter interval from pit bottom to top. Then a regression analyses is completed on the data to calculate the total inflow and outflow rate for 1 m increments. Figure 8.3 shows the net inflow rates for 1 m interval (Note that the negative inflow rates indicate an outflow from the pit lake). As can be noted from this figure, the groundwater inflow rate is calculated as almost 50 L/s at the beginning of the closure period when pit bottom is at 300 m level; while, it decreases to 10 L/s at 820 m of lake level. 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 rising water table increases the area where groundwater discharges into the lake 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 decreasing gradient dominates over this effect and results in a continuous decline in the groundwater flow rates into the pit. Furthermore, at 830 m elevation, the inflow and outflow rates were calculated as 8 L/s and 0.12 L/s respectively, indicating a negligible outflow from the pit lake at 830 m elevation (0.12 L/s). On the other hand, as the lake level increases above 830 m elevation, the pit lake's hydrologic status changes from sink to flow-through condition.

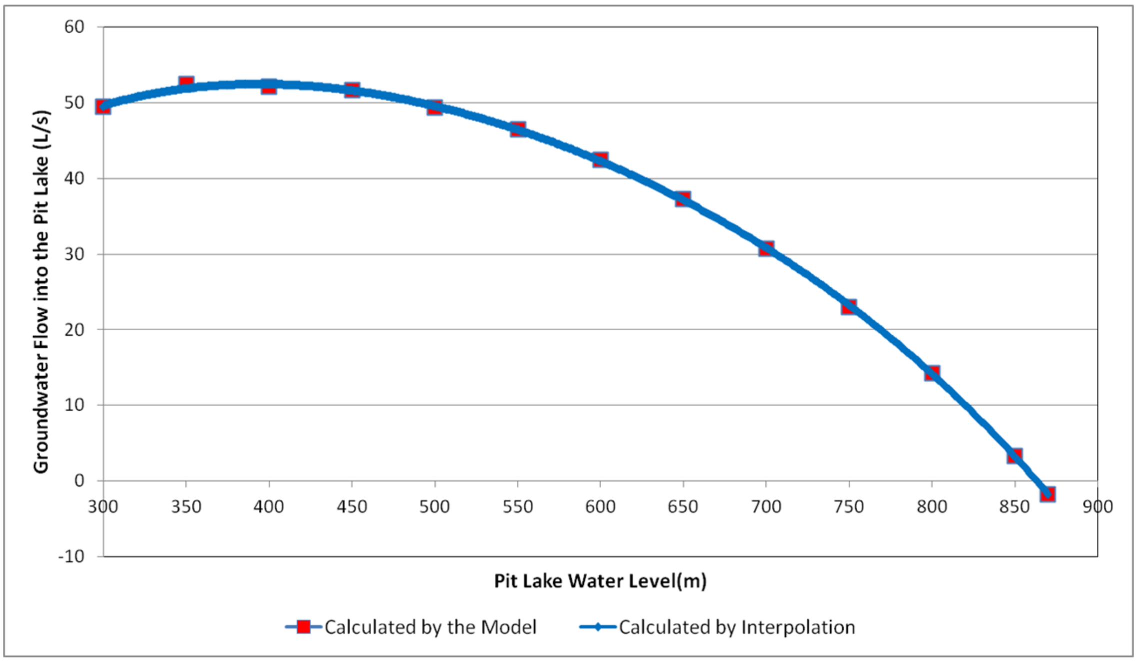

Figure 8.3. Net inflow rate to pit at different elevations

- **Direct Precipitation (V_{DP}):** Long term (1975-2012) daily precipitation series that were generated using the data from both Kışladağ Meteorological Station and MGM's (Turkish Meteorological General Directorate) Uşak Meteorological Station are used in the calculation of this budget component. As previously explained, this 38 years of data series covers three wet (1978-1981, 1997-2002 and 2009-2012) and two dry periods (1984-1996, 2003-2008). Hence, it can be concluded that the data set can represent long-term precipitation patterns expected in the area. The volumetric inflow amount to lake from direct precipitation is calculated by multiplying the daily precipitation with the pit lake surface area (for the same day).

- **Pit Wall Runoff (V_{PWR}):** An analytical model is utilized to predict the runoff rate that will be originated from the precipitation 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 the determination of the runoff rate. Following equations are used for the calculation of the runoff;

$$S = \frac{1000}{CN} - 10 \quad ; \quad Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

- S : potential maximum soil moisture retention after runoff begins (inch)
- CN : Curve Number
- P : Precipitation (inch)
- Q : Runoff (inch)

Considering the hydrogeological and hydrological conditions, together with the geometry of the Kışladağ open pit, the curve number (CN) is determined as 95. However, a series of additional simulations are also completed with CN values of 96, 97 and 98, in order to assess the effects of this parameter on the pit lake water budget and on the equilibrium conditions of the system. The results of the calculations, which are made using different CN values, are presented together. To conclude, during the determination of the volumetric balance, the runoff is calculated by multiplying the daily precipitation with the pit wall area (for the same day). The pit wall area is calculated as the difference between the pit crest area and the lake surface area for the same day.

- **Evaporation (V_E):** The long-term (1975-2012) daily evaporation data set generated for the Kışladağ mine site as explained previously is used in the calculation of the evaporation losses from the lake surface. Daily evaporation values (pan evaporation values) are multiplied with the pan coefficient (taken as 0.75) to calculate the lake evaporation values. The daily evaporation rates calculated in this manner for the 1975-2012 period are introduced to the spreadsheet model, repetitively. Then on a daily basis, lake surface area and daily lake evaporation value is multiplied to calculate the total daily volume evaporating from the pit lake.

As described above, each component of the lake budget is calculated on a daily basis and included in the lake water budget in order to calculate the volume of the lake at that day. The surface area and elevation of the lake corresponding to that volume is determined from above mentioned the pit lake level – lake surface area – lake volume relations (Figure 8.1). These steps are repeated for each day throughout the simulation time, until the lake level stabilizes. Moreover, as it is mentioned above, the spreadsheet models is run with different CN values, and resulting the steady- state pit lake levels, together with the time required to reach those levels, are determined. Figure 8.4 shows the pit lake level changes for a period of 800 years for different CN values. According to the results of these runs, the pit lake level will be stabilized approximately 585 years after the closure of the mine (at year 2615). Furthermore, it is noted that (other than the climatic fluctuations) pit lake level reaches equilibrium at 816 m when CN value is 95, while lake level stabilizes at 829 m when CN value is 98.

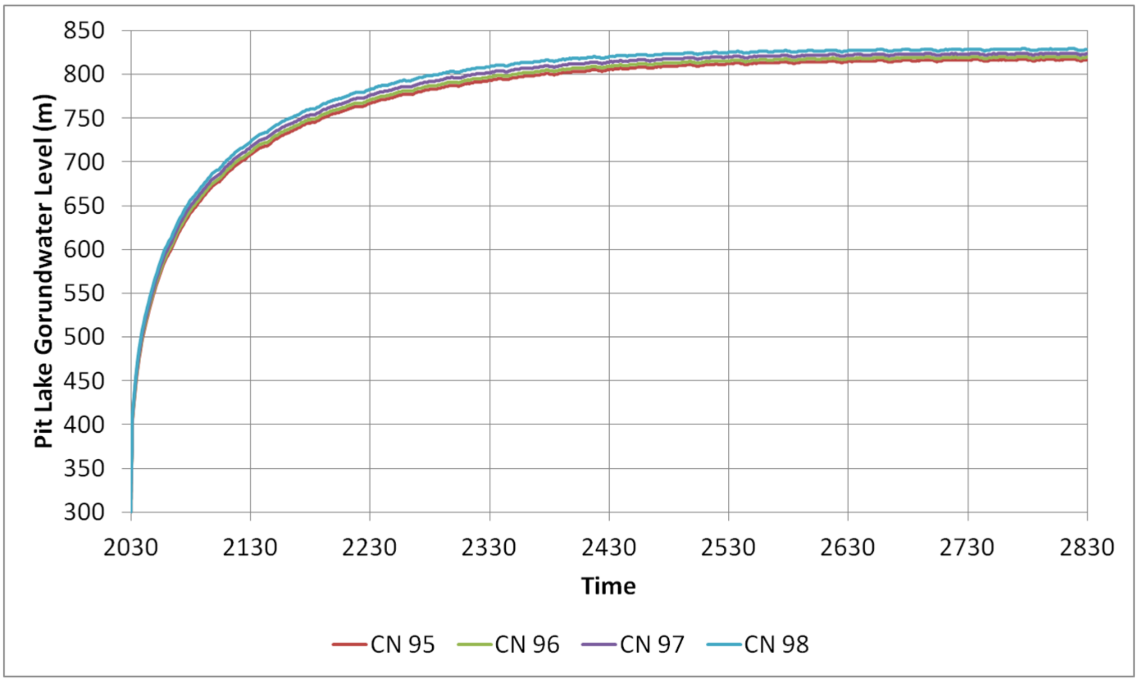

Figure 8.4. Pit lake level changes within time for different CN values

The components of the annual lake water budget for CN 95 over 800 year period are given in Figure 8.5 As can be noted from this figure, the groundwater inflow to the lake will be the most significant component of the pit lake water budget for the first 200 years period, because of the high hydraulic gradient caused by the dewatering operations. Later, as the hydraulic gradient decreases, the significance of groundwater inflow will decrease, and meanwhile as a result of increasing surface area, the significance of inflow from direct precipitation will increase. Similarly, the increase in the surface area of the pit lake will drastically increase the outflow by evaporation. On the other hand, the runoff from pit walls will normally show a decrease within time as the pit lake level increases.

Another important outcome of Figure 8.5 is that components of pit lake water budget, except for the groundwater inflow, are quite sensitive to the climatic changes in precipitation and evaporation. As a consequence of the presence of wet and dry periods within the 38 years of precipitation and evaporation series, which are used repetitively; direct precipitation, pit wall runoff and evaporation components show significant fluctuations. To conclude, it should be noted that the climatic variations have a significant impact on the components of the pit lake water budget and hence on the lake levels at the equilibrium state conditions.

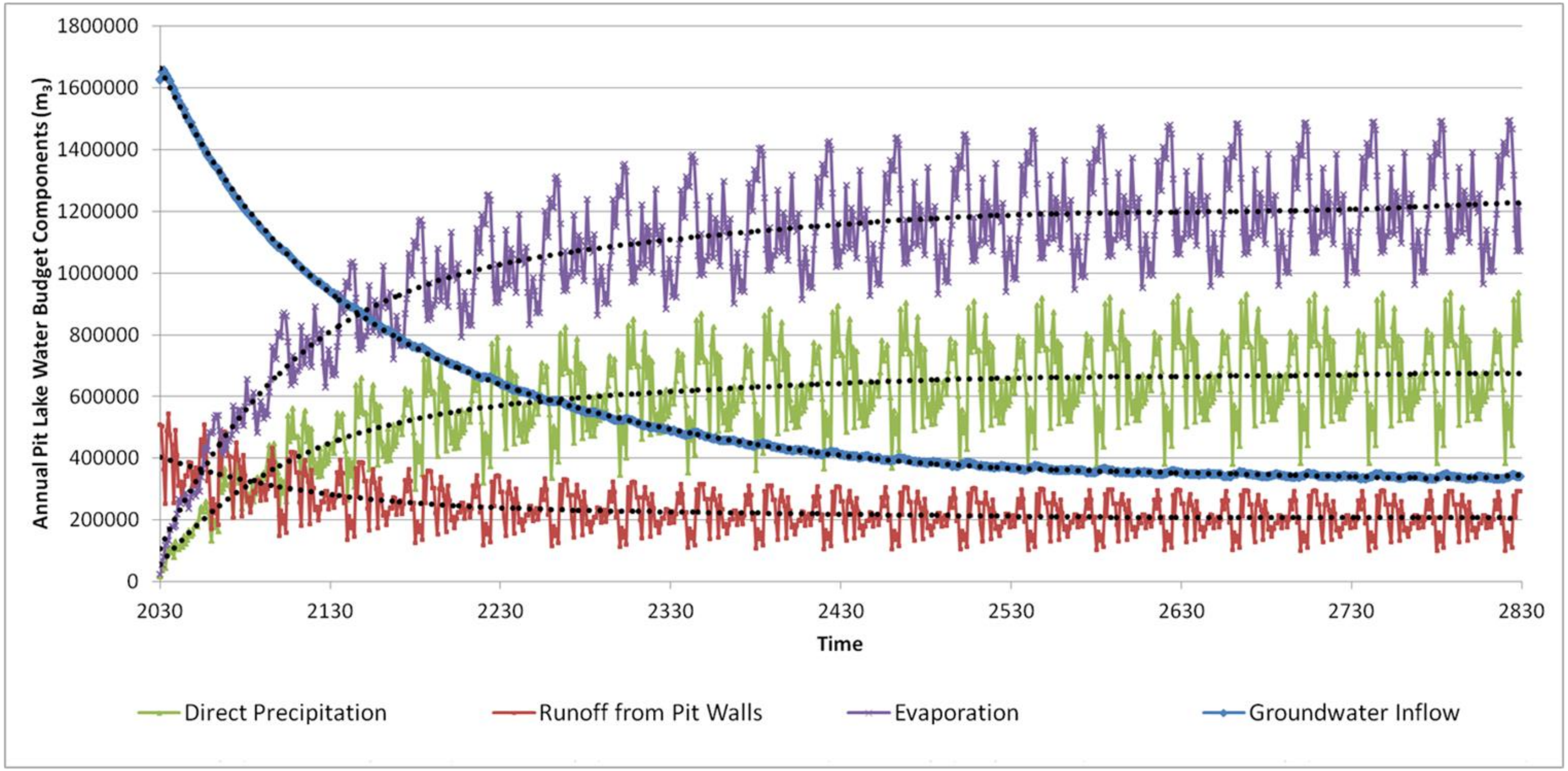

Figure 8.5. Annual volumes of pit lake budget components over 800 year period

As noted in the above sections, pit lake water budget calculations showed that the pit lake level is expected to stabilize between 816 and 829 m for different CN values (95, 96, 97, 98). Furthermore, it is also noted that these equilibrium levels fluctuate in response to the changing climatic conditions introduced by the repetitive time series of precipitation and evaporation. For different scenarios, the highest pit lake levels are determined in the range from 818 m (CN:95) to 830 m (CN:98).

To assses the hydraulic relation between the lake and the groundwater system, the maximum lake levels are simulated using the calibrated steady state numerical groundwater model after a few modifications. As these simulations should represent the post-closure phase of the mine, where open pit will totally be excavated, several approaches are tested to simulate the pit lake. In each approach tested lake level is simulated by the constant head boundary condition assigned to the final surface area of the pit. The approaches differ in the sense they are used to simulate the flow conditions within the open pit. The cells within the open pit are simulated (1) as the same with the surrounding cells without any modification, (2) as inactive cells, (3) with high hydraulic conductivity cells of conductivity set equal to 2000 m/d. A set of simulations are performed and their results as compared. Although computational time differed due to the convergence difficulties, in the end, all methods produced very similar results. The results presented below are obtained from the model where cells within the open pit are simulated with high hydraulic conductivity.

As it is mentioned above, lake levels to be tested (818 and 830 m), are introduced to the numerical groundwater model as the elevation of the constant head boundary cells representing the equilibrium lake levels and steady state simulations are conducted in order to understand the hydraulic relation between the groundwater system and the pit lake. In this manner, it is possible to examine the hydraulic head distribution at the equilibrium conditions and to determine the interactions of the final lake and surrounding groundwater system. Figure 8.6 shows the hydraulic head distributions for the lake levels at 830 and 818 meters under the steady state conditions. It can be depicted from these figures that while the lake level is at 818 meters, the lake behaves as a sink, in other words it becomes a terminal pit lake. As the level increases to 830 meters, the lake will change its hydraulic status from terminal to flow-through pit lake. It should be noted that groundwater outflow from the pit lake, which is negligible at 830 m level, would impact the downstream system at lake levels higher than 830 m.

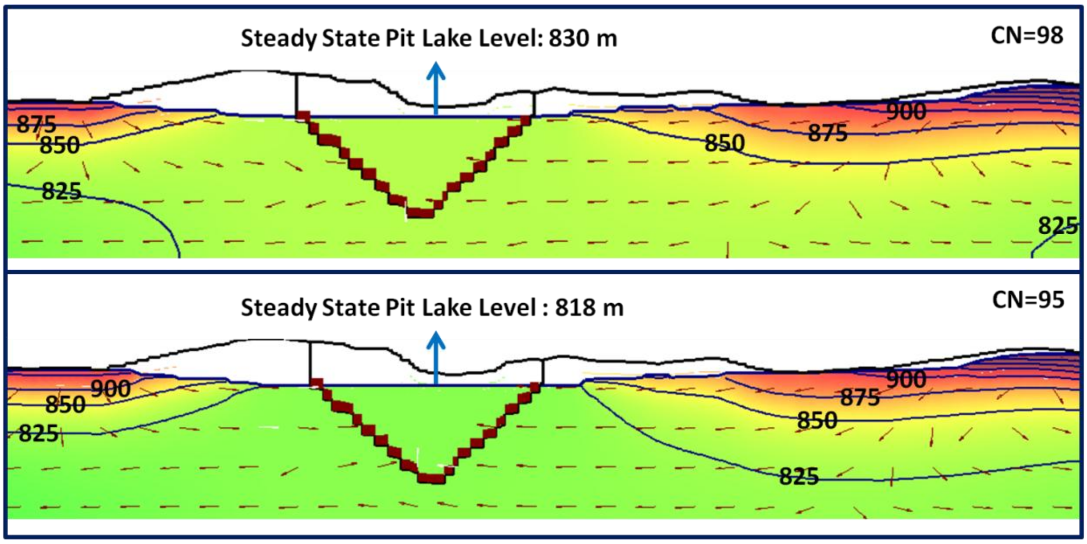

Figure 8.6. Hydraulic head distributions corresponding to pit lake levels of 830 m and 818 m

CHAPTER 9

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

TÜPRAG Metal Mining Company is operating a gold mine in Uşak Province in western Turkey since 2006, currently with the main facilities consisting of a leach pad, waste rock storage area and an open pit. By the end of 2012, pit bottom elevation is almost 1 m above the groundwater level. According to the mine plans, pit bottom elevation is expected to reach 300 m level by the end of 2029. Therefore, during the period between the years 2012-2029, groundwater levels have to be reduced by 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, has to be quantified and based on this rate dewatering systems have to be designed. The mining operations will be finalized in 2030 after which the dewatering program will cease. Thus a lake is expected to form in the open pit area. To assess the impact of the lake on groundwater resources, it is of utmost importance to determine the steady state conditions (lake levels, time required to reach steady state, groundwater-pit lake interactions etc) to be formed at the pit lake during post-closure period.

This study aimed to predict the dewatering discharge rates (groundwater inflow to pit) during the operational period as the excavation advances to the final operational depth; the future pit lake level after closure and filling period to reach the steady-state lake level under historical meteorological conditions and to assess the impact of dewatering operations on existing water resources and users and the hydraulic relation between the final pit lake and groundwater system.

In order to achieve these purposes, a numerical three dimensional groundwater model was constructed to simulate the operational and the post closure groundwater regime. The numerical modeling process was completed within three stages. Initially a conceptual groundwater model was constructed, then based on this conceptual model a numerical groundwater flow model was constructed and calibrated to site conditions (with the observed groundwater levels). Finally, dewatering simulations were completed with the calibrated model in order to predict the groundwater inflows to pit during the dewatering period and the potential impact on the groundwater resources in the close vicinity of the area. To predict the post closure pit lake formation, a spreadsheet model was integrated with the numerical groundwater flow model that predicts groundwater inflow rates to the pit. Then simulations were completed to predict the filling period and the steady pit lake level. The simulations were completed for 800 year period with the spreadsheet model using the daily evaporation and precipitation data set prepared from long term daily meteorological data. Finally, the steady pit lake level was introduced to the numerical groundwater model in order to predict the hydrologic status of the pit lake at its steady state conditions.

The following results and conclusions are made:

Two different approaches are applied for the prediction of the groundwater inflow into the pit when pit bottom reaches to 300 m level. First one is the steady state simulation of pit dewatering, which resulted in a groundwater inflow rate of 57 L/s. However, as this approach (steady state simulation) does not account for the amount of groundwater that will be released from storage, transient simulations are also performed.

The results of the dewatering simulations conducted under transient conditions show that groundwater inflow into the pit increased from zero to a maximum of 81-115 L/s (depending on the storage values used in the simulations) as water table is lowered from 870 m to 300 m elevation during 17 years of operational period. When these inflow rates are averaged over 17 years, expected average groundwater inflow rates are calculated as 41-62 L/s, corresponding to an annual rate of 1.29-1.96 Mm^3/year that has to be dewatered.

When the results of the two approaches are compared, it is obvious that steady state simulations yielded almost half of the maximum rates calculated by the transient simulations, thus underpredicting the groundwater inflows at the later stages of dewatering but overpredicting them at the early stages. As it is mentioned above, this is due to the fact that steady state simulation does not account for the amount of groundwater that will be released from storage, while transient simulation does. However, when groundwater inflow rates calculated under steady state conditions (57 L/s) are compared with average groundwater inflow rates calculated under transient conditions (41-62 L/s), it is seen that they are very close, indicating the reliability of the model results. Transient approach is better in simulating the time-wise progression of the pit and corresponding time-wise change in the groundwater inflow rates into the pit.

At the end of the dewatering period of 17 years when the pit bottom is lowered to 300 m level, due to the anisotropic characteristics of the aquifer, cone of depressions having elliptical shapes are formed and extended 4.6-5.8 km from the center of the open pit in NW-SE direction. However, it is observed that these drawdowns do not affect the interactions between the modeled units and the Ulubey Aquifer significantly. Depending on various storage values used in the simulations, discharge from the model area to the Ulubey Aquifer decreases about 0.13-0.18 Mm^3/year, while the recharge from the Ulubey Aquifer into the model domain is almost not affected at all at the end of 17 years. Decrease in the amount of groundwater discharging to the Ulubey Aquifer is negligible when compared to the annual recharge of the Ulubey Aquifer (190 Mm^3/year) calculated by Yazıcıgil et al. (2008).

At the end of the operational period of 17 years, the dewatering program will cease and groundwater is expected to flow into the pit, forming a pit lake. Pit lake water balance calculations are performed for 800-year period with different CN values. According to the results of these runs, the pit lake filling period will be completed approximately after 585 years (at year 2615). Furthermore, at CN 95, pit lake level reaches to 816 m and at CN 98, lake level reaches to 829 m, except the seasonal fluctuations. It can be concluded that for all

CN values tested, lake levels stabilize at levels below 830 m, such that pit will behave as a sink. Furthermore, it should be noted that as the lake level increases to above 830 meters, the lake will be a flowthrough system that may impact the downstream groundwater resources.

Based on the results of this research following recommendations are made:

The results presented in this study are calculated using a 3-D numerical groundwater flow model. It should be noted that in the whole area of 245 km^2, available data is limited to the mine site. Therefore, the model should be revised as new data becomes available during operations.

Moreover, the lack of data regarding the storage values of the water bearing units within the study area poses uncertainity on the model results. Hence, rather than using a single storage value, a range of values are tested with the simulations and the results are given as ranges. Results indicated a high dependency on the storage value, which is observed in the dewatering simulations as calculated wide range of groundwater flow rates into the pit. As model results are highly sensitive to storage value; in the further studies, this parameter should be determined with the field tests and the model has to be re-run with the value obtained from the tests, if it is not within the range tested.

It should be noted that during these simulations, precipitation that will directly fall on the pit and runoff from the pit walls, are not taken into account. Therefore, in the design of dewatering systems, especially in the selection of pumps, this fact should be considered. Furthermore, all these simulations were conducted using the present pit design, therefore, any possible change in the production plans or the pit design should require the modifications to the groundwater flow model and simulations have to be re-run.

Another issue that has to be pointed out is on the selection of the model to simulate dewatering and pit lake formation processes. A thorough discussion on the selection of a proper model for the solution of any groundwater related mining problem is given in Chapter 2. As it is mentioned in that section, individual codes have slight advantages and disadvantages, depending on the application, and the choice of input parameters and data, as well as the interpretation of the modeling output are more important than the choice of the code itself. There are several analytical and numerical methods that can be applied depending on the size and site-specific conditions of the problem. In this study dewatering simulations are performed using MODFLOW 2000 (Harbaugh et al., 2000) code, where open pit is simulated by defining drain boundary condition to the cells representing the geometry of the pit and are assigned time dependent head values. In the light of the results of these dewatering simulations providing the groundwater flow rates into the pit as the pit progresses, future work could focus on a dewatering system design. Furher simulations could be performed using the 3-D model developed in this study as a tool to design and test the efficiency of several dewatering alternatives. For instance performance of dewatering systems using vertical and horizontal wells or a combination of both could be tested.

Pit lake formation process on the other hand, is simulated with a spreadsheet model, which is fed several inputs (climate data, pit geometry and also the groundwater inflow rates calculated by the 3-D steady state model). Moreover, results of the spreadsheet model are then used as inputs to the 3-D model to simulate the ultimate equilibrium conditions. For the further studies, simulation of the transient pit lake formation using the same 3-D model and LAK3 package (Merritt and Konikow, 2000), with several modifications on the calculation of the pit wall runoff component (which is very significant for this pit geometry and should be linked to the changing pit level) could be recommended. Several models may also be used to cross-check the solutions.

In the lake water budget calculations using the spreadsheet model, runoff rate that will be originated from the precipitation to the pit walls is predicted by means of an analytical model, namely curve number (CN) method (USDA, 1986). Considering the hydrogeological and hydrological conditions, together with the geometry of the Kışladağ open pit, the curve number (CN) is determined as 95; however, different CN values are tested and results are presented within the possible ranges. Furthermore, it is noted that directly affecting the pit wall runoff component of the pit lake water budget, CN parameter is very effective on the model results. Therefore, its precise determination is crutial. It is known that during the ongoing excavations in the open pit throughout the operational phase of the mine, the water accumulating at the bottom of the pit as a consequence of precipitation will be collected in sumps and pumped out. The amount of water that will be pumped should continuously be monitored and recorded so that components of the precipitation, namely direct precipitation falling onto the pit bottom and runoff from the pitwalls, could be quantified. This calculation can be very useful in determination of the runoff ratio and/or CN value, which is a very significant parameter in pit lake water budget calculations for the post-closure period.

Another important point that should be mentioned is that pit lake water budget calculations are conducted based on the the long term meteorological data assuming that past 38 year climatic trend will continue periodically, for the next 800 years. Moreover, the results indicated that direct precipitation, pit wall runoff and evaporation components of pit lake water budget are quite sensitive to the climatic changes in precipitation and evaporation. Hence, the climatic variations have a significant impact on the pit lake water budget and accordingly on the lake levels at the equilibrium state conditions. Therefore, further simulations that will examine the effects of the changing climate on the results are highly recommended. For this purpose, climatic projections should be downscaled to the study area and simulations have to be updated with the long term projected temperature and precipitation values.

However, it should also be noted that both past climatic trends (Tayanç et al., 2009; Durdu, 2013) and future predictions (compiled in Turkey's National Climate Change Adaptation Strategy and Action Plan, by Talu et al., 2010) indicate increasing temperature and decreasing precipitation for this region. These trends in climate will definetly affect the budget of the pit lake so that evaporation component will be increased by increasing temperature; on the other hand direct precipitation and runoff from the pit walls components will be decreased by decreasing precipitation. Considering the combined effects of these changes, it is obvious that pit lake level will be stabilized at a much lower elevation than predicted with the available data and a terminal pit lake will form, which will not affect the downgradient groundwater system. However, increasing evaporation and decreasing precipitation causing lower lake levels may increase the concentrations of the dissolved material within the pit lake, therefore has to be investigated in terms of water quality aspects, which is out of the scope of this work.

Finally, it should be noted that the results presented in this study are calculated using a 3-D numerical groundwater flow model, based on several assumptions and hence, having uncertainities. All the models used in this study should be revised as new data becomes available during operations.

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Environmental Security, Vol. 3, Springer, Dordrecht, The Netherlands, 1st Edition., 318 p., Hardcover, ISBN: 978-94-007-1142-6 **(Chapter in Book)**

- **Unsal-Erdemli, B.** and Yazicigil, H. (2010), *Development of a Dewatering Plan for a High-Rise Hotel Complex in Tripoli, Libya;* IAHR International Groundwater Symposium; September 22-24, 2010; Valencia, Spain **(Oral Presentation)**
- **Unsal-Erdemli, B.** and Yazicigil, H. (2008), *Sustainable Management of Ulubey Aquifer System in Uşak Province, Turkey*; IAHR International Groundwater Symposium on Flow and Transport in Heterogeneous Subsurface Formations: Theory, Modelling & Applications; June 18-20, 2008; Istanbul, Turkiye **(Poster Presentation)**

HONORS AND SCHOLARSHIPS

- TUBITAK (Scientific and Technologic Research Institute of Turkey) Scholarship for PhD Students (November 2008-present)
- TUBITAK (Scientific and Technologic Research Institute of Turkey) Scholarship for Masters Students (May 2006-September 2007)
- METIER Fund (METhods of Interdisciplinary Environmental Research: a Marie Curie Series of Events funded by the European Community) Final Conference: "Climate - Water - Biodiversity - Land Use: Young Scientists Tackling Complex Environmental Challenges", Brussels-Belgium (04–06 November 2009)
- METIER Fund (METhods of Interdisciplinary Environmental Research: a Marie Curie Series of Events funded by the European Community) for Graduate Training Course: Environmental Scenario Analysis, Roskilde-Denmark (16-22 April 2009)
- NATO Scholar, NATO ASI on Overexploitation and Contamination of Shared Groundwater Resources, Varna-Bulgaria (01-12 October 2006)

SELECTED SCIENTIFIC ACTIVITIES ATTENDED

- 6th International Perspective on Water Resources and the Environment; January 7-9, 2013; Izmir, Turkey (Oral Presentation)
- 39th IAH Congress: Confronting Global Change; September 16-21, 2012; Niagara Falls, Canada (Oral Presentation)
- NATO-Advanced Research Workshop (ARW): Climate Change and its Effect on Water Resources - Issue of National and Global Security; September 1-4, 2010; Izmir, Turkey (Oral Presentation)
- IAHR International Groundwater Symposium; September 22-24, 2010; Valencia, Spain (Oral Presentation)
- METIER Final Conference: "Climate - Water - Biodiversity - Land Use: Young Scientists Tackling Complex Environmental Challenges", Brussels-Belgium, 04–06 November 2009 (METIER Fund)
- Fall School: "Developing Foreign Policy on Energy Issues", NIHA, Ankara-Turkey, 28 September-01 October 2009
- Capacity Enhancement for Management of Climate Change in Turkey: Why & How?, NIHA, Ankara-Turkey, 27 May 2009

- METIER Course 7: Environmental Scenario Analysis; Roskilde-Denmark, 16-22 April 2009 (METIER Fund)
- Workshop on Development of an Environmental Management System for Sites Contaminated by Point (Industrial) Source, Ankara-Turkey, 6 November 2008
- Conference on Groundwater and Drought in Konya Closed Basin; Konya-Turkey, 11-12 September 2008
- International Groundwater Symposium; Istanbul-Turkey; 18-21 June 2008 (Poster Presentation)
- Water Policies Congress II; Ankara-Turkey, 20-22 March 2008
- NATO ASI on Overexploitation and Contamination of Shared Groundwater Resources, Varna-Bulgaria, 01-12 October 2006 : NATO Scholar (Oral Presentation)
- World Water Week in Stockholm, Stockholm-Sweden; 20-26 August 2006
- Water Policies Congress I; Ankara-Turkey, 21-23 March 2006
- Mathematical Methods in Engineering International Symposium; Ankara-Turkey, 27-29 April 2006

COMPUTER SKILLS

- Advanced : Visual MODFLOW, MODFLOW FLEX, ArgusONE, FEFLOW, MapInfo Professional, Discover, Discover 3D, Surfer, MT3DMS, SEAWAT, Microsoft Office

LANGUAGE SKILLS

- **English**: Fluent
- **Italian**: Advanced
- **French**: Basic

PERSONAL INTERESTS

- Sports (Volleyball, Rowing, Pilates, Billards)
- Reading
- Travelling
- Foreign Languages