OPTIMUM COVER DESIGN FOR WASTE ROCK STORAGE AREAS

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ABSTRACT

OPTIMUM COVER DESIGN FOR WASTE ROCK STORAGE AREAS

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Developments in mining sector in Turkey necessitate examination of mine effects to the environment in a more extensive way. In this context, cover designs became important for waste rock storage and heap leach areas. Especially, cover design is applied in most of the waste rock areas in order to prevent exposure of minerals in waste rock storage area which may result in unwanted consequences such as acid rock drainage. In this study, North Waste Rock Storage Area in Kışladağ Gold Mine located in Uşak in Western Turkey is modeled to investigate various cover designs and suggest an optimum cover to prevent any damaging consequences. SEEP/W and VADOSE/W softwares are used to model flow in unsaturated zone in order to design an effective (optimum) protective cover. SEEP/W software is used to model bedrock where waste rock storage area will be located under steady state condition. The soil water characteristics and parameters used in the model for saturated and unsaturated conditions were taken from in literature. Accuracy of input data is checked during calibration for steady state condition with SEEP/W. Bedrock is modeled under transient condition with climate boundary condition for

20 years with VADOSE/W. Waste rock was then stored on the bedrock and model was rerun under transient conditions. Climate data such as temperature, relative humidity, wind speed and precipitation data are input to the model and runoff, evaporation and recharge values are simulated. Using the data obtained type of cover and parameters such as permeability and thickness of the material were decided. At the last stage of modeling, cover design and climate boundary condition were assigned on the waste rock and model was re-run. The effectiveness of the cover design for minimizing the ingress of water and air that cause acid rock drainage is checked and recommendations were made so that the impacts to groundwater from the waste rock storage areas during closure period are minimized.

Keywords: Cover design, Acid rock drainage, Unsaturated flow zone, VADOSE/W, SEEP/W, Kışladağ Gold Mine

ÖZ

PASA SAHALARI İÇİN OPTİMUM ÖRTÜ TASARIMI

Argunhan, Çidem

Yüksek Lisans, Jeoloji Mühendisliği Bölümü

Tez Yöneticisi: Prof. Dr. Hasan Yazıcıgil

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Türkiye'de maden sektörünün gelişmesi, beraberinde çevreye olan etkilerinin daha kapsamlı bir şekilde incelenmesini getirmiştir. Bu kapsamda pasa sahaları ve yığın liçi sahaları için örtü tasarımı önemli olmuştur. Özellikle pasa sahalarındaki minerallerin asit kaya drenajı gibi istenmeyen olaylara maruz kalmasını önlemek için örtü tasarımı bir çok pasa sahasına uygulanmaktadır. Bu çalışmada, Batı Türkiye'de yer alan Uşak Kışladağ Altın Madeni Kuzey Pasa Sahası, oluşabilecek olumsuz etkileri engellemek amacıyla çeşitli örtü tasarımlarını incelemek ve optimum tasarımı önermek için modellenmiştir. Örtü tasarımını belirleyebilmek için SEEP/W ve VADOSE/W programları suya doygun olmayan kuşaktaki akımı modellemek üzere kullanılmıştır. Model tasarlanırken SEEP/W programı, pasa sahasının üzerinde yer alacağı temel kaya için kararlı akım koşulunu modellemek amacıyla kullanılmıştır. Modelde kullanılan doygun ve doygun olmayan ortamlara ait toprak özellikleri ve parametreleri literatürdeki çalışmalardan alınmıştır. Girilen verilerin doğruluğu kararlı koşullarda SEEP/W ile yapılan kalibrasyon çalışmalarıyla kontrol edilmiştir. Ana kaya iklim sınır koşulu eklenerek, kararsız akım koşullarında VADOSE/W ile 20 yıl süreyle çalıştırılmıştır. Kararsız koşullarda VADOSE/W ile oluşturulan modelin üzerine pasa malzemesi eklenip model tekrar çalıştırılmıştır. Sıcaklık, bağıl nem, rüzgar hızı ve yağış gibi iklim verileri modele girilmiş ve yüzey akışı, buharlaşma ve net beslenim değerleri çıktı olarak elde edilmiştir. Elde edilen veriler kullanılarak, örtünün tipine ve örtü için kullanılacak malzemenin geçirgenliği ve kalınlığı gibi parametrelerine karar verilmiştir. Modellemenin son aşamasında ise, pasa malzemesinin üzerine örtü tasarımı ve iklim sınır koşulu eklenerek, örtü tasarım modeli tekrar VADOSE/W programında çalıştırılmış ve örtü tabakasının, asit kaya drenajına sebep olan su ve hava intrüzyonunu azaltmakta ne kadar etkili olduğu kontrol edilmiştir. Pasa sahalarının kapama dönemi sonrasında yeraltısularına olası etkilerini en aza indirebilmek üzere örtü tasarımı konusunda öneriler getirilmiştir.

Anahtar kelimeler: Örtü tasarımı, Asit kaya drenajı, Doygun olmayan kuşak, Vadose/W, SEEP/W, Kışladağ Altın Madeni

TO MY BELOVED FAMILY...

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CHAPTER 1

INTRODUCTION

1.1. Purpose and Scope

Soil cover systems are generally used to cover mine waste, municipal solid waste and any hazardous material to prevent ingress of water and oxygen. Especially; in the mine area, waste material causes acid rock drainage by oxidation of sulfide bearing rocks with the water and oxygen. Long term performance of cover designs is important because any failure in the system causes great environmental damage. At this stage numerical modeling of the cover systems is quite useful for the long term prediction of the performance of the suggested cover type.

The purpose of this study is to assess the performance of various cover designs for the North Waste Rock Storage Area of the Kışladağ Gold Mine located in Uşak in Western Turkey and to propose an optimum cover that will minimize the ingress of water and oxygen in the long-term following the mine closure. Kışladağ Gold Mine is the biggest mine in Turkey. There is already south waste rock storage area in the mine site. However, this facility will just provide rock storage through to 2015 with 196 million tons of storage capacity. There will be new waste rock storage area in the northern part of the mine. Total storage capacity of northern waste rock dump area is 928.6 million tons. The ultimate footprint of the facility will be approximately 477 Ha. In this study, cover design is planned for the North Waste Storage Area in Kışladağ Gold Mine. The scope of the work involved modeling the bedrock, waste rock and various types of cover using SEEP/W and VADOSE/W softwares. The model parameters for bedrock were obtained by conducting steady-state and transient model runs. The parameters for waste rock and different covers were obtained from works done in the study area and literature. Finally, the long-term performance of each cover was evaluated to suggest an optimum cover that will minimize the ingress of water and oxygen.

1.2. Location and Extend of the Study Area

The Kışladağ Gold Mine is located in western part of Turkey. It is situated approximately 30 km southwest of Uşak. The mine area is enclosed by Eşme and Ulubey towns from southwest and southeast, respectively (Figure 1.1).

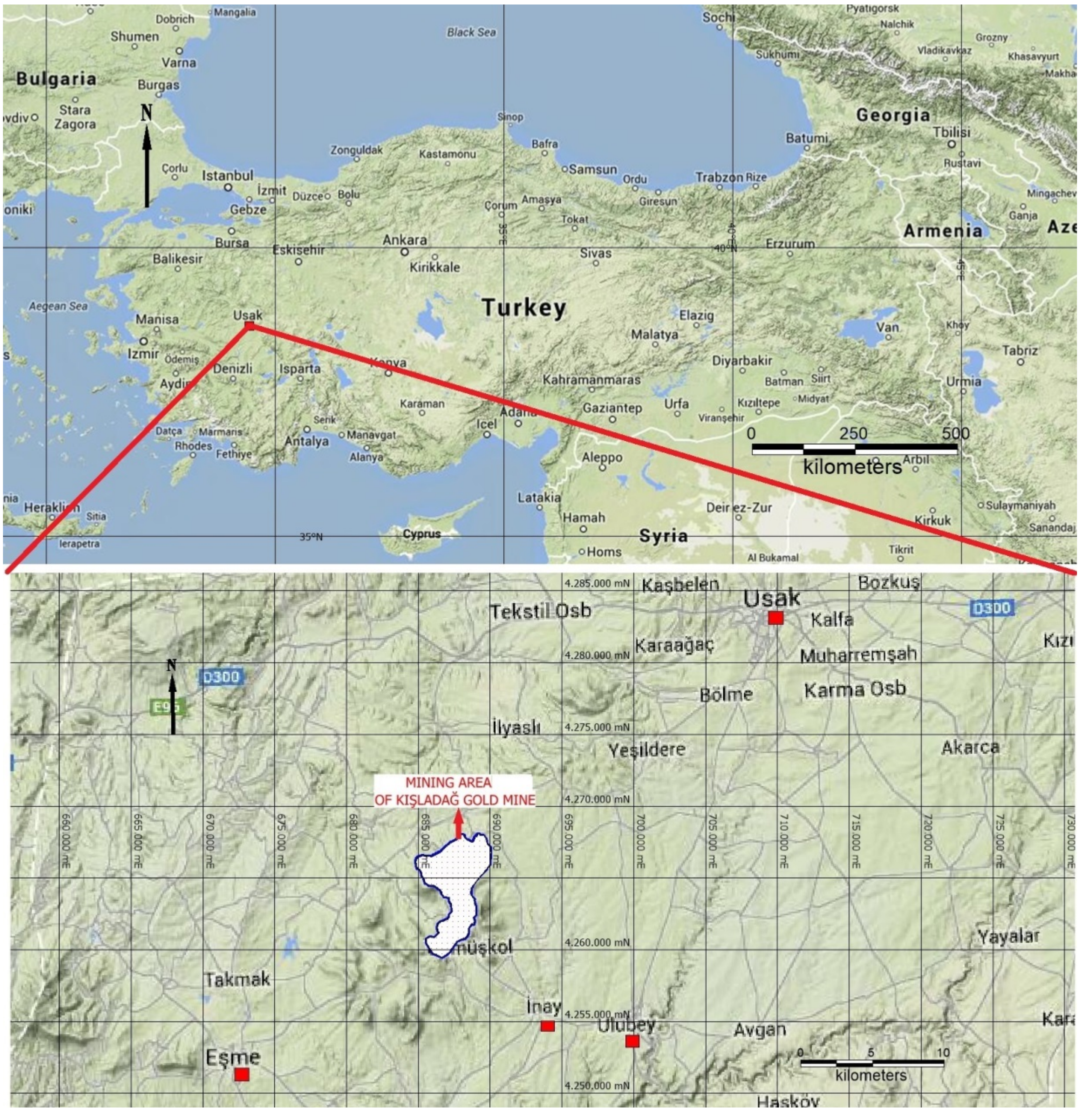

Figure 1.1: Location of the Study Area

1.3. Previous Studies

Kışladağ Gold mine is the biggest gold mine in Turkey and there are many studies conducted in this area. Because this work only covers the North Waste Rock Storage Area (NWRSA), studies that are conducted in the Northern part are considered. In February 2012, Toker Drilling and Construction Company (Toker) completed a geotechnical investigation and laboratory testing program in the North Waste Rock Storage Area. In June 2012, seepage investigation works were also conducted by Toker. In February 2013, an environmental impact assessment-level design study was conducted by the Norwest Corporation. Hydrogeological characterization of the Kışladağ Gold-Mine area was conducted by Yazıcıgil et al., in March 2013. Assessment of open pit dewatering, pit lake formation effects on groundwater for Kışladağ Gold-Mine study was conducted by Yazıcıgil & Unsal, 2013.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

Modern waste containment systems rely on surface and subsurface engineered barriers to contain hazardous and toxic waste, to prevent the offsite flow of contaminants, and/or to render waste less harmful to humans and ecosystems for tens to hundreds or thousands of years, depending on the type of waste, local conditions (e.g., geological setting, climate, land use) and regulations. The barriers might be at the bottom, top (cover), and/or sides (lateral barriers or walls) of the waste contaminant system and they usually employ a variety of materials and mechanism (e.g., liquid extraction) to control contaminant transport (Baecher, et al., 2007). In this work mainly cover barriers for the mining area are considered. Cover barriers basically are engineered structures that are used to cover surface of any hazardous material which are also named as cover designs.

Covers gained popularity around 1980s, especially for waste rock storage areas and remediation of contaminated sites (Fredlund & Stianson, 2009). There are two facilities that should be considered regarding environmental issues during mining operations. These are waste rock storage and mine tailings facilities. However, mainly waste rock storage facility is considered herein. Many of the waste rock storage facilities generate acid mine drainage (AMD) since they contain sulfide-rich minerals (predominately pyrite and pyrrhotite). These minerals oxidize in presence of oxygen and water causing acid mine drainage. Acid mine drainage at waste rock storage areas is controlled by placing covers. Since acid mine drainage occurs in presence of oxygen and water, main objective of placing covers is to decrease oxygen and water ingress to the acceptable level. Because the flow of water through the covers and waste rocks take place under unsaturated conditions, a brief information on unsaturated flow is given below along with various types of cover designs.

2.2. Unsaturated Zone Flow

Unsaturated zone which is the portion between the groundwater table and the ground surface contains both air and water in the pores. This zone is also termed as vadose zone and zone of aeration. Unsaturated zone is considered as buffer zone which provides protection to the underlying materials due to any contamination (Lal and Shukla, 2004).

Unsaturated zone flow is quite different from saturated flow. It is worthwhile to indicate the differences between saturated and unsaturated zone to understand the difference in flows (Table 2.1).

Table 2.1: Difference between saturated and unsaturated zones (Freeze & Cherry, 1979)

Saturated Zone	Unsaturated Zone
It occurs below the water table	It occurs above the water table and above the capillary fringe
The soil pores are filled with water, and moisture content θ equals the porosity *n*	The soil pores are only partially filled with water; the moisture content θ is less than porosity *n*
The fluid pressure *p* is greater than atmospheric, so the pressure head *Ψ* (measured as gage pressure) is greater than zero	The fluid pressure *p* is less than atmospheric; the pressure head *Ψ* is less than zero
The hydraulic head *h* must be measured with piezometer	The hydraulic head *h* must be measured with tensiometer
The hydraulic conductivity *K* is a constant, it is not a function of head *Ψ*	The hydraulic conductivity *K* and the moisture content θ are both function of the pressure head *Ψ*

2.2.1. Unsaturated Flow Equation

Darcy's equation which is originally conceived for saturated flow can also be applied to the unsaturated zone with some modifications. In unsaturated flow, hydraulic conductivity is not constant anymore. It varies with water content and water content changes with pore-water pressure.

Darcy's law for saturated flow is;

$$q = -K\frac{\partial h}{\partial z} \tag{2.1}$$

where q: water flux

K: hydraulic conductivity

h: total head

z: vertical coordinate

It was Buckingham (1907) firstly indicate hydraulic conductivity depends on moisture content in unsaturated zone. Thus, the law is named as Darcy-Buckingham law.

Darcy-Buckingham law for unsaturated flow is;

$$q = -K(\theta)\frac{\partial h}{\partial z} \tag{2.2}$$

where K(θ): hydraulic conductivity as a function of moisture content θ

Total head is defined as sum of suction head (matric potential) and elevation head.

$h = \Psi + z$

where Ψ: suction head (matric potential)

z: elevation head

Thus Darcy-Buckingham equation is defined as:

$$q = -K(\theta)\left[\left(\frac{\partial \Psi}{\partial z}\right) + 1\right] \tag{2.3}$$

The Darcy-Buckingham equation can be applied to the unsaturated flow unless moisture content is constant over time. However, it is quite seldom that moisture content remains constant in unsaturated flows. At this circumstance, Darcy-Buckingham equation is combined with continuity equation and Richard equation is produced (Lal and Shukla, 2004).

Continuum equation is expressed as:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} \tag{2.4}$$

where θ: moisture content

Richard equation is obtained by combining equations (2.3) and (2.4).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial \Psi}{\partial z} + 1\right)\right] \tag{2.5}$$

2.2.2. Unsaturated Soil Hydraulic Properties

There are two main properties that control the flow of water in unsaturated zone. These are hydraulic conductivity and volumetric water content of the soil. These properties are not constant unlike the saturated zone. Accuracy in change of these properties gives more accurate results in flow of water in unsaturated zone.

2.2.2.1. Unsaturated Hydraulic Conductivity

In case of saturated flow all pores are filled with water; however, in unsaturated flow pores are filled with both air and water. At saturated condition conductivity is at maximum; however, at unsaturated condition hydraulic conductivity starts decreasing. The unsaturated hydraulic conductivity is a function of both moisture content (θ) and matric potential (Ψ). Figure 2.1 shows the change in hydraulic conductivity of coarse and fine materials. Sand is coarse textured soil and has higher conductivity than silty sand near saturation. However, as these soils desaturate, hydraulic conductivity of coarser material decrease faster than the fine material and at one point they cross each other. After a certain matric suction (or matric potential) value of the K (θ) of coarser material is always lower than finer material. This is quite reasonable because coarser material has larger pores causing faster drainage than fine material. Thus, water amount will be greater in finer material resulting in less tortuosity and higher K (θ) than coarser material (Lal and Shukla, 2004).

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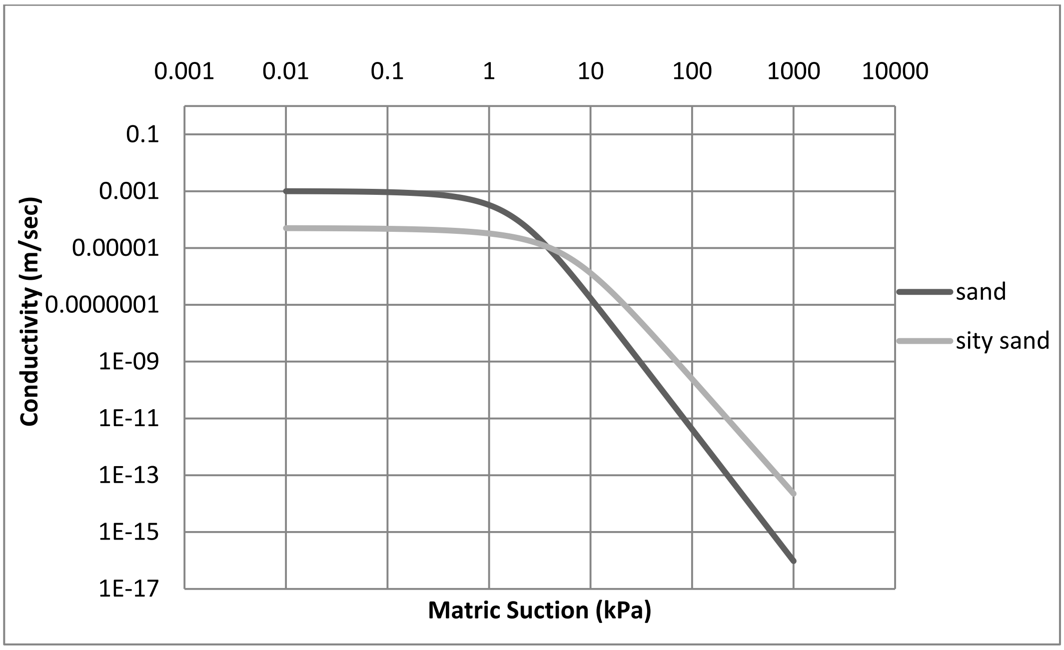

Figure 2.1: Variation of hydraulic conductivity for coarse and fine textured materials (Geo-Slope, 2008)

Unsaturated hydraulic conductivity is difficult to measure and time consuming. In order to overcome these problems, estimation methods are used to predict unsaturated hydraulic conductivity. Estimation methods are used by Green and Corey, 1971, Van Genuchten, 1980 and Fredlund et al, 1994. Van Genuchten estimation method is the most common method. Van Genuchten estimation method uses saturated hydraulic conductivity and volumetric water content curve parameters. Equation is expressed in equation 2.4.

$$k_r(h) = \frac{\left[1 - \left((ah)^{(n-1)}\right)(1 + (ah^n)^{-m})\right]^2}{\left(((1 + ah)^n)^{\frac{m}{2}}\right)} \tag{2.4}$$

where $k_r(h)$: relative hydraulic conductivity

a, n, m : curve fitting parameters

n: 1/(1-m), and

h: pressure head

2.2.2.2. Volumetric Water Content Function (Soil Water (or Moisture) Characteristic Curve)

The volumetric moisture content (or volumetric water content) is defined as the ratio of the volume of water V_w to the total volume, V_T . Volumetric water content is defined as percentage or a decimal fraction like the porosity *n*. For saturated flow θ = n; for unsaturated flow, θ < n (Freeze & Cherry, 1979). Water content in unsaturated zone is not constant unlike saturated zone. It changes with the matric potential. Thus, water content θ is a function of matric potential (matric suction or suction head) Ψ. Relation between matric suction and water content is represented by soil water characteristic curve (SWCC). The SWCC describes the suction and the rate at which a soil would lose water. The SWCC are influenced by particle size distribution, soil structure and hysteresis. There are three important parameters that define the SWCC. These are the air entry value (AEV), the slope of SWCC and residual water content (Adu-Wusu, et al., 2006).

The air entry value (AEV) is defined as negative pore water pressure required to initiate drainage of an initially saturated soil. Since finer textured material has smaller pore sizes than coarser textured material it has the ability to hold the water under higher suction values. The coarser textured material starts to drain first and continue as suction increase. However, the finer textured material remains saturated at the same suction condition. This situation is called as "tension saturated". Finer material starts to drain as the suction increases. For example in Figure 2.2 coarse material starts to drain around 2 kPa suction value where fine material is still saturated. 2 kPa AEV is not enough to drain fine material because AEV for fine material is 10 kPa.

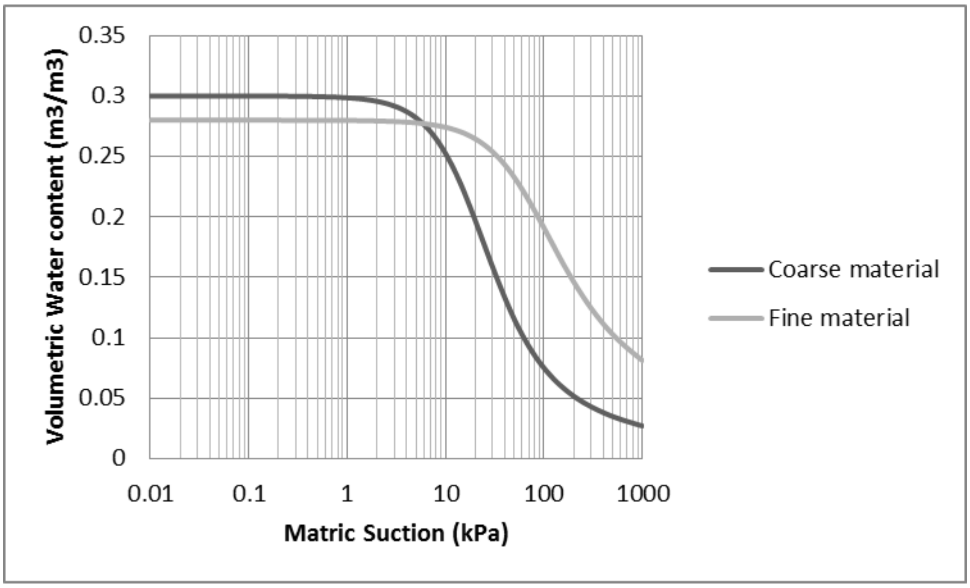

Figure 2.2: Variation at air-entry value (AEV) for coarse and fine material (Geo-Slope, 2008)

The slope of SWCC defines the rate of water loss once the AEV is exceeded. The slope is mainly controlled by pore size distribution and material structure.

Compaction conditions have great impact on fine textured material. A uniform material drains rapidly over a small suction range since the all pores are almost the same size. However, well graded material will have moderate to gentle slope since it has a wide range of pore sizes.

As the suction increase after the AEV point, soil continues to drain until the residual water content. The residual water content point is characterized by relatively flat portion of the SWCC where suction is no longer effective to remove water in liquid form. After the residual water content past, water movement is dominated by vapor flow.

The SWCC is obtained by two ways which are desorption (drying) and sorption (wetting). Both methods yield continuous curves but in different shape shown in Figure 2.3. This phenomenon is named as hysteresis. Primary reason for the hysteresis is non-uniform pore size distribution. It prevents the full development of capillary rise in the soil. Also, entrapped air in the soil reduces the water content of the soil as the suction decreases.

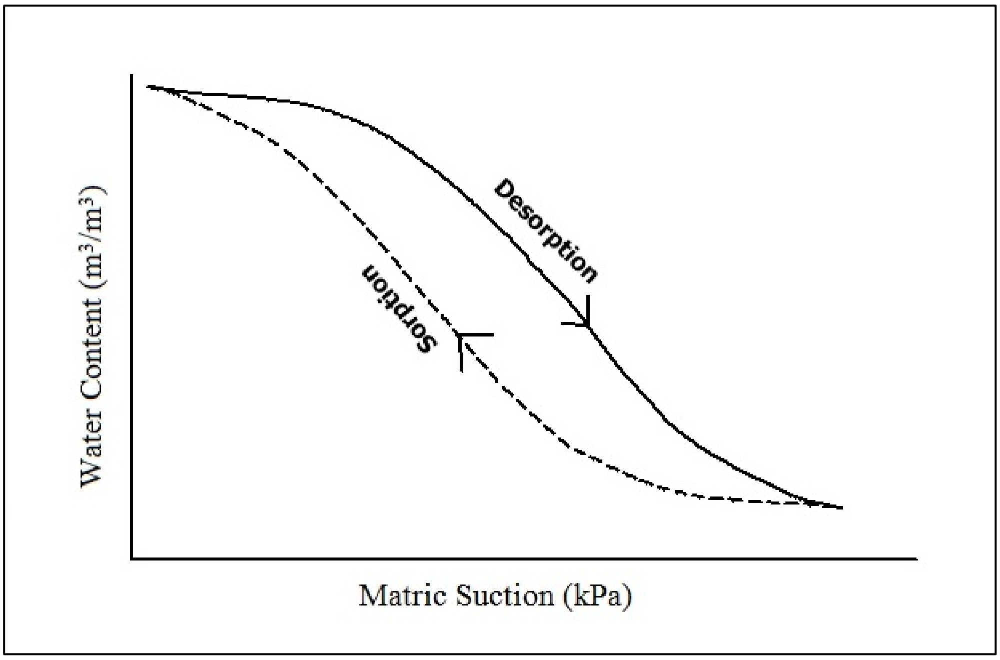

Figure 2.3: Hysteresis effect (Pham et. al., 2005)

Direct measurement of a volumetric water content function in a laboratory is not so difficult but since it requires time and finding geotechnical laboratory that performs the service, this method is not preferable. Instead of direct measurement estimation methods are used for volumetric water content determination. Aubertin et al. (2003) presented a method which is based on grain size distribution. Additionally, Fredlund and Xing (1994) and Van Genuchten (1980) proposed closed form methods.

For SWCC estimation Van Genuchten method is mostly used. Van Genuchten equation is expressed as:

$$\theta_w = \theta_r + \frac{\theta_s - \theta_r}{[1 + (a\Psi)^n]^m} \tag{2.5}$$

where θ_w: the volumetric water content

θ_s: the saturated volumetric water content

θ_r: the residual water content

Ψ: negative pore water pressure

a, n, m: curve fitting parameters

where a : slightly larger than the air entry value

n: controls the slope of curve

m: controls the residual water content and m=1-1/n

2.3. Factors Influencing Cover Design Objective

There are several factors that influence objectives of cover designs. Main factors are climate conditions, type of waste material (i.e. tailings or waste rock) and basal inflow conditions.

When climate aspect is considered one main question arises; is it a wet site or dry site? The amount of precipitation and evaporation in a region has a significant effect on cover design. Types of the waste in a mine area can be waste rock storage and/or tailings area. Both wastes are totally different from each other. Waste rock material is generally coarse and quickly drains, while tailings are fine and slowly drain. Therefore, their behavior to seepage and oxygen transport would vary and cover design should be planned accordingly.

Hydrogeological setting and basal inflow is another condition that affects the cover design. For example if there is fault at the base of waste dump area can it cause flush of groundwater?

2.4. Types of Covers

Designing a cover system is a quite difficult issue. There are many factors that should be considered. Some of them are explained in preceding sections. In the light of these factors, it is quite obvious that there are different types of cover designs. In literature, there are different nomenclatures for the types of cover designs. Figure 2.4 shows general classification which is prepared based on literature research. Types of cover design shown in Figure 2.4 are explained in the following sections.

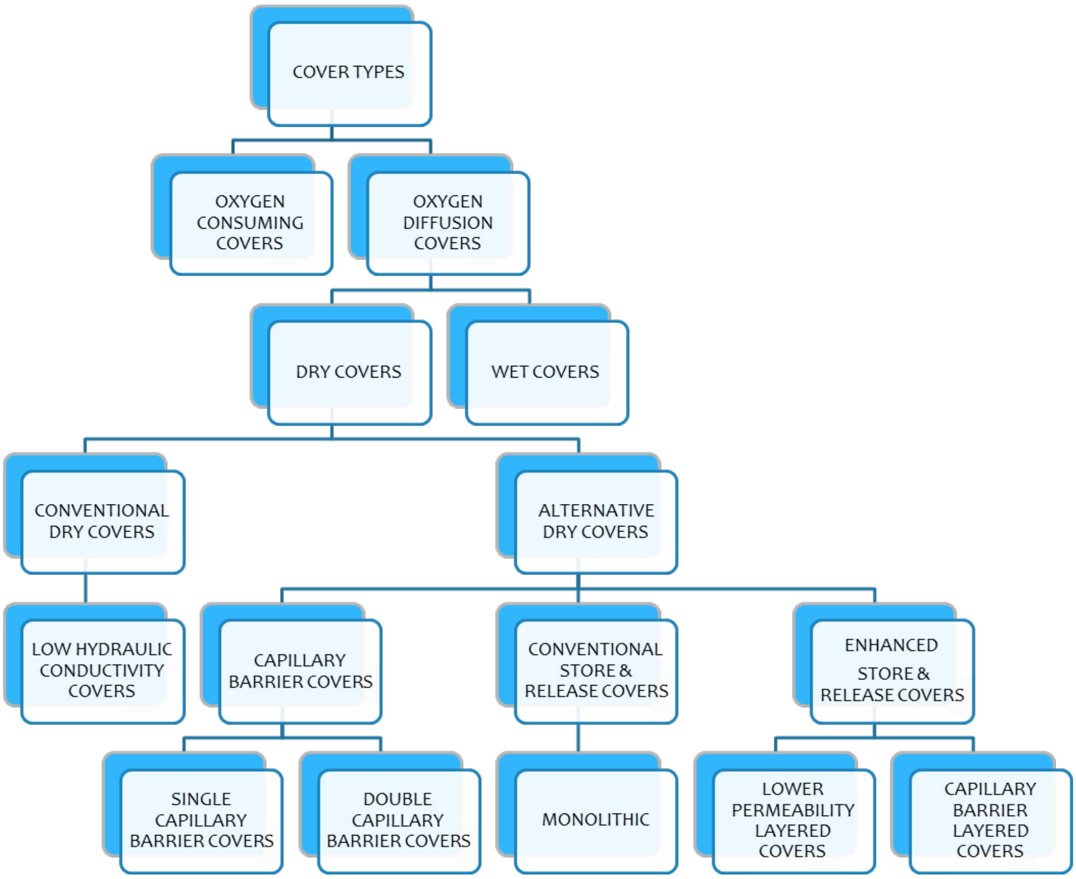

Figure 2.4: Classification of cover designs

2.4.1. Oxygen Consuming Covers

Oxygen transfer into the waste can be diminished by covering the area with oxygen consumption materials. Oxygen consuming cover concept was applied to the Sullivan mine in East Quebec. Mine was closed in 1966 and 15 million ton acid producing waste was left. Dumping of wood wastes was started on 1984 and active reclamation was started in 1990. Cover consists of 2 meter organic waste (bark %85, pulpwood %10, and sawdust % 5). It is indicated that in 1991 oxygen amount is decreased with depth and at 0.7 meter depth oxygen amount was only 1.5%. Monitoring results showed that metal amount is decreased and pH is increased at seepage water.

2.4.2. Oxygen Diffusion Covers

These types of covers prevent the oxygen diffusion into the waste material. In a porous environment; when saturation increases with the water, diffusion of oxygen decreases. In these types of cover, oxygen diffusion is decreased with the presence of the water saturated layer. When the water amount decreases in the layer depending on seasonal conditions, effective diffusion increases and the performance of cover decreases. Thus, cover should be resistant to the drying and has the ability to keep the water in the storage layer.

There are different types of oxygen diffusion cover types. They are explained in the following sections.

2.4.2.1. Dry Covers

There is not one type or just one definition for dry covers. Dry covers vary into different types but all of them serve to one aim. The objective of dry covers is to minimize the ingression of water and oxygen to prevent spoiling of material resulting acid rock drainage.

2.4.2.1.1. Conventional Dry Covers

The conventional dry cover is also named as low hydraulic conductivity cover. As it is understood from the name, there is basically low conductivity layer to prevent water and oxygen ingress. These layers are generally clay or geosynthetic membrane.

The first designed cover systems were mainly composed of compacted clays with an attempt to construct a relatively impervious cover on to waste rock. Drying and desiccation cause cracks on clay layer and this makes the clay layer permeable. As a result, new generation of cover system that is called alternative dry cover became common (Fredlund & Stianson, 2009). In the following section alternative dry covers will be explained.

2.4.2.1.2. Alternative Dry Covers

As it is explained above these types are created as alternative to low hydraulic conductivity layer. There are different types of alternative covers as shown in Figure 2.4. These are explained in the following section based on summary from MEND, 2012.

Capillary barrier cover is commonly used concept for barrier design. Rasmusson and Erikson (1986), Nicholson et al., (1989), O'Kane & Wells (2003) and many other authors explained and also gave examples about this concept. Since it is impossible to explain all the previous works herein, basic explanations are given in this study. A capillary barrier effect occurs when a finer textured material is placed over coarse-textured material. The key point for capillary barrier is the contrast between hydraulic properties of coarse and fine textured materials. The concept is that coarser textured material will drain to residual water content following an infiltration event and suction at this water content is quite low for coarse material. As a result fine textured material will not drain at this low suction and it remains in tension saturated condition. It can be said, capillary break will occur during drainage whenever the residual suction of lower coarse textured material is less than the air entry value of upper fine textured material. The advantage of capillary barriers as compared to low hydraulic conductivity barrier is that this design does not lose its performance because of desiccation and freeze/thaw as low hydraulic conductivity barrier does. Ingress of oxygen cannot be prevented until the fine textured layer is nearly saturated. So, being kept of fine textured layer as tension saturated is also important for capillary break cover design. Capillary barrier covers can be designed as single and double capillary layered system. Both designs are shown in Figure 2.5.

Single capillary barrier design is formed when coarse textured layer is overlain by fine textured layer. Difference in hydraulic properties result in tension saturated condition for fine textured layer. At double capillary barriers a coarser textured layer over the fine textured layer is also included in the system. The role of this coarser layer is simply to prevent evaporation from the finer textured layer. The upper coarser layer may also reduce runoff by increasing available storage during infiltration. Any upward rise of salts and/or oxidation products from underlying waste material into fine textured material is also prevented by capillary barriers (MEND, 2012).

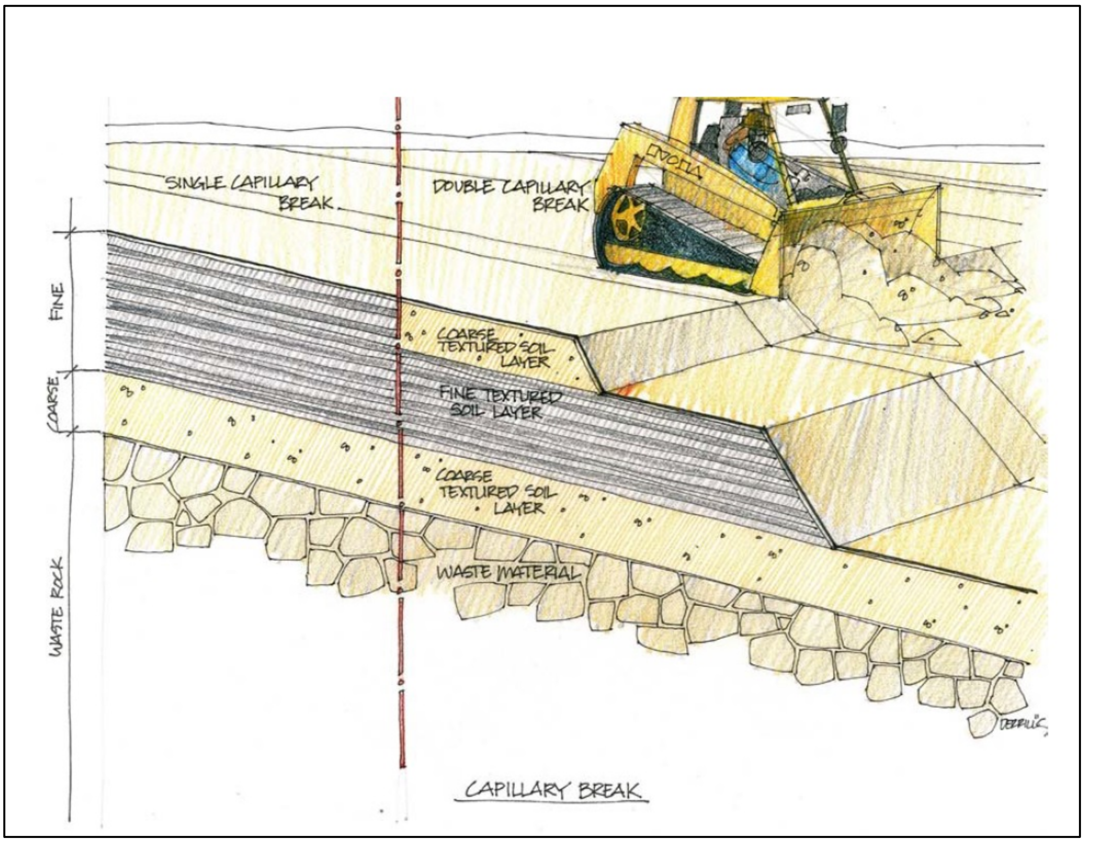

Figure 2.5: Capillary break cover system over waste material (MEND, 2012)

Store and release types of covers differ from the capillary barrier concept. This type of cover depends on the moisture retention and storage characteristics of the cover material. The key concept is that the material must store the infiltration during rainy season and release the water during dormant season via evaporation and transpiration. A store and release cover (also named as evapotranspiration cover and water storage) can consist of one or several layers (O'Kane & Wels, 2003). Simplest type of store and release covers is monolithic covers. At this cover, waste rock is directly overlain by storage layer and a vegetative layer covers storage layer to enable vegetation growth. Figure 2.6 (a) shows a sample of this type. Enhanced store and release cover designs are much more developed comparing to monolithic designs. The term enhanced store and release is used to describe the store and release cover when additional layer is added to the profile to increase the capability of design system. The enhancement may be required to limit the net percolation only until mature vegetation can be established and the full evapotranspirative capacity of the store and release layer can be realized. These enhanced layers can be lower permeability layer or a layer that creates capillary effects. The purpose of the lower permeability layer is to delay the downward percolation. This layer could be locally available clay/silt material or compacted weathered surficial waste rock. Figure 2.6 (b) and (c) show the examples for this type of design. Capillary Break concept was discussed in detail in preceding part. To summarize, coarse textured layer is included to the fine textured profile to create a sharp drop in suction within the coarser layer. The presence of these lower suctions allows the overlying finer textured material to maintain tension saturated condition (MEND, 2012).

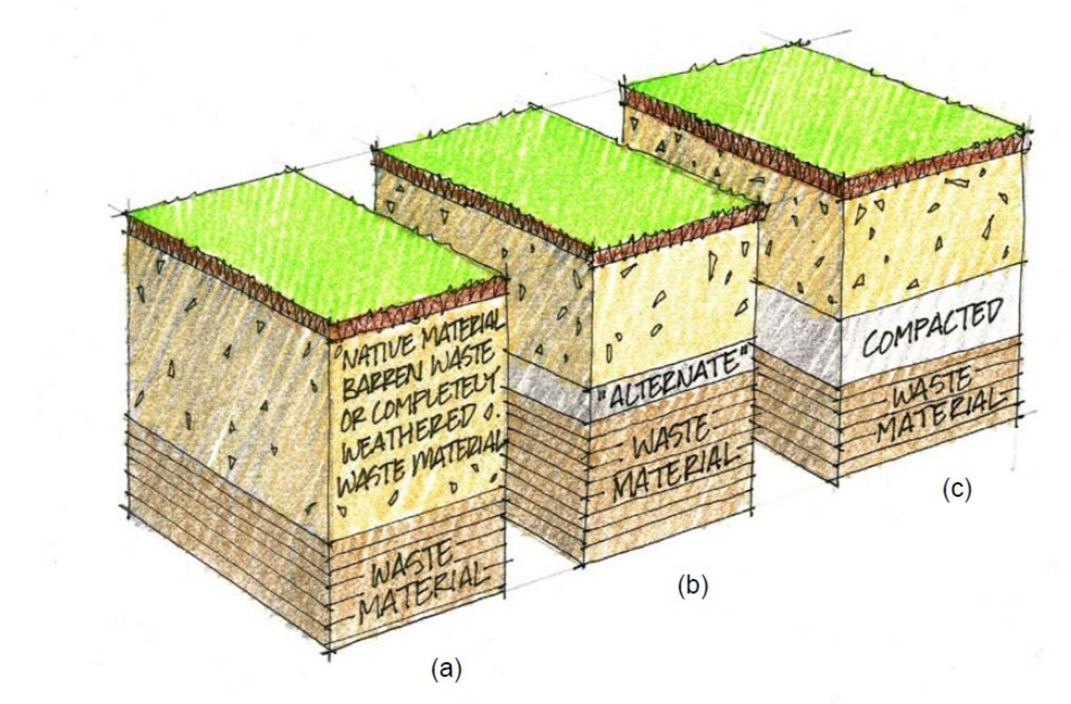

Figure 2.6: Store-and-release cover systems: (a) monolithic store-and-release cover system, (b) and (c) enhanced store-and-release cover systems showing additional lower hydraulic conductivity layers below the storage layer (MEND, 2012)

2.4.2.2. Wet Covers

Wet covers are quite extensive subject. In this work, just the basic principles are given and some figures are shown to help comprehension of the design type.

Wet covers are also named as water covers. Disposal of acid generating materials below a water cover is one of the alternatives to prevent acid rock drainage. This type of cover design is quite effective, because the maximum concentration of dissolved oxygen is approximately 30 times less than in the atmosphere. Additionally, oxygen transport is seriously limited relative to transport in air because of advection and diffusion. For instance, the diffusive transfer of oxygen in water is on the order of 10 000 time slower than diffusive transfer in air.

Submergence of waste disposal is confirmed by the help of field and laboratory tests as one of the best method for limiting acid rock drainage. Some mechanism such as sulphide reduction bacteria, metal hydroxide precipitation can be associated to the water cover to increase the functionality of it (INAP, 1998). Wet covers limit the exposure of spoil material to oxygen. Wet cover may not be amenable for spoil material which has already appreciably oxidized. The “cut off” point at which this distinction is made will be mine-waste specific.

Wet covers requires a climate with positive water balance, long term physical stability of containment facilities and outlet structures and water depth sufficient to prevent resuspension by wind and wave action.

Water covers can be applied in three different ways. These are sub-aqueous emplacement of mine tailings in natural lake, submergence of an existing body of spoil-tailings ("Engineering guidelines for," 2003) or relocating the tailings/waste rock system to an alternative storage basin (such as open pit) (O'Kane & Wels, 2003).

Method of sub-aqueous emplacement of mine tailings in natural lake was implemented with some success in the past in Norway; however; it is no longer used due to EU legislation. Submergence of an existing body of spoil-tailings can be implemented where the site conditions allows spreading of the waste over a larger area than it previously occupied. The biggest drawback with this option is finding a suitable site. For long term submergence to be achieved, site conditions have to be very favorable and few sites are likely to be suitable to this approach ("Engineering guidelines for," 2003). Actually, principle behind the last alternative is same with the submergence of the existing body. In this option, storage basin supplies the suitable area for the submergence.

As it is explained above, emplacement into natural lake is not used anymore. Submergence and relocating waste to the pit has the same principles. Figure 2.7 shows pit disposal concepts. In Figure 2.7, four different alternatives are shown. There are few reasons that produce different alternatives, such as waste rock characteristics, open pit characteristics, etc. These are quite broad subjects, more information can be found in MEND, (1995).

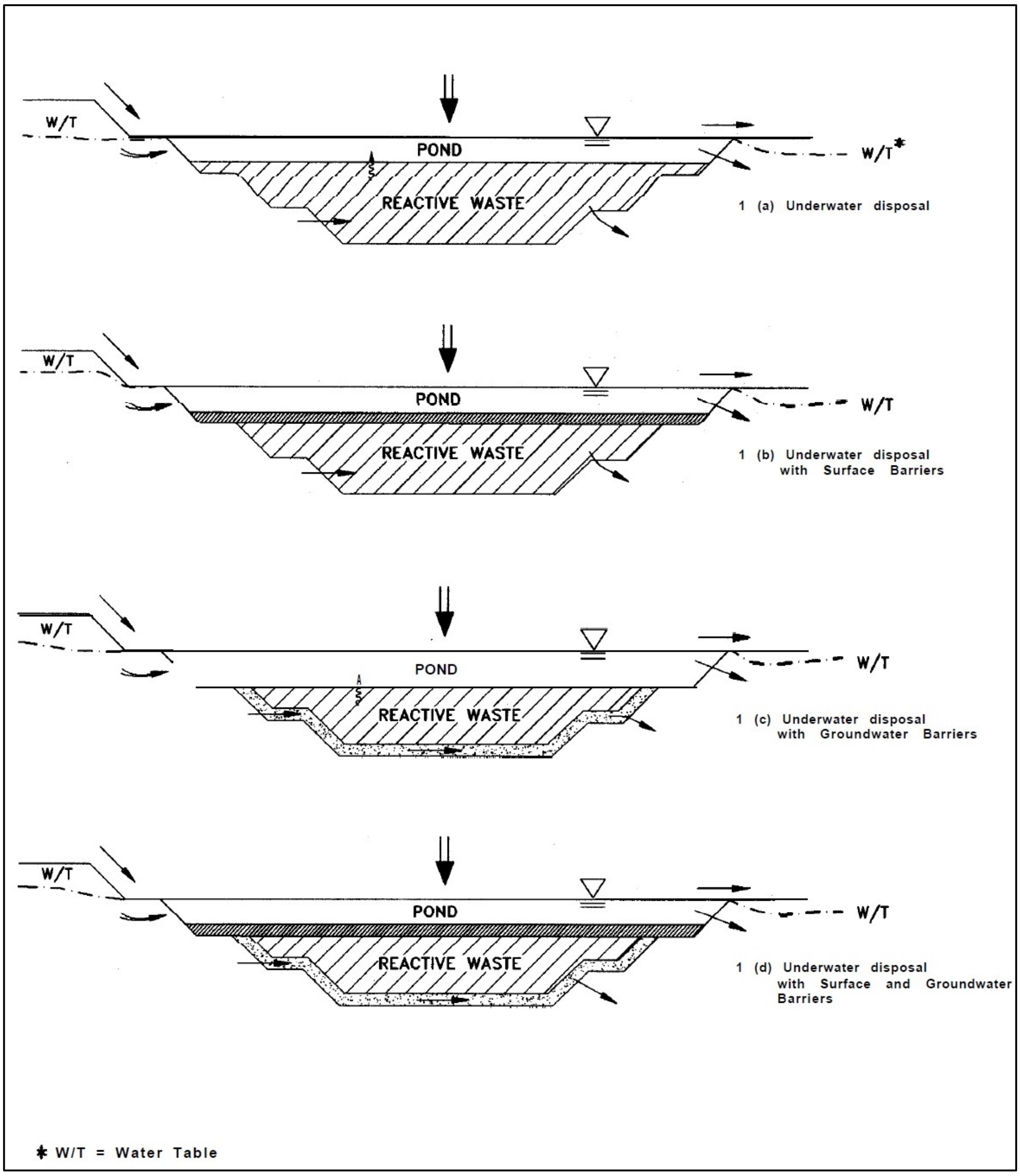

Figure 2.7: Pit Disposal Concepts (MEND, 1995)

CHAPTER 3

DESCRIPTION OF THE STUDY AREA

3.1. Physiography

Kışladağ Gold Mine area is located on the groundwater divide which separates the Gediz and Küçük Menderes River Basins from each other as shown in Figure 3.1. Open pit, North Waste Rock Storage Area, North and South Heap Leach Areas are located on the Gediz River Basin while South Waste Rock Storage Area is located in the Büyük Menderes River Basin (Figure 3.1). Since study area is located on water divide of these two river basins, only ephemeral streams are seen. Topography of the study area varies from 600 meters from the bottom of the valley to 1300 meters on the hills. The regional morphology is characterized by peneplanes on metamorphic terrain in the west whereas flat or nearly flat Neogene plateaus that formed by sedimantery rocks in the east, and young volcanic cones emerging between the peneplanes and the plateaus (Yazicigil, et al., 2013). Figure 3.2 shows the digital elevation model of the study area.

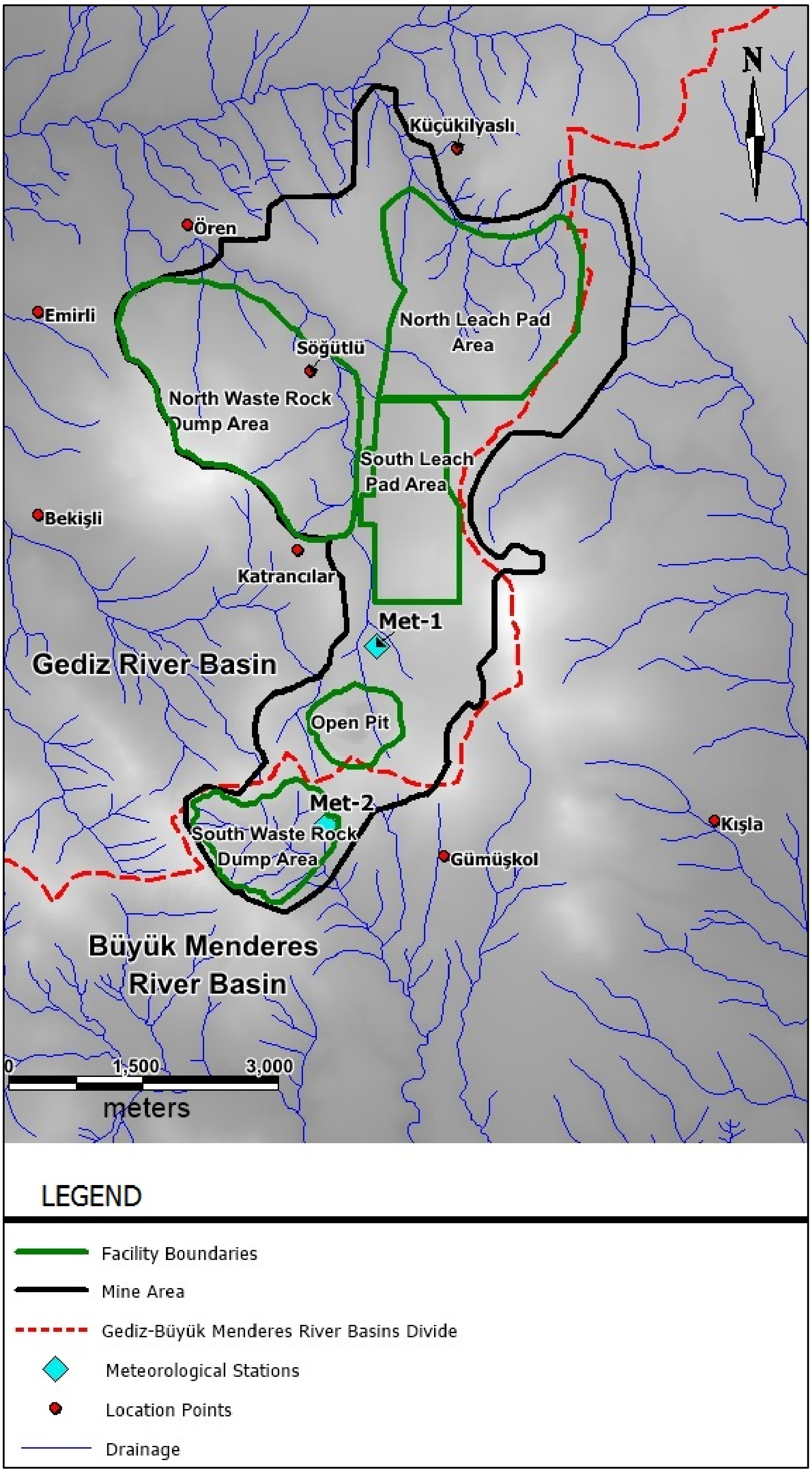

Figure 3.1: Groundwater divide and meteorological stations in the area (modified from Yazıcıgil et al., 2013)

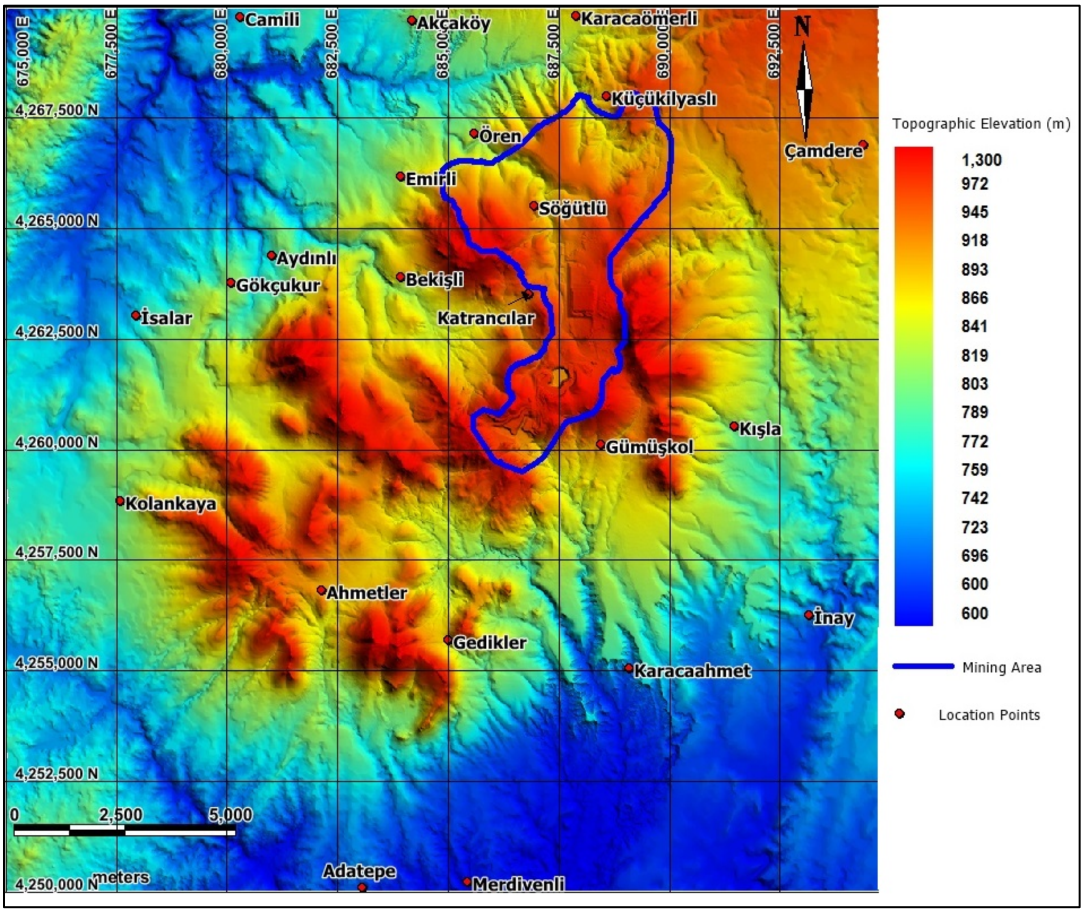

Figure 3.2: Digital Elevation Model of the Study Area (modified from Yazıcıgil et al., 2013)

3.2. Climate

The study area is located between the Aegean and Central Anatolian Regions. Thus Mediterranean Transition Climate which shows climatic features of both regions is dominant (Türkeş, 1996). The area has the medium winter and the spring, which is the most significant property of Mediterranean Transition Climate. According to Turkish State Meteorological Services (MGM) the long term average precipitation amount is 526.1 mm in Uşak province (TC. Meteoroloji Genel Müdürlüğü, 2014).

The highest temperatures are observed between July and August while the lowest temperatures are observed in January as shown in Figure 3.3. Meteorological features in the area have been observed by meteorological stations installed by

TÜPRAG since April 2000. In August 2005, automatic meteorological station (AWOS) is installed. Additionally, in April 2010 a second meteorological station is also installed around open pit by TÜPRAG. The locations of meteorological stations are shown in Figure 3.1. The information for each meteorological station and their observation intervals are given in Table 3.1.

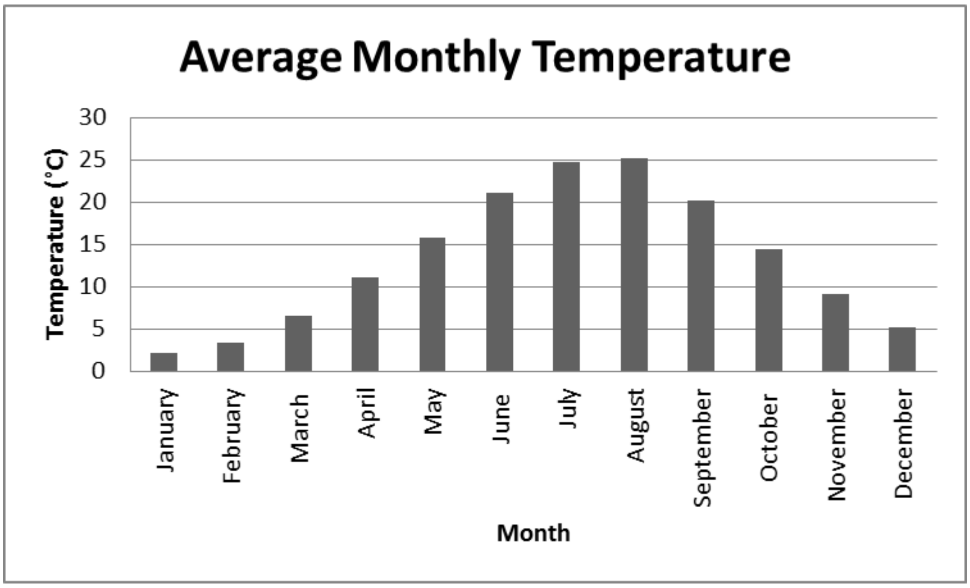

Figure 3.3: Average monthly temperature values from the Kışladağ meteorological station (2006-2012)

Table 3.1: Meteorological stations information table

Station ID	Corporation	Coordinates (m)		Elevation (m)	Operation Period
		X	Y		
Kışladağ Manual	TUPRAG	687692	4262462	997	04/2000-Cont.
Kışladağ AWOS	TUPRAG	687692	4262462	997	08/2005-Cont.
Kışladağ AWOS (Open Pit)	TUPRAG	687130	4260476	1026	04/2010-Cont.
Uşak	MGM	708760	4284370	930	1929-Cont.

Figure 3.4 shows monthly precipitation values for both long term (1975-2012) and short term (2001-2012) periods. Both periods show similar value. As can be seen in

Figure 3.4 precipitation is high between October and May; however, it is low between June and September. Figure 3.5 shows annual precipitation values measured at Kışladağ meteorological station for long term interval. The average precipitation value for the long term data for Kışladağ is 493 mm. According to the precipitation values 2004 year is the driest year with 283 mm precipitation while 2012 is the wettest year with 696 mm precipitation.

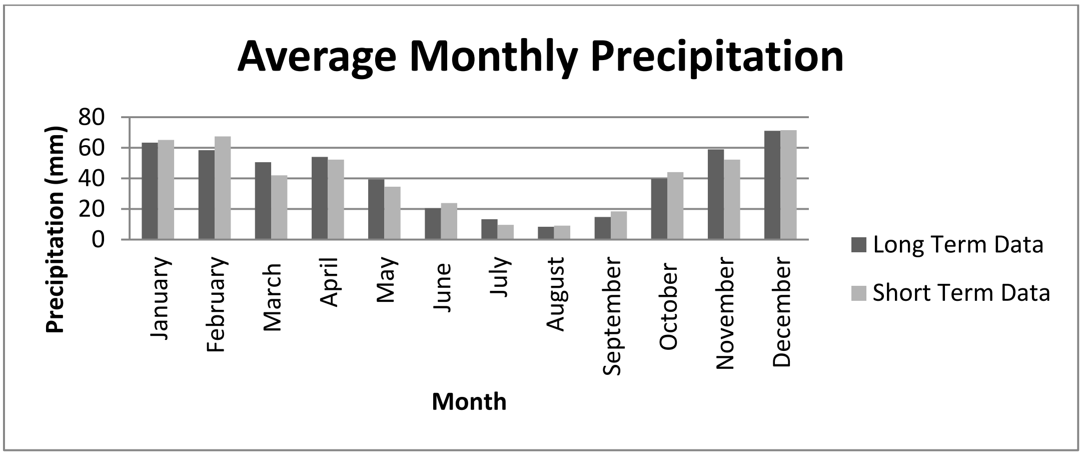

Figure 3.4: Average monthly precipitation values for long term (1975-2012) and short term intervals (2001-2012)

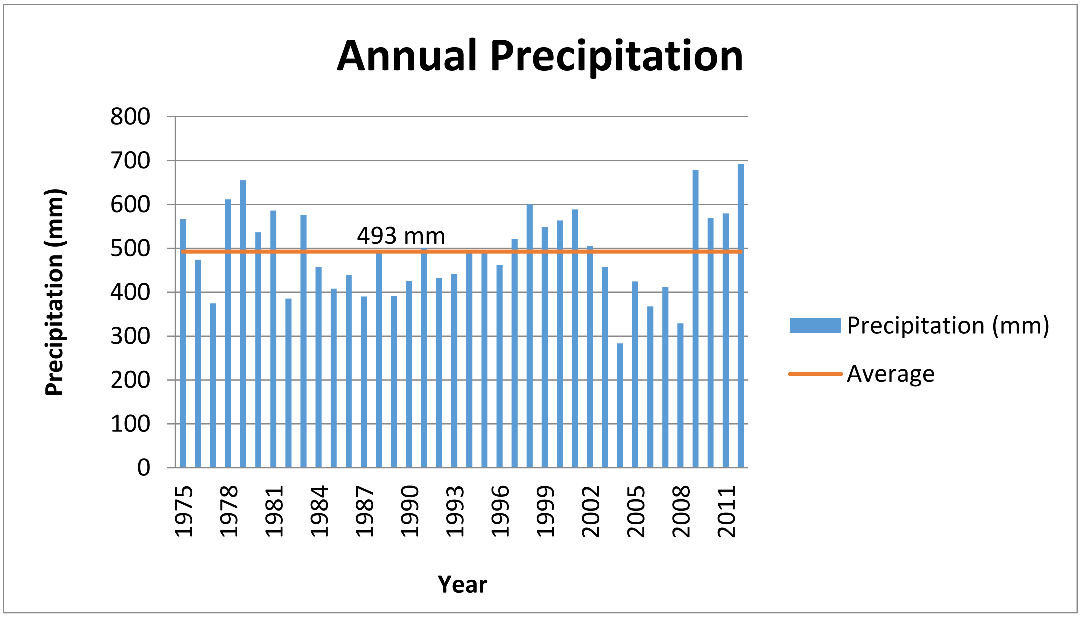

Figure 3.5: Annual precipitation values for long interval

Open surface evaporation values which are measured at Kışladağ meteorological station between 2000 and 2012 generally covers April and October period as shown in Figure 3.6. Kışladağ long term evaporation values are estimated by comparing the measured values at MGM Uşak meteorological station by Yazıcıgil et al., 2013. Long term total annual evaporation is 1198 mm.

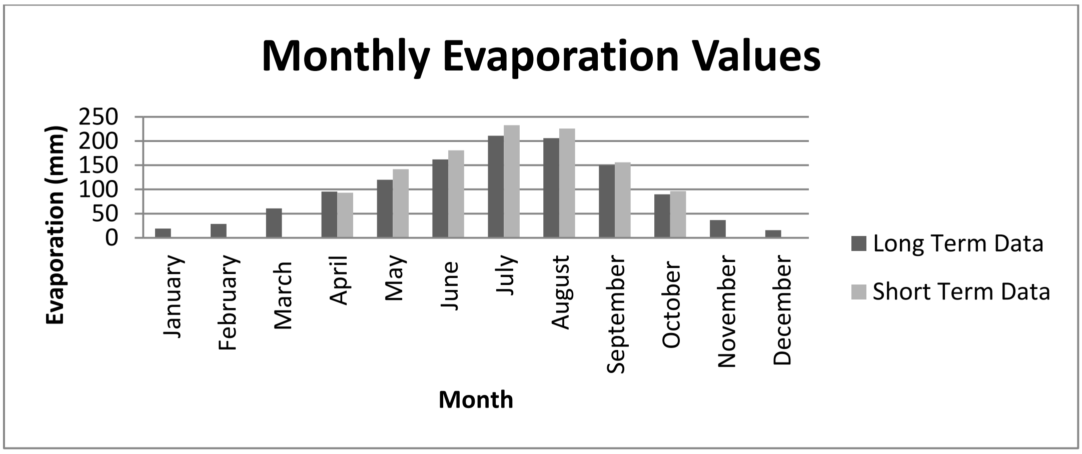

Figure 3.6: Average monthly evaporation values for long term (1975-2012) and short term intervals (2001-2012)

Monthly average relative humidity measured at Kışladağ automatic meteorological station during 2006 and 2012 is shown in Figure 3.7. As can be seen in Figure 3.7, relative humidity is quite low in summer months (around %38-50). This situation shows that summer months are quite dry. However, relative humidity is around %75 in winter months.

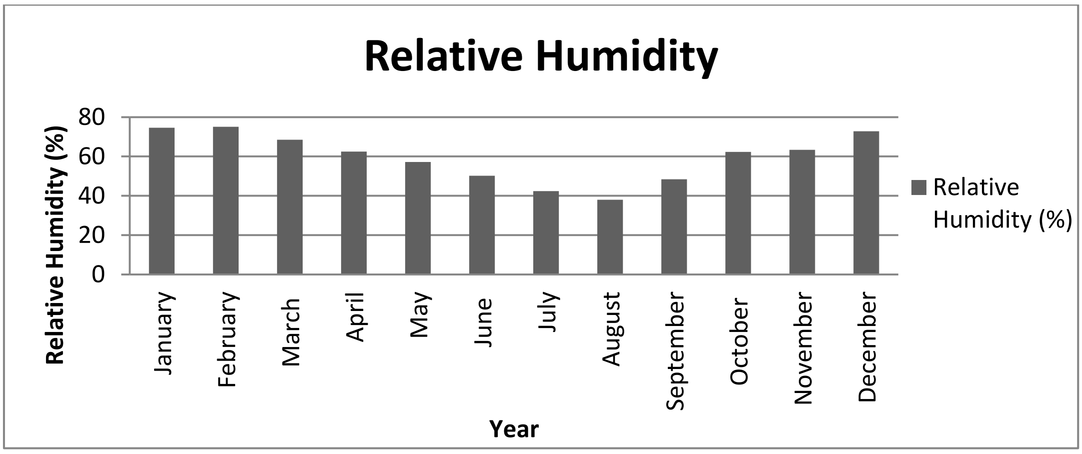

Figure 3.7: Relative humidity values measured at Kışladağ geological station (2006-2012)

3.3. Geology

3.3.1. Regional Geology

Regional geology of the study area has been described by Yazıcıgil et al. (2000). Figure 3.8 shows the regional geology and mine area. Eşme formation is the oldest unit exposed in the area.Lower part of the Eşme formation formed by granitic gneisses which shows lateral and vertical transitions with augen gneisses. There are quartz veins in augen gneisses and it also contains hematite and magnetite. Crystalline gneiss is observed toward upward. Above these, mica, amphibolite, garnet, chloride schist and calc-schist are observed. These units are not identified detailed and grouped under Eşme formation. It is aged as Pre-Permo-Triassic. This formation crops around Takmak, Eşme and Kayalı.

Inay group consists of Ahmetler formation, Ulubey formation and Beydağı Volcanics. Ahmetler formation overlies Eşme formation. Ahmetler formation includes three units which are Merdivenlikuyu, Balçıkdere and Gedikler units. Merdivenlikuyu member is aged as Upper Miocene. It is composed of old talus that is formed by angular blocks and derived from metamorphic rocks. Balçıklıdere member is comprised by conglomerate, sandstone, tuff, claystone, marl and limestone that have been deposited in the stream environment. Gedikler member consist of light yellow, light green and gray siltstone and tuff altermates that comformably overlies the Balçıklıdere member.

Beydağı Volcanics overlies Ahmetler formation. This formation includes three main units that are silica rocks, tuffs and agglomerates and lavas. It is formed by the volcanism which contains andesitic lava, tuff and agglomerates lasting along Pliocene. It shows the lateral transition with the lower part of the Ulubey formation. Hydrothermally formed manganese can be seen in the tuffs and agglomerates. Purple-pink colored lavas and agglomerates and white-yellowish tuffs crops around Beydağı-Kışlaköy. Especially, tuffs form the tuffite levels during the formation of sediments of Ahmetler formation by including to the sedimentation. Agglomerates are formed by various dimensional of andesite particles, metamorphic rock pieces and tuff materials. Andesite generally shows porphyritic structure and hyalopilithic texture (Ercan et al., 1978).

Beydağı Volcanics is overlain by Ulubey formation. It generally consists of lacustrine limestone. Formation includes siltstone, claystone, marl and clayey limestone at the bottom and continues with the pinkish and grayish lacustrine limestone. Ulubey formation is aged as upper-middle Pliocene according to Ercan et al. (1978); however, it is defined as upper Miocene-Pliocene age at MTA Turkey Geological map (2002).

Asartepe formation overlies the Ulubey formation. This formation composed of loose cemented red, brown, dirty yellow, yellow white, mid-thick bedded pebblestone, sandstone, siltstone alternation. Asartepe formation is aged as late Pliocene-Early Quaternary.

Quaternary units consisting of Kula volcanics, terrace deposits and alluvium formed by clay, silt and gravel deposits are the youngests unit in the area.

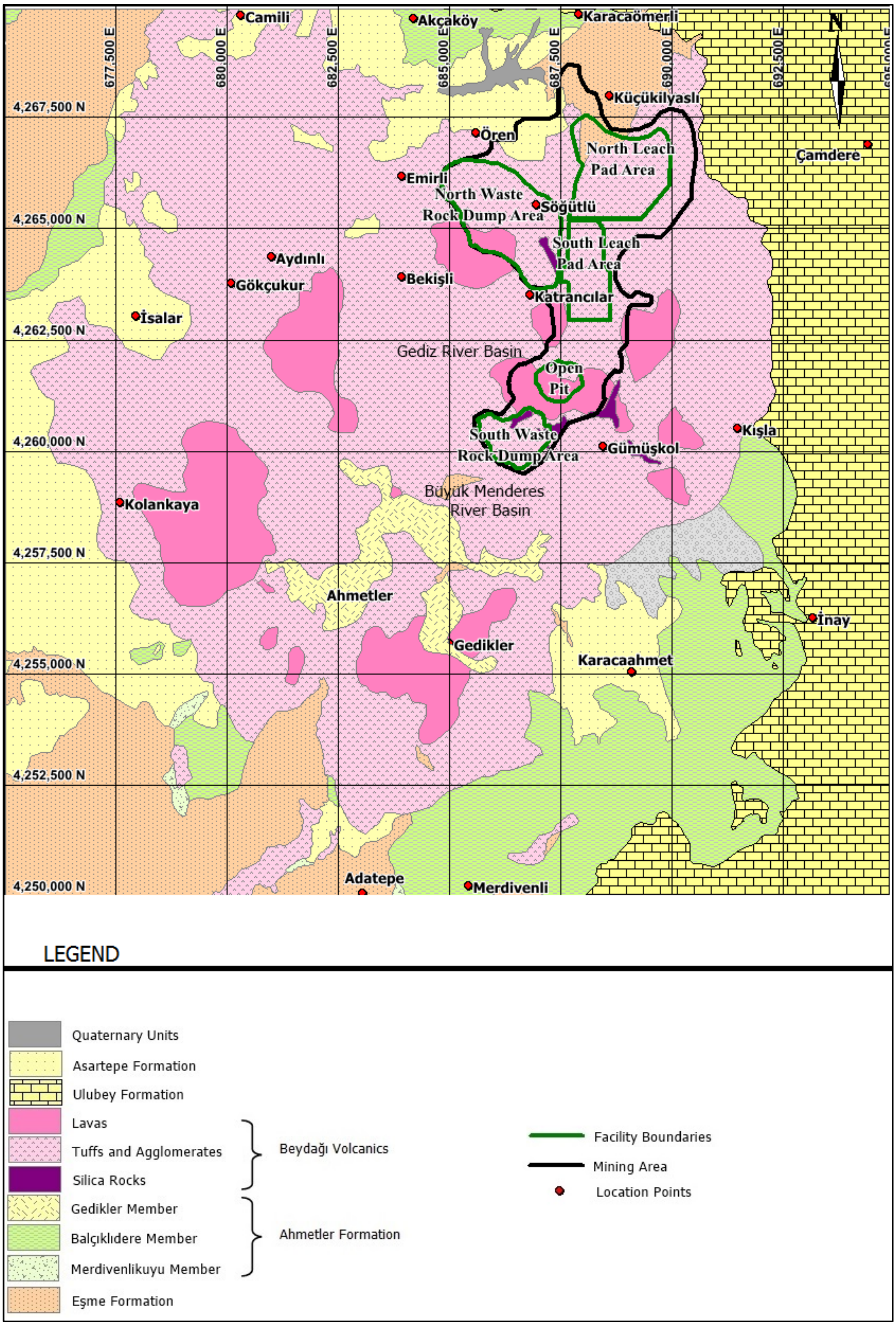

Figure 3.8: Regional Geology of Kışladağ Gold Mine (modified from Yazıcıgil et al., 2013)

The generalized columnar section of Kışladağ Gold mine area is shown in Figure 3.9.

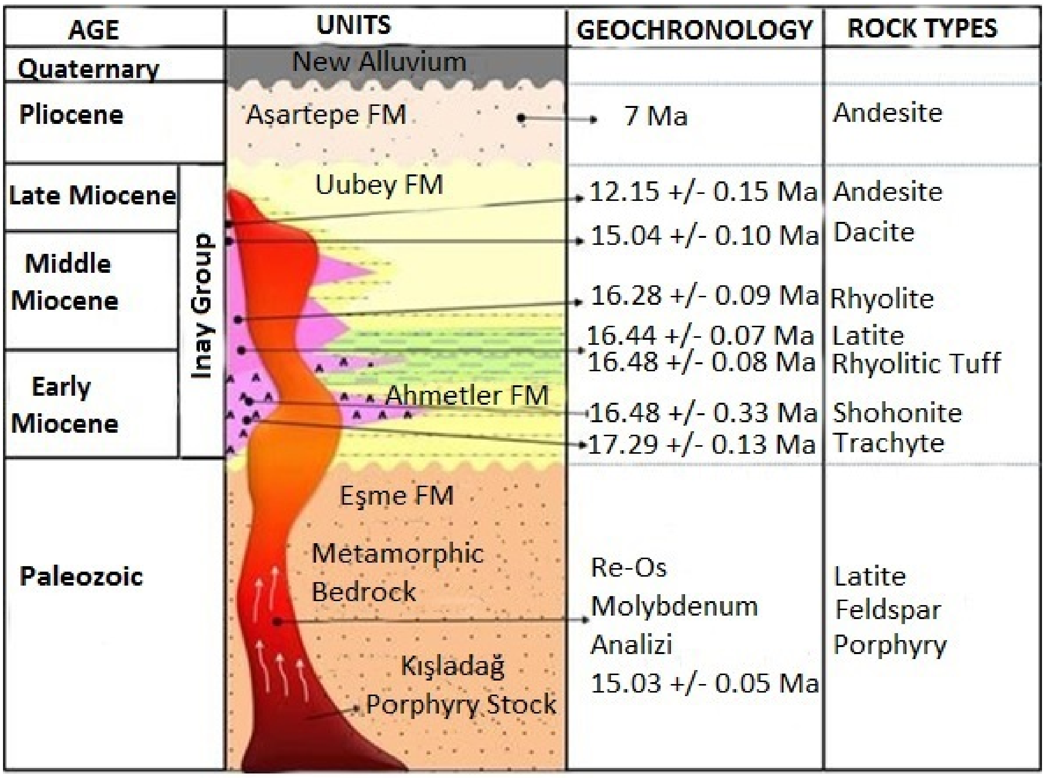

Figure 3.9: Generalized columnar section of Kışladağ Gold Mine Mine area

3.4. Hydrogeology

Kışladağ Gold Mine area is located on the groundwater divide which separates the Gediz and Küçük Menderes River Basins from each other as already mentioned in Chapter 3.1. North Waste Rock Dump Area is located on the Gediz River Basin as shown in Figure 3.1.

Both regional and local hydrogeology of the study area have been studied by researchers (SRK, 2005; Yazıcıgil et al., 2013). This study specifically deals with the North Waste Rock Storage Area; therefore, the hydrogeology of the northern part of the mine site will be summarized from previous studies in the following.

In order to characterize the hydrogeological properties of the northern part of the mine site where planned expansion will take place, several boreholes and monitoring wells were drilled since 2011. The locations of these wells in the northern part are shown in Figure 3.10. These wells are used to monitor groundwater levels and to obtain hydraulic parameters of the various lithologies.

Groundwater level map is produced by using the average water level data obtained from wells shown in Figure 3.10.

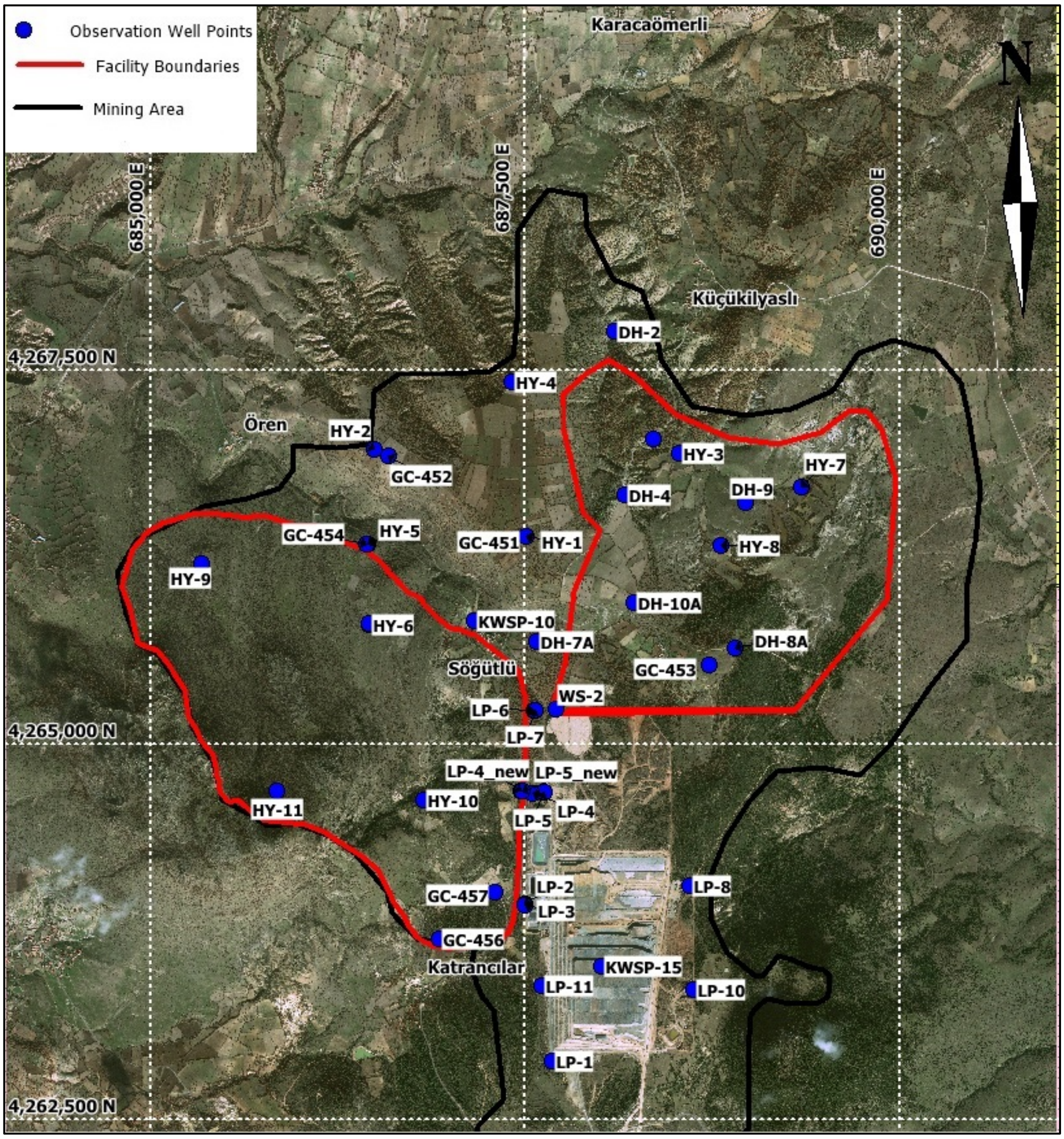

Figure 3.10: Locations of the wells in the North part of Kışladağ Gold Mine (modified from Yazıcıgil et al., 2013)

Areal distribution of groundwater level in the northern part is given Figure 3.11. According to this map, the highest water level can be observed as 1020 meters around present leach pad which takes high precipitation because of high topography and stands on water divide line. Groundwater level is high at the south west of the North Waste Rock Storage Area because of high precipitation received owing to the higher altitude. While groundwater level is 960 meters in the south west, it decreases to 810 and 920 meters towards north and east, respectively. As can been seen in Figure 3.11, there is a groundwater divide around well HY-11.

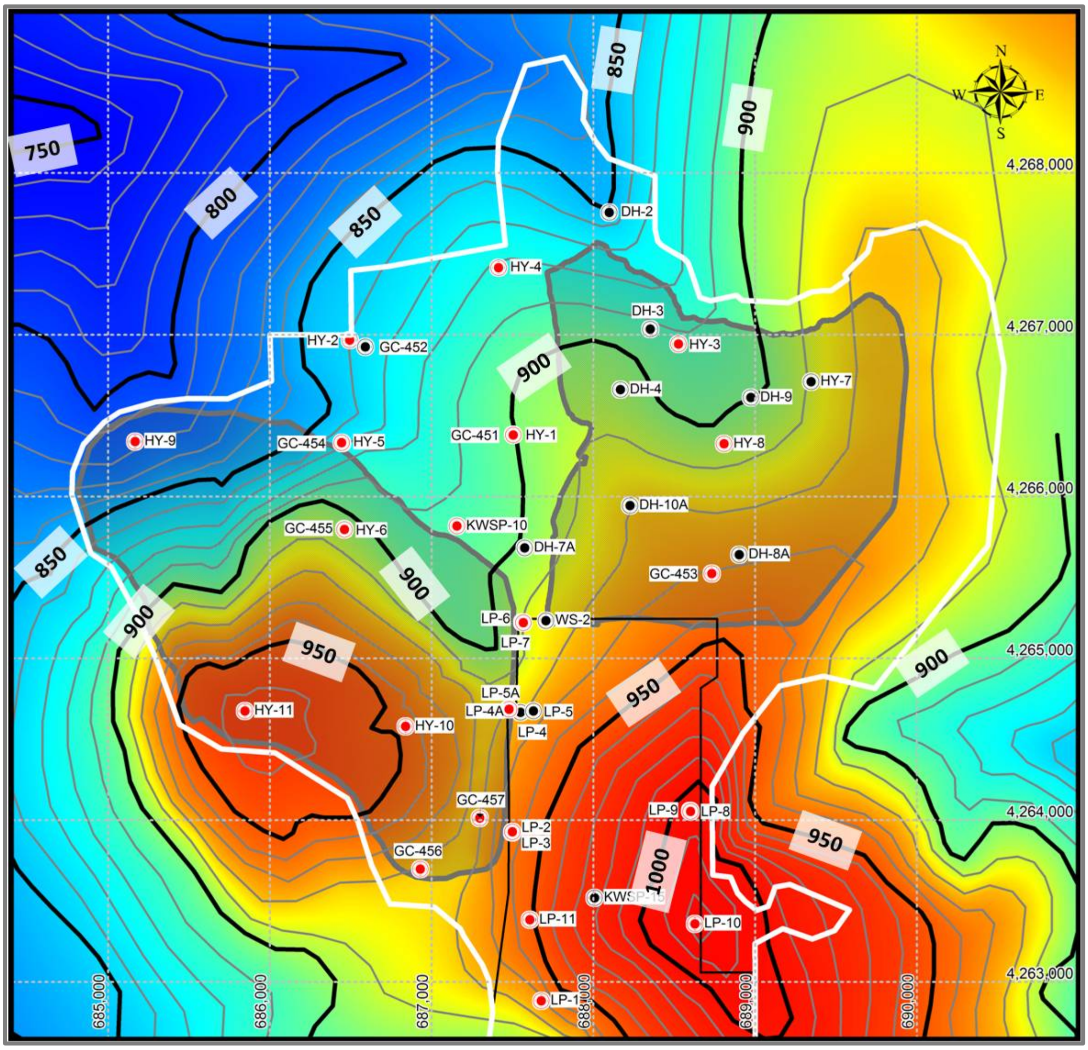

Figure 3.11: Groundwater level map in the study area (Yazıcıgil et al., 2013)

Depth to groundwater table map is obtained by subtracting groundwater levels from topographic elevations (Figure 3.12). When this map is evaluated at high altitude locations, depth to groundwater is around 200-250 meters at the south west of the North Waste Rock Storage Area. Towards north and east depth to groundwater level decreases to 50 and a few meters, respectively.

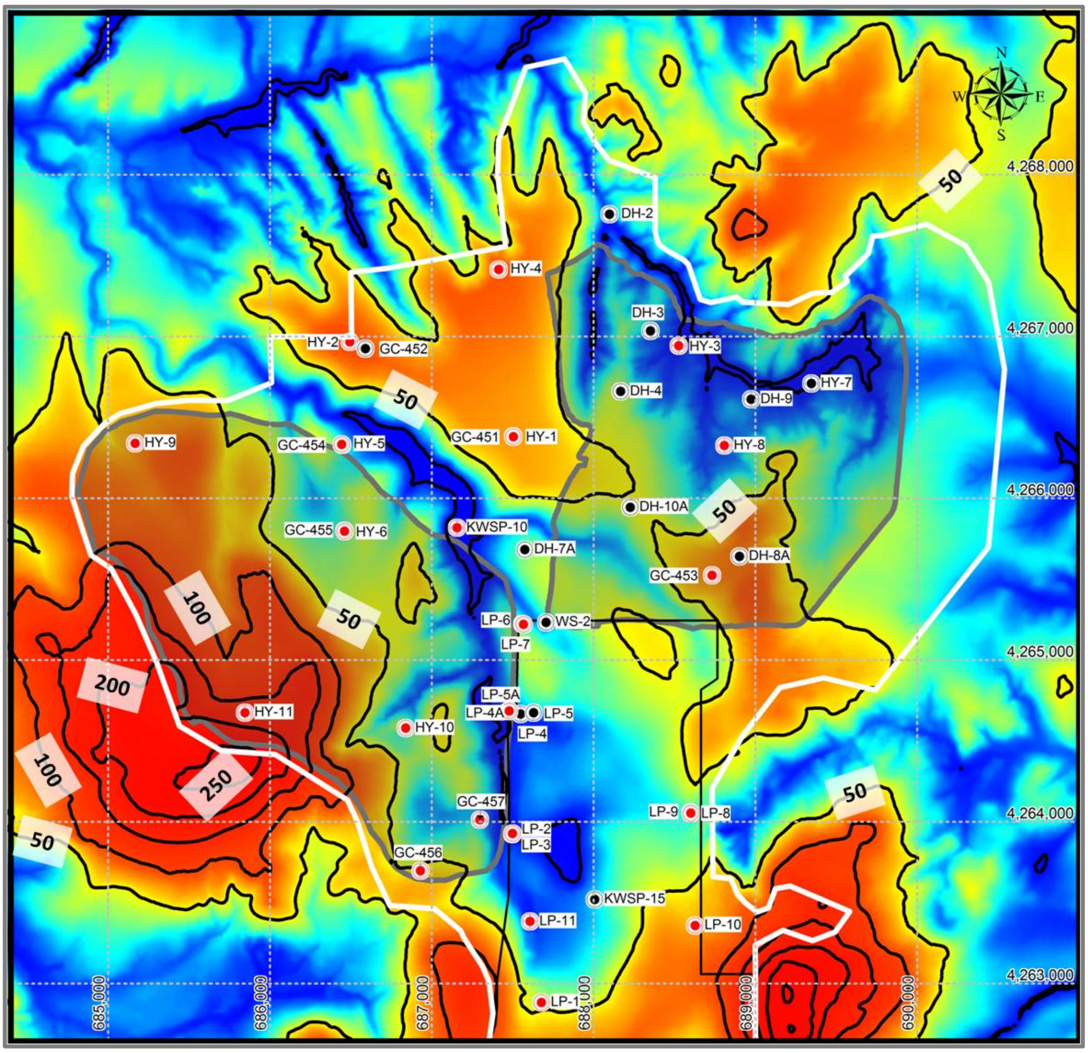

Figure 3.12: Depth to groundwater level map in the study area (Yazıcıgil et al., 2013)

There are two main lithologic units observed around North Waste Rock Storage Area. These are Eşme formation generally consisting of schists and Beydağı Volcanics. Eşme formation is overlain by Beydağı Volcanics in the study area. Their saturated hydraulic properties are taken from previous studies that conducted several pump and slug tests (Yazıcıgil et al., 2013).

Eşme formation is generally considered as poor aquifer with low yields. Well yield of this formation is around 2.5-3 L/s in the mine area and around Eşme. According to the aquifer test results of the wells that are screened in the Eşme formation, hydraulic conductivity of this formation changes between 1.19 x 10^{-8} m/s and 2.61 x 10^{-6} m/s and geometric mean is 1.81 x10^{-7} m/s. Average specific capacity of Eşme formation is 0.032 L/s/m.

Beydağı volcanics are composed of agglomerates, lava flows and tuffs. It outcrops at many places at Kışladağ Gold Mine. When this formation is evaluated from the hydrogeological point of view, water potential of Beydağı Volcanics is also low. According to the pump and slug tests results hydraulic conductivity value changes between 4.56 x 10^{-9} and 1.61 x 10^{-6} m/s. Geometric mean is 1.05 x 10^{-7} m/s. However, Beydağı Volcanics shows slight difference in the North Waste Rock Storage Area. According to the tests results, geometric mean of Beydağı Volcanics is 7.15 x 10^{-8} m/s around the North Waste Rock Storage Area. Average specific capacity of Beydağı volcanic is 0.002 L/s/m.

CHAPTER 4

MODELING METHODOLOGY AND CALIBRATION

4.1. Introduction

In this work unsaturated and saturated flowS are modeled in the proposed North Waste Rock Storage Area to evaluate the performance of various cover designs. Different codes have been used in previous studies to model cover designs such as UNSAT-H (Fayer, 2000), Hydrologic Evaluation of Landfill Performance (HELP, Schroeder et al., 1994), Variably Saturated 2 Dimensional Transport Interface (VS2DTI, Healy 1990), HYDRUS-1D (Simunek et al., 1998), Soil Water Infiltration and Movement (SWIM, Verburg et al., 1996), Soil Cover (Wilson et al., 1996) and Vadose/W (Geo-Slope 2002) (Adu-Wusu et al., 2006).

One-dimensional modeling was used to simulate moisture movement through layered trench covers for radioactive and hazardous waste disposal in early 1980s. However, soil-atmosphere models which incorporate the coupled solution of water and heat (liquid and water) are applied to the modeling of cover design recently (Swanson, Barbour, Wilson & O'Kane, 2003). Vadose/W is one of these models and used to simulate cover design in this work. Detailed information will be explained in the following sections.

4.2. Model Description

4.2.1. Computer Code Selection

In this study, cover design for the North Waste Rock Storage Area for Kışladağ Gold Mine is modeled by the help of SEEP/W and VADOSE/W software.

SEEP/W is a 2D finite element model released by Geo-Studio. It is used to analyze groundwater seepage and excess pore water pressure dissipation problems within porous media such as soil and rock. SEEP/W can be used from simple, saturated steady problems to sophisticated, saturated/unsaturated time dependent problems. Areas of usage of SEEP/W are quite broad. Some of the examples are listed below (SEEP/W 2012 groundwater seepage analysis, (2012)).

- Dissipation of excess pore pressure reservoir drawdown,
- Changes in pore water pressure conditions within earth slopes due to infiltration of precipitation,
- Mounding of the groundwater table beneath water retention structures such as lagoons and tailing ponds,
- Effect of subsurface drains and injection wells,
- Drawdown of a water table due to pumping from an aquifer,
- Seepage flow quantities into excavations.

VADOSE/W is a 2D finite element model developed by Geo-Studio. It is used to analyze flow from environment, across the ground surface, through the unsaturated vadose zone and into the local groundwater regime. The software allows the analysis from simple analysis of groundwater infiltration due to rainfall, to a sophisticated model considering snow melt and root transpiration as well as surface runoff, evaporation, ponding and gas diffusion. Some of the applied areas are listed below (VADOSE/W 2012 vadose zone and soil cover analysis, (2012)).

- Design and performance monitoring of single or multi layered soil covers over mine and municipal waste facilities,

- Development of climate controlled pore-water pressure distributions on natural or manmade slopes for use in stability analyses,
- Determining infiltration, evaporation and transpiration rates from agriculture, irrigation projects, or natural systems.

4.2.2. Mathematical Model

SEEP/W is formulated using Darcy's Law for both saturated and unsaturated soils. However, for unsaturated soils some changes applied. As indicated in former chapters, unsaturated hydraulic conductivity is a function of water content and water content is a function of pore water pressure; thus, both the hydraulic conductivity and water content is function of pore water pressure in unsaturated soils.

The general governing differential equation for two-dimensional seepage can be expressed as:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial_y}\left(k_y \frac{\partial H}{\partial y}\right) + \mathrm{Q} = \frac{\partial \theta}{\partial t} \quad (4.1)$$

where H: total hydraulic head

k_x, k_y : hydraulic conductivity in x and y direction

Q: applied boundary flux

θ: the volumetric water content

t: time

VADOSE/W also uses Darcy's Law.

The general governing differential equation for two-dimensional seepage can be expressed as:

$$\frac{1}{\rho}\frac{\partial}{\partial x}\left(D_v\frac{\partial P_v}{\partial x}\right)+\frac{1}{\rho}\frac{\partial}{\partial y}\left(D_v\frac{\partial P_v}{\partial y}\right)+\frac{\partial}{\partial x}\left(k_x\frac{\partial\left(\frac{P}{\rho g}+y\right)}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial\left(\frac{P}{\rho g}+y\right)}{\partial y}\right)+\mathrm{Q}=\lambda\frac{\partial P}{\partial t} \quad (4.2)$$

where P : pressure

P_v : vapor pressure of soil moisture

λ : storage term for a transient seepage

k_x, k_y : Hydraulic conductivity in x and y directions

Q : applied boundary flux

D_v : vapor diffusion coefficient as described by Wilson (1990)

Y : elevation head

ρ : density of water

g : acceleration due to gravity

t : time

For heat transfer:

$$L_v\frac{\partial}{\partial x}\left(D_v\frac{\partial P_v}{\partial x}\right)+L_v\frac{\partial}{\partial_y}\left(D_v\frac{\partial P_v}{\partial y}\right)+\frac{\partial}{\partial x}\left(k_{tx}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{ty}\frac{\partial T}{\partial y}\right)+Q_t+\rho cV_x\frac{\partial T}{\partial x}+\rho cV_y\frac{\partial T}{\partial y}=\lambda_t\frac{\partial T}{\partial t} \quad (4.3)$$

where ρc: volumetric specific heat value

K_{tx}: thermal conductivity in x direction

K_{ty}: thermal conductivity in y direction and assumed equal to K_{tx}

V_{xy}: the Darcy water velocity in x and y directions

Q_t: applied thermal boundary flux, and

L_v: latent heat of vaporization.

VADOSE/W is capable of calculating the infiltration, evaporation and transpiration components of the hydrological system. In order to do this, VADOSE/W couples the moisture and heat stress state at the ground surface with climate conditions present above the ground surface (Geo-Slope, 2008).

Climate data can be applied as an upper boundary condition and actual evaporation is calculated using Penman-Wilson formulation (Wilson 1990) as follows:

$$AE = \frac{\Gamma Q + \upsilon E_a}{\upsilon A + \Gamma} \tag{4.4}$$

where AE: actual evaporative flux

Γ: slope of saturation vapor pressure versus temperature curve at the mean temperature of the air (kPa/°C)

Q: net radiant energy available at the surface (mm/day)

E_a: $f(u)P_a(B\text{-}A)$

u: pychrometric constant

f(u): function dependent on wind speed, surface roughness, and eddy diffusion = $0.35 (1 + 0.15U_a)$

U_a: wind speed

P_a: vapor pressure in the air above the evaporating surface (kPa)

B: inverse of the relative humidity of the air

A: inverse of relative humidity at the soil surface

4.2.3. Numerical Solution

SEEP/W applies Galerkin method of weighed residual to governing equation to derive 2D finite element seepage equation, which is:

$$\tau \int_A ([B]^T [C][B]) dA\{H\} + \tau \int_A (\lambda < N >^T < N >)\, dA\{H\},t = q\tau \int_L (< N >^T)\, dL \tag{4.5}$$

where [B]: the gradient matrix

[C]: the element hydraulic conductivity matrix

{H}: the vector of nodal heads

<N>: the vector of interpolating function

q: the unit flux across the edge of an element

τ: the thickness of the element

t: time

λ: storage term for a transient seepage equals to $m_w\gamma_w$

A: a designation for summation over the area of element, and

L: a designation for summation over the edge of an element.

Applying the Galerkin method of weighed residual to the governing differential equation the finite element for two dimensional seepage equation can be derived as:

$$\tau \int_A ([B]^T [C][B]) dA \{P\} + \tau \int_A ([B]^T [D_2][B])\, dA\{T\} + \tau \int_A ([B]^T [K][B])\, dA\{y\} + t \int_A (\lambda < N >^T < N >) dA\{P\}, t = qt \int_L (< N >^T)\, dL \quad (4.6)$$

where [B]: gradient matrix,

[C]: element stiffness matrix = [K/ρg+D1]

D1: Dvd1/ρ

[D2]: [Dvd2/ρ]

{P}: vector of nodal pressures

{y}: vector of elevation heads

[K]: element hydraulic conductivity matrix

λ: storage term

<N>T<N>: [M], the mass matrix

{P},t: change in pressure with time

Q: unit flux across the side of an element

<N>: vector of interpolating function

τ: element thickness

4.2.4. Conceptual Model

Conceptual model is the starting point for the numerical modeling. It gives information about the flow regime, boundary conditions, topography, areal extents of the lithologies that are modeled. Thus, correct conceptual model is important for the accuracy of the numerical modeling.

In order to develop a conceptual model for the North Waste Rock Storage Area, a cross section is taken from southwest to northeast direction as shown in Figure 4.1. This cross section is oriented such that it passes through existing monitoring wells (HY-11 and HY-6) and is also parallel to the groundwater flow direction in the study area. Flow direction is from HY-11 to HY-6 through the section. Topographic elevation decreases from HY-11 to HY-6. Depth to groundwater level is around 166 meters at HY-11 and 22 meters around HY-6.

Study area is bounded by groundwater at northeast. At southwestern boundary there is a water divide, which represents no flow boundary condition. Ground surface is exposed to meteorological events so recharge is considered as upper boundary. There are two different recharge zones in the study area according to Yazıcıgil & Unsal, 2013.

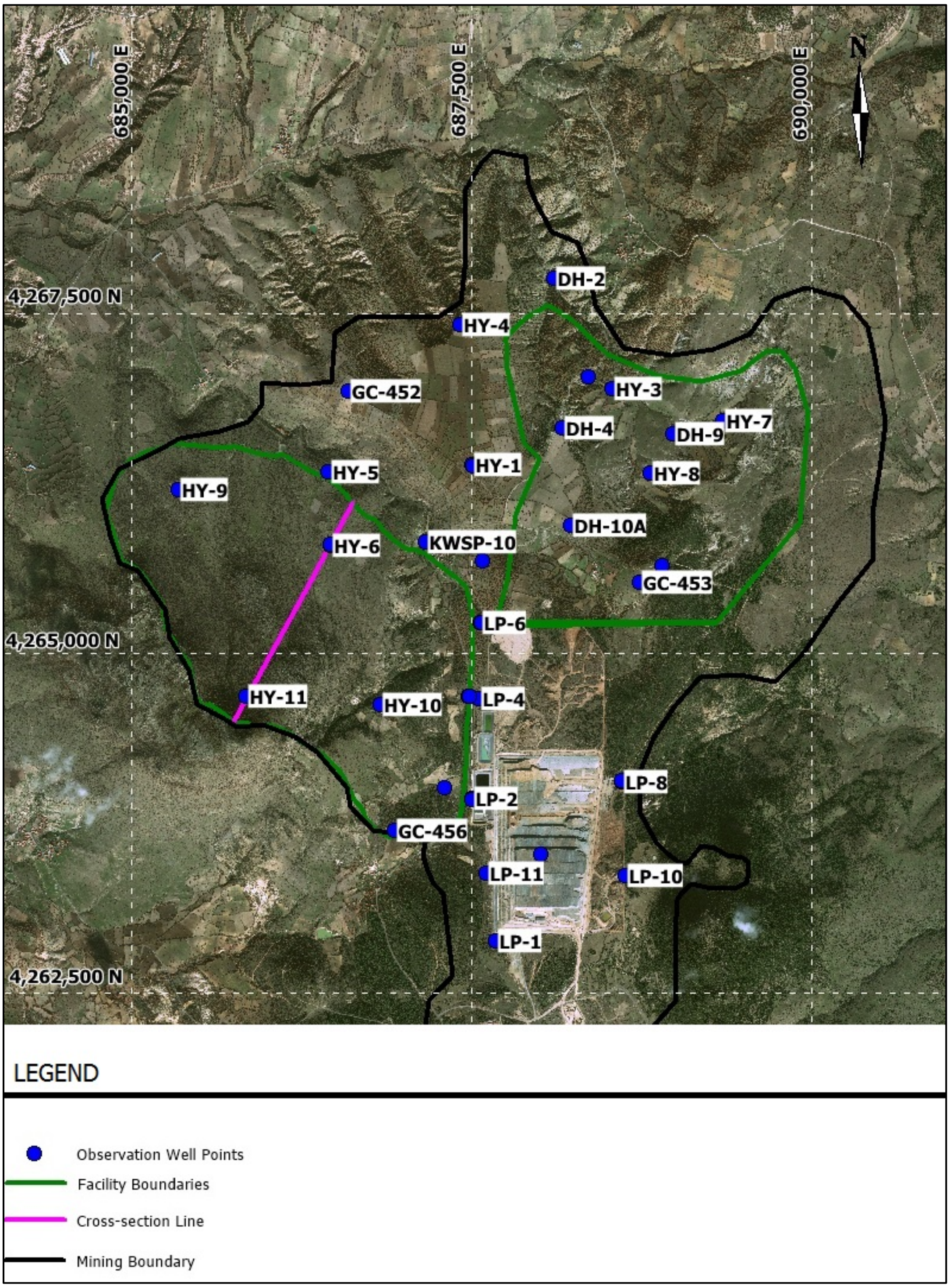

Figure 4.1: Cross-section location at the north waste rock storage area (modified from Yazıcıgil et al., 2013)

4.2.5. Numerical Model

Since groundwater level measurements are available for bedrock and bedrock represents the lower boundary condition of the waste rock, it is modeled firstly. Modeling for bedrock was completed in two stages. First was steady state run and the other stage was transient run. Calibration was done due to steady-state run and result of this run was used as initial head condition for transient run. Model extents and grid properties were same for both runs, but boundary conditions change for steady and transient models.

4.2.5.1. Model Domain

For the bedrock modeling, initially, a 2 layered system is set up referring to two formations in the study area. Beydağı Volcanics shows different properties in the model area; thus, this formation is modeled as two different zones. The model domain is 1750 meters in length with a unit width; however, the thickness varies due to topographic elevation. Eşme formation is modeled with constant thickness of 250 meters while Beydağı Volcanics is modeled with varied thickness between 446 and 183 meters in the model domain as shown in Figure 4.2. For the steady state calibration, groundwater levels in HY-6, HY-11 wells and groundwater level map in the study area (Yazıcıgil et al., 2013) are used. Groundwater elevation is from 961 to 890 meters from southwest to northeast through the model domain.

4.2.5.2. Finite Element Grid

Discretization (or meshing) is an important step in numerical modeling. Discretization is splitting the model domain into small blocks which are called elements. In VADOSE/W different types of mesh which are triangles, rectangular and quadrilaterals are available. Domain geometry is one of the important parameter to decide types of mesh. For example, rectangular mesh generally fits to four sided domain; however, upper border of our domain is always changing due to topography. At this condition, combination of rectangular and triangular types of mesh is chosen as mesh types. Element size is also important for discretization step.

Smaller size of elements gives more accurate result, but smaller elements takes longer time to solve. Actually, after a certain size, making the elements smaller does not change the results so much. It only takes more computational time. Thus, optimum size of elements is necessary to be determined. Mesh size automatically assigned by the software is 45 meter considering the optimum conditions. However, in order to see changes in more detail around HY-11 and HY-6 wells, mesh sizes are changed at these areas. Mesh size is assigned as 22.5 meters for Beydağı Volcanics. However, mesh size of the Eşme formation is set up as 45 meters because of its greater saturated thickness. Model is composed of totally 3484 nodes and 3411 elements for the bedrock part.

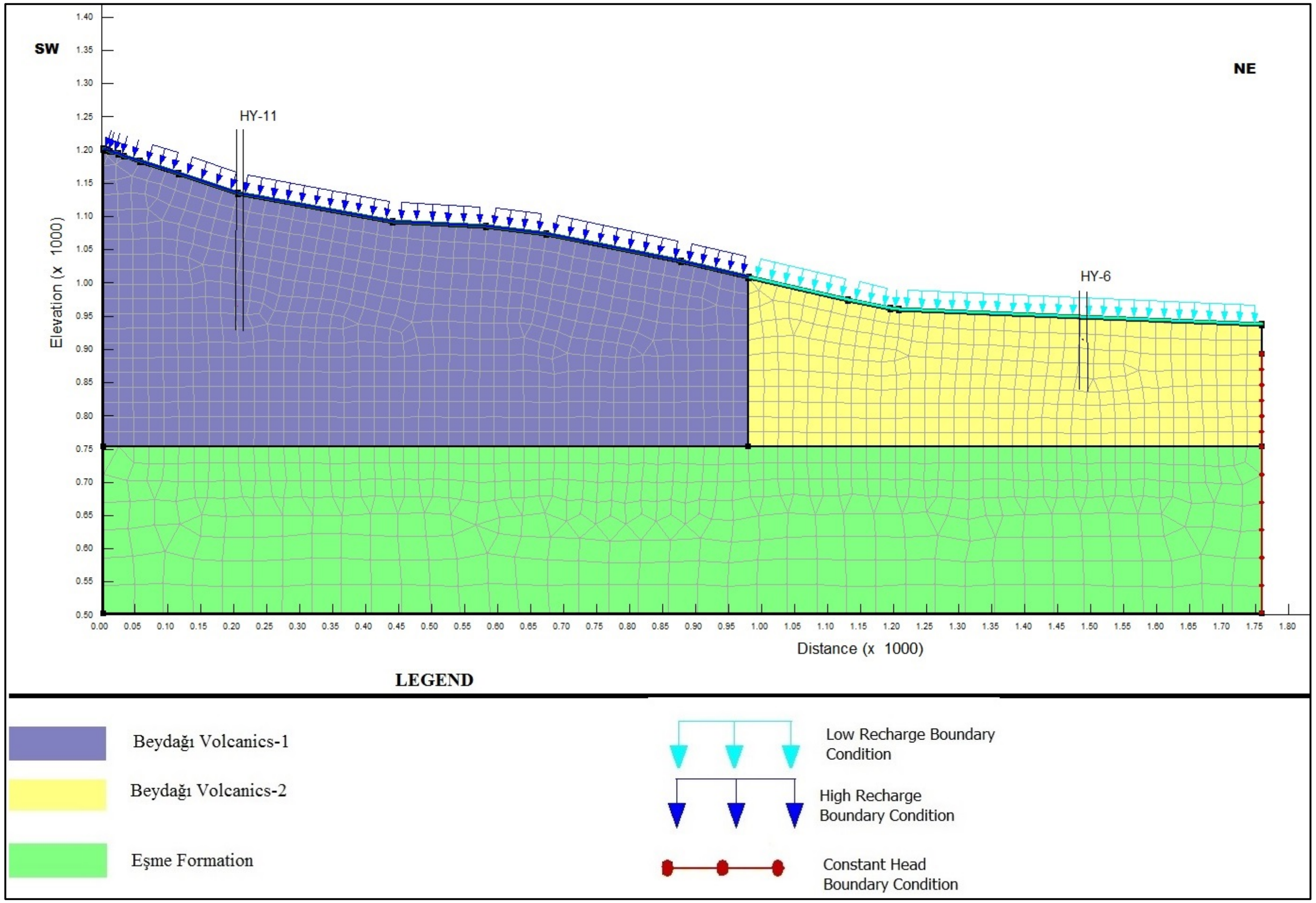

Figure 4.2: Discretized model domain

4.2.5.3. Boundary Conditions

Boundary condition is one of the important steps because it is the part that links the numerical model to conceptual model. Boundary conditions of the model are determined by the help of the hydrogeological and geological information in the previous studies. Boundary conditions change for steady and transient conditions.

For the steady-state analysis, two types of boundary conditions are assigned. One is the constant head boundary which represents the constant groundwater elevation condition. Groundwater level is taken as 890 meter at the north east of the model according to groundwater table map given in Figure 3.10. As indicated in Chapter 3.4, there is a water divide around HY-11. Southwest part of the model is located on the groundwater divide. Thus, no boundary condition is assigned to the southwest part of the model. SEEP/W and VADOSE/W take no boundary condition as an impervious boundary. Boundary condition for the upper border of the model domain is assigned according to the study conducted by Yazıcıgil & Unsal, 2013. Two different recharge rates are assigned along the topography. Southwest part of the model domain having higher altitudes receives more recharge than the northeast part where elevations are lower. High recharge zone is named as highland recharge zone while low recharge zone is named as lowland recharge zone. In order to represent recharge condition, unit flux boundary is assigned. High recharge rate is assigned as 76 mm/year while low recharge rate is assigned as 29 mm/year; however, these values are changed during the calibration. Figure 4.2 shows the boundary conditions for the steady-state run.

Transient model runs had different boundary conditions than the steady-state model runs. At the transient run, upper boundary is assigned as climate boundary. At the bedrock transient run, the northeast boundary is no longer kept as constant head. Unit flux boundary is assigned to the northeast boundary where the assigned unit flux amount is obtained from the steady state calibrated model. Seepage boundary condition is assigned above the unit flux boundary condition in case if groundwater level increases in the wet season this boundary condition will help to remove the excess water at that boundary (Figure 4.3).

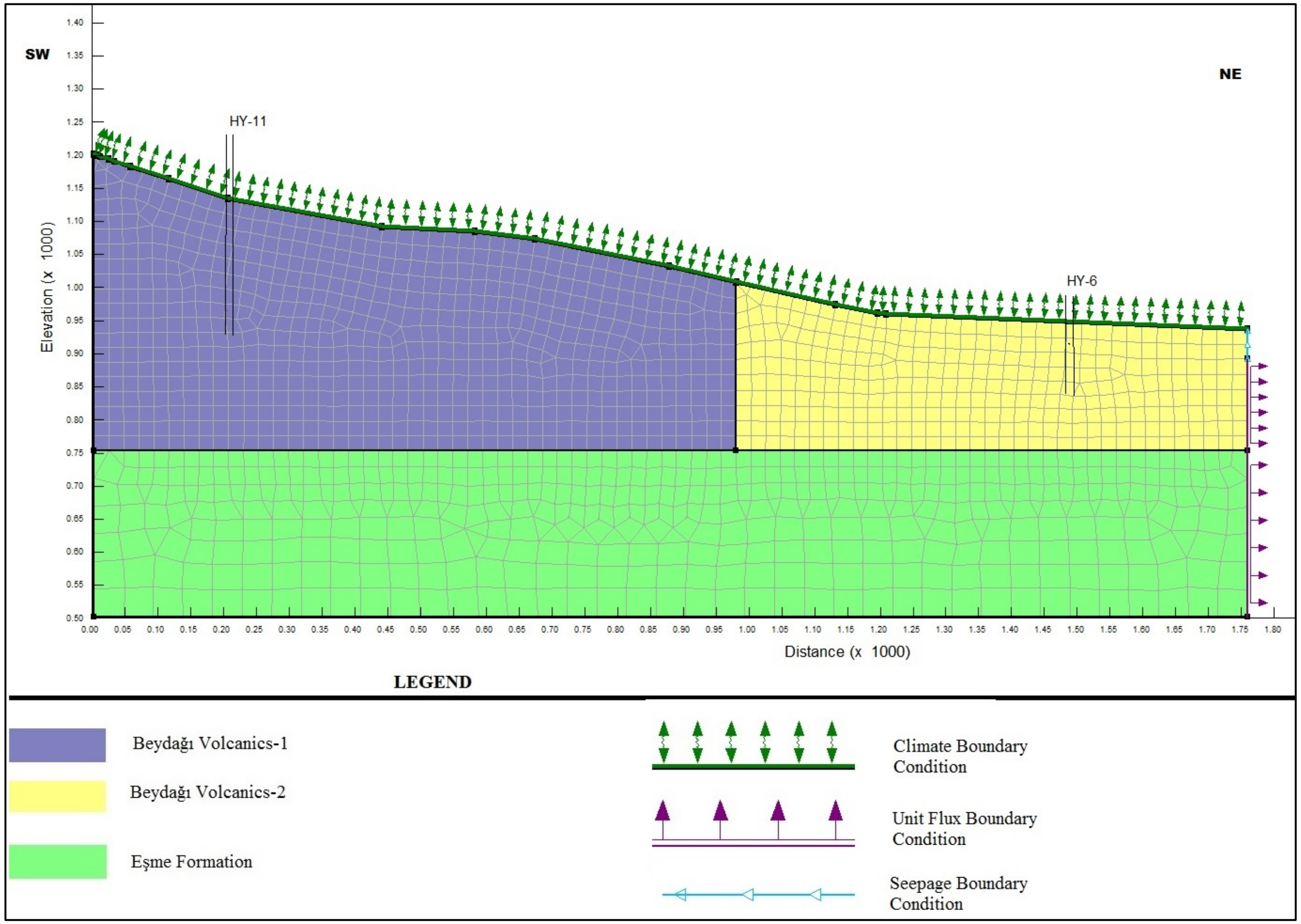

Figure 4.3: Boundary conditions for bedrock at transient condition

4.2.5.4. Model Parameters

In SEEP/W software just soil parameters are important. However, in VADOSE/W software in addition to soil parameters, vegetation parameters and climate parameters are also important parameters to consider. All parameters are explained in the following sections.

4.2.5.4.1. Soil Parameters

Hydraulic properties for soil parameters are the same in both SEEP/W and VADOSE/W softwares. Hydraulic properties that are determined using SEEP/W software for steady state model calibration are then transferred to the VADOSE/W software. After that, thermal properties of soil parameters are assigned in VADOSE/W.

4.2.5.4.1.1. Volumetric Water Content Function (Soil Water (or Moisture) Characteristic Curve)

Volumetric water content function or soil water characteristic curve (SWCC) is an important parameter for the unsaturated zone flow modeling. It defines how much water will be held in the system depending on matric suction. It changes with the matric suction. Volumetric water content curve can be determined by grain size analysis, laboratory and in situ analysis. However, in the absence of data, volumetric water content curve can be obtained from the literature. In this study, volumetric water content curves for the bedrock, waste rock and other soils for the cover design alternatives are taken from the similar previous works (Benson et al., 2007, Stormont & Morris, 1998, Parent & Cabral, 2006, Stormont & Morris, 1998; Benson et al., 2007; Parent & Cabral, 2006; Noel & Rykaart, 2003). SEEP/W and VADOSE/W use Van Genuchten and Fredlund & Xing estimation methods to draw SWCC. However, Van Genuchten method is more commonly used in literature so Van Genuchten estimation method is used in the model. As mentioned earlier in the modeling methodology, Van Genuchten estimation formula uses saturated and residual water contents and curve fitting parameters (air entry value and slope) to obtain the change in water volume with respect to changes in matric suction. According to Freeze & Cherry, 1979, porosity cannot be larger than 2% in unfractured metamorphic and plutonic igneous rocks. Thus, saturated water content is taken as %2 for the bedrock formations consisting of Beydağı Volcanics and Eşme schists. According to Freeze and Cherry, 1979, unfractured rocks can be modeled like fine grained layer. In our study, bedrock was assumed as unfractured rock. However, for the fractured rock dual porosity system should be considered. Flow shows different properties at fracture and matrix part. In order to determine Van Genuchten parameters for bedrock, both fine grained soil and matrix part of the rocks are considered. Table 4.1 shows the input Van Genuchten and unsaturated hydraulic conductivity parameters based on the similar works in the literature (Rasmussen, 2001, Benson et al., 2007, Stormont & Morris, 1998, Parent & Cabral, 2006). Figure 4.4, shows the resulted SWCC.

Table 4.1: Parameters for soil water characteristic curve (SWCC) and unsaturated hydraulic conductivity functions for bedrock

	Van Genucten Parameters					
	a (air-entry value, kPa)	n	m	K_{sat} (m/s)	θ_s	θ_r
Beydağı Volcanics Part-1	100	1.23	0.186	9×10^{-8}	0.02	0.005
Beydağı Volcanics Part-2	80	1.3	0.23	1×10^{-7}	0.02	0.005
Eşme Formation	70	1.35	0.26	2×10^{-7}	0.02	0.005

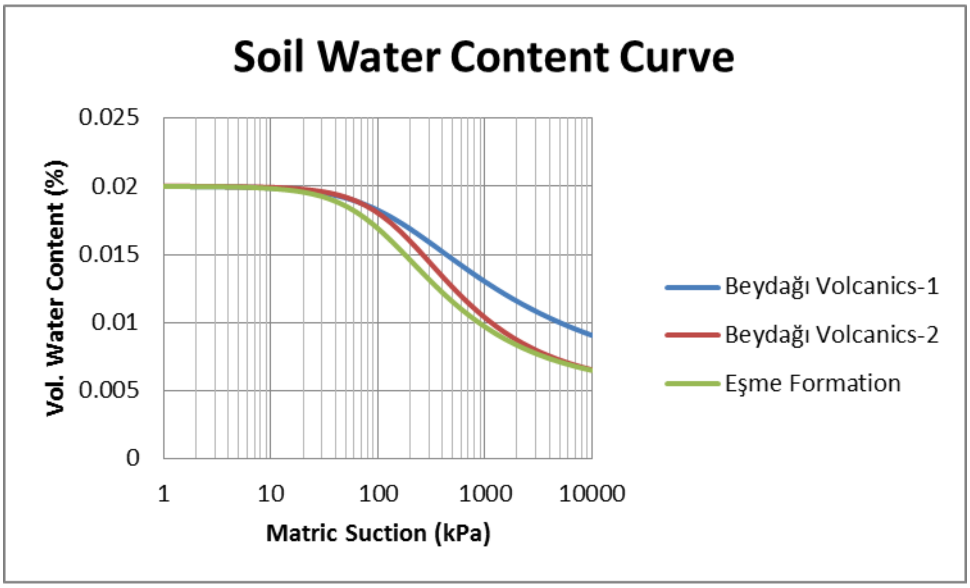

Figure 4.4: Soil water characteristic curve (SWCC) for the bedrock modeling

4.2.5.4.1.2. Saturated & Unsaturated Hydraulic Conductivity

Hydraulic conductivity value is constant for the saturated zone. There are three different saturated hydraulic conductivity values assigned to the model domain. A value of 7.8 x 10^{-8} and 9.2 x 10^{-8} m/s is assigned for the ^{8} m/s is assigned to the Beydağı Volcanics part-1 and Beydağı Volcanics part-2, respectively. The value of 1.8 x 10^{-7} m/s is assigned for the Eşme formation. These values are obtained from the previous study conducted by Yazıcıgil et al., 2013. During the calibration of the model these values are changed slightly, final results will be given in the calibration part.

Hydraulic conductivity value for the unsaturated zone is not constant like saturated zone. It changes with water content. As mentioned in the previous section water content changes with matric suction and unsaturated hydraulic conductivity changes with water content. This gives us the inference that both water content and hydraulic conductivity are functions of matric suction in the unsaturated zone flow. In the absence of field and/or laboratory methods to derive these curves, estimation methods such asVan Genuchten and Fredlund & Xing can be used. In this study, Van Genuchten method which is more commonly used in the literature works is chosen. Unsaturated hydraulic conductivity curves used in bedrock model are given in Figure 4.5.

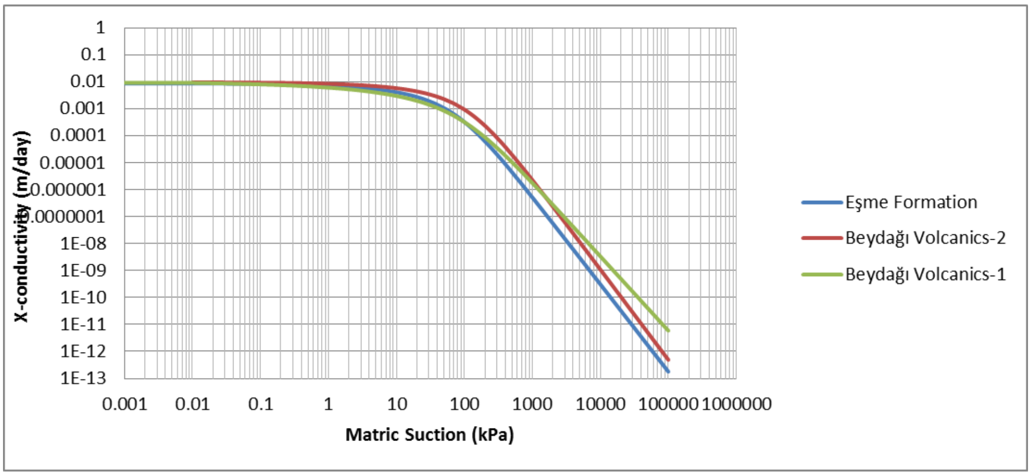

Figure 4.5: Unsaturated hydraulic conductivity curves used in bedrock modeling

4.2.5.4.1.3. Thermal Properties

Thermal properties are only applicable to VADOSE/W. In the program either full thermal model or simplified thermal model can be chosen. If the study area is under thermal effect, it is wise to choose full thermal model. In the full thermal model, thermal hydraulic conductivity and volumetric specific heat capacity are assigned as function of volumetric water content. However, on the simplified thermal model, thermal hydraulic conductivity and volumetric specific heat capacity are assigned as constant values. According to old studies, there is no evidence that the study area is under great thermal effect. Additionally, results obtained assigning different thermal properties did not show much sensitivity to thermal conductivity and volumetric specific heat values. As a result, simplified thermal model is used in this study. Typical values of volumetric specific heat capacity and thermal conductivity are obtained from Vadose Zone Modeling with VADOSE/W 2007 manual (Geo-

Slope, 2008) based on mineralogy that is shown in Table 4.1. Thermal properties are used in similar ways by Adu-Wusu et al., 2006.

Table 4.2: Thermal properties

	Thermal Properties	
	Themal Conductivity (kJ/days/m/°C)	Volumetric Heat Capacity (kJ/m^3/°C)
Unfrozen	150	2500
Frozen	125	2300

4.2.5.4.2. Vegetation Parameters

Vegetation data is only applicable to VADOSE/W software which is used to model cover design alternatives. Grasses are generally preferred for soil covers because they minimize erosion, transpire stored water and have shallow roots that do not result in the creation of preferential flow paths. There are 3 components as input for the vegetation data. These are leaf area index (LAI), plant moisture limiting point and root depth. In order to determine LAI, grass quality and growth season are necessary. Plant growth season is between April, 15 and October, 10 (Yazıcıgil et. al., 2013). For the LAI, the vegetation can be defined as poor, good and excellent quality. Root depth can be measured in the field or average grass depth can be assigned referring to the similar works. In this study grass is chosen as poor quality and root depths in the cover designs are taken as 30 cm comparing precipitation, growth season and actual evaporation to the similar works in the literature. (Christensen, D. and O'Kane, M. 2005; Adu-Wusu, C. et al., 2006). Plant moisture limiting factor obtained from the program which have a value of -100 kPa and wilting point of -1500 kPa.

4.2.5.4.3. Climate Parameters

Climate data is only applicable to the VADOSE/W like vegetation parameters. Input for climate data in VADOSE/W is daily minimum and maximum temperature, minimum and maximum relative humidity, daily wind speed and daily precipitation. Daily climate data belonging to 5 years (2008-2012) period is used in the model. According to Bohnhoff, et al., 2009, runoff is predicted more accurately when the precipitation is applied uniformly throughout the day; thus precipitation is distributed for 24 hours. Climate parameters are assigned with a sinusoidal distribution pattern. Air temperature and relative humidity is applied in a sinusoidal pattern between sunrise and sunset times. Air temperature slopes to a minimum value at midnight, while relative humidity slopes to maximum value at midnight. Wind speed is applied as a constant value through the day (Geo-Slope, 2008). Location latitude is also input to the model in order to determine the time of day the sun rises and sets.

4.3. Steady-State Bedrock Model Calibration

Steady-State Bedrock Model calibration is used to check whether the initially assigned input parameters of the system reflect the actual field condition or not. During calibration trial and error method is used to modify parameters such as saturated hydraulic conductivity values, flux amount, volumetric water content functions, etc. These parameters are adjusted within reasonable limits, until there is a good match between measured and simulated groundwater levels. Model is calibrated under steady state condition because just short term field measured data is available.

The initial values assigned for the setup of the model are changed during the steady-state calibration. Saturated hydraulic conductivity of Beydağı volcanics part-1 and part-2 were assigned as 7.8 x 10^{-8} m/s and 9.2 x 10^{-8} m/s, respectively. Then they are changed to 9 x 10^{-8} m/sand 1 x 10^{-7} m/s. Saturated hydraulic conductivity for the Eşme formation was assigned as 1.8 x 10^{-7} m/s at the beginning, then modified to 2 x 10^{-7} m/s. Volumetric water content function curve is also adjusted during the calibration. Both the slopes of curves and air-entry value points are modified during calibration. The last calibrated parameter is recharge amount that is applied as flux amounts from top of the model. Recharge amount is taken from the study that is conducted by Yazıcıgil and Unsal, 2013. According to this study, there are two recharge zones, which are named as highland and lowland, in the study area. Highland recharge value was assigned as 76 mm and lowland recharge value was assigned as 29 m before the calibration. During the calibration, these values are changed to 60 mm and 27 mm for the highland recharge value and lowland recharge value, respectively. Simulated groundwater level profile is shown in Figure 4.6.

Calibration of the model was conducted under steady state condition and goodness of the fit was checked by comparing the simulated groundwater levels with the measured groundwater levels. There are two important statistical values used to check goodness of fit between simulated and measured values. These are root mean square error, and normalized mean square error.

Root mean square error (RMSE) is frequently used to measure differences between values simulated by a model or an estimator and the values actually measured. Basically, the RMSE represents the sample standard deviation of the differences between simulated and measured.

$$\text{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i^2\right]^{0.5} \qquad (4.7)$$

where h_m is measured groundwater level

h_s is simulated groundwater level

n is number of observations.

The normalized root mean square error (NRMSE) is presentation of RMSE as percentage. It is an important value because if NRMSE is less than 5% it means fit between the measured and simulated values is acceptable.

$$\text{NRMSE} = \frac{RMSE}{h_{m(max)} - h_{m(min)}} * 100 \qquad (4.8)$$

The simulated and measured groundwater levels are plotted (Figure 4.6) and two statistical values are calculated after the calibration part. RMSE is 0.93 meter and NRMSE is 1.37 %. Since NRMSE is less than 5% the steady-state model calibration is acceptable. Simulated groundwater level profile is shown in Figure 4.7.

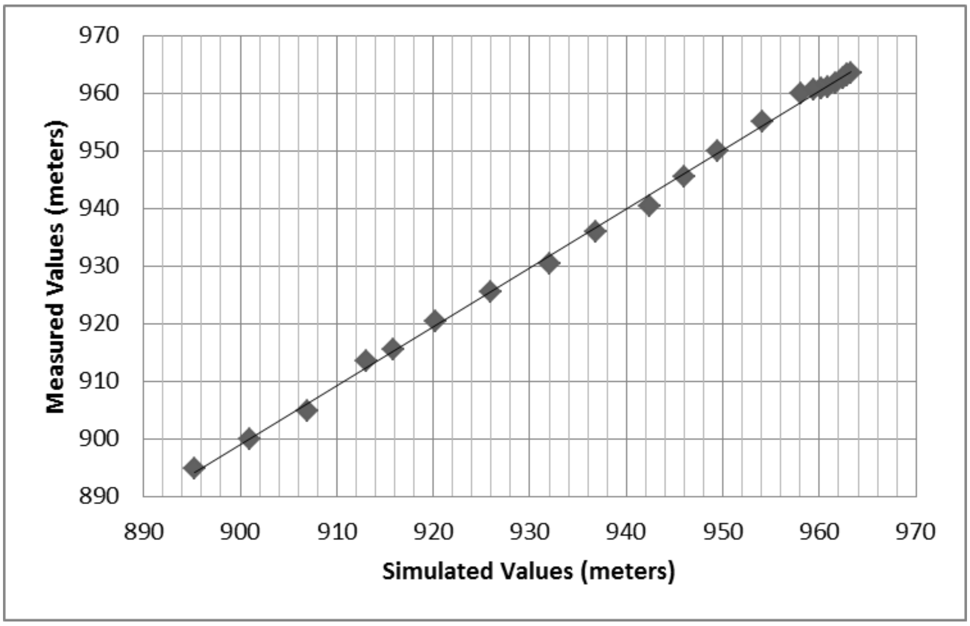

Figure 4.6: Relation between simulated and measured groundwater levels

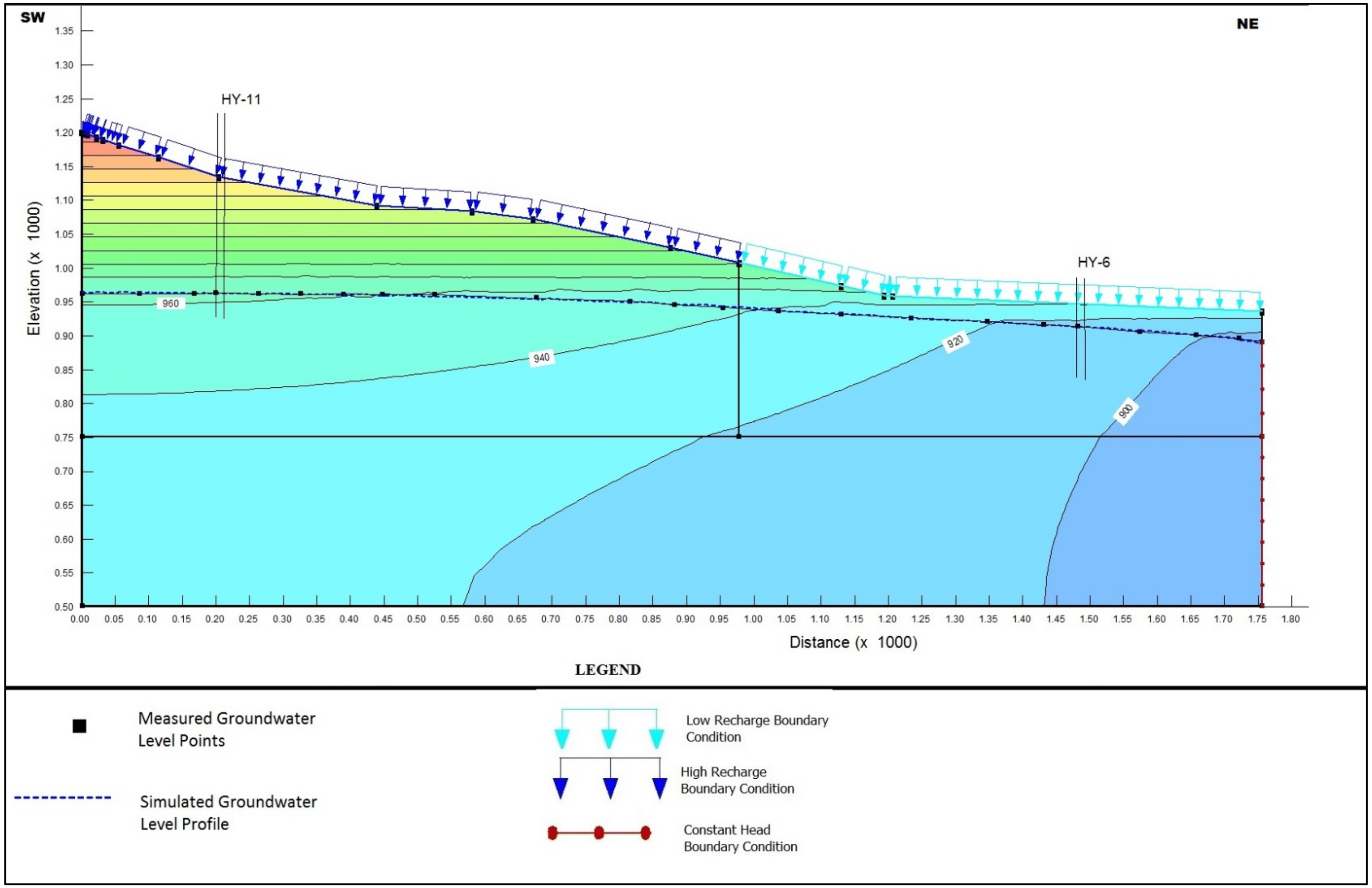

Figure 4.7: Groundwater level profile after calibration

4.4. Sensitivity Analysis

Sensitivity analysis is quite useful to determine which parameters have effects on model results. During the sensitivity analysis, just one parameter is modified while the other parameters are kept constant. Resulting NRMSE value from the sensitivity analysis is compared with the NRMSE obtained from the calibration. Five different parameters are checked for the sensitivity analysis. The resulting NRMSE values are shown in Figures 4.8-4.12. Recharge value was applied as two different zones (highland and lowland recharge) and both recharge values were checked. According to the Figure 4.8, model is much more sensitive to highland recharge. Saturated hydraulic conductivity was tested for all three formations. According to Figure 4.9, all three formations' hydraulic conductivity have effect on the model. However, Beydağı Volcanics Part-1 is a little bit more sensitive than the others. Northeast boundary condition was assigned as constant head boundary condition and this boundary condition was also checked. Figure 4.10 shows the sensitivity of the constant head boundary condition. It shows that model is sensitive to it under steady condition. So, constant head boundary condition was also checked under transient condition assigning different flux amount calculated at steady condition.

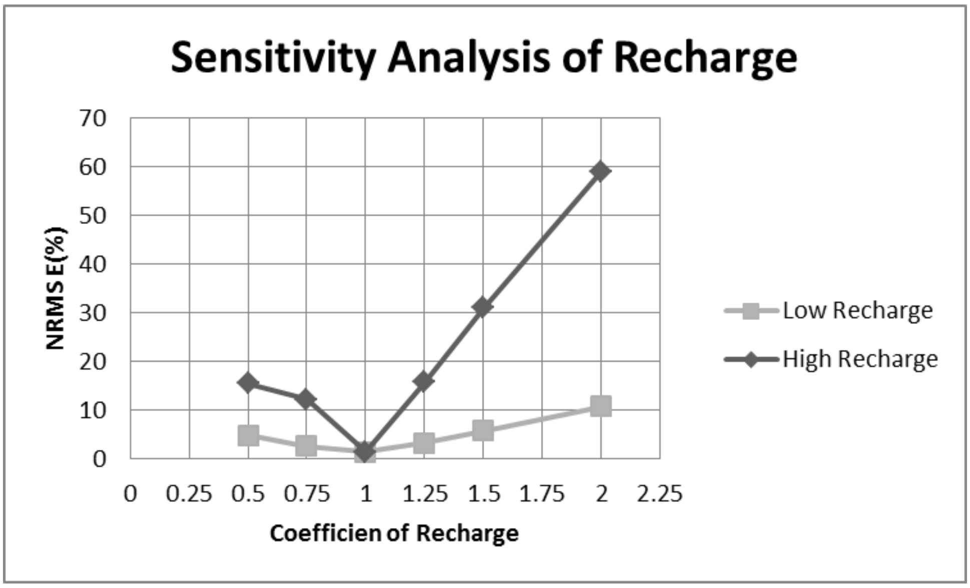

Figure 4.8: Results of sensitivity analysis for recharge

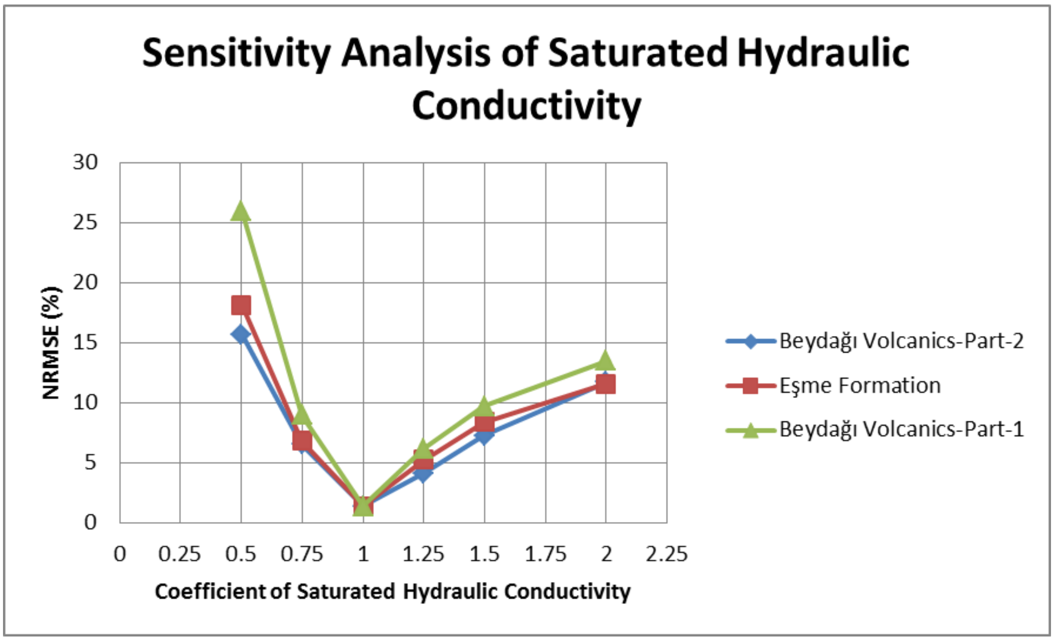

Figure 4.9: Results of sensitivity analysis for saturated hydraulic conductivity

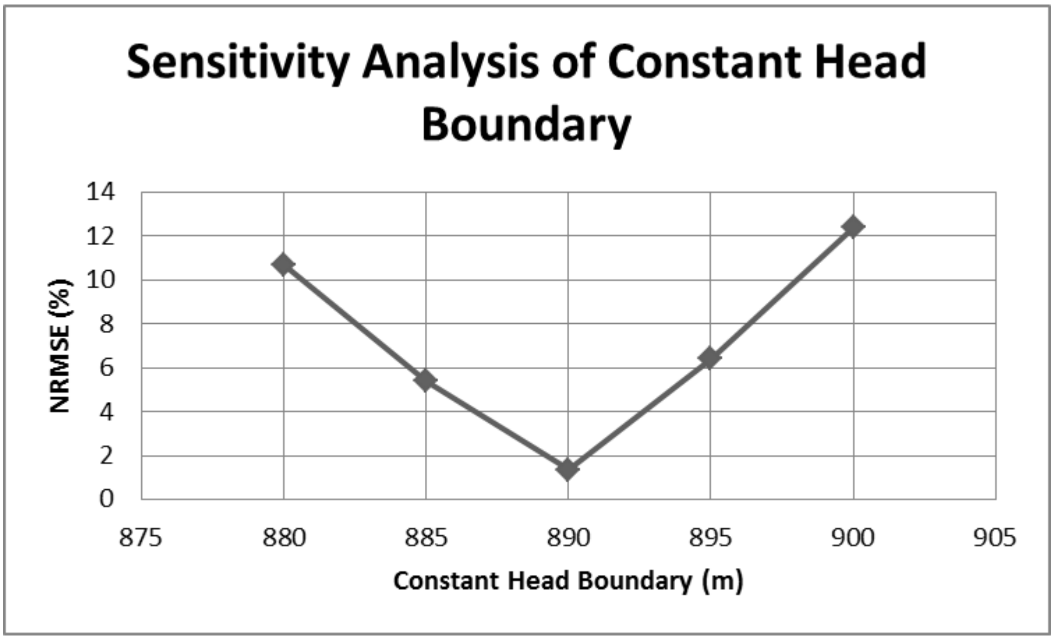

Figure 4.10: Results of sensitivity analysis for constant head boundary

Sensitivity analysis for soil water content curve parameters are also done under steady condition. Since Eşme formation is fully saturated, SEEP/W does not ask unsaturated parameters for steady-state condition. Thus SWCC parameters are just checked for Beydağı Volcanics part-1 and part-2.

As seen in Figure 4.11 and 4.12 model is not sensitive to SWCC parameters under steady-state condition. However, model is quite sensitive to SWCC parameters under transient analysis, because SWCC controls the storativity. In order to assign the reasonable curve parameters, these parameters are checked under transient condition. Since long term measured data are not available in the field, it is not possible to make a calibration like in the steady model. So, while curve parameters are checked, water levels at HY-6 and HY-11 are checked whether they show seasonal changes or not. Additionally, water budget is controlled if the results are reasonable. Especially, infiltration amount is checked to see if the calculated value is similar to the infiltration amount applied in the steady-state model or not. In the transient analysis of the bedrock part, water level graphics and water budget table will be given for the bedrock transient model.

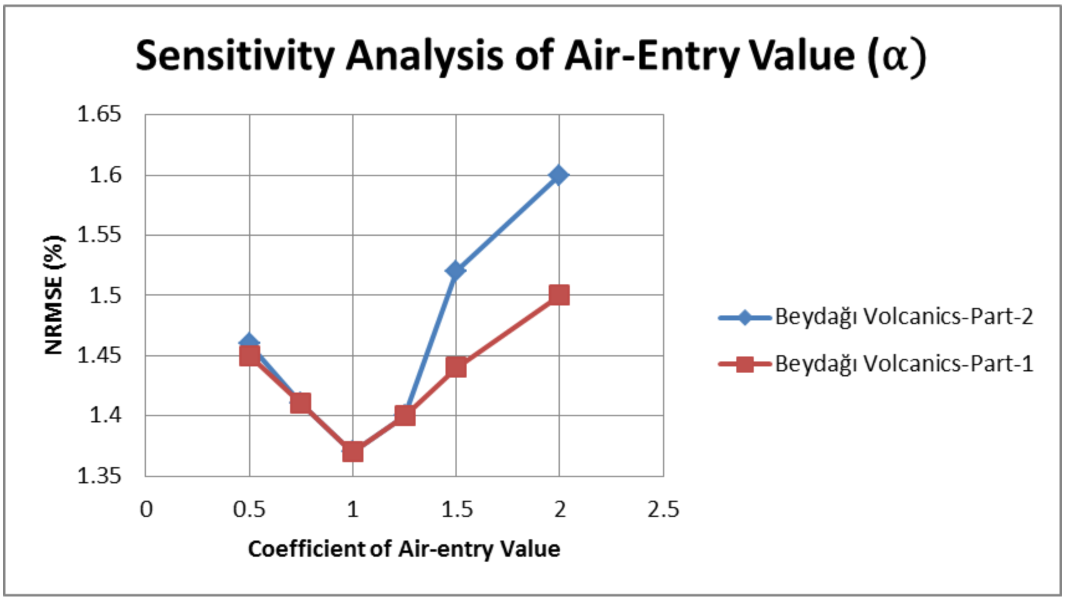

Figure 4.11: Results of sensitivity analysis for air-entry value (α)

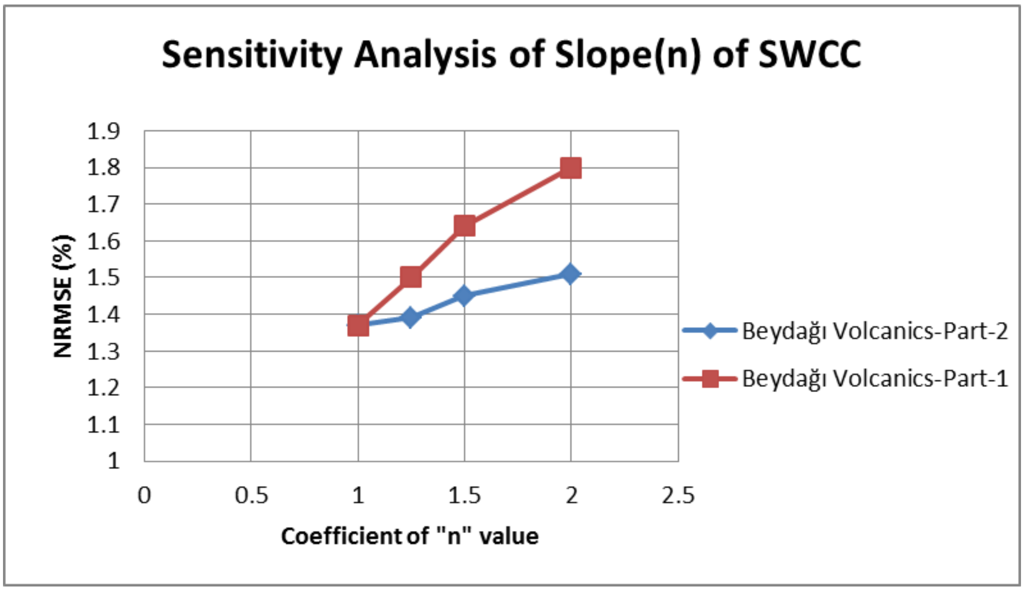

Figure 4.12: Results of sensitivity analysis for Slope (n) of SWCC

4.5. Transient Analysis of Bedrock

In order to assess the performance of alternative covers in the long-term, all cover design alternatives are modeled with climate boundary condition for 20 years under transient condition. This brings us that bedrock also must be modeled under same conditions. Additionally, model was run under transient condition in order to see whether water levels at wells HY-6 and HY-11 show the seasonal changes and head values are close to the ones calculated in steady or not. Also, water budget is checked under transient condition.

Transient analysis of the bedrock was started from January 2008 and was run for 20 years. For the climate parameter, 5 year daily climate data (2008-2012) measured in Kışladağ Gold Mine AWOS meteorological station was repeated 4 times. Daily minimum-maximum temperature, daily minimum-maximum relative humidity, daily wind speed and daily precipitation values are input to the model and actual evaporation, precipitation, runoff and infiltration amounts are simulated.

Figure 4.13 shows the simulated and measured water levels for the HY-6. Groundwater level at this area is close to ground surface. So any changes in the precipitation amount show rapid effect on the water level here. First measured water level is 913.5 meter at HY-6. Groundwater level was measured for six months period here. As shown in Figure 4.13, measured values show oscillation during this short time similar to simulated values. Simulated values oscillate between 912.5 and 914.5 for the dry and wet seasons with respect to groundwater recharge amount.

Figure 4.14 shows simulated ground water level for HY-11. There is no oscillation at ground water level for HY-11 contrary to HY-6. Groundwater level is quite deep around HY-11, so changes in precipitation don’t reflect immediately to the water level at HY-11. Additionally, there is general decrease in groundwater level at HY-11. According to Bohnhoff, et al., 2009 VADOSE/W can overpredict runoff value after dry period. This can be the reason for the decrease at groundwater level at HY-11.

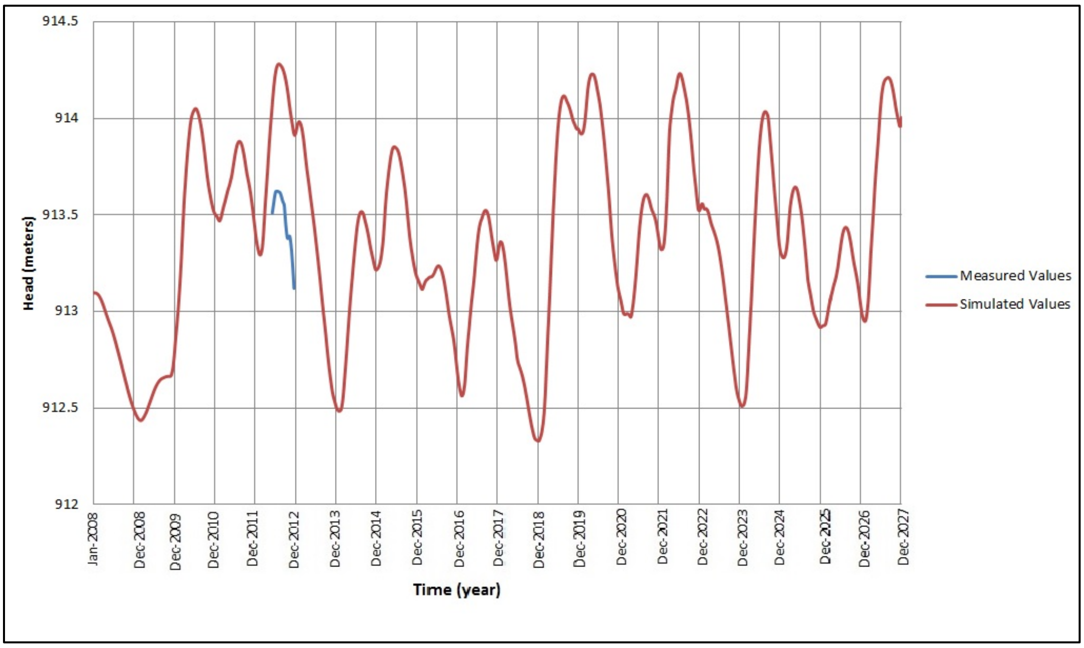

Figure 4.13: Simulated water level at well HY-6

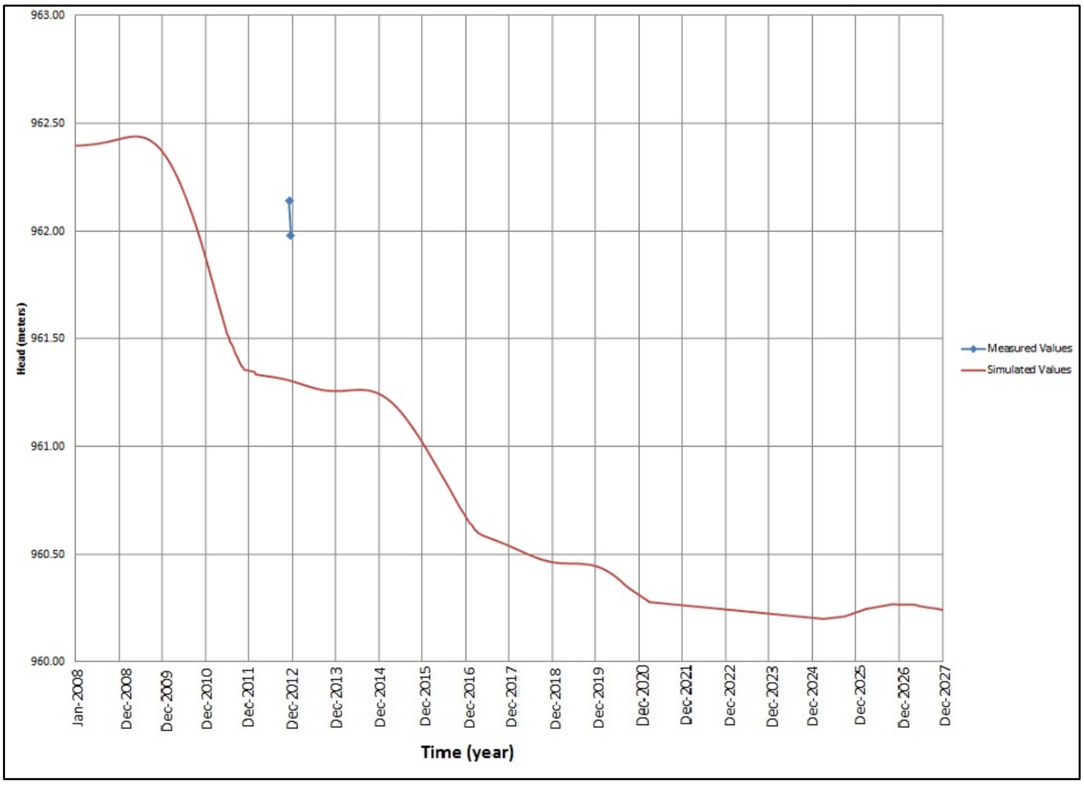

Figure 4.14: Simulated water level at well HY-11

Table 4.1 shows the average water budget components obtained from the transient model run for bedrock. Results are given as annual average. Precipitation is the only water budget component that is measured in the study area. According to the model, precipitation is calculated as 543 mm for the annual average; however measured precipitation is 569 mm. There is 26 mm lost in the precipitation, annually. Figure 4.15 shows the measured and calculated cumulative precipitation values for 20 years. As shown, model is able to accurately predict the trends in cumulative precipitation but cannot calculate the exact measured value. This is because of sublimation (Song & Yanful, 2008). In the winter time sublimation is high, so difference between model calculated and measured precipitation increases. When the temperature increases during the spring time, model converts part of snowfall into infiltration, resulting in a decrease in the difference. In Figure 4.15, it is difficult to see this change because of long time interval. So short time period like only one year is graphed to show the changes in different seasons. Figure 4.16 represents cumulative precipitation in year 2022. In Figure 4.16 difference between calculated and measured cumulative precipitations reaches its maximum value at February month because of high sublimation, then in the spring time this difference decreases because of melted snow and during the summer months difference is almost constant.

Fourth column in Table 4.1 shows percentage of the water budget components due to precipitation. According to this 38.22% of the precipitation is lost by evaporation and 54.66 % is lost by runoff. The remaining amount is calculated as infiltration from the surface. After that, infiltrated water is either lost by boundary flux or kept in the system as storage amount. This means summation of the storage and boundary flux equals to the infiltration amount. As seen from the table, infiltration value is calculated as 39 mm after 20 year. It is the uniform value for the model; this value splits as 45 mm and 27.5 mm for the highland and lowland area, respectively. After the steady-state model calibration, highland recharge value was assigned as 60 mm and lowland recharge value was assigned as 27 mm. Model-calculated lowland recharge value is close to the one used in the steady-state model. However, highland recharge value was calculated as 45 mm and this results a decrease in groundwater level at well HY-11. As indicated above, less infiltration is caused by overpredicted runoff. Vegetation is not included to the bedrock since the vegetative soil was removed before the waste rock settlement. Thus, there is no transpiration amount calculated for the bedrock model under transient conditions.

Table 4.3: Average water budget components for bedrock under transient condition

Bedrock			
Water Budget Components	**m^3/yıl**	**mm/year**	**Percentage of precipitation (%)**
Precipitation	969.00	543.16	
Actual Evaporation	368.00	206.28	38.22
Runoff	535.00	299.89	54.66
Infiltration from surface	69.00	38.68	7.22
Transpiration	0.00	0.00	0.00
Boundary Flux	84.00	47.09	8.68
Storage	-12.00	-6.73	-1.20

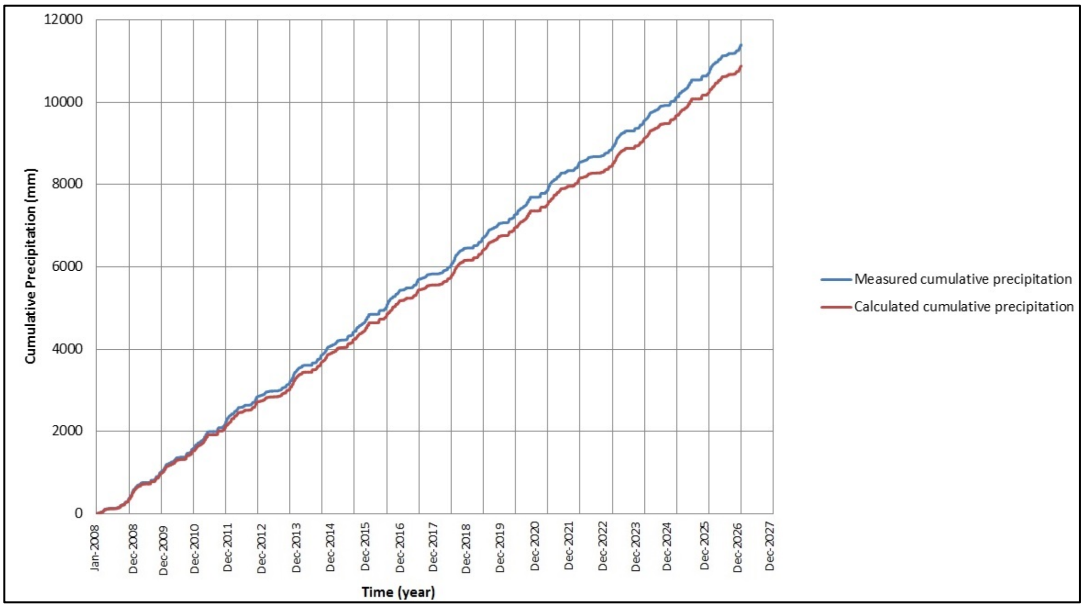

Figure 4.15: Comparison of measured precipitation to calculated precipitation for 20 years

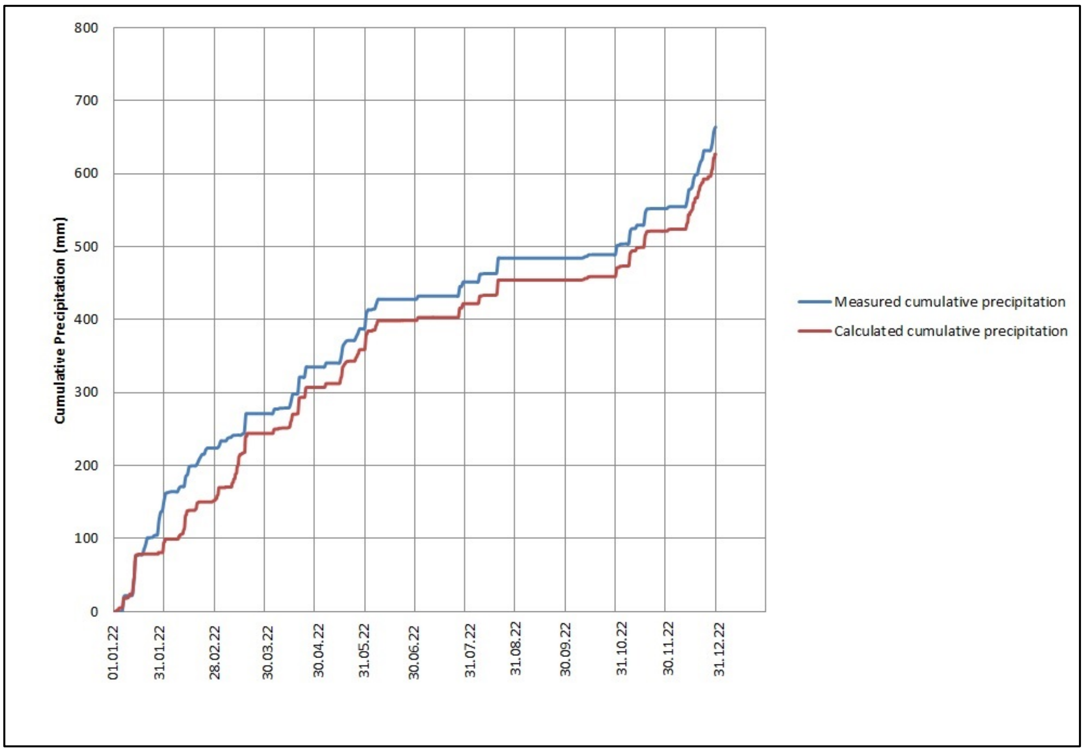

Figure 4.16: Comparison of measured precipitation to applied precipitation in the model for year 2022

CHAPTER 5

ALTERNATIVE COVER SCENARIOS

5.1. Introduction

In this part, four different models which are named as no cover alternative (just waste rock), proposed cover design alternative, enhanced store and release alternative and capillary barrier alternative are evaluated. Although configuration and outputs of the models differ from the each other, inputs and boundary conditions show similarity. Thus, in order to avoid repetition in each section, common properties are given in this part.

All models are run for 20 years under transient conditions in VADOSE/W. In order to increase runoff and minimize ponding, surface of waste rock and other alternatives are graded as 5 %. Sides of the models are graded as 20 % (Norwest, 2013). Soil water content curve (SWCC), thermal properties and unsaturated hydraulic conductivity curves are input to the models. Most of the SWCC parameters are taken from similar works in the literature. Since field measured data are not available for the unsaturated hydraulic conductivity curve, Van Genuchten estimation method is used by VADOSE/W to draw the curve. Unsaturated hydraulic conductivity curve is derived from saturated hydraulic conductivity value and SWCC. Thermal properties are obtained from Vadose Zone Modeling with VADOSE/W 2007 manual (Geo-Slope, 2008) based on mineralogy. Climate boundary condition is assigned as upper boundary condition in all models.

Vegetation function is not assigned to no-cover alternative because waste is generally composed of coarse grained material and it is nearly impossible to grow vegetation in this area. However, vegetation function is included to the other three models. Other boundary conditions are kept the same as in bedrock transient analyses which is described in detail in Chapter 4.2.5.3. Unit flux boundary and seepage boundary condition are assigned to the northeast boundary at all models (Figures 5.1, 5.5, 5.10 and 5.13).

In order to compare the performance of the various cover types, water budget components, especially infiltration amount into the waste rock, and oxygen concentration in the waste are evaluated. In order to see oxygen amount in the waste rock, a cross section is taken from the ground surface into the waste rock. Since all covers designed in this work have different thicknesses, ground surface elevation is different for various cover alternatives. Thus, in order to compare the oxygen concentration in cover alternatives a reference elevation is chosen as 1258 meters. Oxygen concentration is checked from the ground surface to the reference point (1258 m). Oxygen concentration percentage is accepted as 100 % at the ground surface. The differences among various models and the results obtained are given separately in the following sections.

5.2. No Cover Alternative

The first alternative considered is no cover placement on the waste rock material. Thus, this alternative is the modeling the bare waste rock. Test results of the samples from the waste show that waste rock material has the acid rock drainage (ARD) potential (Encon, 2013). Water and oxygen are the two triggering parameters for ARD. Therefore, modeling the bare waste rock will provide information on the amount of water infiltration and oxygen ingress.

The final configuration of the waste rock stored on bedrock is shown in Figure 5.1. The highest altitude of the waste rock will reach is 1280 meters. The mesh size for this model domain is assigned as 22.5 meters.

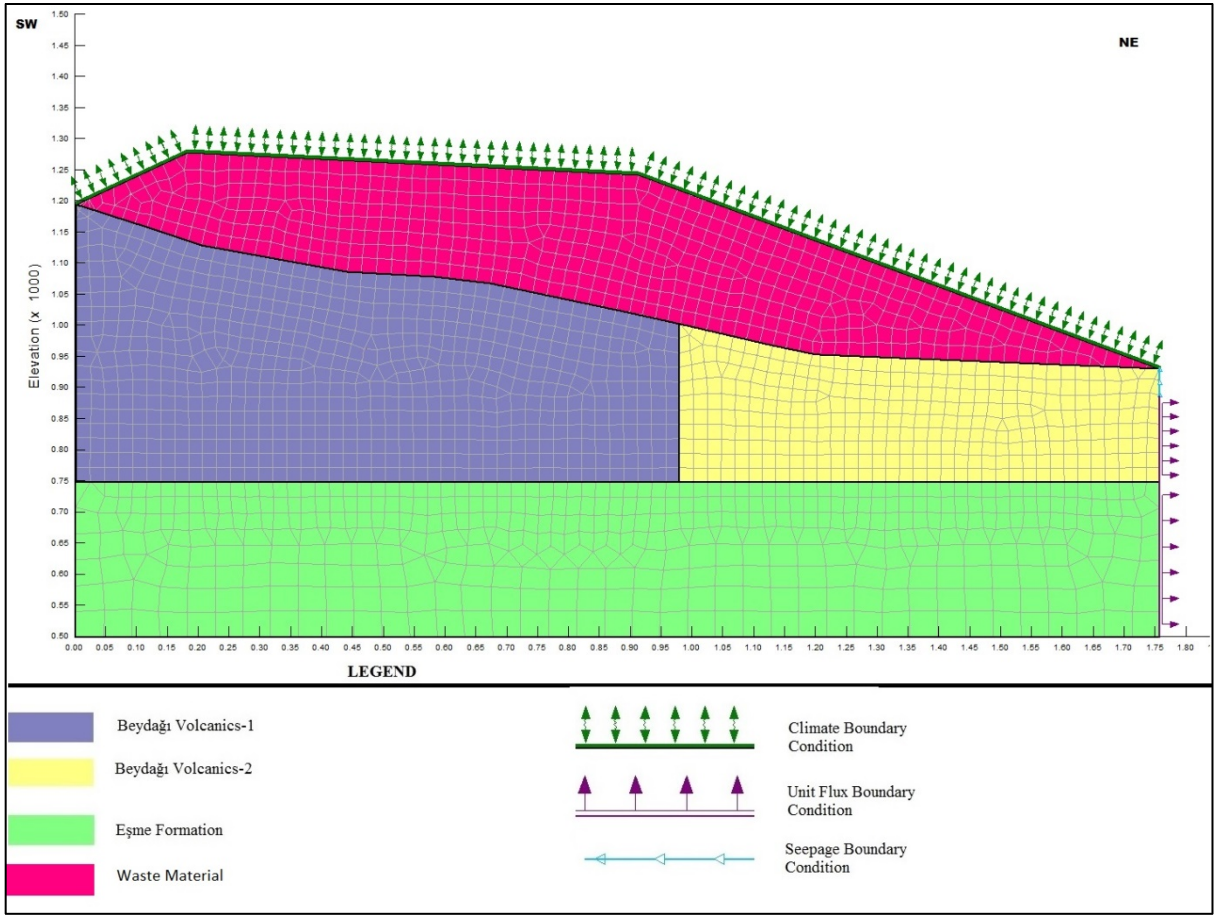

Figure 5.1: No cover alternative

Saturated hydraulic conductivity used for the waste rock material is taken from the report prepared by Encon (2013) for Kışladağ Gold Mine. According to this work, the saturated hydraulic conductivity value is found as 2.32 x 10^{-4} m/s after conducting hydraulic conductivity tests in the laboratory on the samples obtained from south waste rock material and this value is used for the modeling part in this study. The saturated and residual water content values were also taken from the same work. Saturated water content (θ_s) was assigned as 0.437 and residual water content (θ_r) is taken as 0.025. Soil water content curve fitting parameters, which are air-entry value and slope of curve (Table 5.1), are also taken from the same report, but the parameters are slightly modified referring to similar work in the literature (Hopp et al., 2011). Table 5.1 both shows values taken from Encon, 2013 and input values for the waste rock modeling. Besides, both Van Genuchten and unsaturated hydraulic conductivity function parameters that are obtained from literature are shown. Figure 5.2 shows the resulted SWCC curve used in this study based on the input Van Genuchten parameters for the waste material. Figure 5.3 shows the unsaturated hydraulic conductivity curve for the waste material.

Table 5.1: Parameters for soil water characteristic curve (SWCC) and unsaturated hydraulic conductivity functions for waste rock

	a (air-entry value)	n	m	K_{sat} (m/s)	θ_s	θ_r
Encon,2013	0.2	1.32	0.24	2.32 x 10^{-4}	0.437	0.025
Input Values	2	1.5	0.33	2.32 x 10^{-4}	0.437	0.025

Table 5.2: Literature obtained parameters for soil water characteristic curve (SWCC) and unsaturated hydraulic conductivity functions for waste rock

	Van Genucten Parameters					
Literature Sources	**a (air-entry value)**	**n**	**m**	**K_{sat} (m/s)**	**θ_s**	**θ_r**
Hopp et al., 2011	1.8	2.03	0.51	2 x 10^{-5}	0.41	0.012

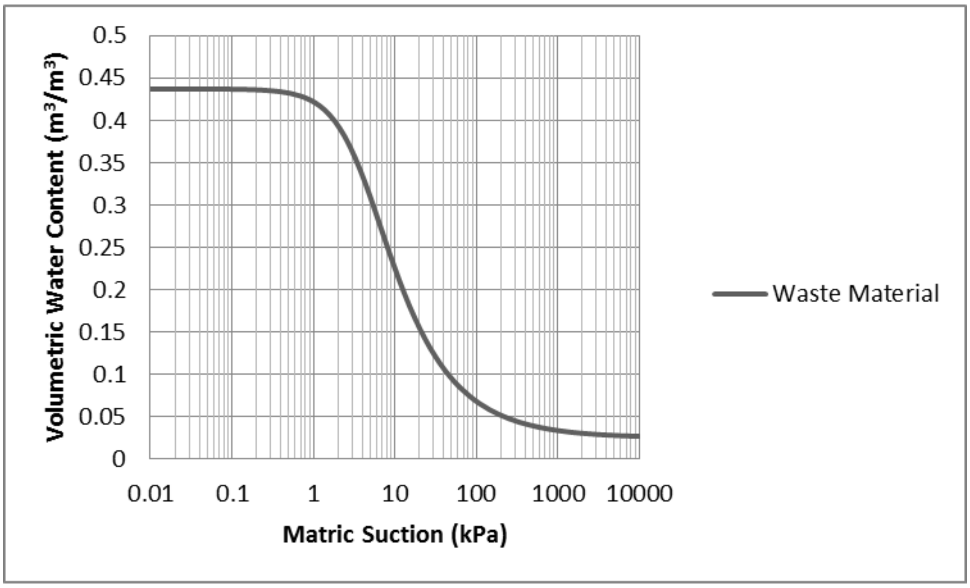

Figure 5.2: SWCC for waste material

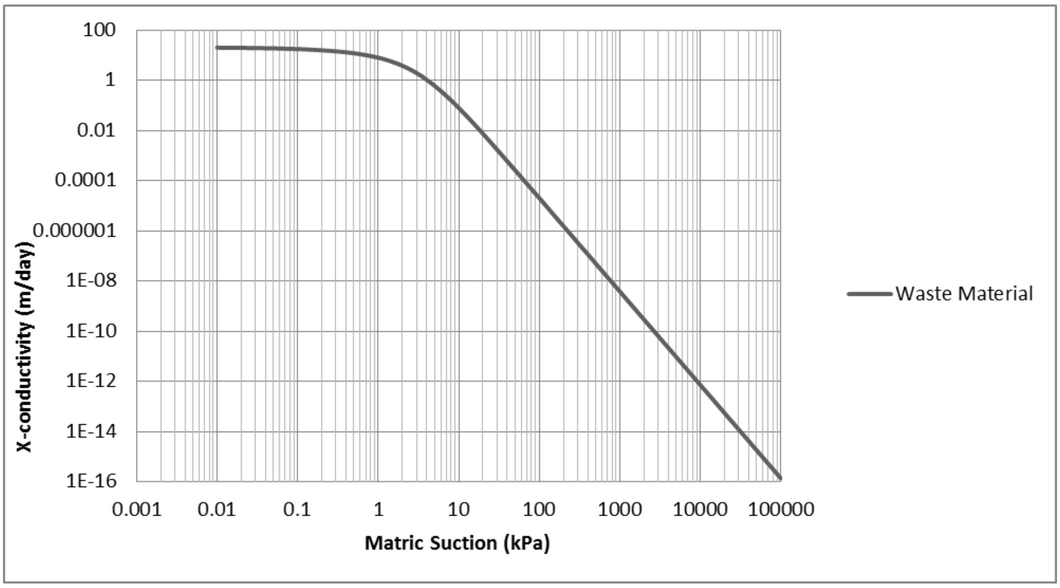

Figure 5.3: Unsaturated hydraulic conductivity curve for waste material

Table 5.1 shows comparison of average water budget components for the waste rock and the bedrock with no waste on it. Both models calculate almost the same precipitation amount. The calculated runoff in the waste rock model is quite low compared to the bedrock model. This is expected because the waste rock is composed of coarser grains compared to the bedrock and has higher hydraulic conductivity resulting in higher infiltration and lower runoff. Since more water infiltrates into the waste rock and the calculated evaporation rate is also higher.

The calculated infiltration rate to the waste rock model is more than twice the original amount to the bedrock system, consituting 16 % of the precipitation. However, the infiltration amount should not exceed 4% of precipitation in semi-arid climates, if the waste has the ARD potential to minimize the impacts to groundwater system (Ayres et al., 2003). Thus, the calculated infiltration amount into the waste rock is four times greater than the suggested limiting value. This amount of infiltration is expected to lead to ARD problems in the study area if the waste rock material will have no cover.

Table 5.3: Average water budget components for waste rock and bedrock under transient condition

	Bedrock			Waste Rock (No Cover Alternative)		
Water Budget Components	**m^3/yıl**	**mm/year**	**Percentage of precipitation (%)**	**m^3/yıl**	**mm/year**	**Percentage of precipitation (%)**
Precipitation	969.00	543.16		993.00	543.16	
Actual Evaporation	368.00	206.28	38.22	668.00	365.00	67.00
Runoff	535.00	299.89	54.66	160.00	87.40	16.00
Infiltration from surface	69.00	38.68	7.22	160.00	87.40	16.00
Transpiration	0.00	0.00	0.00	0.00	0.00	0.00
Boundary Flux	84.00	47.09	8.68	90.25	47.23	8.68
Storage	-12.00	-6.73	-1.20	70.00	40.13	7.38

Another parameter that causes ARD is the oxygen ingress. Figure 5.4 shows oxygen concentration in the waste rock at the end of 20 years. As can be seen from Figure 5.4, oxygen concentration is 96 % at the reference point (at 1258 m) at the end of 20 years.

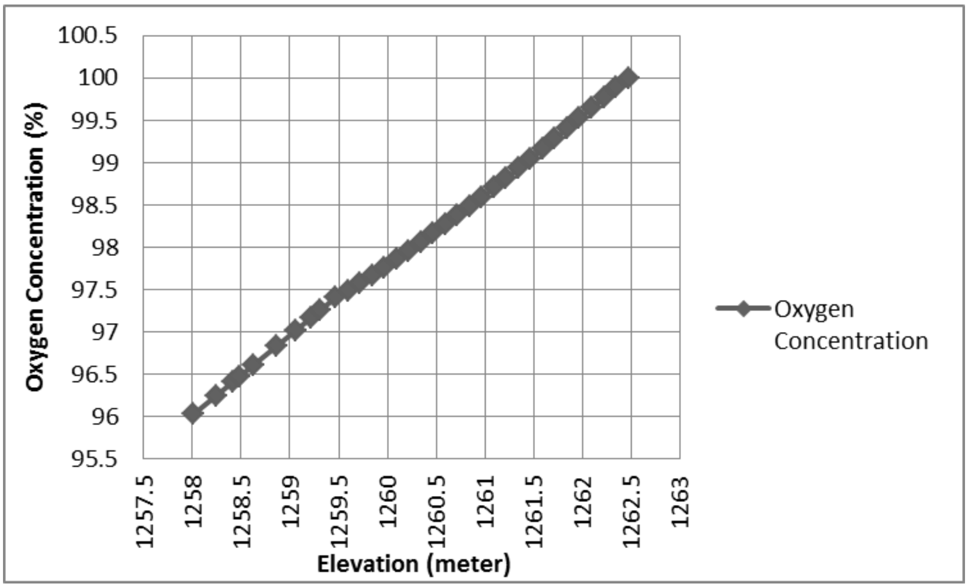

Figure 5.4: Oxygen concentration in the waste rock at the end of 20 years

Results of this model indicate that there is significant amount of water infiltration and oxygen migration into the waste material. If water infiltration and oxygen ingress are not limited to the tolerated values, the resulting ARD problems will provide leaching of metals from the waste rock which will then contaminate surface water and groundwater in the study area. In order to mitigate the ARD problem, covers are used as closure option. Designed covers will be explained in the following sections.

5.3. Proposed Cover Design Alternative

The first alternative for the cover type for the waste material in Kışladağ Gold Mine is proposed by Norvest (2013). Store and release cover system is chosen as the cover type. This type of cover is commonly used in arid and semi-arid climates (Junqueira et al., 2006, Caldwell et al., 2003, O'Kane & Ayres, 2012). Store and release type covers may consist of one or several layers. In this work, cover consists of three layers. At this situation, store and release cover is named as enhanced store and release cover.

Cover is placed on the waste rock as shown in Figure 5.5. In the suggested cover design, 1.3 meters silty sand (storage layer) is underlain by 5 meters compacted waste rock to create capillary break effect. This method is used by many researchers (Albright, 2008; Christensen & O'Kane, 2005). Capillary break layer is added below the storage layer to keep the storage layer saturated and prevent the downward percolation. Additionally, 0.2 meters vegetation layer is added to the top of the system.

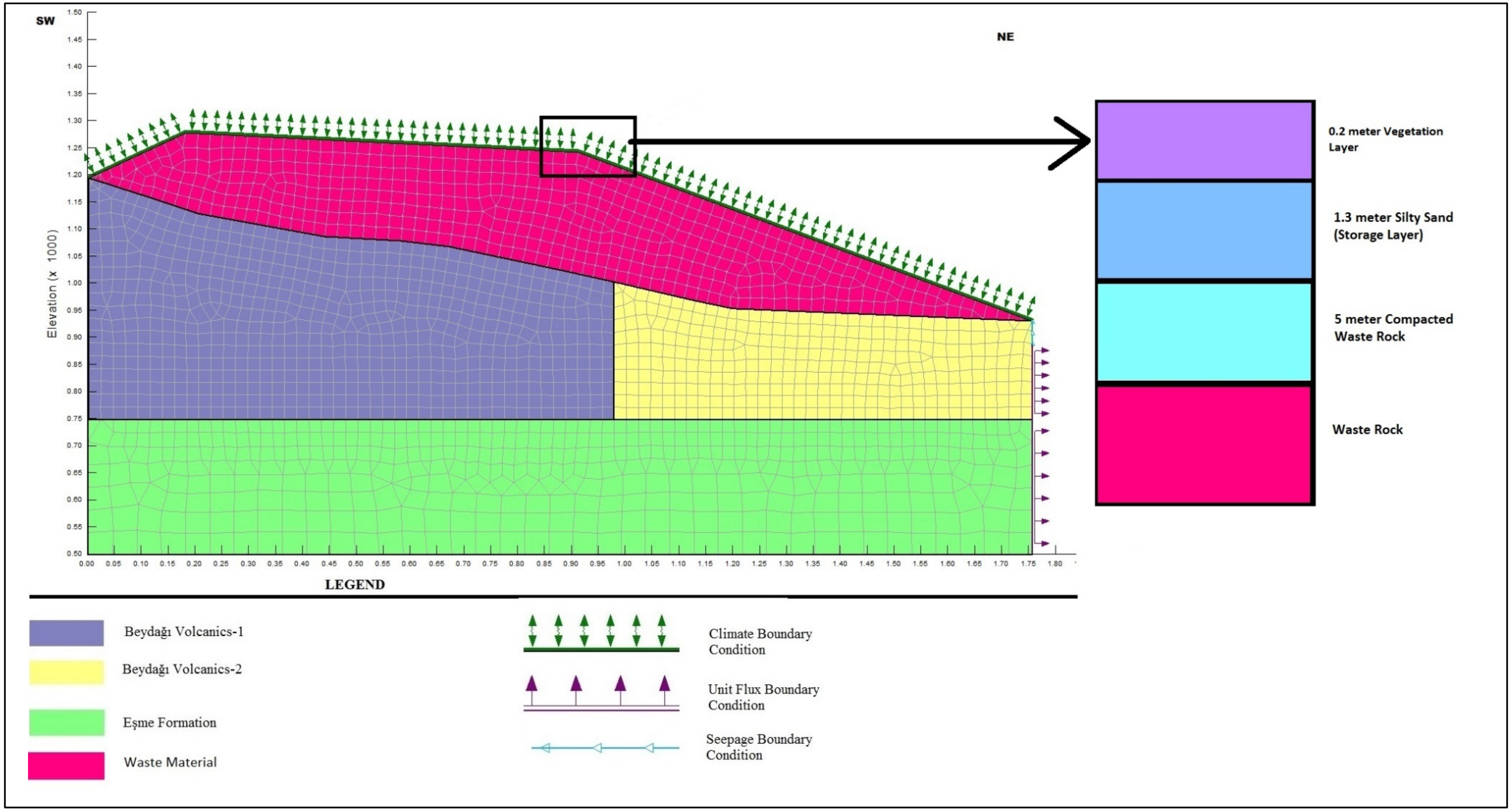

Figure 5.5: Proposed alternative design

SWCC for the compacted waste material is modified from the waste material SWCC curve. When the material is compacted, air-entry value increases and porosity decreases although the slope of SWCC is similar (Ayres et al., 2003). Saturated hydraulic conductivity decreases due to compaction. SWCC and saturated hydraulic conductivity value of silty sand are obtained from literature survey. According to unified soil classification system, saturated hydraulic conductivity for silty sand changes between 10^{-5} – 10^{-8} m/s. Saturated hydraulic conductivity was assigned as 2 x 10^{-6} m/s for storage layer considering the similar works which used silty sand as storage material (Stormont & Morris, 1998; Benson et al., 2007; Parent & Cabral, 2006; Noel & Rykaart, 2003). Norvest (2013) defined vegetation layer as sandy loam according to the analysis results which are done in the study area. SWCC and saturated hydraulic conductivity of sandy loam were assigned referring to similar works in the literature (Stormont & Morris, 1998; Hopp et al., 2011).

Table 5.4 shows the input Van Genuchten and unsaturated hydraulic conductivity curve parameters. Table 5.5 shows these parameters used in the similar works at literature. Figure 5.6 shows the SWCC for the materials used in this alternative. Figure 5.7 shows the unsaturated hydraulic conductivity curves used in this cover design.

Table 5.4: Parameters for soil water characteristic curve (SWCC) and unsaturated hydraulic conductivity functions for proposed cover alternative materials

	Van Genucten Parameters					
	a (air entry value)	n	m	K_{sat} (m/s)	θ_s	θ_r
Silty Sand	20.00	1.25	0.20	1.8 x 10^{-6}	0.50	0.02
Sandy Loam	15.00	1.30	0.23	3.3 x 10^{-6}	0.40	0.07
Waste Rock	2.00	1.50	0.33	2.32 x 10^{-4}	0.44	0.03

Table 5.5: Literature obtained parameters for soil water characteristic curve (SWCC) and unsaturated hydraulic conductivity functions for proposed cover alternative materials

		Van Genucten Parameters					
	Literature Sources	**a (air entry value)**	**n**	**m**	**K_{sat} (m/s)**	**θ_s**	**θ_r**
Silty Sand	Stormont & Morris, 1998	6.70	2.03	0.51	1.4×10^{-6}	0.44	0.08
	Noel & Rykaart, 2003	6.80	1.11	0.10	9×10^{-7}	0.38	0.02
	Parent & Cabral, 2006	23.25	3.40	0.71	5×10^{-7}	*	*
Sandy Loam	Hopp et al., 2011	29.00	1.18	0.15	2.27×10^{-5}	0.31	0.08
	Stormont & Morris, 1998	1.40	1.89	0.47	2.27×10^{-6}	0.43	0.07
Waste Rock	Hopp et al., 2011	1.80	2.03	0.51	2×10^{-5}	0.41	0.01
	* Indicates that these values are not given in the study						

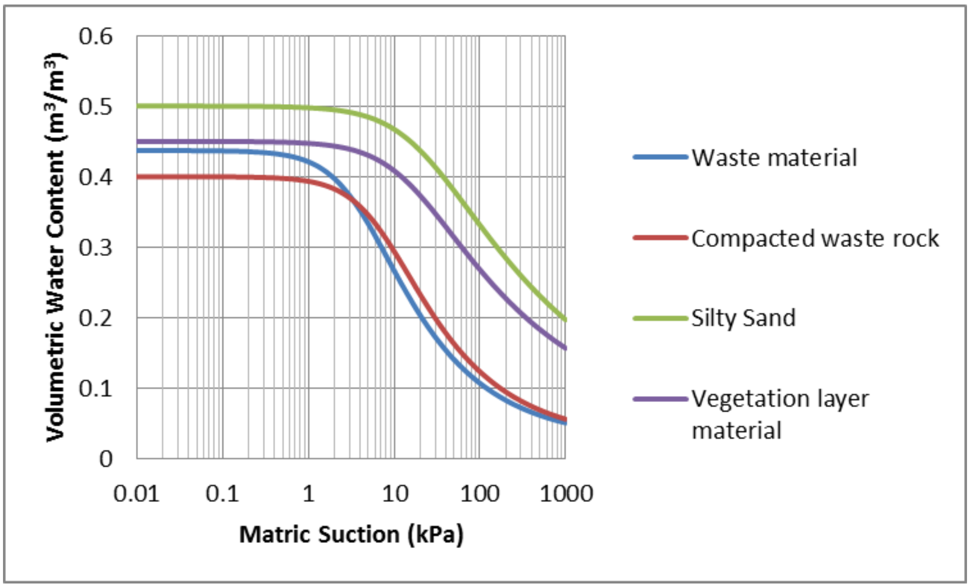

Figure 5.6: SWCC for proposed cover alternative

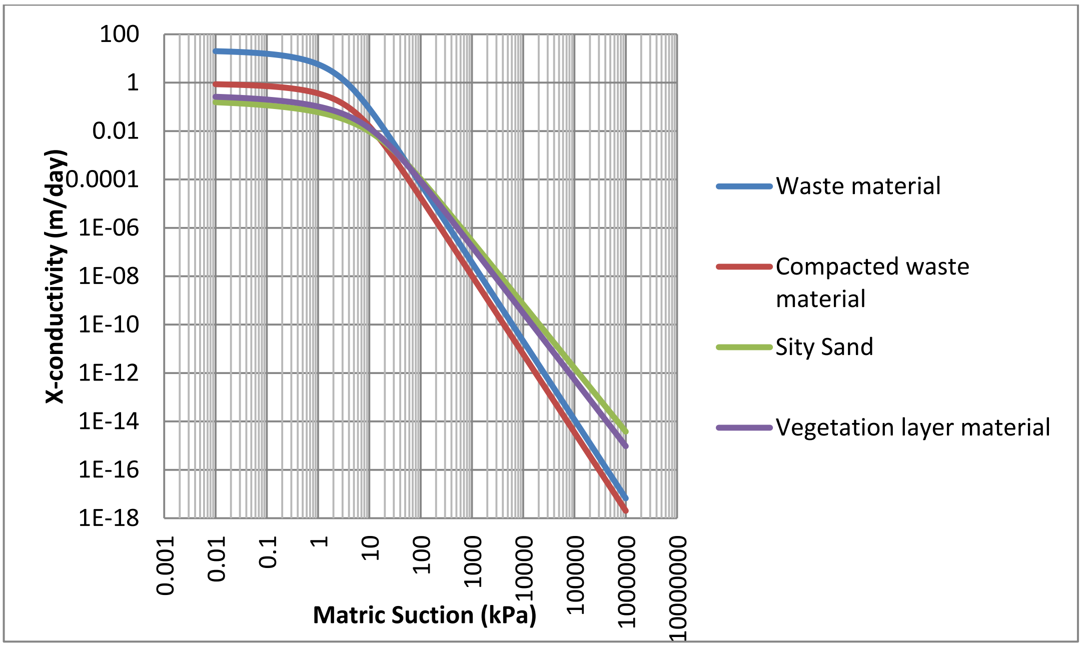

Figure 5.7: Unsaturated hydraulic conductivity curves for proposed cover alternative

The model results are summarized in Table 5.2 which shows the average water budget components for the cover alternative. As it can be seen from Table 5.2, significant part of the precipitation is removed by evaporation. This is quite consistent with the purpose of the store and release type covers. The cover system allowed 10.5 % of the precipitation to infiltrate from the surface, but then 9.94 % is removed by transpiration by vegetation. The water budget shows that nearly 68 % of the water is removed by the help of evaporation and transpiration from the system. Finally, 0.66 % of the precipitation infiltrated into the waste rock. Because this amount is less than 4 %, this alternative can be considered as capable of limiting water ingress.

Table 5.6: Average water budget components for proposed alternative under transient condition

Proposed Cover Alternative			
Water Budget Components	**m^3/yıl**	**mm/year**	**Percentage of precipitation (%)**
Precipitation	993.00	543.16	
Actual Evaporation	581.00	317.00	58.00
Runoff	310.00	169.58	31.18
Infiltration from surface	105.00	57.37	10.50
Transpiration	98.00	53.90	9.94
Infiltration into waste rock	6.50	3.60	0.66
Boundary Flux	89.00	48.70	8.68
Storage	-82.00	-44.81	-8.24

One of the purposes of the capillary break layer is to keep the storage layer saturated. However, when the saturation percentage of the storage layer is checked as shown in Figure 5.8, it is seen that the saturation percentage was less than 85% (i.e., varied between 80% and 48% depending on seasons); thereby, it is incapable of limiting the oxygen ingress. In order to observe saturation amount in the storage layer, 5 different points were taken from the storage layer and average of these points are graphed in Figure 5.8. In order to decrease oxygen ingress, the storage layer must be at least 85% saturated, but storage layer never reaches this value. This ends up with oxygen ingress. Figure 5.9 shows the oxygen concentration from the ground surface to the reference point (1258 m) in the waste rock. Oxygen concentration is decreased from 100 % to 88 % through the surface to the reference point. Although there is a decrease in oxygen amount, 88 % of oxygen is still quite high. Oxygen ingress cannot be limited because of low saturation content in the storage layer.

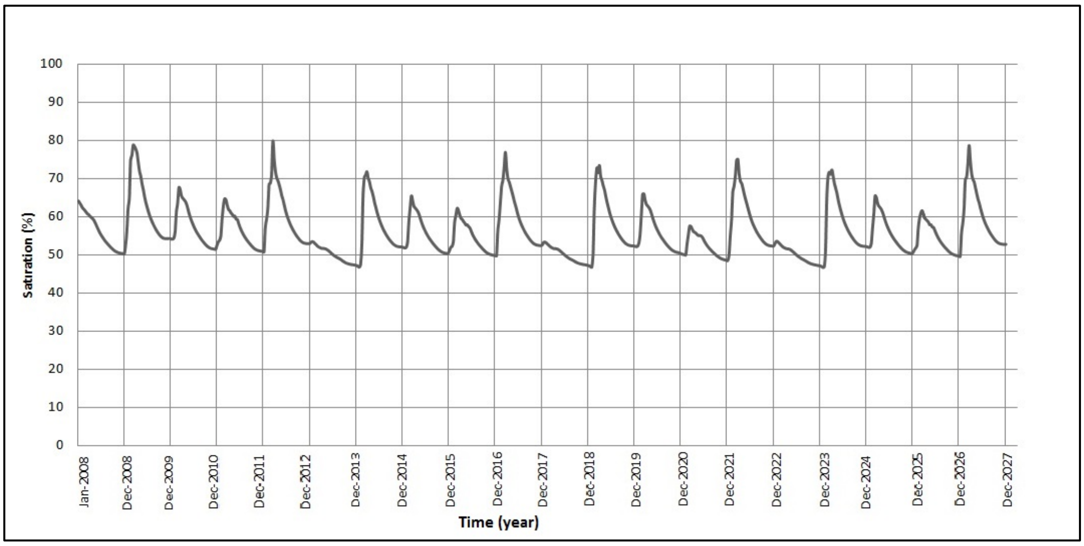

Figure 5.8: Saturation percentage in the storage layer throughout the 20 years

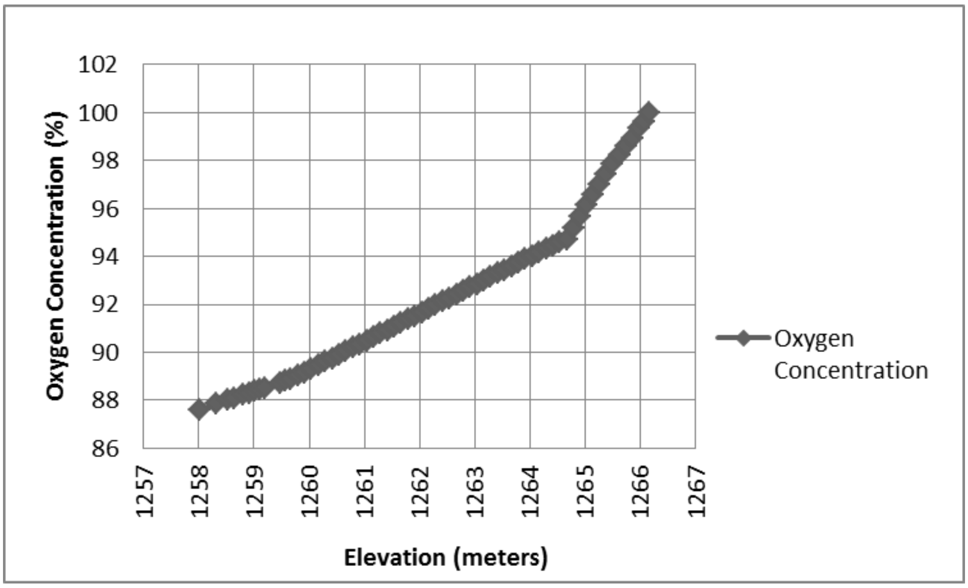

Figure 5.9: Oxygen concentration through the proposed alternative after 20 years

Thus, results of the model for this cover design show that designed cover can create barrier to the water ingress, but not to oxygen migration due to limited saturation. Furthermore, the thickness of the suggested storage layer (1.3 m) is excessive with significant costs of material and placement. In the following, another design is formulated to see if a similar performance can be obtained with a less thick storage layer.

5.4. Enhanced Store and Release Alternative

This alternative is quite similar to the preceding cover design that was proposed for Kışladağ Gold Mine, except the reduced thickness for the storage layer. Thickness of the storage layer (silty sand) is the only parameter that is changed. This change is done to see if there is an alternative that has lower cost than previous model, which is still effective to limit water and oxygen ingress. Additionally, effects of different thickness on net infiltration and saturation content are evaluated.

All materials used in this alternative are exactly the same with the proposed alternative. So, SWCC and unsaturated hydraulic conductivity curve do not change (Figures 5.6 and 5.7). As seen in Figure 5.10, thickness of the storage layer is lowered from 1.3 to 0.65 meters.

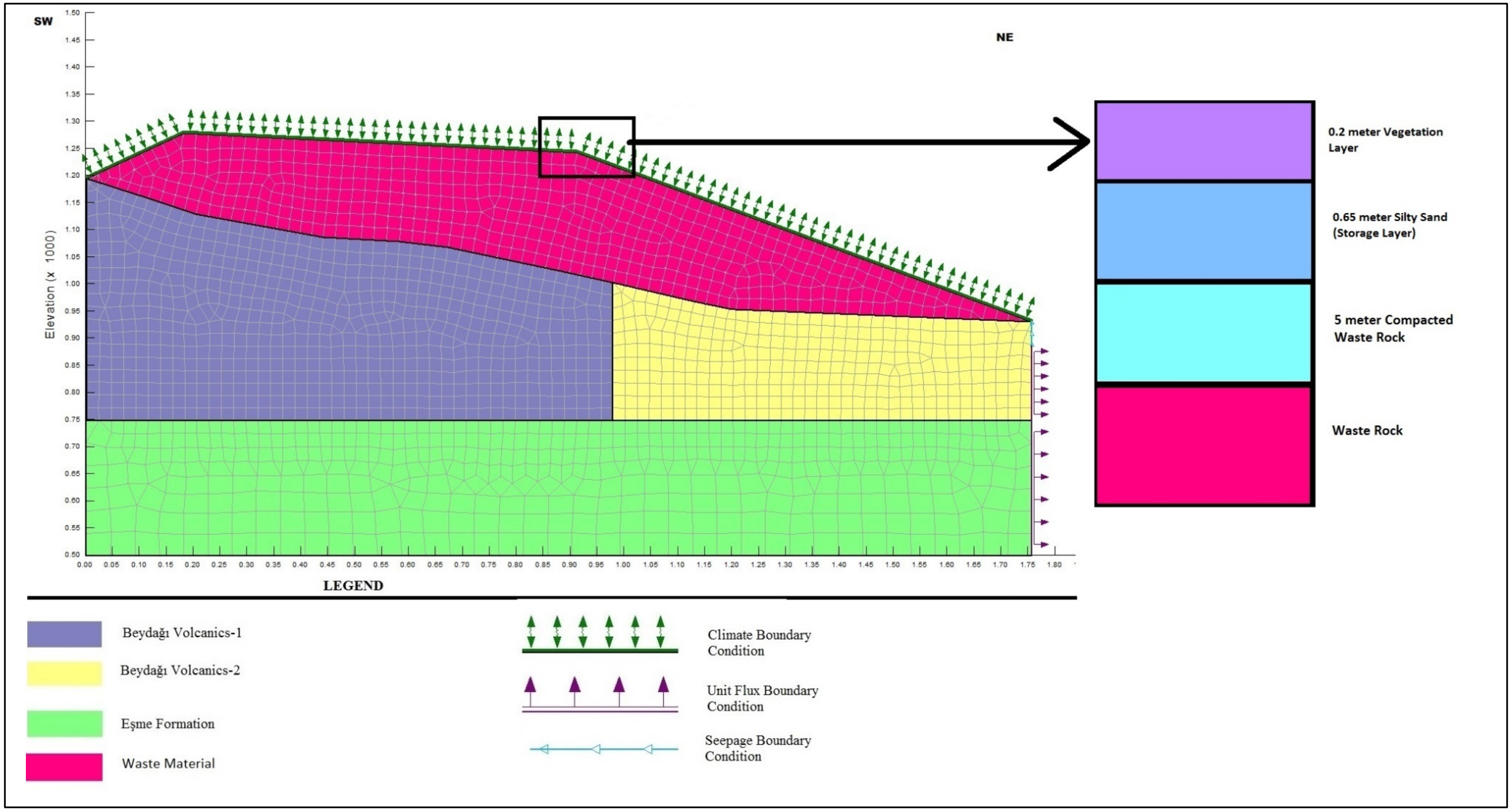

Figure 5.10: Enhanced store and release alternative

Table 5.3 shows a comparison of average water budget components for the proposed alternative and this alternative. Proposed alternative calculated higher actual evaporation than enhanced store and release alternative. Because of the reduced thickness of the storage layer, the latter model should have less water content. In the proposed alternative 317 mm/year amount of water is evaporated from 1.7 meters (including vegetation layer) while in the latter alternative 306.73 mm/year is evaporated from 0.85 meters (including vegetation layer). Lower water content also results in lower unsaturated hydraulic conductivity value; thereby, producing low infiltration amount from the surface in store and release alternative. Excess water amount (not infiltrated) is calculated as runoff since the ground surface is inclined to prevent ponding. Transpiration amounts are also different although the inputs for the transpiration are the same in both models. Transpiration depends on root depth, root distribution and negative pore water pressure. Root depth and root distribution are same in both models, but negative pore water pressure changes with the water amount in the models. Lack of available plant water causes most plants to biologically react by closing stoma and reduce transpiration (Saxton, 1982). Therefore, the lower water content in store and release model also produce lower amount of transpiration. On the other hand, the amount of infiltrating water into the waste rock is higher in store and release alternative. Thus, 0.65 meter thick storage layer is not as capable as 1.3 meters storage layer to hold the water until the dormant season. Consequently, during the wet season some water seeped from the storage layer to the lower layer. Although the amount of infiltration is more than double the amount of infiltration in the proposed alternative, it is still less than 4 % of precipitation.

Table 5.7: Average water budget components for proposed and store & release alternative under transient condition

	Proposed Cover Alternative			Enhanced Store and Release Alternative		
Water Budget Components	**m^3/yıl**	**mm/year**	**Percentage of precipitation (%)**	**m^3/yıl**	**mm/year**	**Percentage of precipitation (%)**
Precipitation	993.00	543.16		993.00	543.16	
Actual Evaporation	581.00	317.00	58.00	561.32	306.73	56.48
Runoff	310.00	169.58	31.18	370.00	203.42	37.46
Infiltration from surface	105.00	57.37	10.50	59.60	32.58	6.00
Transpiration	98.00	53.90	9.94	44.30	24.21	4.46
Infiltration into waste rock	6.50	3.60	0.66	15.32	8.37	1.54
Boundary Flux	89.00	48.70	8.68	90.25	49.30	9.00
Storage	-82.00	-44.81	-8.24	-74.95	-40.92	-7.54

Figure 5.11 shows the water saturation percentage in the storage layer. Unfortunately, this model also cannot the keep the storage layer at 85 % saturated. Figure 5.12 shows the oxygen concentration. There is only minor decrease in the oxygen concentration.

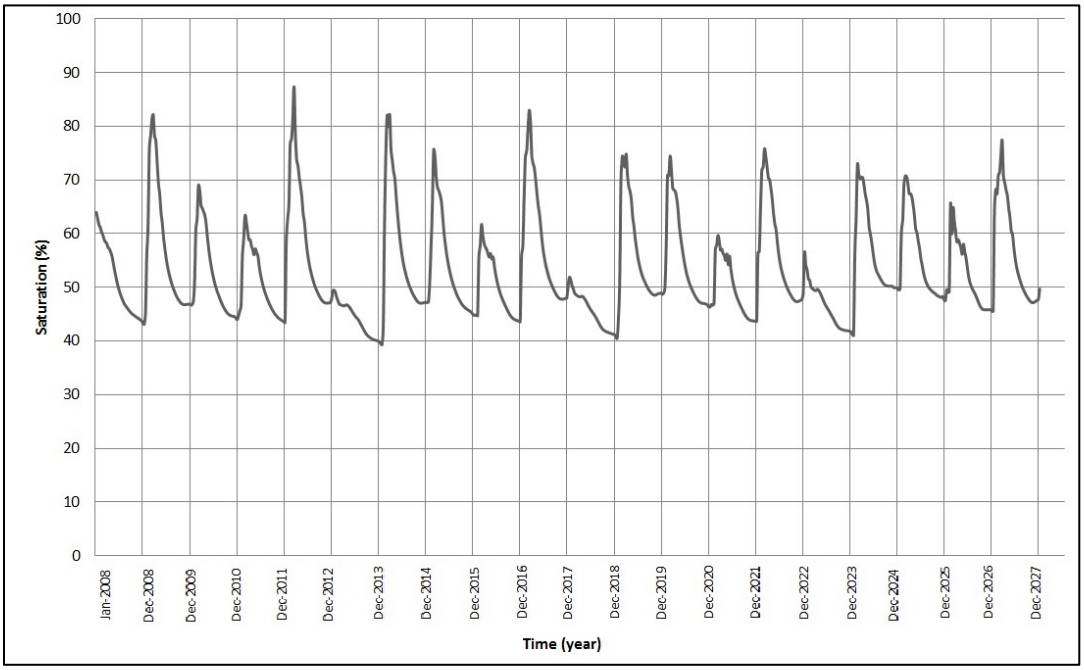

Figure 5.11: Saturation percentage in the storage layer throughout the 20 years

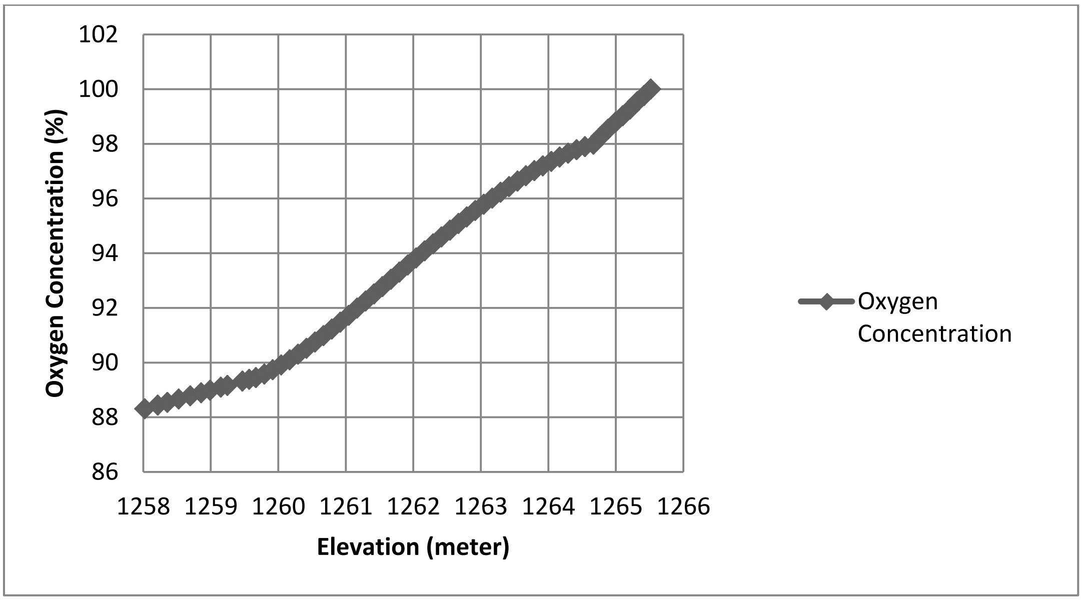

Figure 5.12: Oxygen concentration through the store and release alternative after 20 years

The results of the both models show that despite the reduced thickness in the storage layer, it is still effective to limit water infiltration to the desired limits. Both models however are incapable of limiting the oxygen migration.

5.5. Capillary Barrier Alternative

This alternative is especially designed to limit the oxygen ingress into the waste rock. Capillary barrier covers have been used in recent years to solve ARD problems. These types of covers can be used to limit oxygen and/or water ingress. When they are properly constructed, they are quite effective to limit water migration in semi-arid areas. However, it can be difficult to design a cover which contains a layer that stays 85% saturated in prolonged dry period. In this alternative, cover is designed by considering material properties, optimum thickness and fine and coarse layer alternation to keep the fine layer 85% saturated.

Cover is placed on the waste rock as shown in Figure 5.13. Double capillary barrier type is used in this alternative. Design consists of 4 layers. Each layer has one or more specific roles. A 0.6 m thick coarse grained layer (capillary break layer) placed underneath the 0.5 meter thick fine grained layer (moisture-retaining layer) limits downward movement of the water and prevents desaturation of the fine grained layer. The upper coarse grained layer placed over the fine grained soil acts as the drainage layer to limit the loss of water by evaporation from the moisture retaining fine layer. A 0.2 meter thick vegetative layer placed over the upper coarse grained layer is protective against erosion and creates suitable environment for the vegetation. The thickness of the various layers is determined from similar works in the literature. According to Parent & Cabral (2006), when thickness of the lower coarse grained layer is smaller than 0.60 m, it causes decrease in suction value at the interface, resulting in seepage from the fine grained layer. Storage layers thicker than 0.45 meters do not transmit significant amount of percolation (Khire et al., 2000). The fine grained layer is assigned as silty material while coarse grained layer is assigned as sandy gravel mixture to create capillary break effect between the layers.

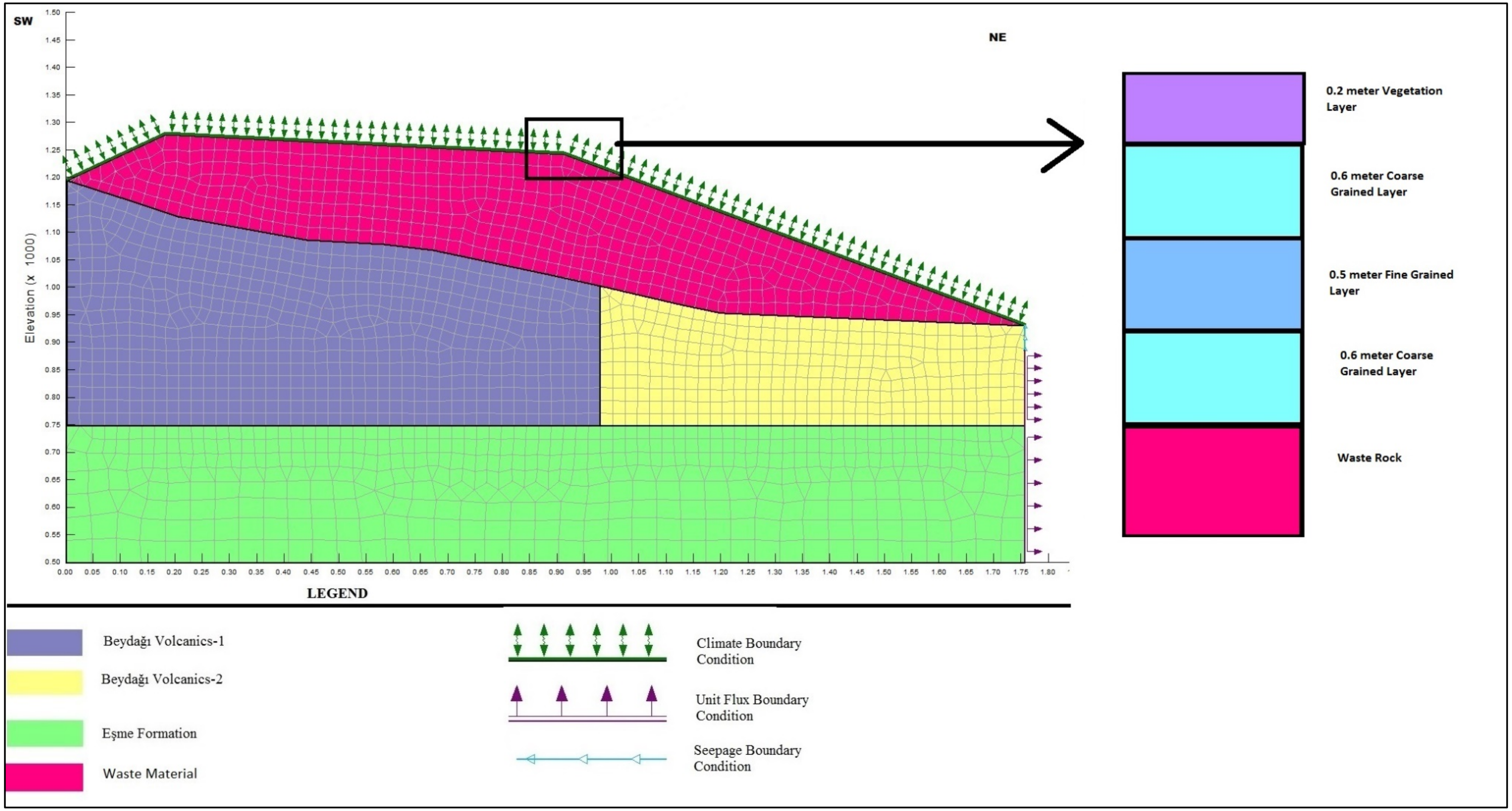

Figure 5.13: Capillary barrier alternative

Figure 5.14 shows the SWCC for the materials used in the capillary barrier alternative (Bussiere et al., 2003, Benson et al., 2007, Mbonimpa et al., 2008, Khire et al., 2000, Parent & Cabral, 2006, Hopp et al., 2011). Figure 5.15 shows the unsaturated hydraulic conductivity curves for the materials.

Table 5.8: Parameters for soil water characteristic curve (SWCC) and unsaturated hydraulic conductivity functions for capillary barrier alternatives

	Van Genucten Parameters					
	a (air entry value)	n	m	K_{sat} (m/s)	θ_s	θ_r
Fine Material	50.00	1.15	0.13	1×10^{-8}	0.47	0.09
Coarse Material	4.00	1.40	0.29	1×10^{-5}	0.42	0.02

Table 5.9: Literature obtained parameters for soil water characteristic curve (SWCC) and unsaturated hydraulic conductivity functions for capillary barrier alternatives

		Van Genucten Parameters					
	Literature Sources	a (air entry value)	n	m	K_{sat} (m/s)	θ_s	θ_r
Fine Material	Bussiere et al., 2003	12.00	*	*	1×10^{-8}	0.38	0.06
	Benson et al., 2007	62.90	1.49	0.33	1.2×10^{-7}	0.39	*
	Benson et al., 2007	208.00	1.34	0.25	3.1×10^{-7}	0.29	*
	Mbonimpa et al., 2008	12.00	*	*	5×10^{-7}	0.44	0.05
	Parent & Cabral, 2006	6.13	1.37	0.27	6.94×10^{-7}	*	*
	Khire et al., 2000	8.30	1.13	0.12	9×10^{-7}	0.35	0.02
Coarse Material	Mbonimpa et al., 2008	1.00	*	*	1.16×10^{-3}	0.36	0.06
	Hopp et al., 2011	0.10	2.19	0.54	1.2×10^{-3}	0.42	0.05
	Khire et al., 2000	2.60	2.69	0.63	2.9×10^{-5}	0.40	0.01
	* Indicates that these values are not given in the study						

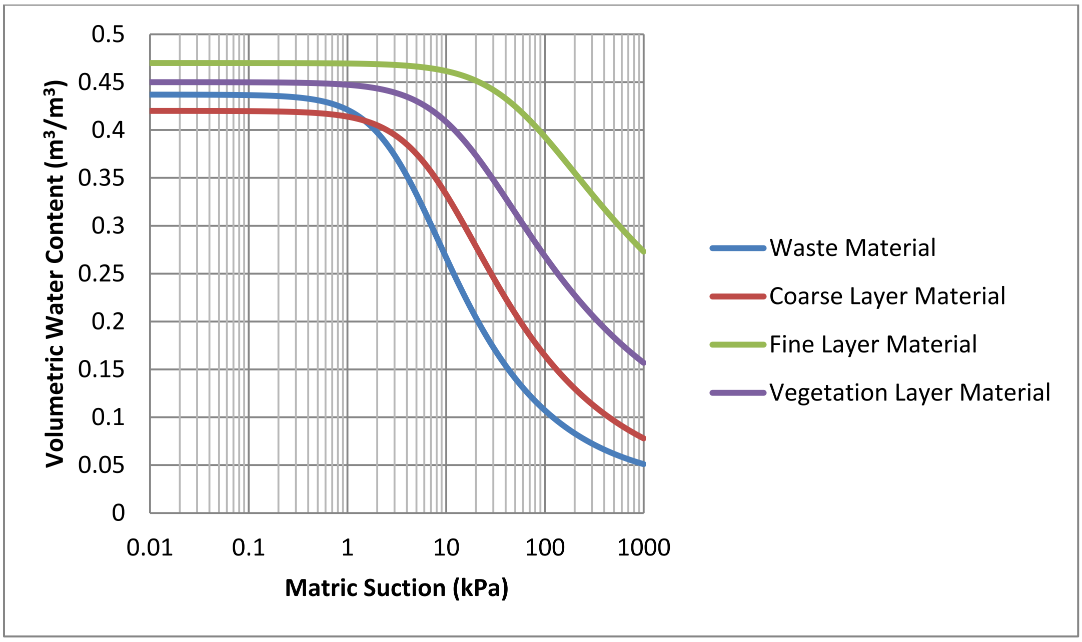

Figure 5.14: Soil water characteristic curve (SWCC) for capillary barrier alternative

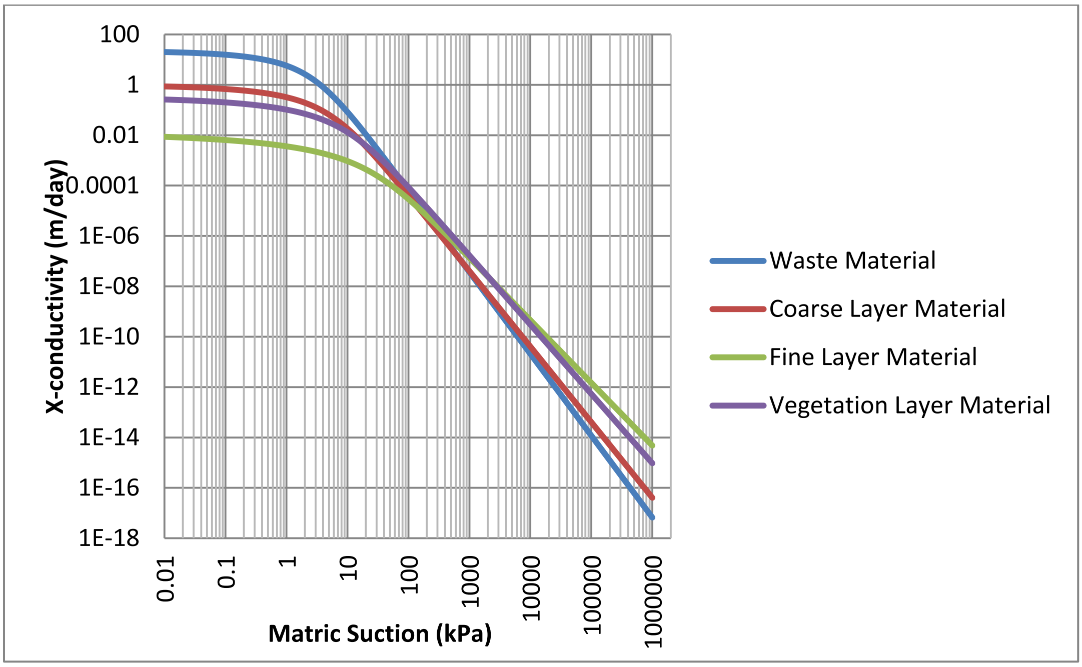

Figure 5.15: Unsaturated hydraulic conductivity curves for capillary barrier alternative

The model results are summarized in Table 5.3 which shows the average water budget components for the capillary barrier alternative. The results show that infiltration into the waste rock is significantly reduced (i.e., 0.6 % of precipitation). Thus, this alternative is quite effective to create a barrier to water infiltration.

Table 5.10: Average water budget components for capillary barrier alternative under transient condition

Capillary Barrier Alternative			
Water Budget Components	**m^3/yıl**	**mm/year**	**Percentage due to precipitation (%)**
Precipitation	993.00	543.16	
Actual Evaporation	623.80	340.80	62.70
Runoff	305.45	166.90	31.44
Infiltration from surface	63.75	34.80	5.80
Transpiration	32.94	18.00	3.31
Infiltration into waste rock	6.00	3.30	0.60
Boundary Flux	90.25	49.30	9.00
Storage	59.44	-32.48	-5.98

Figure 5.16 shows the water saturation percentage in the storage layer. As seen from Figure 5.16, saturation percentage is higher than 85 % most of the time. However, in dry seasons, saturation percentage decreases below 85 %. This model also produced low amount of oxygen ingress (Figure 5.17). As seen in Figure 5.17 oxygen concentration is lowered to 30 %. Especially there is a sharp decrease in the oxygen amount in the storage layer because of high saturation. Result of the model shows that this alternative is much better than former alternatives in limiting the oxygen migration.

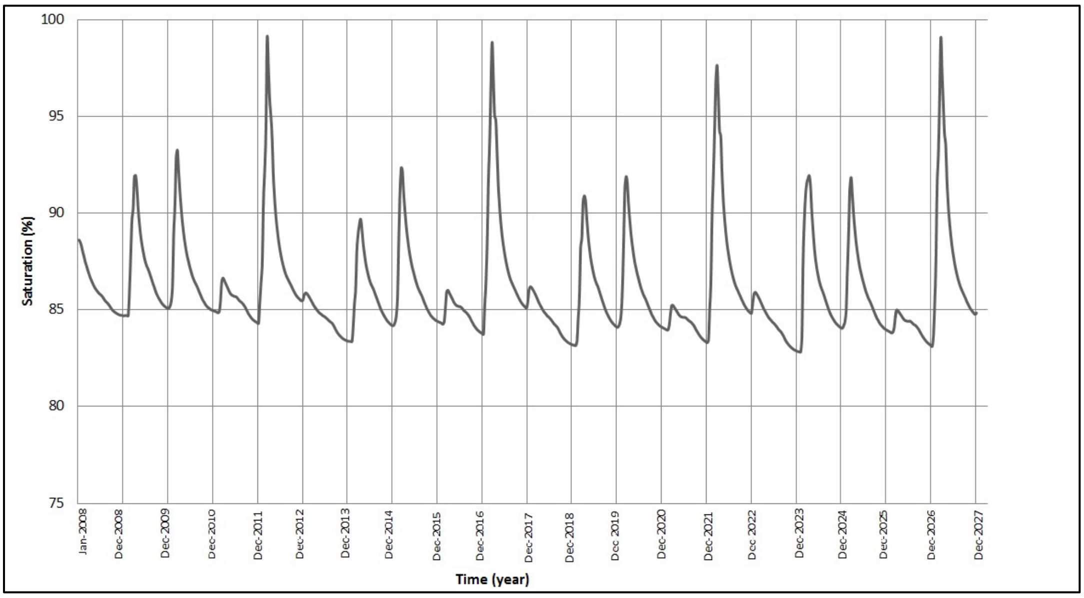

Figure 5.16: Saturation percentage in the storage layer throughout the 20 years

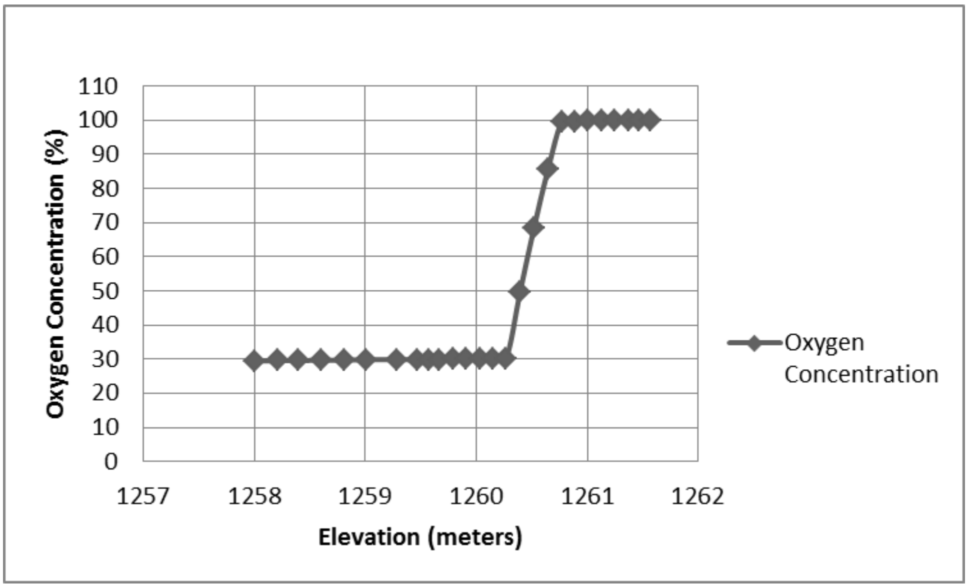

Figure 5.17: Oxygen concentration at the end of 20 years

CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1. Summary and Conclusion

The purpose of this study is to make a preliminary work to evaluate the performance of different cover designs for the planned North Waste Rock Storage Area of the Kışladağ Gold Mine and propose an optimum cover that will minimize the water and oxygen ingress. All the available data on physiography, geology and hydrogeology were used to develop a conceptual model for the system.

Two-dimensional finite element models SEEP/W and VADOSE/W were used to model various cover types. Modeling of covers was completed in different but connected stages. The lithologies of the covers modeled in different stages show changes from each other. For the material properties both site specific data and literature obtained data were used. First modeling step was bedrock calibration under steady state condition with SEEP/W. Boundary condition and material properties were changed to obtain good match between measured and simulated groundwater levels. Then, bedrock was modeled under transient conditions with VADOSE/W for a 20 year period using daily time steps. The result of the calibrated steady-state model was used as initial head distribution for the transient analysis of the bedrock system. Water levels at two observation wells were checked if groundwater level at these wells showed the expected seasonal changes. Groundwater level at HY-6 showed seasonal changes while groundwater at HY-11 showed a general decrease. Over prediction of the runoff value could be the reason for decrease in groundwater level at HY-11. Additionally, water budget components were evaluated. Calculated cumulative precipitation was compared with the measured cumulative precipitation. Their patterns were same, but the calculated cumulative precipitation was less than measured cumulative precipitation because of sublimation. Infiltration amount was also checked to see if the calculated value was close to the one in the steady model which was assigned as recharge. Calculated value was uniformly 38.68 mm however in the steady model infiltration was uniformly assigned as 47 mm.

After transient analysis of the bedrock system, waste rock was located on bedrock and they were modeled together. Waste rock was modeled without any cover to see if there were any water and oxygen ingress that cause ARD. The results showed that there were significant amount of water infiltration and oxygen migration into the waste rock. In order to limit water and oxygen ingress, covers were designed as closure options. Three different cover alternatives were designed and their results were evaluated.

Table 6.1 shows the water budget components for four alternatives. Precipitation is same in all alternatives. Evaporation and runoff values change in all alternatives depending on water content in the system and material properties. Vegetation was not assigned to no-cover alternative, so transpiration was not calculated for this alternative. Calculated transpiration amounts are different for other three models because of different available water amount for the plants in the system. When the infiltration amount into the waste material is checked, it is seen that all three models are quite effective to limit water infiltration. Proposed alternative and enhanced store and release alternative are designed according to the available materials in the field to reduce the cost in addition to limiting water and oxygen ingress. However, capillary barrier is especially designed to see if this configuration is capable of keeping the storage layer at 85% saturated in semi-arid areas. So, the cost is not the privileged concern in this alternative.

Table 6.1: Average water component for all cover alternatives

No Cover Alternative				Proposed Cover Alternative				Enhanced Store and Release Alternative			Capillary Barrier Alternative		
Water Budget Component	m^3/yıl	mm/year	Percentage of precipitation (%)	Water Budget Components	m^3/yıl	mm/year	Percentage of precipitation (%)	m^3/yıl	mm/year	Percentage of precipitation (%)	m^3/yıl	mm/year	Percentage of precipitation (%)
Precipitation	993.00	543.16		Precipitation	993.00	543.16		993.00	543.16		993.00	543.16	
Actual Evaporation	668.00	365.00	67.00	Actual Evaporation	581.00	317.00	58.00	561.32	306.73	56.48	623.80	340.80	62.70
Runoff	160.00	87.40	16.00	Runoff	310.00	169.58	31.18	370.00	203.42	37.46	312.40	170.70	31.44
Infiltration from top of surface layer	160.00	87.40	16.00	Infiltration from surface	105.00	57.37	10.50	59.60	32.58	6.00	57.60	31.50	5.80
Transpiration	0.00	0.00	0.00	Transpiration	98.00	53.90	9.94	44.30	24.21	4.46	51.60	28.00	5.16
				Infiltration into waste rock	6.50	3.60	0.66	15.32	8.37	1.54	6.00	3.30	0.60
Boundary Flux	90.25	47.23	8.68	Boundary Flux	89.00	48.70	8.68	90.25	49.30	9.00	90.25	49.30	9.00
Storage	70.00	40.13	7.38	Storage	-82.00	-44.81	-8.24	-74.95	-40.92	-7.54	-84.25	-46.00	-8.48

Figure 6.1 shows the saturation percentage in storage layers in the three alternatives. As can be seen from Figure 6.1 proposed alternative and enhanced store and release alternative are not effective to keep the storage layer saturated at 85 %. However, saturation percentage of the storage layer in capillary barrier alternative reaches to 85 % during the wet season, but in dry season this percentage decreases below the 85 %. In order to prevent this drop, storage layer thickness can be increased to hold more water. However, this can be economically expensive alternative. Thus, according to the results obtained in this work and similar studies in the literature it can be said that in the semi-arid areas privileged choice is to limit the water ingress rather than oxygen migration.

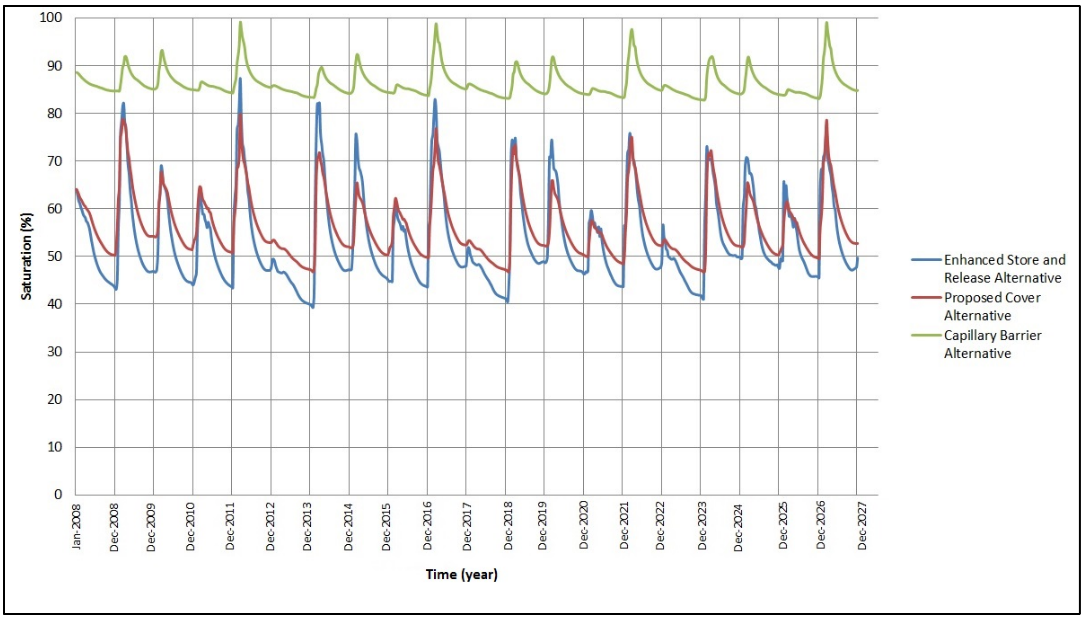

Figure 6.1: Saturation percentage in the storage layers of cover alternatives throughout the 20 years

6.2. Recommendation

Based on the results of this study following recommendations can be made:

- It seems that capillary barrier alternative is the best alternative since it both limits oxygen and water ingress. However, capillary barrier alternative needs to be optimized to prevent desaturation of storage layer during dry season.
- It appears that the proposed cover design for Kışladağ will limit water infiltration into the waste rock if the material properties used conform to the material properties used in the modeling work. A reduced thickness for the storage layer will also perform equally well in limiting the water infiltration with significant reduction in cost.
- As indicated at the beginning of this chapter this study is just a preliminary work. Numerical modeling was conducted by the help of the available site specific data and material properties obtained from the literature survey. After alternatives are determined, test plots should be constructed in the field to provide evaluation of the effectiveness of soil covers to reduce ARD, with the goal of choosing the best option for final closure option for the waste rock. In order to build the test plots, 4 x 5 x 5 m excavations can be operated and four covers designed in this work are constructed in these excavations. Instrumentation must be installed in test plots to measure volumetric water content, soil suction, soil temperature and oxygen amount. The runoff volumes of each test plot should be collected and measured after the rainfall event. The model should be rerun with the same climate period of measured data to see if the measured data support the simulated ones.
- The biggest problem of that study was the simulation time. Twenty years transient analysis takes at least seven days with the computer which has the I7-3630 QM., 2.4 GHz CPU and the memory of 16 GB properties. So, instead of twenty years analysis, shorter period can be analyzed if the measured data available for the analyzed period.

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