PERFORMANCE EVALUATION OF WASTE ROCK DUMP COVER SYSTEMS IN DIFFERENT CLIMATE ZONES OF TURKEY

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

BARIŞ CAN BAYSAL

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
GEOLOGICAL ENGINEERING

NOVEMBER 2022

Approval of the thesis:

PERFORMANCE EVALUATION OF WASTE ROCK DUMP COVER SYSTEMS IN DIFFERENT CLIMATE ZONES OF TURKEY

submitted by **BARIŞ CAN BAYSAL** in partial fulfillment of the requirements for the degree of **Master of Science in Geological Engineering, Middle East Technical University** by,

Prof. Dr. Halil Kalıpçılar
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Erdin Bozkurt
Head of the Department, **Geological Engineering**

Assoc. Prof. Dr. Koray K. Yılmaz
Supervisor, **Geological Engineering, METU**

Examining Committee Members:

Prof. Dr. M. Lütfi Süzen
Geological Engineering, METU

Assoc. Prof. Dr. Koray K. Yılmaz
Geological Engineering, METU

Assoc. Prof. Dr. Harun Aydın
Hydrogeological Engineering, Hacettepe University

Assoc. Prof. Dr. Özlem Yağbasan
Geography Education, Gazi University

Assist. Prof. Dr. Ali İmer
Geological Engineering, METU

Date: 24.11.2022

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name : Barış Can Baysal

Signature :

ABSTRACT

PERFORMANCE EVALUATION OF WASTE ROCK DUMP COVER SYSTEMS IN DIFFERENT CLIMATE ZONES OF TURKEY

Baysal, Barış Can
Master of Science, Geological Engineering
Supervisor: Assoc. Prof. Dr. Koray K. Yılmaz

November 2022, 122 pages

One of the tasks to be considered during the closure stage of mining is the closure of the waste rock dump (WRD). A suitable top cover system shall be applied for closure to mitigate the impacts of mine wastes on the environment and human health. The regulatory requirements for closure activities vary from one country to another. The purpose of this study is to evaluate the performances of cover system types, including the one that is described in Turkish Mining Waste Regulation (TMWR), for different climate zones of Turkey according to Köppen-Trewartha Climate Classification. In this study, five (5) different cover system types were modeled for five (5) different climate zones of Turkey. The performances of cover system types were evaluated by the ability to limit atmospheric water ingress towards WRD.

SEEP/W software is used to model numerical seepage analyses for long-term (30 years) performances of cover system types under different climatic conditions. At the end of the model runs, water balance calculations were reported by the software. Thus, the performances of cover systems were compared considering the net percolation rates calculated for each study area. Consequently, successful model results were obtained for TMWR type cover system for all climate types of Turkey. It was also found that less complex and hence more economical cover systems, that are mainly used globally in certain type of climates, also achieved some successful results in terms of providing very low net percolation rates (<5%). The results revealed that the climate has a major impact on the performance of the cover systems. In this study, it was also revealed that a site-specific study utilizing local meteorological conditions as well as specific design criteria and parameters shall be conducted for each case since each study area is unique by its own hydroclimatic, hydrogeologic, and design characteristics.

Keywords: Mine Closure Plan, Turkish Mining Waste Regulation, Cover System Design, Waste Rock Dump, Numerical Modeling

ÖZ

PASA SAHASI ÖRTÜ SİSTEMLERİNİN TÜRKİYENİN FARKLI İKLİM BÖLGELERİNE GÖRE PERFORMANSLARININ DEĞERLENDİRİLMESİ

Baysal, Barış Can
Yüksek Lisans, Jeoloji Mühendisliği
Tez Yöneticisi: Doç. Dr. Koray K. Yılmaz

Kasım 2022, 122 sayfa

Maden kapatma işlemleri sırasında önem gösterilmesi gereken işlemlerden biri de pasa sahalarının (WRD) kapatılmasıdır. Kapatma sırasında maden atıklarının çevre ve insan sağlığına etkilerini azaltmak için uygun bir üst örtü sistemi uygulanmalıdır. Kapatma faaliyetleri için gerekli yönetmelikler bir ülkeden diğerine değişiklik göstermektedir. Bu çalışmanın amacı, Türkiye maden atıkları yönetmeliğinde (TMWR) tarif edilmiş olan örtü sistemi de dahil olmak üzere farklı örtü sistemlerinin Türkiye'nin Köppen-Trewartha İklim Sınıflandırmasına göre belirlenmiş olan farklı iklim bölgelerindeki performanslarını değerlendirmektir. Bu çalışmada, Türkiye'nin beş (5) farklı iklimine göre beş (5) farklı örtü sistem tipi modellenmiştir. Örtü sistemi tiplerinin performansları, pasaya atmosferik su girişini sınırlama kabiliyetlerine göre değerlendirilmiştir.

Örtü sistemi tiplerinin farklı iklim koşullarındaki uzun dönem (30 yıl) performanslarının sızıntı analizlerinin sayısal olarak modellenmesi için SEEP/W yazılımı kullanılmıştır. Her model çalışmasının sonucunda yazılım tarafından su dengesi hesabı yapılmıştır. Böylelikle, örtü sistemlerinin performansları her çalışma alanı için hesaplanan net sızma oranlarına göre karşılaştırılmıştır. Sonuç olarak, Türkiye'nin tüm iklim tipleri için TMWR tipi örtü sistemi başarılı model sonuçları ortaya çıkarmıştır. Ayrıca daha az karmaşık ve dolayısıyla daha ekonomik olup dünya genelinde çoğunlukla belirli iklim tiplerinde kullanılan örtü sistemleri de çok düşük net sızma oranları (<%5) sağlama açısından bazı başarılı sonuçlar elde etmiştir. Sonuçlar, iklimin örtü sistemlerinin performansı üzerinde önemli bir etkiye sahip olduğunu ortaya koymuştur. Bu çalışmada ayrıca, her çalışma alanı kendi hidroklimatik, hidrojeolojik ve tasarım özellikleriyle benzersiz olduğundan, yerel meteorolojik koşulların yanı sıra spesifik tasarım kriterleri ve parametrelerin kullanıldığı sahaya özgü bir çalışmanın her durum için yürütülmesi gerektiği ortaya konmuştur.

Anahtar Kelimeler: Maden Kapatma Planı, Maden Atıkları Yönetmeliği, Örtü Sistem Tasarımı, Pasa Sahası, Sayısal Modelleme

ACKNOWLEDGMENTS

Foremost, the author would like to express his sincere gratitude to his supervisor Assoc. Prof. Dr. Koray K. Yılmaz for his continuous support, motivation, enthusiasm, and immense knowledge.

Besides, the author would like to thank his colleagues, especially Ü. Giray Pelenk, from his company, Golder Associates, for their support, advice, and guidance.

Most importantly, the author also wishes to express his gratitude to his family, Akgül Baysal and A. Savaş Baysal, for their endless support.

Lastly, the author also would like to thank his relatives and friends for their understanding and respect while he was working on this thesis.

TABLE OF CONTENTS

CHAPTERS

APPENDICES

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

CHAPTER 1

INTRODUCTION

Mine wastes are non-economic rocks that are generated during the extraction of the ore or produced during the processing of ore deposits. They are generally stored above the ground at the mining plants such as Waste Rock Dump (WRD). Once the mining of the ore is ceased due to run-out of the ore or it is no longer economically feasible to continue mining, closure activities begin. One of the important tasks to be considered during the closure stage is the reclamation of the WRD.

Mining wastes should be properly managed in order to prevent adverse environmental impacts such as Acid Mine Drainage (AMD). Cover systems for closure phases of these facilities are designed to avoid potential impacts of mine wastes on the environment and human health.

1.1 Purpose and Scope

The main purpose of this study is to evaluate and compare the long-term performance of the cover system design mentioned in Turkish Mining Waste Regulation (TMWR) which was published on July 15, 2015, and put into force on July 15, 2017, by Ministry of Environment, Urbanization and Climate Change (MoEUaCC). On the contrary of global cover system design selection criteria, “one size fits for all” type cover system design is obligatory in TMWR. In this study, the cover system mentioned in TMWR is modeled for five (5) different climate zones of Turkey in order to assess the performance of the cover system. Additionally, four (4) global cover system designs, namely basic erosion protection system, store & release system, enhanced store & release system, and barrier-type system, were selected and then modeled for the same climate zones of Turkey for comparison purposes.

1.2 Location of the Study Areas

A total number of six (6) provinces, namely Iğdır, Rize, İzmir, Sivas, Bitlis, and Balıkesir, in Turkey were selected to represent five (5) different climate regions of the country according to Köppen-Trewartha climate classification. Note that Bitlis province was selected only for comparison purpose with Sivas province. Information regarding the climate classification and representative province selection criteria is given in CHAPTER 3. Six (6) representative provinces were highlighted on the location map presented in Figure 1.1.

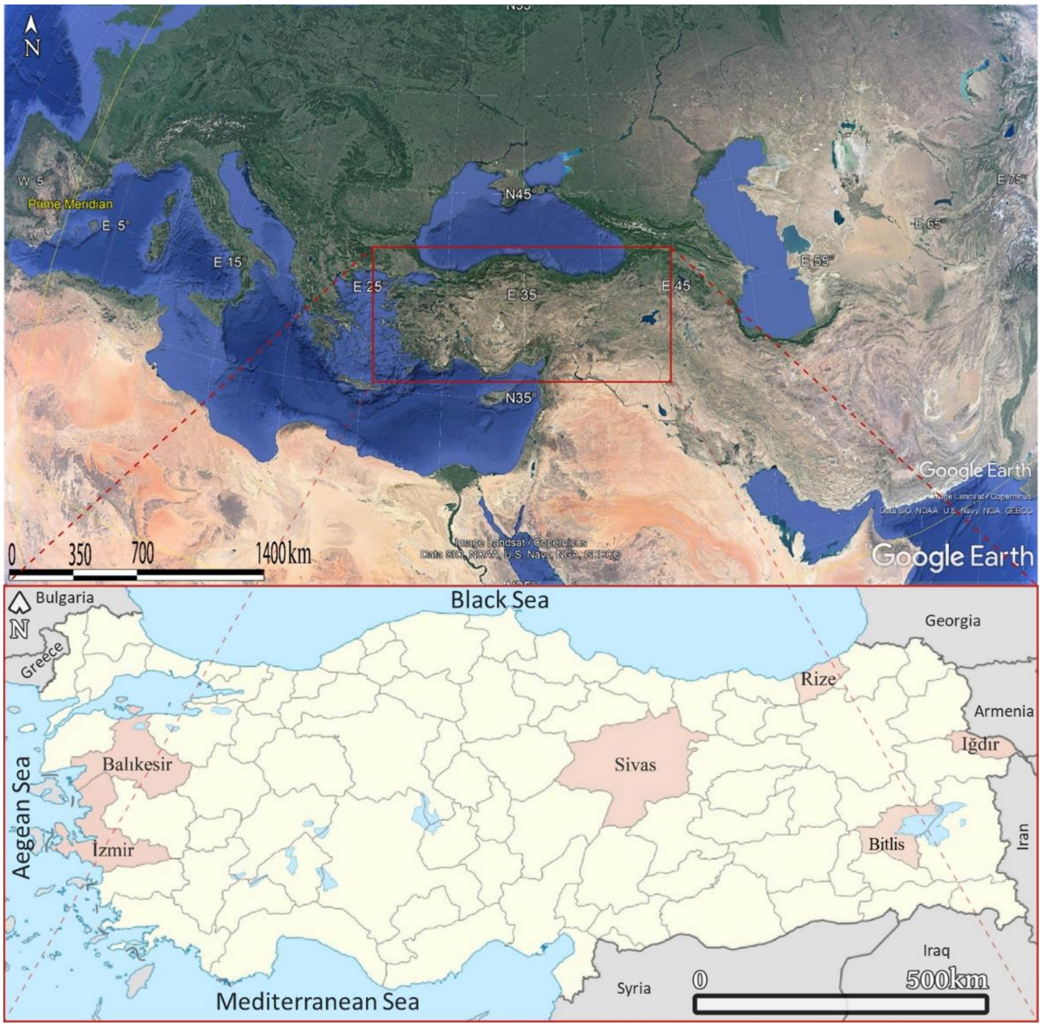


Figure 1.1. Location map of the study areas (Google Earth, 2022).

CHAPTER 2

LITERATURE REVIEW

2.1 Cover System Design

The main idea behind a cover system is placing an interface, which provides the required technical properties, between the mine waste and its surrounding environment for the closure of a mining facility. Geometry, physical and chemical properties of the mine waste, climate, and the characteristics of the cover material are some of the important design factors that should be considered prior to evaluate the cover types (INAP, 2017).

General objectives, that can vary from one site to another, of a cover system are (MEND, 2004);

- to control dust and erosion,
- to stabilize acid-forming mine waste by controlling the influx of atmospheric water and oxygen,
- to control release of contaminants through infiltration,
- to provide suitable environment for sustainable vegetation.

Cover system types described in the international (section 2.1.1) and the local (section 2.1.2) sources are mentioned below.

2.1.1 Global Cover System Types

The importance of climate on cover system design is once again emphasized in GARD (Global Acid Rock Drainage) Guide (2014) prepared by INAP (International Network for Acid Prevention). A ternary diagram plotted by ICMM (International Council on Mining & Metals) in 2019 was presented to indicate the relationship between cover systems and climatic characteristics of the location (Figure 2.1). It can be understood that the classification of cover system design varies according to climate types.

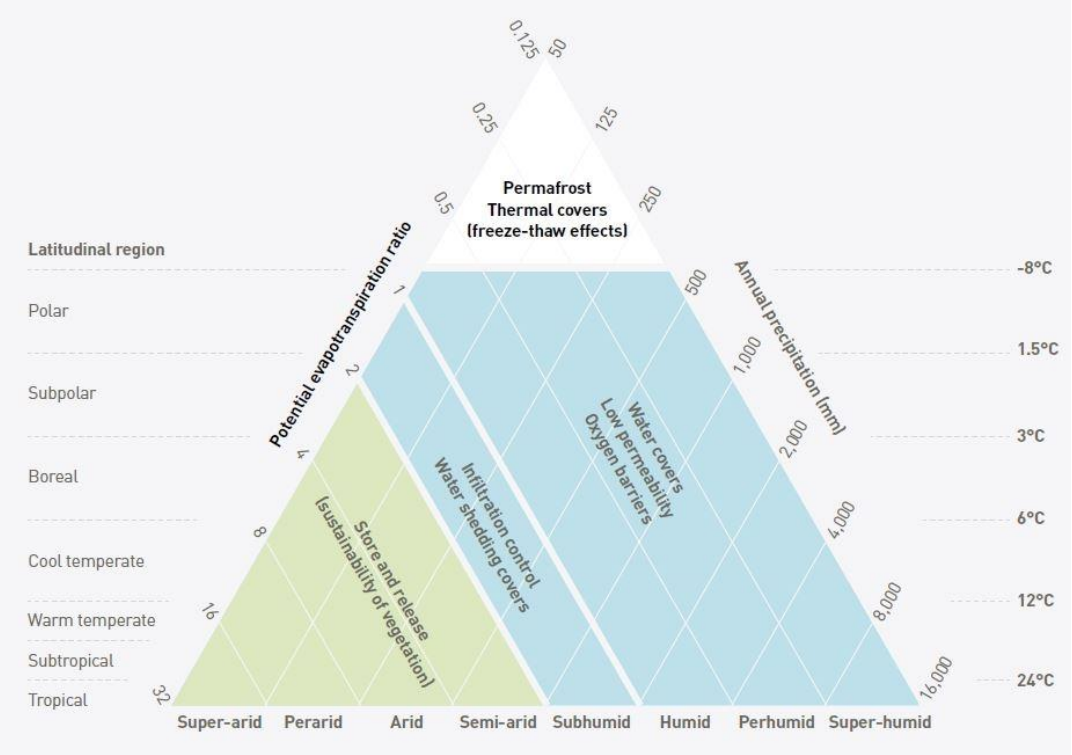


Figure 2.1. Cover system design according to climate types (ICMM, 2019)

In addition to GARD Guide (INAP, 2014), the most applicable cover system design alternatives for mine waste from INAP (2017) and MEND (2004 and 2012) were summarized below from the simplest and cheapest ones to the most complex and costly ones:

- Basic erosion protection cover system (section 2.1.1.1),
- Store and release cover system (section 2.1.1.2),
- Enhanced store and release cover system (section 2.1.1.3),
- Barrier type cover system (section 2.1.1.4), and
- Cover system with engineered layers (section 2.1.1.5).

2.1.1.1 Basic Erosion Protection Cover System

The main purpose of this cover system is to protect the waste from erosion. It is mainly useful at the places where control of the water ingress is not the main concern. Basically, a 0.3 m thick topsoil layer seeded with native grass is placed over the waste rock dump. At the places where vegetation is not desired, coarse gravel material with a thickness of 0.3 m also could be used to prevent waste rock from erosion. Sketches of two (2) types of basic erosion protection cover systems are shown in Figure 2.2.

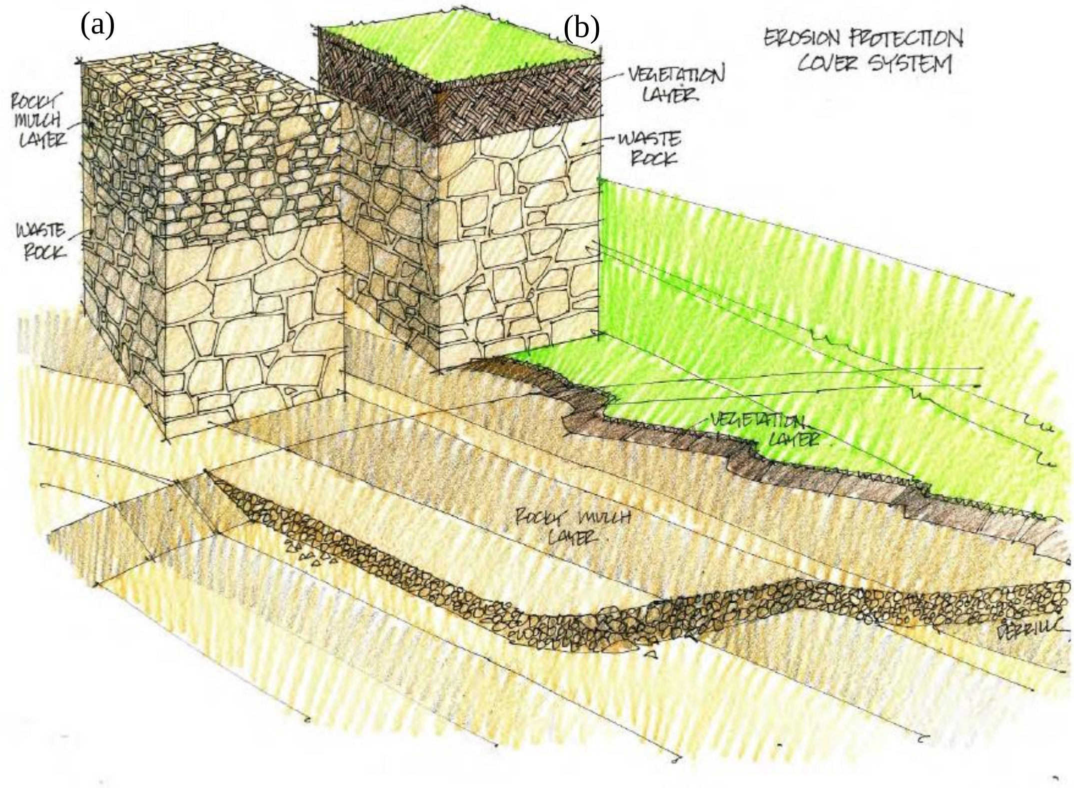


Figure 2.2. Erosion protection cover system with (a) gravel layer and (b) vegetation layer (MEND, 2012).

2.1.1.2 Store and Release Cover System

Store and release type cover system is best suited for arid and semi-arid regions where sustainable vegetation is crucial. This type of cover system is also called as evapotranspiration cover system. The main idea behind this system is to store atmospheric water in the cover until the water is released through evapotranspiration. Thus, the amount of water provided for the vegetation will be tried to be maximized at the places where it is hard to supply water. In this type of covers, there exists a well-graded storage layer between the growth medium (topsoil) and the waste rock dump (Figure 2.3).

2.1.1.3 Enhanced Store and Release Cover System

Similar to store and release cover system, it is also best suited for arid and semi-arid regions. However, this cover system has an additional reduced permeability layer(s), which is placed between the overlying storage layer and underlying waste rock dump to increase the storage capacity by limiting net percolation into waste rock dump (Figure 2.3). As a result, the amount of net percolation will be reduced, and the higher soil water will be provided for the vegetation layer. Compacted weathered waste rock or compacted locally available silt/clay deposits can be used as the reduced permeability layer.

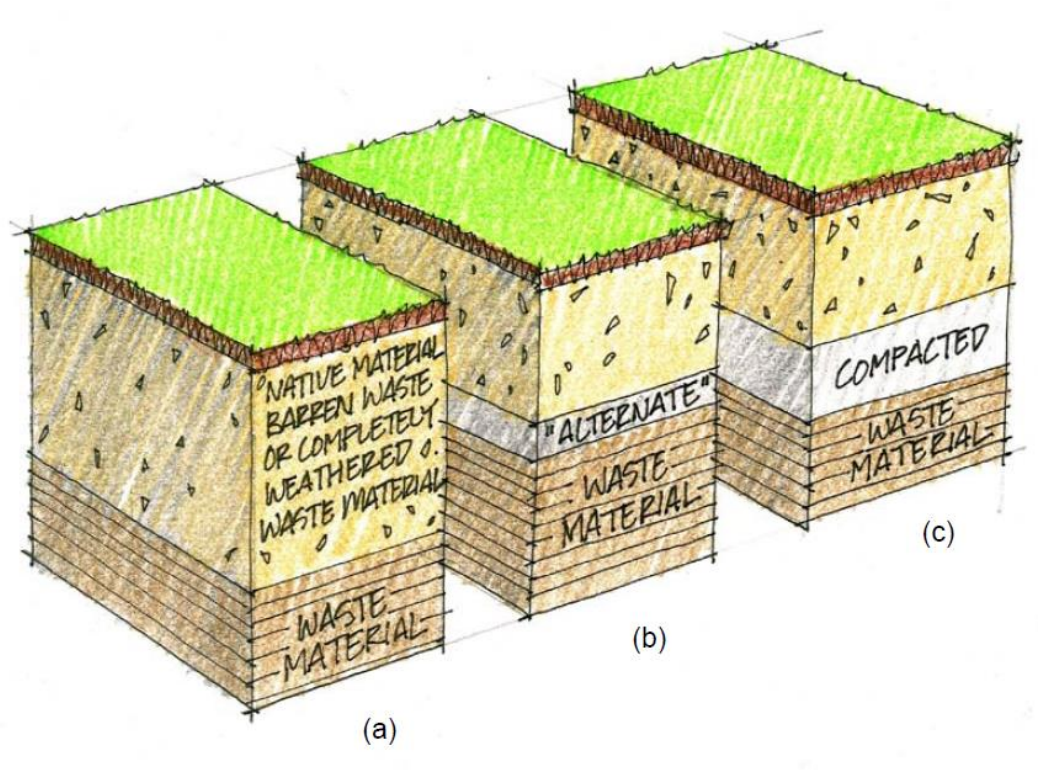


Figure 2.3. (a) Store and release cover system, (b) and (c) Enhanced store and release cover systems (MEND, 2012)

2.1.1.4 Barrier Type Cover System

Barrier type cover system is best suited for semi-humid and humid regions where control of water ingress is the main concern. There exists a low permeability layer which is placed top of the waste rock dump. It controls the net percolation into the waste rock dump. The compacted clay layer or geosynthetic clay liner can be used as a low hydraulic conductivity (≤1x10^{-9} m/s) barrier layer. The illustration of the barrier type cover system is shown in Figure 2.4.

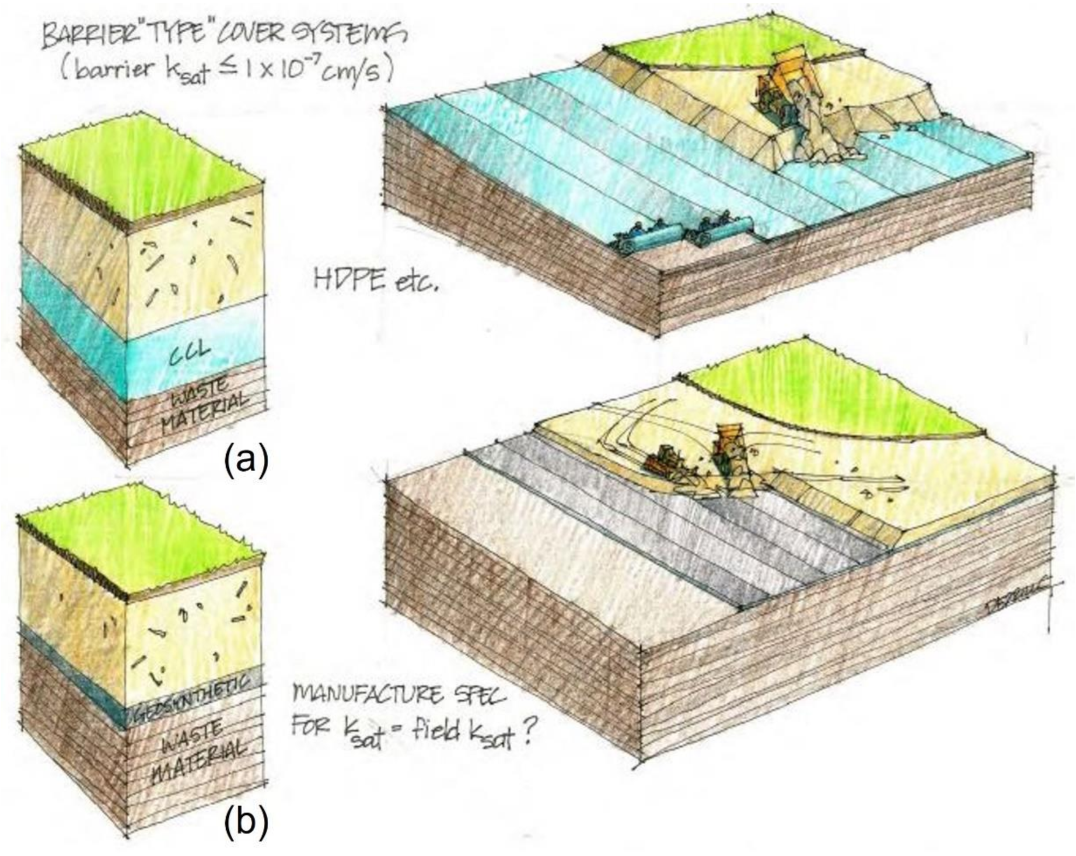


Figure 2.4. Barrier type cover system with (a) compacted clay layer and (b) geosynthetic clay liner (MEND, 2012)

2.1.1.5 Cover Systems with Engineered Layers

Cover Systems with Engineered Layers are also best suited for semi-humid and humid regions where control of water ingress is the main concern. In addition, very low (<5%) net percolation rates are desired. Similarly, there exists an artificial low permeability layer (e.g., geomembrane), which is placed between the overlying vegetation layer and underlying waste rock dump, that controls the net percolation into the waste rock dump. Additionally, a drainage layer is also required to remove the water from the cover system. This type of cover system is very similar to the cover system type described in the Turkish Mining Waste Regulation (TMWR).

2.1.2 Cover System Type according to TMWR

The TMWR requires that the cover system should be consisted of the following layers from top to bottom, respectively:

- Topsoil/vegetation layer,
- Natural or geosynthetic drainage material layer,
- Clay group minerals or geosynthetic clay liner (GCL) layer, and
- Buffer layer (excavated soil or non-acid generating waste rock).

According to TMWR, the buffer layer with thickness of at least one (1) meter thick will be placed on top of waste rock dump for the final grading. Then, the clay group mineral or GCL will be placed for reducing permeability. Afterwards, the drainage material with an appropriate thickness will be placed for discharging the atmospheric water from the cover system. Finally, a topsoil layer with an appropriate thickness will be placed for growing vegetation. Figure 2.5 represents the cover system type described in TMWR.

This type of cover system is required by TMWR (2015) for all mining facilities that contain mining wastes in Turkey independent from their climatic properties.

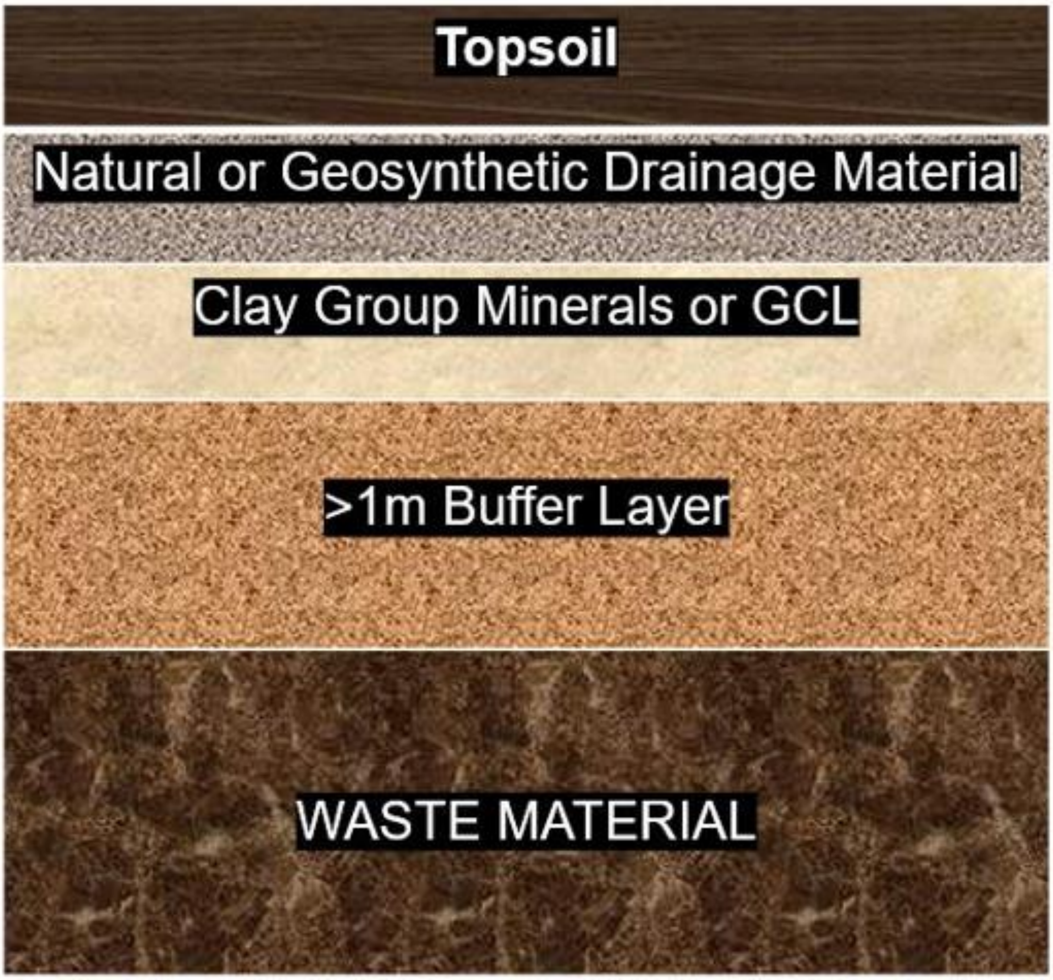


Figure 2.5. Cover System Type according to TMWR (2015).

2.2 Acid Mine Drainage

Acid Mine Drainage (AMD) is a phenomenon that is described by formation of Acid Rock Drainage due to mining activities (Nordstrom & Alpers, 1999). It can be formed because of the oxidation of sulfide minerals, i.e., pyrite (FeS_2), when exposed to atmospheric conditions because of mining activities like excavation. Oxidation of pyrite can be summarized as the following formula (INAP, 2014):

$$FeS_2 + \frac{15}{4} O_2 + \frac{7}{2} H_2O = Fe(OH)_3 + 2SO_4^{2-} + 4H^+ \qquad (2\text{-}1)$$

When sulfide minerals oxidize, they generate sulfuric acid and increase the acidification of the environment. Sulfuric acid promotes the release of the heavy metals in the hydrogeological environment. These waters with toxic heavy metal concentrations and low pH values can deteriorate the quality of the nearby groundwater and surface-water resources when they mix (Yılmaz & Kesimal & Erçıkdı, 2004).

Once AMD is initiated, it is really hard to stop this process until one of the reactants is removed from the reaction. Thus, it is important to plan cover system design prior to closure stage of the mining facility in order not to face with adverse outcomes. Figure 2.6 below demonstrates the long-term continuity of AMD formation impact centuries after the mining operation have been ceased in the portal operated during Roman-era in Spain. Consequently, cover systems can help to minimize the impact of AMD formations at mining facilities.

AMD can be one of the most serious environmental issues related with the mining sector. A comprehensive assessment of AMD potential should be carried out prior to mining and maintained throughout the life of mine. Rather than control or treatment, main strategies for dealing with AMD should focus on prevention and minimization (INAP, 2014).

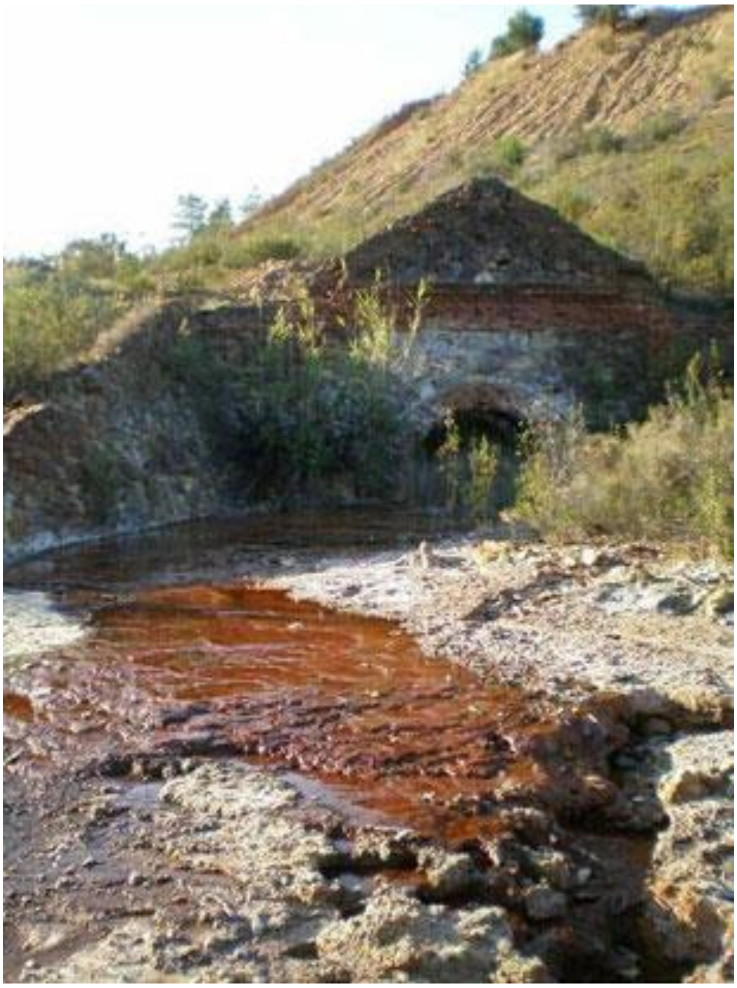


Figure 2.6. AMD formation at Roman-era portal in Spain (INAP, 2014).

2.3 Previous Studies

Since the study areas in this study are specified mainly on climate types, previous studies related with the use of numerical modeling for mine waste cover systems modeled under different climatic conditions around the globe were collected herein. The general objectives of all studies are optimizing net percolation into WRD for minimizing AMD potential. Previous studies are sorted by chronological order:

Williams et. al. (2006) tested the long-term performance of a barrier type cover over potentially acid forming WRD in a semi-arid climate (Kidston Gold Mine). According to cover system, WRD is overlain by a 1-meter thick compacted WRD, 0.5-m thick compacted clay seal as a barrier layer and 1.5-meter-thick rocky soil mulch layer as a storage layer, respectively. According to the modeling results, 1% net infiltration could be achieved by using barrier type cover system in the project area. Thus, very low (<5%) percolation rate was obtained for the project area using this cover design.

Ayres et. al. (2013) evaluated the performance of an enhanced store & release type cover system constructed for a uranium mine WRD which is located in a semi-arid region. The store and release type cover system consisted of 0.20-meter-thick reduced permeability layer (compacted waste rock) overlain by a 1-meter-thick silty-sand layer with vegetation. The average net percolation rate between 2007 and 2012 were calculated as 23% for the plateau section of WRD. Although this cover system evaluated as stable in terms of growing native plant species, a more advanced type of cover system could be applied to reduce net percolation rates to desired levels.

Argunhan (2014) modeled two (2) different cover systems, namely, enhanced store & release type and capillary barrier type, for a WRD of Kışladağ Gold Mine in Uşak, Turkey. Oceanic-temperate climate type parameters were applied to the model to obtain long-term (20 years) performances of cover systems. Enhanced store & release type consisted of WRD, 5-meter thick compacted WRD, 0.65-meter thick storage layer as silty sand, and 0.2-meter thick vegetation layer, respectively from bottom to top. On the other hand, capillary barrier type cover system comprised of WRD, 0.6-meter thick coarse grained layer, 0.5-meter thick fine grained layer, 0.6-meter thick coarse grained layer, and 0.2-meter thick vegetation layer. Net percolation rates for enhanced store & release and capillary barrier type cover systems were calculated as 1.54% and 0.60%, respectively. The performances of both cover systems were assessed as quite effective to limit net percolation rates. Since the Turkish Mining Waste Regulation (TMWR) was not published back then, this study did not include the required type of cover system by TMWR.

Birkham et. al. (2014) focused on the performance of basic erosion protection type cover system compared to bare WRD in humid climate. Vegetation layers with different kind of species, i.e., grasses and trees, were modeled to understand the effectiveness of this type of cover. According to the results obtained from 12 sites, approximately 15% less net percolation rates were estimated for waste rock dumps with vegetation layers. Very high (>40%) net percolation rates (between 52% and 86%) were calculated for 12 sites. This study revealed the poor performance of basic erosion protection type cover systems in humid climate.

SRK (2015) worked on a 1-D model with 20 years of climate data using a cover system similar to basic erosion protection system for Minto Mine in Yukon territory of Canada. According to the model results, the net percolation rates less than 20% were achieved by using local soil material as a vegetation layer with a 1-meter thickness. This study implies that additional layering shall be included in a cover system to achieve lower percolation rates for Minto Mine.

Power et. al. (2018) assessed the performance of store and release type cover system for WRD in a seasonally humid region (Nova Scotia, Canada) with a 5-year available climate data. Although store & release type cover system is more suitable for arid and semi-arid climates, authors aimed to test the performance of this type of cover system in humid climate because of its low cost and ease of installation. As a result, limited amount of reduction in net percolation rates, from 34% to 28%, into WRD was calculated in the water balance. This outcome reveals that store and release type cover systems may not be effective to limit net percolation into WRD in humid climates.

Hersey (2021) highlighted the role of geomembranes and geonets in cover systems with engineered layers for limiting the net percolation into WRD in a humid region (Sydney Coalfield, Canada). A high-density polyethylene (HDPE) geomembrane material (with an underlying protective geotextile layer) was applied over the WRD to create a barrier for atmospheric water. In order to drain water in the cover, a special type of geo-composite drainage system called as geonet was placed over the geomembrane. Finally, a vegetation layer with a thickness of 0.6 meter was placed at the top to provide sustainable vegetation at project site. The successful results were obtained in this study with average net percolation ratio of approximately 0.4%.

In summary, it can be understood that there are different types of cover systems modeled or constructed for different types of climates around the world. However, there is currently no available academic study that examines the performance of TMWR type cover system. Therefore, this thesis would improve our understanding about the performance of TMWR type cover for different climate zones of Turkey. Additionally, it will give a chance to compare the performance of TMWR type cover system with respect to performances of globally used cover systems.

CHAPTER 3

DESCRIPTION OF THE STUDY AREA

In this study, six (6) provinces, namely Iğdır, Rize, İzmir, Sivas, Bitlis, and Balıkesir, representing five (5) different climate zones in Turkey were selected as study areas. Note that Bitlis and Sivas are in the same climate type according to Köppen-Trewartha climate classification. These two (2) stations were selected to compare the design performance at two (2) different locations within the same climate zone. Information regarding the Köppen-Trewartha climate classification, and climate types of Turkey according to Köppen-Trewartha climate classification is summarized below. Meteorological data obtained from Turkish State Meteorological Service (MGM) is also presented in the following sections.

3.1 Köppen-Trewartha Climate Classification

Köppen (1936) created one of the most widely used climate classification systems based on seasonal temperature and precipitation patterns. Subsequently, Trewartha and Horn (1980) modified Köppen’s climate classification to clarify some of the uncertainties in the classification. They made adjustment on both temperature criteria and threshold values that separates dry and wet climates (Belda et.al., 2014). According to Köppen-Trewartha Climate Classification, terrestrial climates were divided into six (6) major types:

- Type A – tropical humid climates (section 3.1.1),
- Type B – dry climates (section 3.1.2),
- Type C – sub-tropical climates (section 3.1.3),
- Type D – temperate climates (section 3.1.4),
- Type E – boreal climates (section 3.1.5), and
- Type F – polar climates (section 3.1.6).

Six (6) major climate types and their sub-types were explained below and summarized in Table 3.1.

3.1.1 Type A – tropical humid climates

Type A is defined based on the condition that the mean air temperature of the coldest month should be above 18 °C. Moreover, the sub-types are determined by the number of dry months that are defined as having an average precipitation total of less than 55 mm and an average annual temperature of around 25-27 °C.

- If there is 10 to 12 wet months (or 0 to 2 dry months) in a year, the sub-type of the regions is Ar.
- If there is more than 2 dry months during winter, the sub-type of the regions is Aw.
- If all summer months are dry, the sub-type of the regions is *As*.

3.1.2 Type B – dry climates

Type B is defined based on the condition that the mean annual rainfall is less than a threshold value (R) determined by Köppen (1936) and modified by Patton (1962).

$$R = 2.3T - 0.64Pw + 41 \tag{3-1}$$

where:

R (in cm): mean annual precipitation threshold

T (in °C): mean annual air temperature

Pw: percentage of annual precipitation concentrated in winter

The subtypes are also determined by using the following threshold values:

- If mean annual rainfall is higher than R/2, the sub-type of the regions is *BS*.
- If mean annual rainfall is less than R/2, the sub-type of the regions is *BW*.

3.1.3 Type C – sub-tropical climates

Type C is defined based on the condition that the mean air temperature of 8 to 12 months in a year is more than 10 °C, and the temperature of the coldest month is less than 18 °C. Also, the sub-types are determined by the annual precipitation cycle.

- If the summer is dry, the sub-type of the regions is *Cs*.
- If the winter is dry, the sub-type of the regions is *Cw*.
- If there is no dry season, the sub-type of the regions is *Cf*.

3.1.4 Type D – temperate climates

Type D is defined based on the condition that the mean air temperature of 4 to 7 months in a year is more than 10 °C. In addition, the sub-types are determined by the mean air temperature of the coldest month.

- If the coldest month is more than 2 °C, the sub-type of the regions is *Do*.
- If the coldest month is less than 2 °C, the sub-type of the regions is *Dc*.

3.1.5 Type E – boreal climates

Type E is defined based on the condition that the mean air temperature of 1 to 3 months in a year is more than 10 °C. There are no sub-types of this type of climate.

3.1.6 Type F – polar climates

Type F is defined based on the condition that the mean air temperature of all months in a year is less than 10 °C. Furthermore, the sub-types are determined by the mean air temperature of the warmest month.

- If the warmest month is more than 0 °C, the sub-type of the regions is *Ft*.
- If the warmest month is less than 0 °C, the sub-type of the regions is *Fi*.

Table 3.1 Summary of Köppen-Trewarth Climate Classification (modified from Belda et. al., 2014)

Type/*Sub-type*	Description	Criteria (Rainfall/temperature regime)
A	Tropical Humid Climates	$T_{cold} \geq 18°C$; $P_{mean} \geq R$
A_r	Tropical Wet, Tropical Rainforest Climate	10 to 12 months wet; 0 to 2 months dry
A_w	Tropical Wet and Dry-Winter (Savanna) Climate	Dry winter; > 2 months dry
A_s	Tropical Wet and Dry-Summer (Savanna) Climate	Dry summer (rare)
B	Dry Climates	$P_{mean} < R$
B_s	Semi-Arid or Steppe Climate	$R/2 < P_{mean} < R$
B_w	Arid, Desert Climate	$P_{mean} \leq R/2$
C	Subtropical Climates	$T_{cold} < 18$ °C; 8 to 12 months with $T_{mo} > 10°C$
C_s	Subtropical Dry-Summer (Mediterranean) Climate	Dry summer; $P_{winter} \geq 3P_{summer}$; $P_{dry} < 3$ cm; $P_{total} < 89$ cm
C_w	Subtropical Dry-Winter	Dry winter; $10P_{winter} \leq P_{summer}$
C_f	Subtropical Humid Climate	No dry season; difference between driest and wettest month less than required for C_s and C_w; $P_{dry} > 3$ cm
D	Temperate Climates	4 to 7 months with $T_{mo} > 10°C$
D_o	Oceanic Climate	$T_{cold} \geq 2°C$
D_c	Continental Climate	$T_{cold} < 2°C$
E	Boreal Climates	1 to 3 months with $T_{mo} > 10°C$
F	Polar Climates	$T_{warm} < 10°C$
F_t	Tundra Climate	$T_{warm} > 0°C$
F_i	Ice Cap Climate	$T_{warm} \leq 0°C$
Explanations:		
T:	Mean annual temperature (°C)	
T_{mo}:	Mean monthly temperature (°C)	
$T_{cold/warm}$:	Monthly mean temperature of the coldest/warmest month (°C)	
P_{mean}:	Mean annual rainfall (cm)	
P_{total}:	Total annual rainfall (cm)	
P_{dry}:	Monthly rainfall of the driest summer month (cm)	
$P_{winter/summer}$:	Rain in winter/summer half-year (cm)	
R:	Patton's precipitation threshold, defined as $R = 2.3T - 0.64\ Pw + 41$ (Patton, 1962)	
Pw	Annual precipitation percentage occurring in winter	

3.2 Climate Types of Turkey according to Köppen-Trewartha Climate Classification

Bölük and Kömüşçü (2018) from Turkish State Meteorological Service generated a climate classification map of Turkey (Figure 3.1a) by using monthly average temperature and monthly average total precipitation data recorded between 1981 and 2010 from 252 meteorological stations in Turkey.

According to this study, 47.22% of Turkey (central and eastern Anatolia regions) is defined as continental-temperate (Dc) type of climate while 30.95% of Turkey (Aegean, Mediterranean and southeastern Anatolia regions) shows sub-tropical dry-summer (Cs) climate, also called as Mediterranean climate, characteristics. While some of the provinces, that cover 11.52% of Turkey, located at inner Aegean and Thrace regions represent oceanic-temperate (Do) type of climate, the provinces located at the coastal areas, that cover 7.94% of Turkey, of Black Sea region demonstrated sub-tropical humid climate (Cf). Finally, the remaining minor part (2.38%) of Turkey, including Iğdır and some districts of Konya, Urfa and Çorum provinces, is represented by semi-arid or steppe climate (BS).

It is noteworthy that there is neither Type A (tropical humid) nor Type E (boreal) nor Type F (polar) classification in Turkey since the average temperature of the coldest month of a province is not above 18 °C and all provinces have more than three (3) months which have average temperature values more than 10 °C.

3.2.1 Selection of the Representative Study Areas

According to the aforementioned study conducted by Bölük and Kömüşçü (2018), there exist five (5) climate types, namely BS (semi-arid or steppe), Cf (sub-tropical humid), Cs (sub-tropical dry-summer), Dc (continental-temperate) and Do (oceanic-temperate) in Turkey.

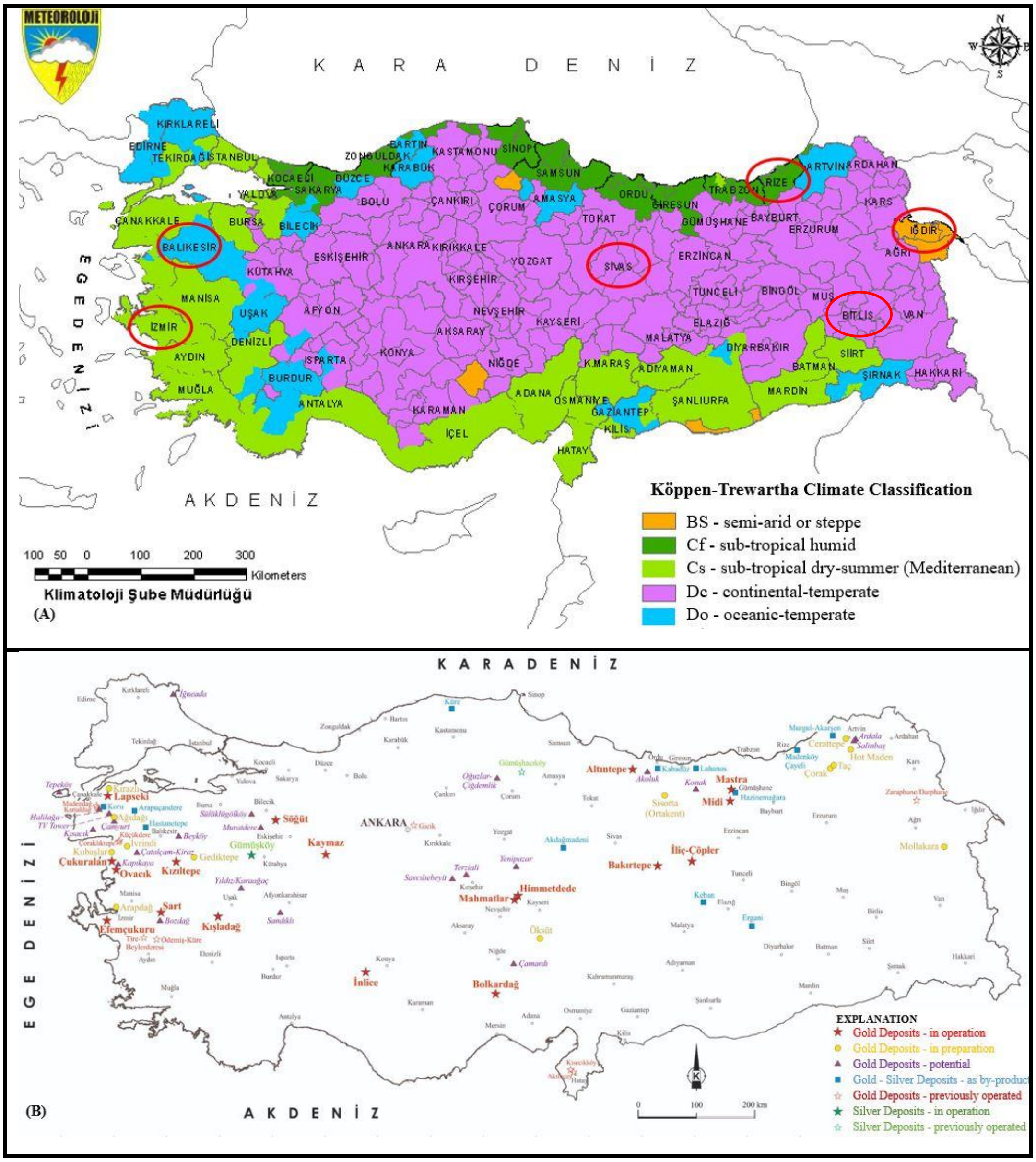


Figure 3.1. (a) – Climate classification map of Turkey modified from Bölük and Kömüşçü (2018), (b) – Gold and silver deposits map of Turkey modified from MTA (2019).

In this study, six (6) provinces were selected that represent each climate types in Turkey. Additionally, it is aimed to choose provinces that contain gold & silver deposits where closure operation would be carried out once the operation activities are completed. The location map of gold & silver deposits of Turkey prepared by MTA (2019) is presented in Figure 3.1b. Thus, the selected six (6) representative provinces are:

- Iğdır (BS),
- Rize (Cf),
- İzmir (Cs),
- Sivas (Dc),
- Bitlis (Dc), and
- Balıkesir (Do).

Tatvan station from Bitlis province was selected to compare the cover system performances for a specific climate type (Dc). The selection criteria and the meteorological conditions of Tatvan station area are not discussed in the next section but in section 5.3.

3.3 Meteorological Conditions of the Project Areas

Meteorological stations located at the five (5) provinces, namely Iğdır, Rize, İzmir, Sivas and Balıkesir, were selected to obtain long-term data for 30 years between 1981 and 2010 that is the same interval used by Bölük and Kömüşçü (2018) to specify climate classifications of Turkey.

Information regarding the meteorological stations selected to represent the study areas is given in Table 3.2, and the location map of the meteorological stations is presented in Figure 3.2. Note that, the operation of Balıkesir station (17152) was completed on June 30, 1998. Instead, a nearby station (17150), which was constructed at the same elevation (102 m), took its place for data recording operation as of July 01, 1998.

Table 3.2 Meteorological Station Data obtained from five (5) representative provinces

Köppen-Trewartha Climate Classification Type	BS	Cf	Cs	Dc	Do	
Climate Definition	Semi-arid or steppe	Sub-tropical humid	Sub-tropical dry-summer (Mediterranean)	Continental-temperate	Oceanic-temperate	
Station Name	Iğdır	Rize	İzmir	Sivas	Balıkesir	
Station Number	17100	17040	17220	17090	17152	17150
Latitude	39.9227	41.0400	38.3949	39.7437	39.6500	39.6326
Longitude	44.0523	40.5013	27.0819	37.0020	27.8666	27.9201
Elevation (m)	856	3	29	1294	102	102
Data from (d.m.y)	01.01.1981	01.01.1981	01.01.1981	01.01.1981	01.01.1981	01.07.1998
Data to (d.m.y)	31.12.2010	31.12.2010	31.12.2010	31.12.2010	30.06.1998	31.12.2010
Data length (Days)	10957	10957	10957	10957	6390	4567

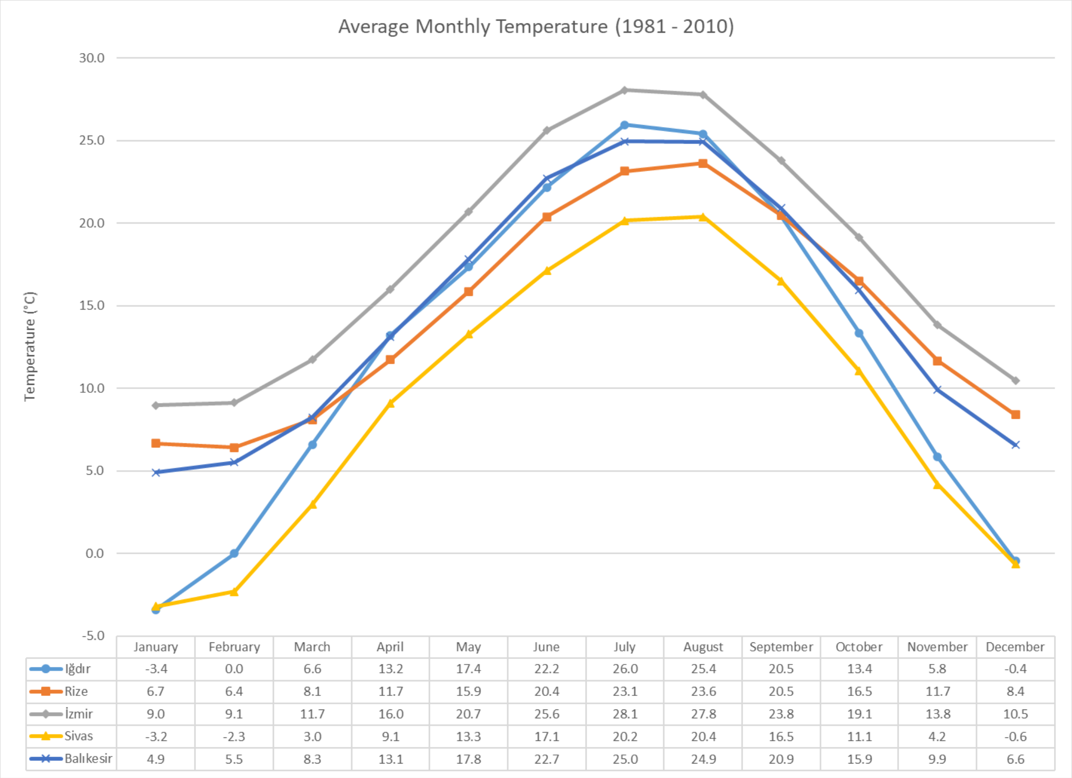
Figure 3.2. Location map of the meteorological stations (Google Earth, 2022)

The meteorological parameters, that were obtained from MGM to use in the numerical model, are sorted below:

- Daily maximum, minimum and mean temperature,
- Daily maximum, minimum and mean relative humidity,
- Daily mean wind speed,
- Daily snow depth, and
- Daily total precipitation.

3.3.1 Temperature

The average monthly temperature (1981-2010) graph of five (5) provinces is presented in Figure 3.3. Among all locations, -3.4 °C is the coldest average monthly temperature measurement recorded at Iğdır station in January, whereas 28.1 °C is the hottest average monthly temperature measurement recorded at İzmir station in July. It can be said that while the warmest months are in between May and October, the coldest months are in between November and April. On daily basis, the average temperature values can be sorted as İzmir (18.0 °C), Balıkesir (14.7 °C), Rize (14.5 °C), Iğdır (12.3 °C), and Sivas (9.1 °C) from highest to lowest, respectively.

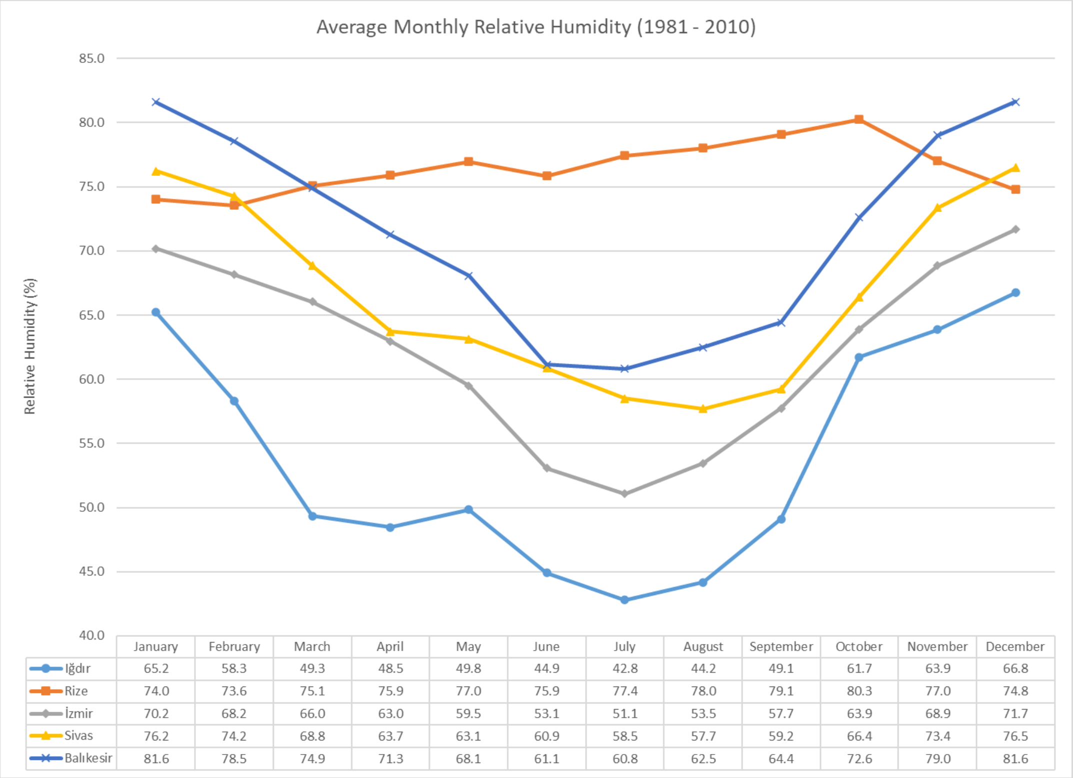


	January	February	March	April	May	June	July	August	September	October	November	December
Iğdır	-3.4	0.0	6.6	13.2	17.4	22.2	26.0	25.4	20.5	13.4	5.8	-0.4
Rize	6.7	6.4	8.1	11.7	15.9	20.4	23.1	23.6	20.5	16.5	11.7	8.4
İzmir	9.0	9.1	11.7	16.0	20.7	25.6	28.1	27.8	23.8	19.1	13.8	10.5
Sivas	-3.2	-2.3	3.0	9.1	13.3	17.1	20.2	20.4	16.5	11.1	4.2	-0.6
Balıkesir	4.9	5.5	8.3	13.1	17.8	22.7	25.0	24.9	20.9	15.9	9.9	6.6

Figure 3.3. Average monthly temperature values measured at meteorological stations of five (5) provinces for 30 years between 1981-2010.

3.3.2 Relative Humidity

The average monthly relative humidity (1981-2010) graph of five (5) provinces is presented in Figure 3.4. Among all locations, 42.8 % is the lowest average monthly relative humidity measurement recorded at Iğdır station in July, whereas 81.6 % is the highest average monthly relative humidity measurement recorded at Balıkesir station in both January and December. Note that, the average monthly relative humidity values of Rize are consistently more than 70% for all months in a year. The remaining four (4) locations have seasonal descent and ascent periods. On daily basis, the average relative humidity values can be sorted as Rize (76.5 %), Balıkesir (71.3 %), Sivas (66.5 %), İzmir (62.2 %), and Iğdır (53.7 %) from highest to lowest, respectively.

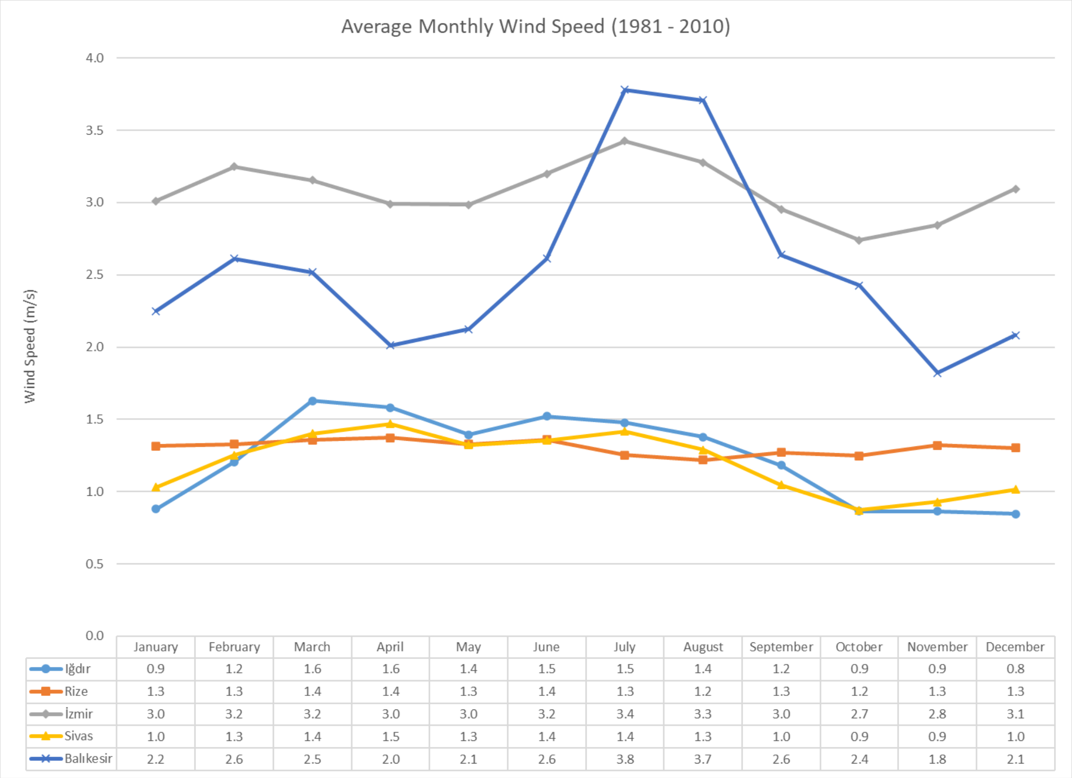


	January	February	March	April	May	June	July	August	September	October	November	December
Iğdır	65.2	58.3	49.3	48.5	49.8	44.9	42.8	44.2	49.1	61.7	63.9	66.8
Rize	74.0	73.6	75.1	75.9	77.0	75.9	77.4	78.0	79.1	80.3	77.0	74.8
İzmir	70.2	68.2	66.0	63.0	59.5	53.1	51.1	53.5	57.7	63.9	68.9	71.7
Sivas	76.2	74.2	68.8	63.7	63.1	60.9	58.5	57.7	59.2	66.4	73.4	76.5
Balıkesir	81.6	78.5	74.9	71.3	68.1	61.1	60.8	62.5	64.4	72.6	79.0	81.6

Figure 3.4. Average monthly relative humidity values measured at meteorological stations of five (5) provinces for 30 years between 1981-2010.

3.3.3 Wind Speed

The average monthly wind speed (1981-2010) graph of five (5) provinces is presented in Figure 3.5. Among all locations, 0.8 m/s is the slowest average monthly wind speed measurement recorded at Iğdır station in December, whereas 3.8 m/s is the fastest average monthly wind speed measurement recorded at Balıkesir station in July. Note that, the average monthly wind speed values of İzmir are more than 2.5m/s for all months in a year. On daily basis, the average wind speed values of İzmir (3.1 m/s) and Balıkesir (2.6 m/s) are quite higher than the remaining three (3) locations, namely Rize (1.3 m/s), Iğdır (1.2 m/s), and Sivas (1.2 m/s).

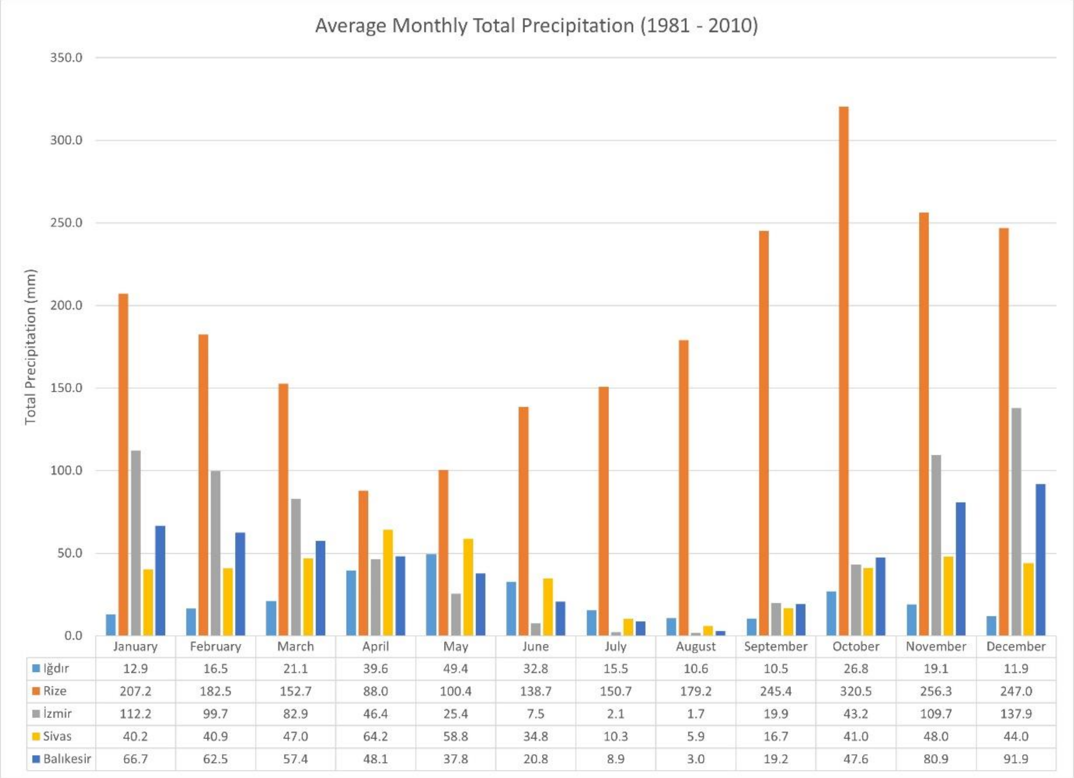


	January	February	March	April	May	June	July	August	September	October	November	December
Iğdır	0.9	1.2	1.6	1.6	1.4	1.5	1.5	1.4	1.2	0.9	0.9	0.8
Rize	1.3	1.3	1.4	1.4	1.3	1.4	1.3	1.2	1.3	1.2	1.3	1.3
İzmir	3.0	3.2	3.2	3.0	3.0	3.2	3.4	3.3	3.0	2.7	2.8	3.1
Sivas	1.0	1.3	1.4	1.5	1.3	1.4	1.4	1.3	1.0	0.9	0.9	1.0
Balıkesir	2.2	2.6	2.5	2.0	2.1	2.6	3.8	3.7	2.6	2.4	1.8	2.1

Figure 3.5. Average monthly wind speed values measured at meteorological stations of five (5) provinces for 30 years between 1981-2010.

3.3.4 Precipitation

The average monthly total precipitation (1981-2010) graph of five (5) provinces is presented in Figure 3.6. Among all locations, 1.7 mm is the driest average monthly total precipitation measurement recorded at İzmir station in August, whereas 320.5 mm is the wettest average monthly total precipitation measurement recorded at Rize station in October. Note that, the average monthly total precipitation values of Rize are always higher than the remaining locations. The average annual total precipitation values can be sorted as Rize (2268.5 mm), İzmir (688.5 mm), Balıkesir (544.8 mm), Sivas (451.7 mm) and Iğdır (266.8 mm) in descending order, respectively.

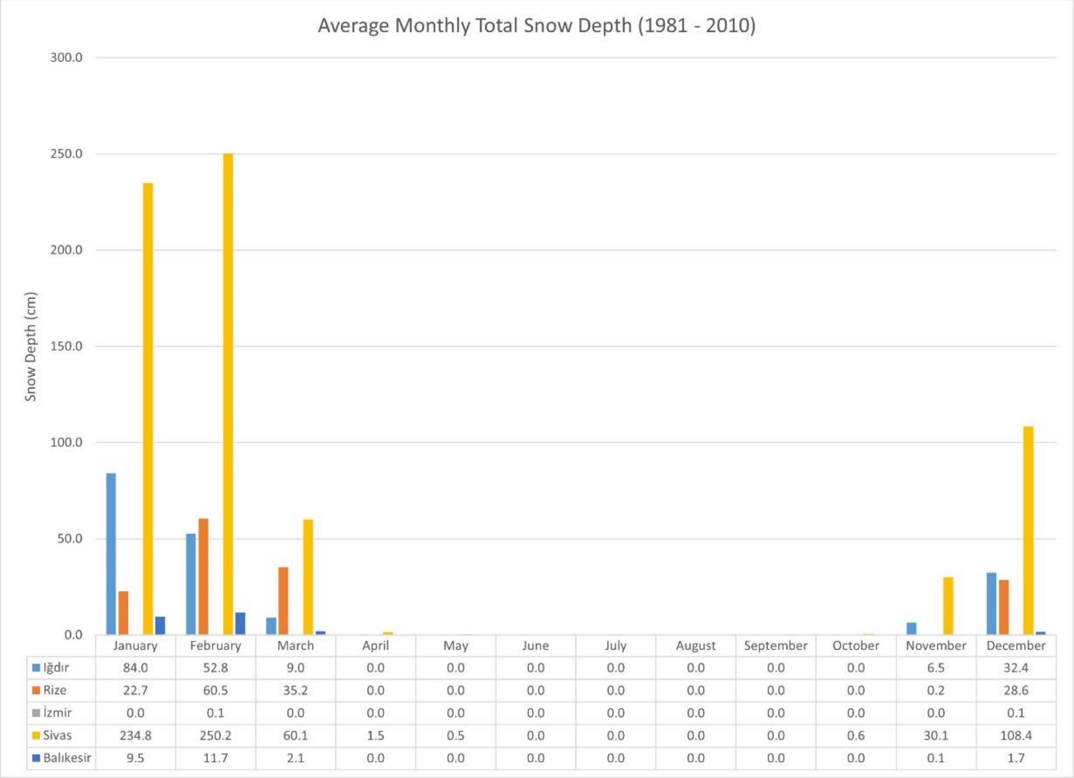


	January	February	March	April	May	June	July	August	September	October	November	December
■ Iğdır	12.9	16.5	21.1	39.6	49.4	32.8	15.5	10.6	10.5	26.8	19.1	11.9
■ Rize	207.2	182.5	152.7	88.0	100.4	138.7	150.7	179.2	245.4	320.5	256.3	247.0
■ İzmir	112.2	99.7	82.9	46.4	25.4	7.5	2.1	1.7	19.9	43.2	109.7	137.9
■ Sivas	40.2	40.9	47.0	64.2	58.8	34.8	10.3	5.9	16.7	41.0	48.0	44.0
■ Balıkesir	66.7	62.5	57.4	48.1	37.8	20.8	8.9	3.0	19.2	47.6	80.9	91.9

Figure 3.6. Average monthly total precipitation values measured at meteorological stations of five (5) provinces for 30 years between 1981-2010.

3.3.5 Snow Depth

The average monthly total snow depth (1981-2010) graph of five (5) provinces is presented in Figure 3.7. Among all locations, 250.2 cm is the highest average monthly total snow depth measurement recorded at Sivas station in February. There is no snow depth data recorded in June, July, August, and September months for all locations. The average annual total snow depth values can be sorted as Sivas (686.2 cm), Iğdır (184.7 cm), Rize (147.2 cm), Balıkesir (25.1 cm) and İzmir (0.2 cm) from highest to lowest, respectively.



	January	February	March	April	May	June	July	August	September	October	November	December
■ Iğdır	84.0	52.8	9.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.5	32.4
■ Rize	22.7	60.5	35.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	28.6
■ İzmir	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
■ Sivas	234.8	250.2	60.1	1.5	0.5	0.0	0.0	0.0	0.0	0.6	30.1	108.4
■ Balıkesir	9.5	11.7	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.7

Figure 3.7. Average monthly total snow depth values measured at meteorological stations of five (5) provinces for 30 years between 1981-2010.

3.4 Confirmation of the Climate Types of Selected Provinces with Meteorological Data obtained from MGM

As it was already mentioned in Section 3.2 that there is neither Type A (tropical humid) nor Type E (boreal) nor Type F (polar) climate classification in Turkey since the average temperature of the coldest month is not above 18 °C and all provinces have more than three (3) months which have average temperature values more than 10 °C.

In order to classify climate type of a province as Type B, threshold values (R) of all provinces were compared with the mean annual rainfall value in Table 3.3 as described in Section 3.1.2. the mean annual rainfall is less than the threshold value (R), then the location is classified as Type B – dry climate.

Table 3.3 Comparison of threshold value vs. mean annual rainfall value of the representative provinces

Province Name (Climate Type)	*Mean Annual Rainfall (in cm)*	*Threshold Value* R (in cm)*	*Result (Type B if Mean Annual Rainfall is less than R)*
Iğdır (BS)	26.7	40.2	Type B
Rize (Cf)	226.9	42.3	Not
İzmir (Cs)	68.9	27.6	Not
Sivas (Dc)	45.2	21.7	Not
Balıkesir (Do)	54.5	26.9	Not

*Threshold Values were calculated from the Equation *(3-1)*.

So, the sub-type of Iğdır is *BS*, since the mean annual rainfall is higher than R/2. On the other hand, Type C (see section 3.1.3) and Type D (see section 3.1.4) are defined based on the condition that the mean air temperature of 8 to 12 months (for Type C) and 4 to 7 months (for Type D) in a year is more than 10 °C. The number of months which have the mean air temperature more than 10 °C for İzmir, Rize, Sivas, and

Balıkesir are ten (10), eight (8), seven (7) and six (6), respectively (see section 3.3.1). Therefore, İzmir and Rize are classified as Type C while Sivas and Balıkesir are classified as Type D. Rize can be classified as *Cf* since there is no dry season, whereas İzmir can be classified as *Cs* since the summer is dry. Furthermore, Sivas and Balıkesir can be classified as *Dc* and *Do*, respectively, since the temperatures of the coldest months are less than 2 °C for Sivas and more than 2 °C for Balıkesir. As a result, it can be said that the representative provinces, that were selected for the analysis, are coherent with the Köppen-Trewartha Climate Classification criteria.

CHAPTER 4

METHODOLOGY

4.1 Introduction

In this study, numerical modeling with finite element method was used to simulate cover systems for reclamation of the waste rock dump. The model was created by using SEEP/W (Geoslope, 2012) software in order to evaluate performance of cover systems in different climate zones of Turkey.

A numerical model is the transformation of a real physical process into a computer based mathematical representation called as simulation. The purpose of creating a model is to represent the simplified version of the real system (Wang & Anderson, 1982).

Some of the advantages of the numerical modeling over physical modeling are;

- Numerical models can be set up and revised very quickly compared to physical models.
- Numerical models utilize computer power; therefore, a great number of alternatives or scenarios can be tested for the study by numerical modeling.
- Less physical effort required by numerical models, and
- Numerical models provide more information from the discretized sections of the model, which is not very likely by physical models.

The information regarding SEEP/W software is given in the following section.

4.2 Numerical Modeling with SEEP/W Software

SEEP/W is one of the most widely used two-dimensional (2-D) finite element software for simulating both liquid water and vapor transfer through saturated and unsaturated porous media such as soil and rock. From the simplest steady-state saturated conditions to very complex transient unsaturated/saturated conditions with atmospheric conditions at the ground can be modeled via SEEP/W (Geoslope, 2012; 2014; and 2021).

Typical application fields of SEEP/W related with hydrogeology are:

- Mining or municipal waste facilities: cover system design,
- Man-made or natural systems: infiltration and evapotranspiration processes,
- Dams or levees: Hydraulic response of the structures to fluctuations of water level,
- Earth slopes: Pore water pressure changes due to infiltration within the slopes,
- Water retention structures: Groundwater table mounding underneath these structures like tailing ponds and lagoons,
- Pumping wells: Drawdown of water table, and
- Pre-Construction: Dewatering design.

Three (3) basic steps for a seepage analysis are described in the following sections:

1. The numerical forms of the fundamental flow laws for both steady and transient states,
2. Material properties, and
3. Boundary conditions.

4.2.1 Fundamental Flow Laws

SEEP/W formulates the water flow through saturated and unsaturated media based on Darcy's Law (1856):

$$q = k * i \tag{4-1}$$

where:

q is the specific discharge,

k is the hydraulic conductivity, and

i is the gradient of total hydraulic head.

Darcy's Law was originally formulated for saturated medium; however, the studies (Richards, 1931 and Childs & Collins-George, 1950) have shown that it can also be applied to unsaturated medium under the condition that rather than being a constant, the hydraulic conductivity varies with water content and indirectly varies with pore water pressure.

For 2-D representation of liquid water flow through porous medium, the general governing differential equation is:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = \frac{\partial \theta}{\partial t} \tag{4-2}$$

where:

k_x and k_y are the hydraulic conductivities in the x and y directions,

H is the total head,

Q is the applied boundary flux,

θ is the volumetric water content, and t is the time.

For 2-D representation of liquid water and vapor flow through porous medium, the following general governing differential equation is used:

$$\frac{1}{\rho}\frac{\partial}{\partial x}\left(D_v\frac{\partial P_v}{\partial x}\right)+\frac{1}{\rho}\frac{\partial}{\partial y}\left(D_v\frac{\partial P_v}{\partial y}\right)+ \\ \frac{\partial}{\partial x}\left(k_x\frac{\partial\left(\frac{P}{\rho g}+y\right)}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial\left(\frac{P}{\rho g}+y\right)}{\partial y}\right) \\ +Q=\lambda\frac{\partial P}{\partial t} \qquad (4\text{-}3)$$

where:

ρ is the density of water,

P_v is the vapor pressure of soil moisture,

D_v is the vapor diffusion coefficient as described by Wilson (1990),

k_x and k_y are the hydraulic conductivities in the x and y directions,

P is the pressure,

g is the acceleration due to gravity,

y is the elevation head,

Q is the applied boundary flux,

λ is the storage term for transient flow, and

t is the time.

For 2-D heat transfer, the general governing differential equation is:

$$
\begin{gathered}
L_v \frac{\partial}{\partial x}\left(D_v \frac{\partial P_v}{\partial x}\right) + L_v \frac{\partial}{\partial y}\left(D_v \frac{\partial P_v}{\partial y}\right) + \\
\frac{\partial}{\partial x}\left(k_{tx} \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{ty} \frac{\partial T}{\partial y}\right) \\
\rho c V_x \frac{\partial T}{\partial x} + \rho c V_y \frac{\partial T}{\partial y} \\
+ Q_t = \lambda_t \frac{\partial T}{\partial t}
\end{gathered}
\qquad (4\text{-}4)
$$

where:

L_v is the latent heat of vaporization,

P_v is the vapor pressure of soil moisture,

D_v is the vapor diffusion coefficient as described by Wilson (1990),

k_{tx} and k_{ty} are the thermal conductivities in the x and y directions,

T is the temperature,

Q_t is the applied thermal boundary flux,

ρc is the volumetric specific heat value,

V_x and V_y are the Darcy water velocity in x and y directions, and

t is the time.

The interaction between land and climate can be simulated by applying a boundary condition in SEEP/W. Therefore, water balance calculations can be made using this Land-Climate Interaction (LCI) boundary condition. By this way, the net percolation through a cover system can be evaluated.

The basic surface mass balance equation is given below to calculate the water flux (q) at the ground surface:

$$q_P + q_M - q_{ET} - q_R = q_I \tag{4-5}$$

where:

P is the rainfall as an inflow,

M is the snow melt as an inflow,

E is the evapotranspiration as an outflow,

R is the surface runoff as an outflow, and

I is the net infiltration as a resultant.

Water flux of snow melt can be calculated based on the change in snow depth with respect to change in time multiplied by the ratio (≈10%) of snow density (≈100 kg/m^3) divided by water density (≈1000 kg/m^3):

$$q_M = \frac{\Delta h_{snow}}{\Delta t} \frac{\rho_{snow}}{\rho_{water}} \tag{4-6}$$

where:

Δh_{snow} is the change in the snow depth,

Δt is the time increment, and

$\rho_{snow,\ water}$ are the snow density and water density.

The actual evaporation can be calculated from the Penman-Wilson Evapotranspiration Method (Wilson et al., 1997):

$$q_{AE} = \frac{\Gamma q_n^* + \gamma E_a}{\Gamma + \gamma/h_s} \tag{4-7}$$

where:

q_{AE} is the actual evaporation flux,

Γ is the slope of saturation vapor pressure vs. temperature curve,

q_n^* is the net radiation in terms of water flux,

γ is the physchrometric constant (0.0665 kPa/°C),

E_a is the aridity $(2.625(1+0.146u))p_v^a(1/h_a - 1/h_s))$,

 u is the wind speed,

 p_v^a is the vapor pressure in the air,

 h_a is the relative humidity of air, and

 h_s is the relative humidity of soil.

Finally, the governing equation for 2-D finite element for both water and vapor flow can be derived by applying Galerkin method of weighted residual:

$$\begin{aligned} &t \int_A ([B]^T[C][B])\, dA\{P\} + t \int_A ([B]^T[D_2][B])\, dA\{T\} + \\ &t \int_A ([B]^T[K][B])\, dA\{y\} + t \int_A (\lambda\langle N\rangle^T\langle N\rangle)\, dA\{P\}, t = \\ &qt \int_L (\langle N\rangle^T)\, dL \end{aligned} \tag{4-8}$$

where:

t is the element thickness,

[B] is the gradient matrix,

[C] is the element stiffness matrix [K/ρg+D1],

D1 and D2 are coefficient matrices,

{P} is the vector of nodal pressures,

{y} is the vector of elevation heads,

[K] is the element hydraulic conductivity matrix,

ρ is the water density,

g is the gravitational constant,

λ is the storage term,

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

{P},t is the change in pressure with time,

q is the unit flux across the side of an element, and

<N> is the vector of interpolating function.

4.2.2 Material Properties

There exist two (2) important material properties in SEEP/W. One of them is volumetric water content function and the other one is hydraulic conductivity. If the medium is saturated, the hydraulic conductivity is referred as K_{sat}. On the other hand, if the medium is unsaturated, the hydraulic conductivity is described as a function that varies with changes in negative pore water pressure (or suction). The environments of saturated and unsaturated flows are presented in Figure 4.1.

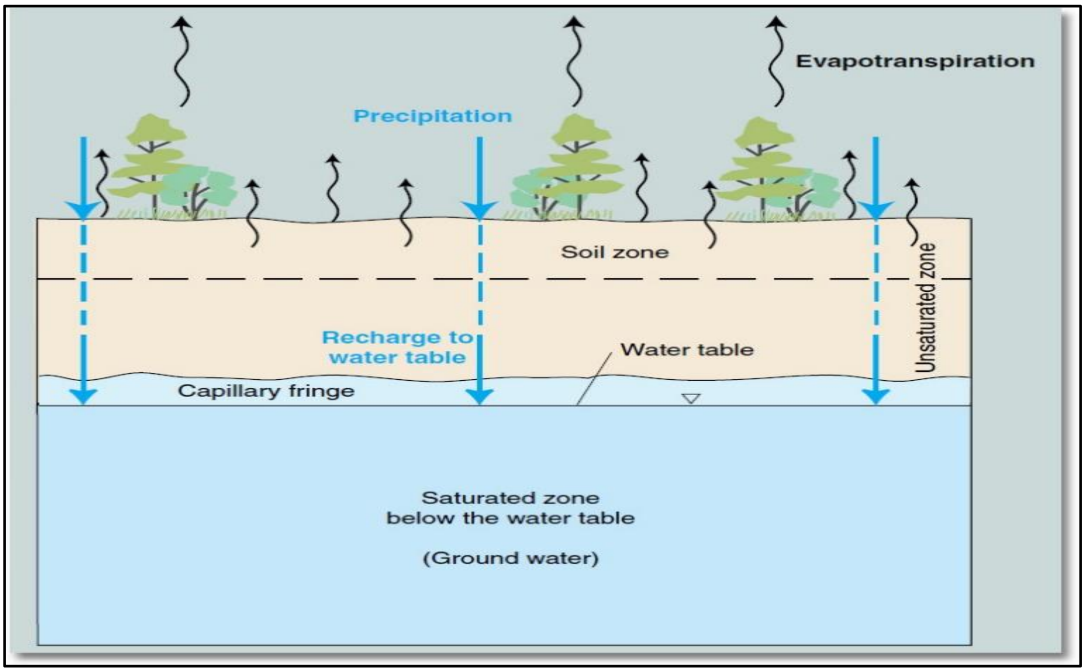


Figure 4.1. Saturated and unsaturated zones (USGS, n.d.)

All voids between soil particles are filled with water in saturated soil. Thus, it can be understood K_{sat} is the material property of the condition that a soil has the maximum ability to transport water. As it can be seen in Figure 4.2, it is more difficult for water (W) to flow when there are voids filled with air (A) between soil particles (SP). This difficulty results in a significantly lower hydraulic conductivity value for unsaturated flow. Moreover, residual water content is a state when there is no continuous flow path for water. Therefore, there is a reverse proportion between the degree of saturation and the amount of air voids in the soil medium.

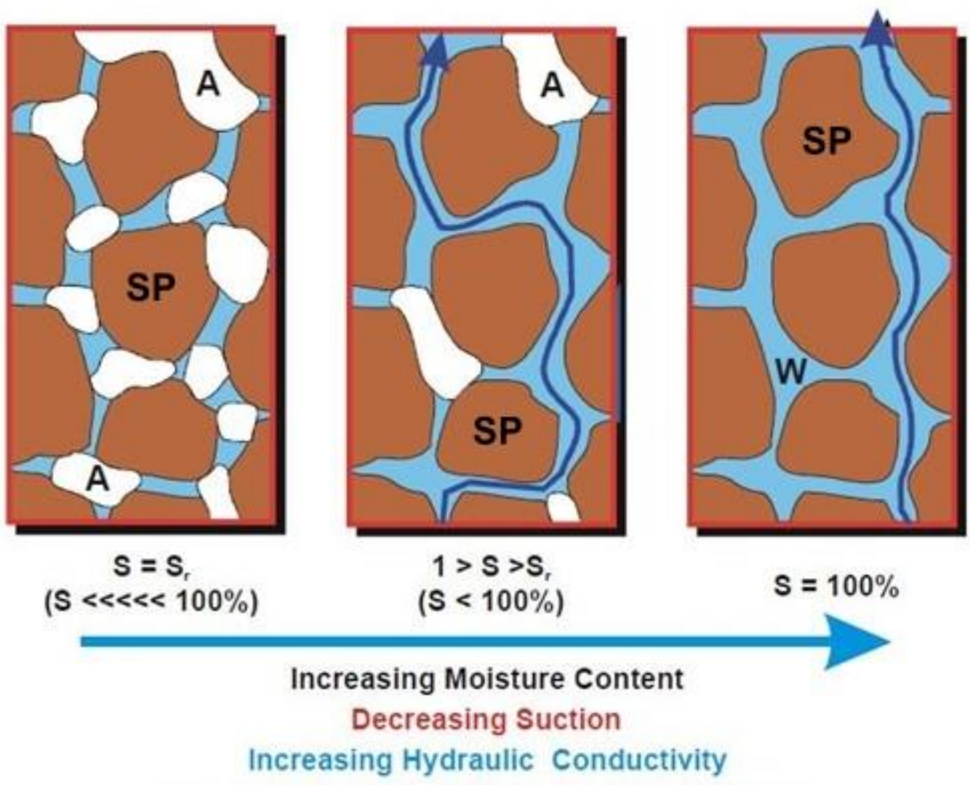


Figure 4.2. Schematic view of flow paths from residual (S_r) to saturation (S=100%) (O'Kane et. al., 2002)

In this study, unsaturated flow will be selected for both waste rock dump and materials in the cover system. Therefore, this section was mainly focused on unsaturated conditions.

4.2.2.1 Volumetric Water Content (VWC) Function

The relationship between the VWC (or degree of saturation) and pore water pressure (PWP) for different soil types can be seen in Figure 4.3. The horizontal axis shows the pore water pressure. There is a positive PWP on the left side whereas the negative PWP is presented on the right side of the coordinate system. When the PWP is equal to zero (0) the VWC is equal to the porosity of the soil. As water is draining out of the medium, the water content will decline, and then air will begin to enter in medium. This point is called as air entry value (AEV). While the water continues to drain out of the medium, the negative PWP (or suction) will be increased. Finally, the medium will reach to the residual water content. The slope of the curve is related to the type of soil material or grain size distribution.

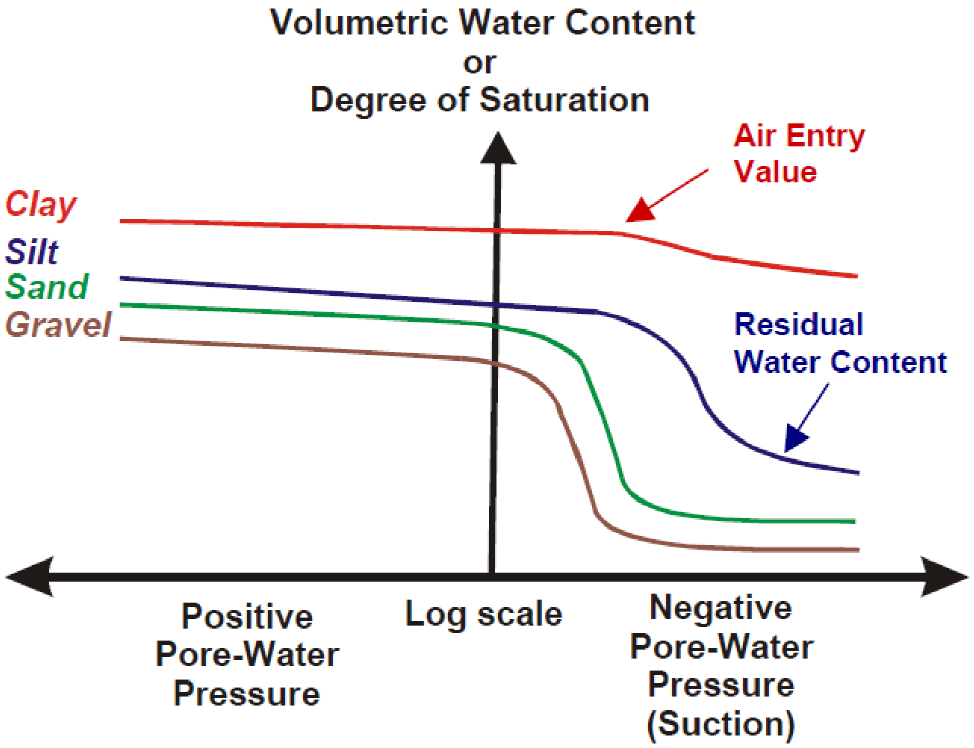


Figure 4.3. Soil-water characteristic curve for different soil types (MEND, 2004)

4.2.2.2 Hydraulic Conductivity Function

As it was already mentioned, the hydraulic conductivity (K) at unsaturated zone is not constant; on the contrary, it is a function of VWC. Furthermore, it is indirectly related to the negative PWP (or suction). The shape of conductivity function is derived from VWC function. Similarly, as water drains out of the porous medium (or the degree of saturation decreases, or negative PWP and suction increases), the hydraulic conductivity gets lower as it can be seen in Figure 4.4.

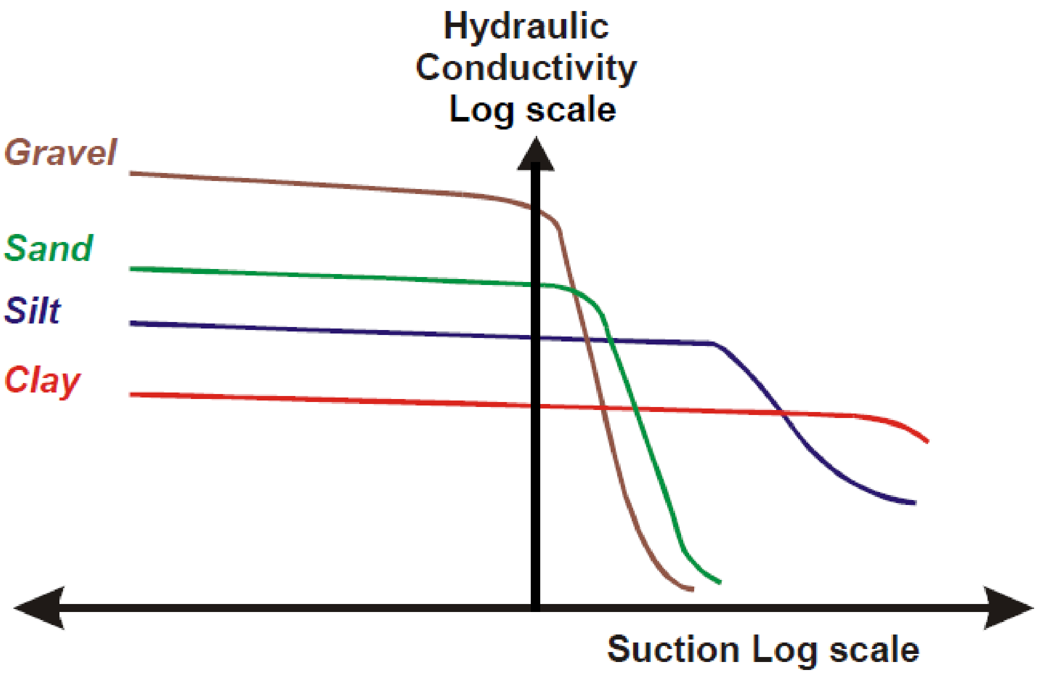


Figure 4.4. K as a function of suction for different soil types (MEND, 2004)

In SEEP/W, there are pre-defined functions of some soil types, namely clay, silty clay, silt, silty sand, sand, and gravel for the estimation of VWC function. Otherwise, grain-size distribution data or other estimation techniques are required for the estimation of VWC function.

Van Genuchten Method (1980) is a widely used estimation technique for VWC function. The equation of Van Genuchten can be stated as in Equation (4-9):

$$\theta_w = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + \left(\frac{\Psi}{a}\right)^n\right]^m} \tag{4-9}$$

where:

θ_w is the VWC,

$\theta_{s,r}$ are the saturated and residual VWC,

Ψ is the negative PWP,

a is the air entry value,

n control the slope of the curve, and

m controls residual water content (also m=1-1/n).

Van Genuchten Method was used in this study for estimating VWC function of topsoil and WRD. Pre-defined functions were used for the remaining soil types in the cover systems. The information regarding the data used for estimation of Van Genutchen parameters is given in section 5.2.

Once the VWC function is estimated, now it is time to estimate hydraulic conductivity function by using VWC function and K_{sat} value. In order to do so, another formula of Van Genutchen Method (1980) was used:

$$k_w = k_{sat} + \frac{\left[1 - (a\Psi^{(n-1)})\left(1 + (a\Psi^{(n)})^{-m}\right)\right]^2}{[(1 + a\Psi)^n]^{\frac{m}{2}}} \tag{4-10}$$

where:

k_w is the unsaturated hydraulic conductivity,

k_s is the saturated hydraulic conductivity,

Ψ is the required suction range, and

a, n and m are the curve fitting parameters.

In this study, all hydraulic conductivity functions were estimated using VWC functions and K_{sat} values. K_{sat} value for a given material type was obtained from the literature. K_{sat} values of materials obtained from the literature studies were listed in Table 4.1 together with the related cover types.

Table 4.1 K_{sat} values of material types used in different cover types

Material Type	**K_{sat} (m/sec)***	**Cover Type**				
		Basic Erosion Protection	**Store & Release**	**Enhanced Store & Release**	**Barrier Type**	**TMWR Type**
WRD Layer	1.00E-05	X	X	X	X	X
Topsoil Layer	1.60E-06	X	X	X	X	X
Storage Layer	1.40E-06		X	X	X	
Reduced Permeability Layer	5.56E-08			X		
Low Permeability Layer	1.00E-09				X	X
Drainage Layer	4.70E-03					X

* References of K_{sat} values obtained from literature studies will be given in the related sections of Chapter 5.

4.2.2.3 Other Properties

In addition to hydraulic properties mentioned above, there are also thermal properties of a medium. Parameters of a simplified thermal model are thermal conductivity and volumetric heat capacity. Constant values were assigned for these parameters as it was assigned in the similar work of Geoslope’s Vadose Tutorial document (2008).

Unfrozen thermal conductivity: 0.0017 kJ/sec/m/°C

Frozen thermal conductivity: 0.0014 kJ/sec/m/°C

Unfrozen volumetric heat capacity: 2500 kJ/m^3/°C

Frozen volumetric heat capacity: 2300 kJ/m^3/°C

4.2.3 Boundary Conditions

Boundary conditions (BCs) that were used in this study are summarized below:

4.2.3.1 Water Table and Zero Pressure BC

Bottom of the model area was bounded by the water table to set the PWP of the basement of WRD (bottom of the model) as zero (0). Thus, negative PWP values were distributed to the remaining of the model area for creating a model area with unsaturated flow. In order to prevent ponding of water at the bottom of the model (in WRD), the water pressure head at the bottom of the model was set to zero (0). Because the main concern in the study is to evaluate the performance of the cover system.

Similar application of water table and zero pressure boundary condition was observed from two (2) solution examples of Geoslope (2017a) and Geoslope (2017b).

4.2.3.2 Drainage BC and no flow BC

Drainage type of boundary condition was used when a drainage material (gravel) is used in the cover system. It helps to drain out the water from the system with specific properties of the material to an outer collection system.

The remaining part that is not assigned drainage BC of the left and right sides of the model will be act as a no flow boundary similar to study of Garneau et. al. (2016).

4.2.3.3 Land-Climate Interaction BC

Land-climate interaction (LCI) is the final and the most important boundary condition since it computes water balance calculations (see Equation (4-5), (4-7) and (4-7)). LCI is assigned to the upper surface of the model where topsoil is located. The required inputs of the LCI boundary condition are:

- Air temperature,
- Relative Humidity,
- Wind Speed,
- Precipitation,
- Snow Depth,
- Radiation, and
- Vegetation data.

Daily measurements recorded by MGM were used for air temperature, relative humidity, wind speed, precipitation, and snow depth parameters. Daily minimum and maximum measurements (see Appendix A for monthly average graphs) were used for air temperature and relative humidity parameters by applying a min/max sinusoidal distribution to represent the difference between day and night. While the daily average measurements were assigned for wind speed, daily total measurements were assigned for both precipitation and snow depth parameters.

Radiation data was estimated with the property of SEEP/W using the latitude of locations (see Table 3.2) and the project dates (from January 01, 1981 to December 31, 2010). The estimated daily solar radiation flux values were given in Figure 4.5. According to this graph, İzmir has higher and Rize has lower values since İzmir is located at relatively south and Rize is located at relatively north of the remaining locations (Iğdır, Rize and Sivas). On the other hand, Iğdır, Rize, and Sivas have similar solar radiation flux values because their latitudes are also similar.

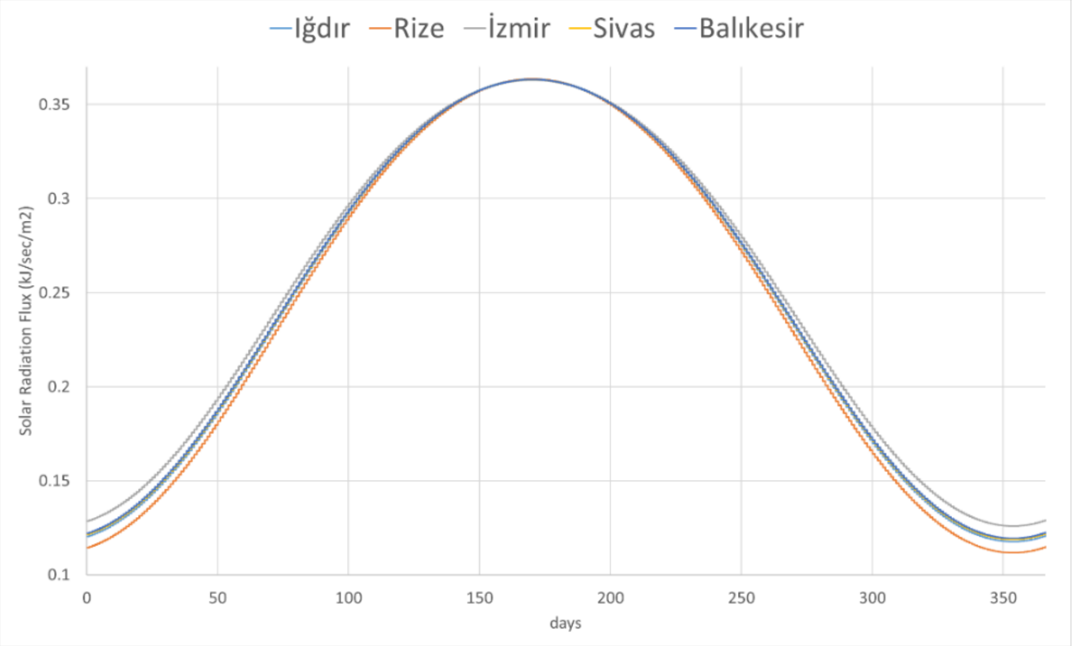


Figure 4.5. Estimated solar radiation flux values for the study areas

Vegetation data comprise of the following parameters:

- Leaf area index,
- Plant moisture limit,
- Root depth,
- Normalized root density, and
- Soil cover fraction.

Although vegetation data of all locations would probably be different from each other in real case, the same properties of grass was assigned to all climates. By this means, cover performances will be compared with each other independent from the different vegetation species, and also the impact of transpiration will be lowered for creating more challenge for cover system performances.

The parameters for grass type vegetation are assigned by using two (2) solution examples of Geoslope (2017b) and Geoslope (2017c). While the functions for grass type vegetation were used for plant moisture limit, normalized root density and soil cover fraction parameters, constant values for leaf area index as one (1) and root depth as 0.25 m were assigned similarly to the two (2) aforementioned solution examples.

CHAPTER 5

COVER SYSTEM ALTERNATIVES

5.1 Introduction

In this chapter, performances of cover system alternatives will be evaluated in terms of their long-term (30 years from January 01, 1981, through December 31, 2010) performances. A hypothetical model will be created with WRD and cover system materials. The performance evaluation will be conducted by comparing the water ingress (net percolation) amounts into the WRD.

Twenty-five (25) model results were obtained in order to evaluate five (5) cover system alternatives, namely basic erosion protection, store & release, enhanced store & release, barrier-type and TMWR type, for five (5) representative locations, namely Iğdır (BS), Rize (Cf), İzmir (Cs), Sivas (Dc), and Balıkesir (Do). Additional five (5) model results were obtained to compare the cover system performances for a specific climate type by using Tatvan station from Bitlis (Dc).

The main properties of the models were explained in this section, and specific parts of the models were explained in the related sections.

5.1.1 Time Steps

A transient seepage analysis for a duration of 10,957 days (or for 30 years) with a time increment 0.5 day was run in order to include minimum and maximum temperature and relative humidity values representing midnight and midday hours. Thus, the number of time steps is equal to 21,914 (2 times 10,957 days). The steps were increased linearly during the analysis.

5.1.2 Model Geometry and Discretization

In order to reduce simulation time from weeks to hours, model geometry was defined as simple as possible. The WRD is represented by 10 m x 10 m square with an element size of 0.5 m which is the optimum size suggested by the software. However, the size of the elements was adjusted with respect to the position of the area of interest. The element size was increased up to 0.75 m at the bottom of the model, where it is away from the area of interest. On the other hand, a special type of layering was applied to the surface in order to calculate the critical mass balance process by using finer discretization near ground surface. These surface layers are very beneficial especially for cover studies since it can create several relatively thin layers for detailed analysis. In this study, surface layers were generated between 10 cm and 25 cm. Mesh pattern consists of both triangles and quadrilaterals to get more efficient results by easily fitting to the geometry.

5.1.3 Material Properties

General information about the thermal and hydraulic properties of a material was already discussed in detail in Section 4.2.2. In this section, the hydraulic properties of WRD material are detailed. Volumetric Water Content (VWC) function and hydraulic conductivity (K) function of WRD was estimated by Van Genuchten Method (see Equation (4-9) and Equation (4-10)). The data required for this method was gathered from the literature as it is presented in Table 5.1. Mean values of Van Genuchten parameters were calculated from a total of thirty-one (31) different waste parameters. The studies and the waste types are also summarized in the Table 5.1.

Table 5.1 Van Genuchten parameters gathered from literature to estimate hydraulic properties of WRD material

Source	**Waste Type**	**a - air entry value in kPa**	**n - controls slope of the curve**	**m (1 – 1/n)**	**θs - sat. water content**	**θr - res. water content**	**Ksat (m/s)**
Lamontagne et. al. (2000)	Copper/Zinc Waste	12.50	2.22	0.55	0.38	0.26	1.00E-07
Qui & Sego (2000)	Gold Waste	6.00	1.33	0.25	0.45	0.00	4.30E-07
Noel and Rykaart (2003)	Weathered Waste Rock	0.56	1.09	0.08	0.31	0.00	8.30E-08
Noel and Rykaart (2003)	Mine Waste Rock	7.54	1.18	0.15	0.24	0.00	1.40E-07
Golder (2006)	Copper Waste Rock	0.65	1.16	0.14	0.21	0.00	7.30E-06
Golder (2006)	Copper Waste Rock	0.57	1.18	0.15	0.23	0.00	8.50E-06
Golder (2006)	Copper Waste Rock	0.97	1.17	0.14	0.30	0.00	5.10E-06
Golder (2006)	Copper Waste Rock	0.77	1.17	0.15	0.26	0.00	8.40E-06
Golder (2006)	Copper Waste Rock	0.72	1.18	0.15	0.28	0.00	1.40E-05
Golder (2006)	Copper Waste Rock	1.62	1.20	0.16	0.27	0.00	1.60E-06
Golder (2006)	Copper Waste Rock	2.16	1.20	0.16	0.17	0.00	7.10E-07
Golder (2006)	Copper Waste Rock	1.56	1.19	0.16	0.18	0.00	8.50E-07
Azam et. al. (2007)	Gold Waste Rock	8.08	3.13	0.68	0.31	0.14	3.50E-05
Azam et. al. (2007)	Gold Waste Rock	3.98	1.56	0.36	0.30	0.19	3.50E-05
Azam et. al. (2007)	Gold Waste Rock	7.70	4.17	0.76	0.22	0.12	3.50E-05
Demers et. al. (2010)	Mine Waste Rock	1.64	3.61	0.72	0.35	0.07	5.00E-04
Hopp et. al. (2011)	Silver Waste Rock	1.81	2.03	0.51	0.41	0.01	2.00E-05
Neuner et. al. (2013)	Diamond Waste Rock	6.25	4.00	0.75	0.07	0.01	1.00E-02
Broda et. al. (2014)	Coarse Grained Waste Rock	0.34	9.60	0.90	0.24	0.06	1.00E-03
Hajizadeh (2014)	Coal Waste Rock	0.79	3.30	0.70	0.43	0.02	1.75E-06
Hajizadeh (2014)	Coal Waste Rock	0.59	3.20	0.69	0.39	0.02	2.58E-06
Hajizadeh (2014)	Coal Waste Rock	0.22	3.40	0.71	0.51	0.01	3.90E-06
Hajizadeh (2014)	Coal Waste Rock	0.35	3.30	0.70	0.40	0.01	8.44E-06
SRK (2015)	Gold Waste Rock	1.81	2.03	0.51	0.41	0.01	2.00E-05
SRK (2015)	Gold Waste Rock - finer	0.30	1.22	0.18	0.36	0.00	5.54E-05
SRK (2015)	Gold Waste Rock - coarser	4.90	2.50	0.60	0.45	0.02	5.79E-05
Gonzales (2016)	Mine Waste Rock	2.00	5.75	0.83	0.47	0.00	4.89E-04
Blackmore et. al. (2018)	Copper/Zinc Waste Rock	3.50	1.22	0.18	0.23	0.05	4.63E-05
Blackmore et. al. (2018)	Copper/Zinc Waste Rock	5.45	1.30	0.23	0.24	0.15	6.94E-07
Blackmore et. al. (2018)	Copper/Zinc Waste Rock	1.66	1.50	0.33	0.29	0.06	9.26E-05
Raymond et. al. (2021)	Mine Waste Rock	1.96	2.70	0.63	0.30	0.22	1.00E-05
Geometric mean values used in this study for WRD		**1.66**	**2.00**	**0.34**	**0.29**	**0.05**	**1.00E-05**

The graph of VWC function estimated by Van Genuchten Method using the mean values calculated in Table 5.2 for WRD is given in Figure 5.1.

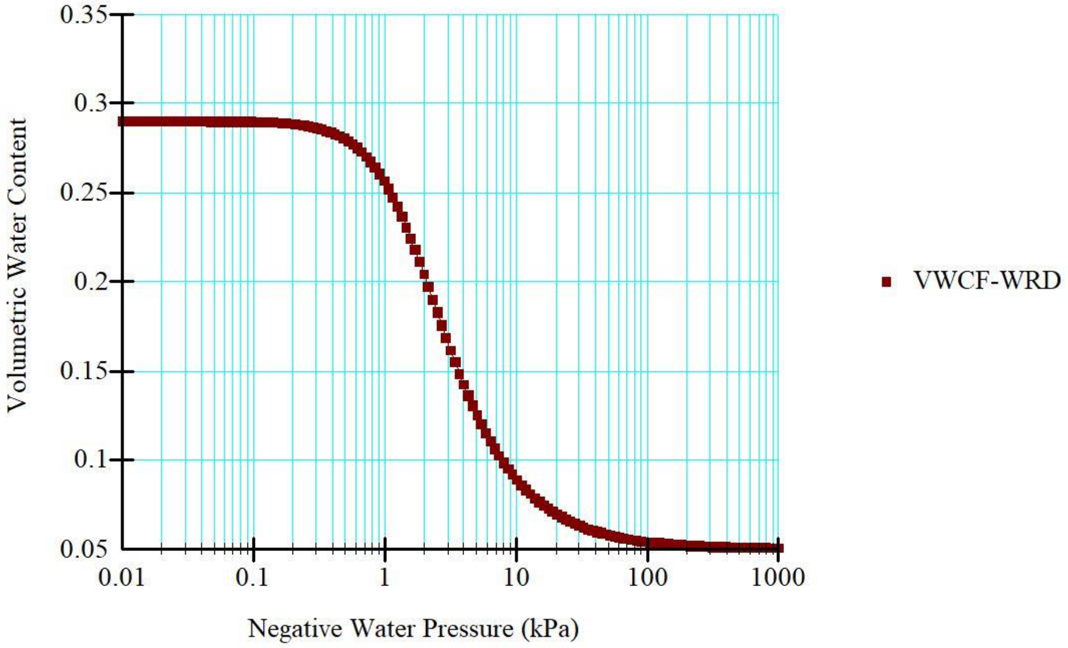


Figure 5.1. VWC function estimated for WRD

The graph of K function estimated by Van Genuchten Method using the mean values calculated for WRD is also given in Figure 5.2.

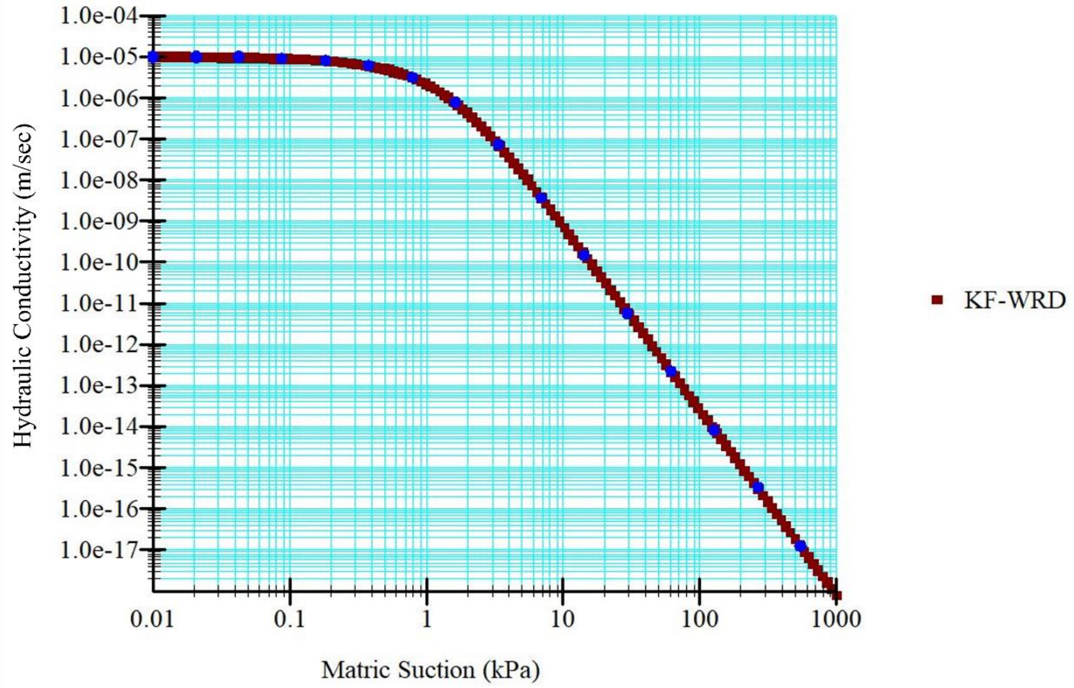


Figure 5.2. K function estimated for WRD

5.2 Performances of Cover System Alternatives

Performances of cover system alternatives were evaluated herein. As explained before in section 5.1, each cover system alternative was evaluated for five (5) representative locations, namely Iğdır (BS), Rize (Cf), İzmir (Cs), Sivas (Dc), and Balıkesir (Do). The performance results of cover system alternatives are given in the related sections:

- Basic Erosion Protection Cover System (5.2.1),
- Store & Release Cover System (5.2.2),
- Enhanced Store & Release Cover System (5.2.3),
- Barrier-Type Cover System (5.2.4), and
- TMWR-Type Cover System (5.2.5).

Main properties of the cover system types were explained in detail in section 2.1.

5.2.1 Performance of Basic Erosion Protection Cover System

Since the main purpose of this cover system is to protect the waste from erosion, not to control water ingress, only a 0.3 m thick topsoil layer seeded with native grass was placed over the waste rock dump (Figure 5.3).

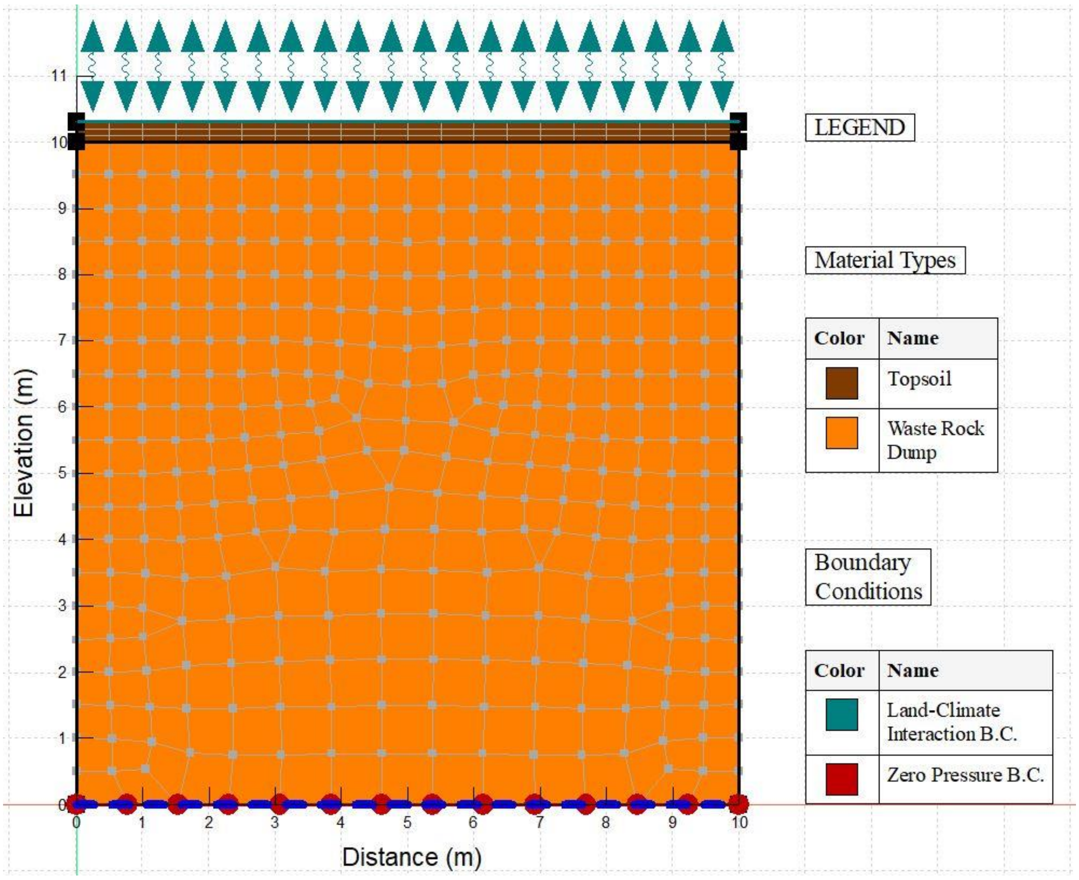


Figure 5.3. Cover System Alternative 1 – Basic Erosion Protection

The parameters required to use Van Genuchten Method for topsoil was gathered from the literature as it is presented in Table 5.2. Mean values of Van Genuchten parameters were calculated from totally three (3) different topsoil/growth medium parameters. The studies and the material types are also summarized in Table 5.2.

Table 5.2 Van Genuchten parameters gathered from literature to estimate hydraulic properties of topsoil material

Source	**Material Type**	**a (air entry value) in kPa**	**n (controls slope of the curve)**	**m (controls res. water content)**	**θs (sat. water content)**	**θr (res. water content)**	**Ksat (m/s)**
Noel and Rykaart (2003)	Topsoil	6.41	1.11	0.10	0.40	0.00	6.50E-06
Hopp et al. (2011)	Growth medium	28.76	1.18	0.15	0.31	0.08	2.28E-05
Benson & Bareither (2012)	Topsoil	20.16	1.33	0.25	0.50	0.00	2.80E-08
MEAN VALUES used in this study for Topsoil		**15.49**	**1.20**	**0.15**	**0.40**	**0.03**	**1.60E-06**

The graph of VWC functions estimated by Van Genuchten Method using the mean values calculated for WRD and topsoil are given in Figure 5.4.

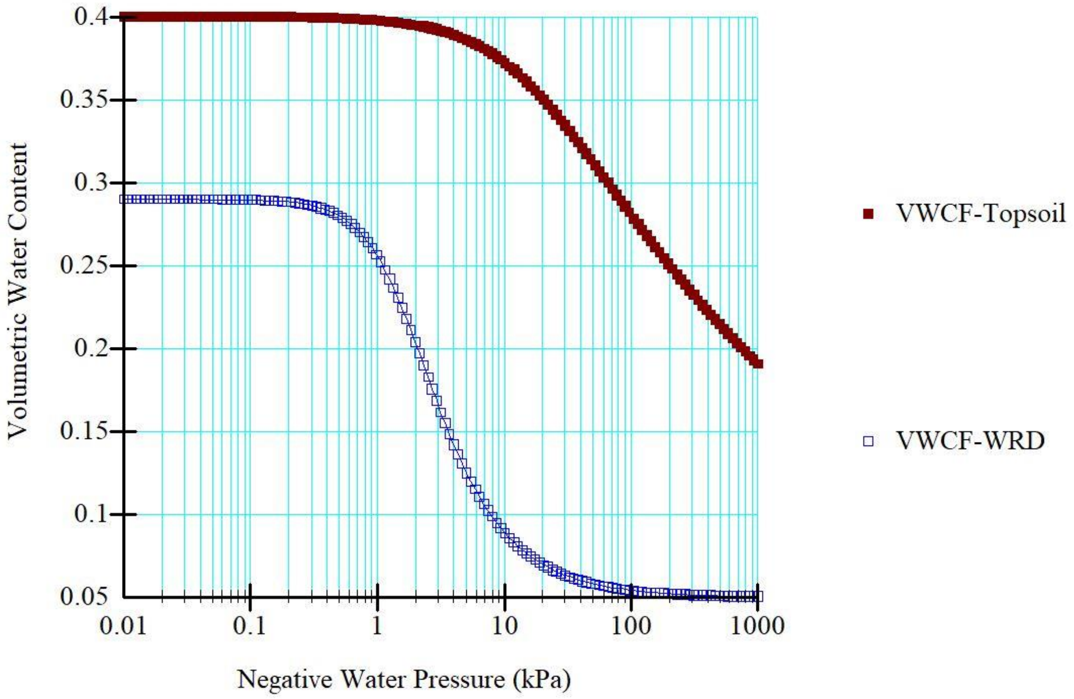


Figure 5.4. VWC function estimated for topsoil and WRD

The graph of K functions estimated by Van Genuchten Method using the mean values calculated for WRD and topsoil are given in Figure 5.5.

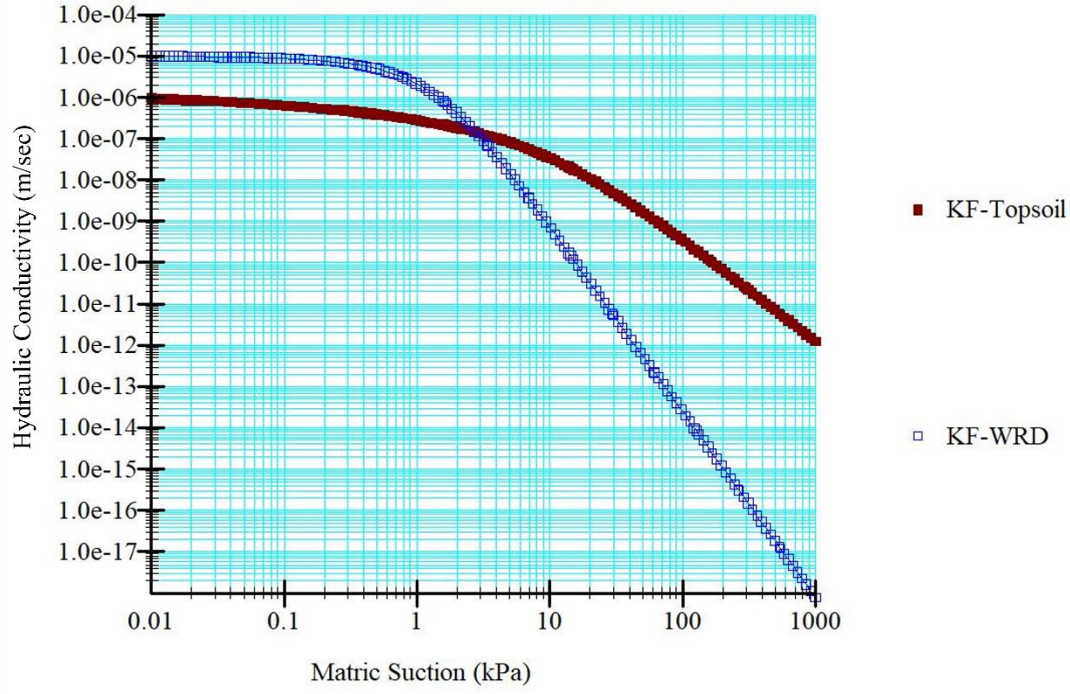


Figure 5.5. K function estimated for topsoil and WRD

The transient seepage analysis for a duration of 10,957 days (or for 30 years) with a time increment 0.5 day was run for five (5) representative locations. The water balance results were given in Table 5.3.

Table 5.3 Water Balance Result for Cover System Alternative 1 – Basic Erosion Protection Cover System

Location – Climate Zone	**Unit**	**Parameters**						
		Rainfall	**Snow melt***	**Evapo-transpiration**	**Surface Runoff**	**Net Infiltration**	**Storage**	**Net Percolation**
Iğdır – BS	mm/year	235.8	13.5	155.4	97.4	-3.5	-3.5	≈0.0
	mm/year	249.3		249.3			-3.5	
	%	94.6	5.4	62.3	39.1	-1.4	-1.4	**0.0**
Rize – Cf	mm/year	2188.0	35.7	696.7	97.6	1429.5	23.8	1405.7
	mm/year	2223.8		2223.8			1429.5	
	%	98.4	1.6	31.3	4.4	64.3	1.1	**63.2**
İzmir – Cs	mm/year	683.4	0.2	286.3	145.1	252.2	16.5	235.7
	mm/year	683.6		683.6			252.2	
	%	100.0	0.0	41.9	21.2	36.9	2.4	**34.5**
Sivas – Dc	mm/year	346.7	38.0	265.3	82.5	36.9	9.6	27.3
	mm/year	384.8		384.8			36.9	
	%	90.1	9.9	69.0	21.4	9.6	2.5	**7.1**
Balıkesir – Do	mm/year	501.5	4.7	244.9	130.6	130.7	14.0	116.7
	mm/year	506.2		506.2			130.7	
	%	99.1	0.9	48.4	25.8	25.8	2.8	**23.0**

*Water equivalent of snow melt.

At the end of 30 years, the water balance result revealed that the amount of net percolation into WRD is higher in Rize with 1405.7 mm per year. This means 63.2% of precipitation (as both rainfall and snow) in Rize reaches to WRD if this type of cover system is constructed in Rize. On the other hand, almost 0.0% net percolation was observed in Iğdır. Interestingly, there is negative storage in the system due to very dry climate condition. The remaining locations, namely, İzmir, Balıkesir, and Sivas, have net percolation percentages of 27.3%, 23.0% and 7.1%, respectively. It can be said that very low (<5.0%) net percolation rate was achieved only in Iğdır for Basic Erosion Protection Cover System.

5.2.2 Performance of Store & Release Cover System

In addition to 0.3 m thick topsoil layer, there exists a storage layer with a thickness of 1.0 m between topsoil and WRD in order to increase evapotranspiration rates by providing more water for vegetation (Figure 5.6).

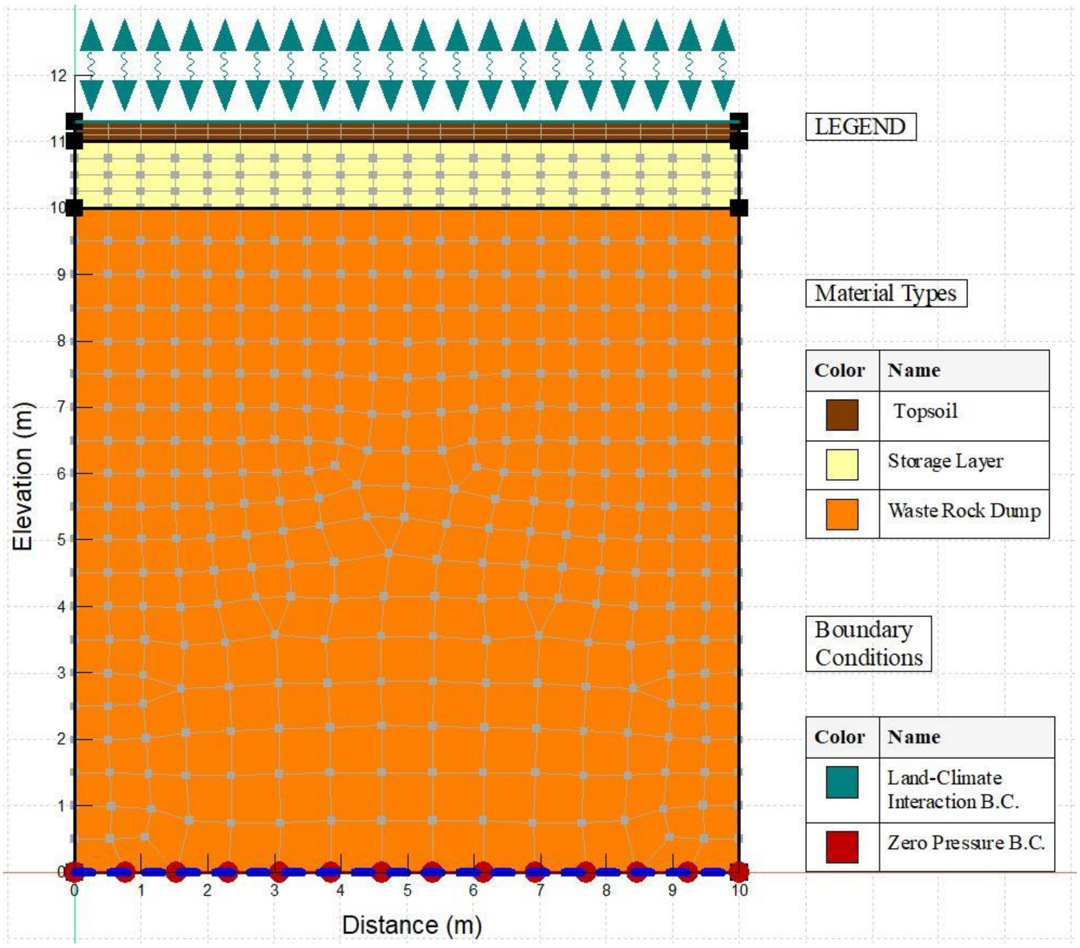


Figure 5.6. Cover System Alternative 2 – Store & Release

The hydraulic data required for storage layer was estimated from the pre-defined functions library of SEEP/W. Silty sand was used as a well-graded storage layer. Additional information regarding saturated VWC and saturated K values of silty sand was gathered from the similar work of Stormont & Morris (1998). According to this study, saturated VWC value and saturated K value of silty sand were determined as 0.442 and 1.40×10^{-6} m/s, respectively.

In addition to VWC functions of WRD and topsoil, VWC function estimated using the pre-defined functions library of SEEP/W for storage layer is also presented in Figure 5.7.

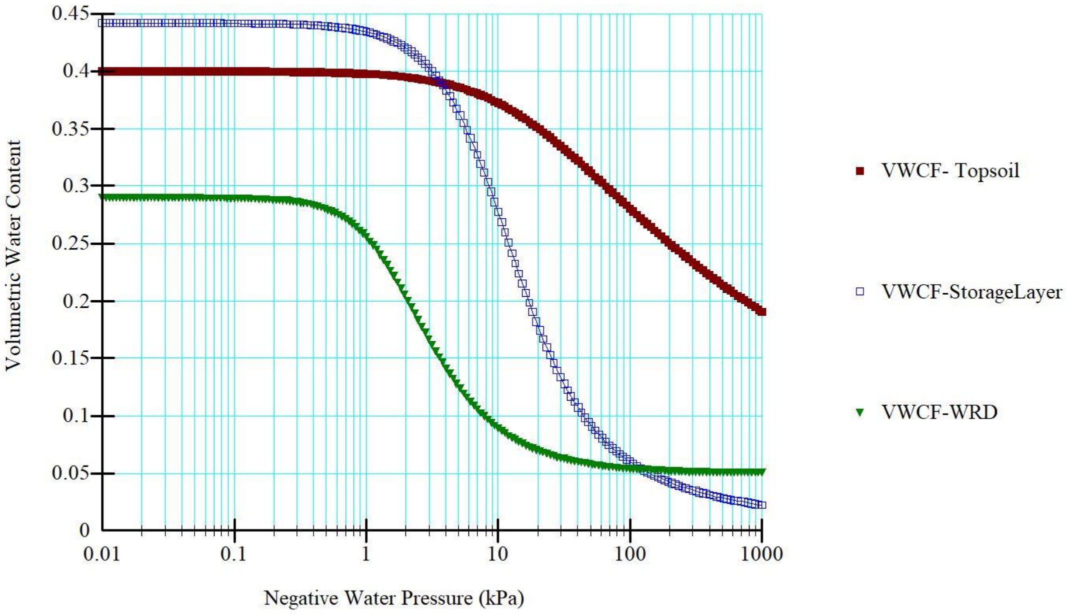


Figure 5.7. VWC function estimated for topsoil, storage layer, and WRD

The graph of K functions estimated by Van Genuchten Method for WRD, storage layer, and topsoil are given in Figure 5.8.

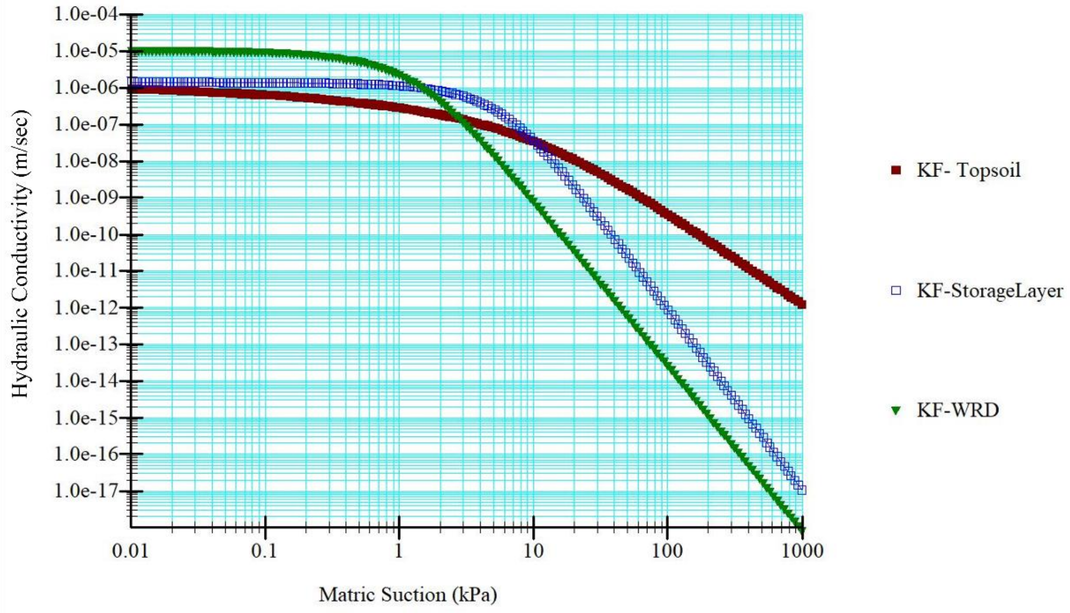


Figure 5.8. K function estimated for topsoil, storage layer, and WRD

The transient seepage analysis for a duration of 10,957 days (or for 30 years) with a time increment 0.5 day was run for five (5) representative locations. The water balance results were given in Table 5.4.

Table 5.4 Water Balance Result for Cover System Alternative 2 – Store & Release Cover System

Location-Climate Zone	**Unit**	**Parameters**						
		Rainfall	**Snow melt***	**Evapo-transpiration**	**Surface Runoff**	**Net Infiltration**	**Storage**	**Net Percolation**
Iğdır – BS	mm/year	235.8	13.5	157.6	97.6	-5.9	-5.9	≈0.0
	mm/year	249.3		249.3			-5.9	
	%	94.6	5.4	63.2	39.2	-2.4	-2.4	**0.0**
Rize – Cf	mm/year	2188.0	35.7	772.3	34.2	1417.3	28.8	1388.5
	mm/year	2223.8		2223.8			1417.3	
	%	98.4	1.6	34.7	1.5	63.7	1.3	**62.4**
İzmir – Cs	mm/year	683.4	0.2	356.4	148.9	178.3	19.0	159.3
	mm/year	683.6		683.6			178.3	
	%	100.0	0.0	52.1	21.8	26.1	2.8	**23.3**
Sivas – Dc	mm/year	346.7	38.0	295.4	80.1	9.3	7.0	2.3
	mm/year	384.8		384.8			9.3	
	%	90.1	9.9	76.8	20.8	2.4	1.8	**0.6**
Balıkesir – Do	mm/year	501.5	4.7	290.0	129.1	87.1	15.7	71.4
	mm/year	506.2		506.2			87.1	
	%	99.1	0.9	57.3	25.5	17.2	3.1	**14.1**

*Water equivalent of snow melt.

At the end of 30 years, the water balance result revealed that the amount of net percolation into WRD is higher in Rize again with 1388.5 mm per year. This means 62.4% of precipitation (as both rainfall and snow) in Rize reaches to WRD if this type of cover system is constructed in Rize. On the other hand, almost 0.0% net percolation was observed in Iğdır. One more time, there is negative storage in the system due to very dry climate condition. The remaining locations, namely, İzmir, Balıkesir, and Sivas, have net percolation percentages of 23.3%, 14.1% and 0.6%, respectively. It can be observed that evapotranspiration rates were increased for all locations, in parallel with the purpose of this cover system. According to results, very low (<5.0%) net percolation rates were achieved in Iğdır and Sivas for Store & Release Cover System.

5.2.3 Performance of Enhanced Store & Release Cover System

In order to limit net percolation (more than store & release cover system) into WRD, this cover system has an additional reduced permeability layer placed between the overlying storage layer and underlying WRD to increase the storage capacity compared to store & release cover system (Figure 5.9). The lower half of the storage layer (0.5 m) was replaced with low permeability layer in this case.

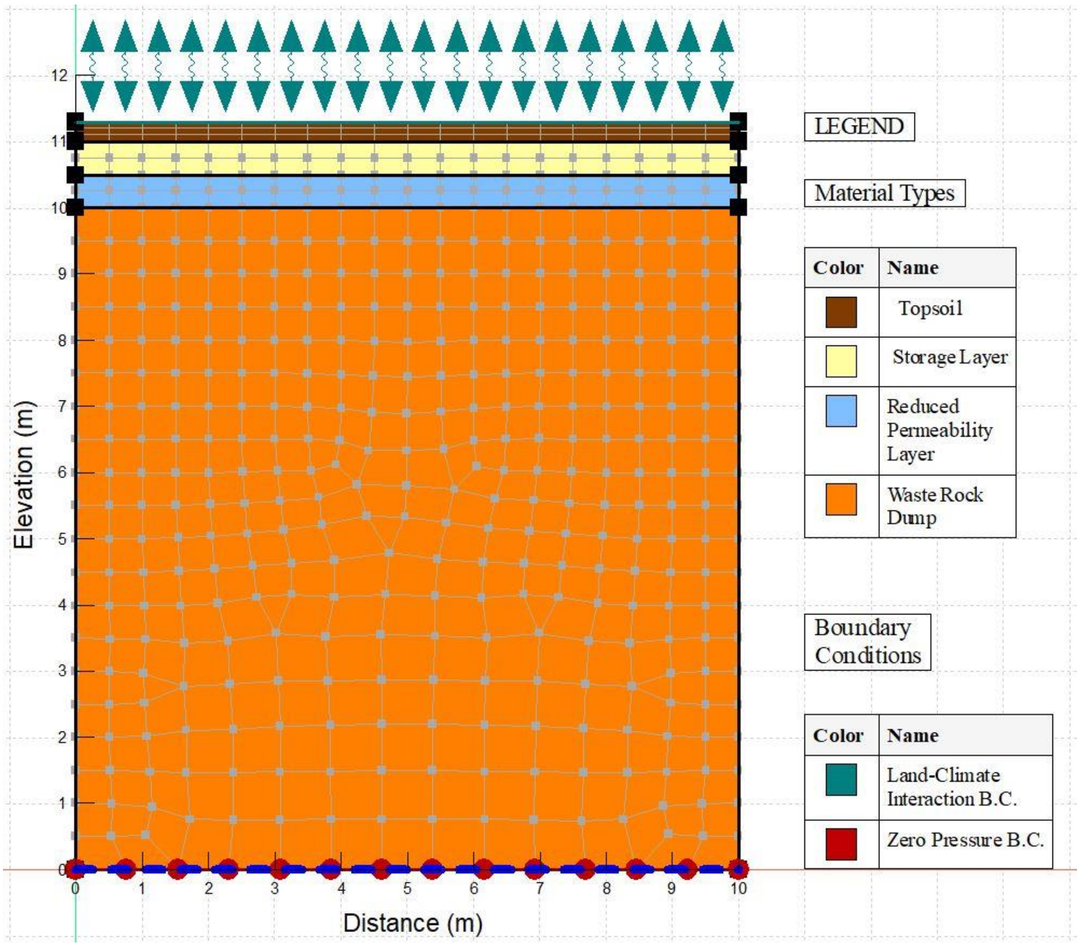


Figure 5.9. Cover System Alternative 3 – Enhanced Store & Release

The hydraulic parameters required for reduced permeability layer was also estimated from the pre-defined functions library of SEEP/W. Since compacted weathered waste rock or compacted locally available silt/clay deposits can be used as the reduced permeability layer, silty clay was used as a reduced permeability layer. Additional information regarding saturated VWC and saturated K values of silty clay was gathered from unsaturated hydraulic functions table of UNSODA (1996). According to this table, saturated VWC value and saturated K value of silty clay were determined as 0.36 and 5.56x10^{-8} m/s, respectively.

In addition to VWC functions of WRD and topsoil, VWC functions estimated using the pre-defined functions library of SEEP/W for reduced permeability layer, and storage layer are also presented in Figure 5.10.

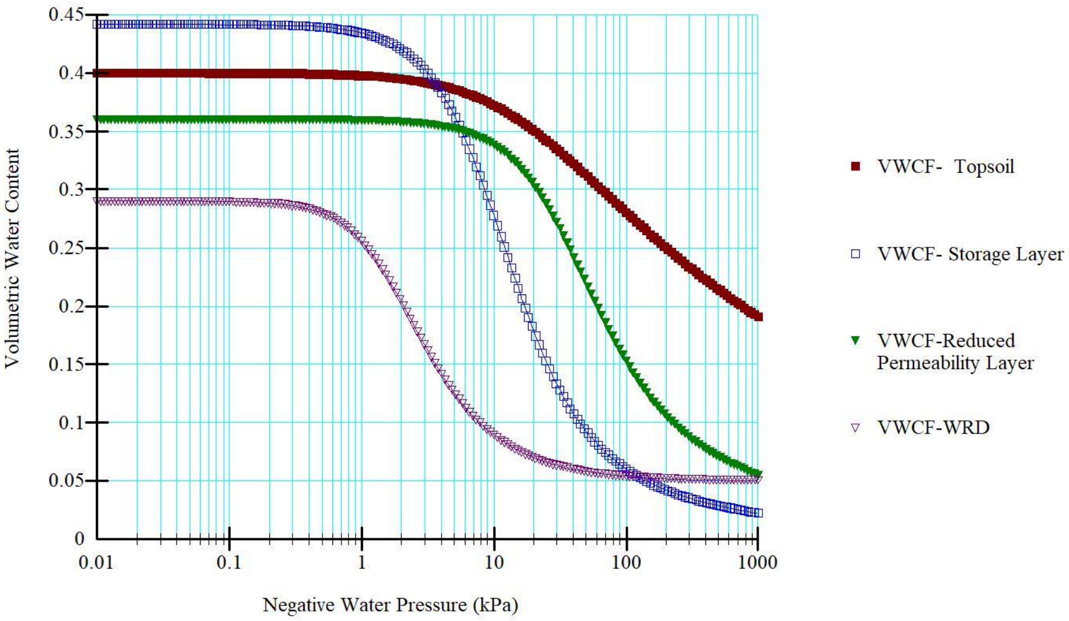


Figure 5.10. VWC function estimated for topsoil, storage layer, reduced permeability layer, and WRD

The graph of K functions estimated by Van Genuchten Method for WRD, reduced permeability layer, storage layer, and topsoil are given in Figure 5.11.

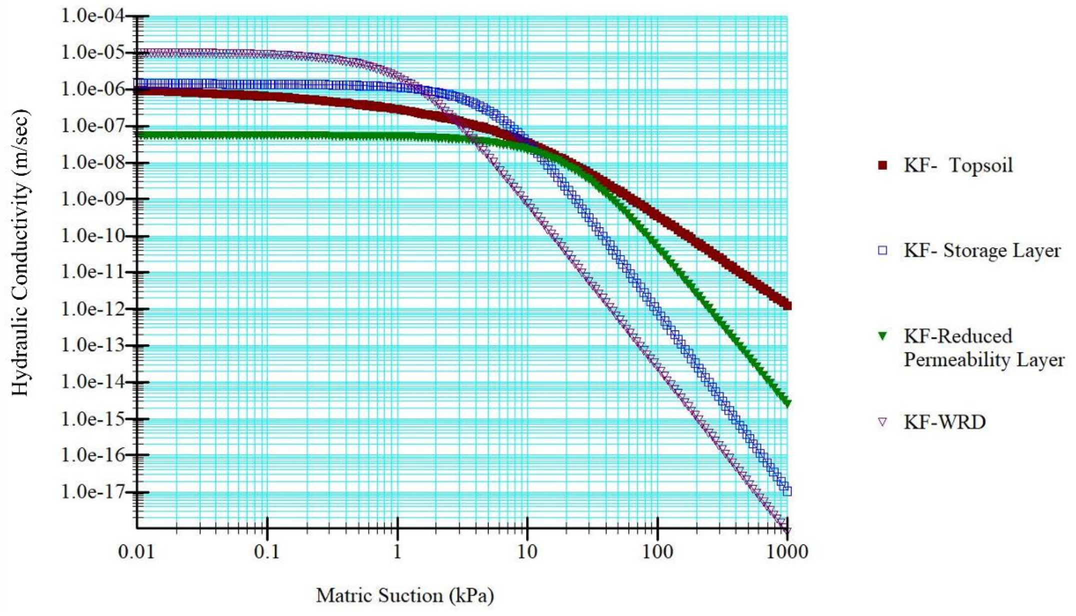


Figure 5.11. K function estimated for topsoil, storage layer, reduced permeability layer, and WRD

The transient seepage analysis for a duration of 10,957 days (or for 30 years) with a time increment 0.5 day was run for five (5) representative locations. The water balance results were given in Table 5.5.

Table 5.5 Water Balance Result for Cover System Alternative 3 – Enhanced Store & Release Cover System

Location-Climate Zone	**Unit**	**Parameters**						
		Rainfall	**Snow melt***	**Evapo-transpiration**	**Surface Runoff**	**Net Infiltration**	**Storage**	**Net Percolation**
Iğdır – BS	mm/year	235.8	13.5	158.1	97.6	-6.4	-6.4	≈0.0
	mm/year	249.3		249.3			-6.4	
	%	94.6	5.4	63.4	39.2	-2.6	-2.6	**0.0**
Rize – Cf	mm/year	2188.0	35.7	779.3	245.6	1198.8	28.1	1170.7
	mm/year	2223.8		2223.8			1198.8	
	%	98.4	1.6	35.0	11.0	53.9	1.3	**52.6**
İzmir – Cs	mm/year	683.4	0.2	362.6	150.1	170.9	18.3	152.6
	mm/year	683.6		683.6			170.9	
	%	100.0	0.0	53.0	22.0	25.0	2.7	**22.3**
Sivas – Dc	mm/year	346.7	38.0	295.8	80.5	8.5	6.6	1.9
	mm/year	384.8		384.8			8.5	
	%	90.1	9.9	76.9	20.9	2.2	1.7	**0.5**
Balıkesir – Do	mm/year	501.5	4.7	292.7	129.1	84.4	16.7	67.7
	mm/year	506.2		506.2			84.4	
	%	99.1	0.9	57.8	25.5	16.7	3.3	**13.4**

*Water equivalent of snow melt.

At the end of 30 years, the water balance result revealed that the amount of net percolation into WRD is higher in Rize again with 1198.8 mm per year. This means 52.6% of precipitation (as both rainfall and snow) in Rize reaches to WRD if this type of cover system is constructed in Rize. On the other hand, almost 0.0% net percolation was observed in Iğdır. One more time, there is negative storage in the system due to very dry climate condition. The remaining locations, namely, İzmir, Balıkesir, and Sivas, have net percolation percentages of 22.3%, 13.4% and 0.5%, respectively. It can be observed that evapotranspiration rates were increased for all locations, in parallel with the enhanced purpose of this cover system. Similar to Store & Release Cover System, very low (<5.0%) net percolation rates were achieved in Iğdır and Sivas for Enhanced Store & Release Cover System.

5.2.4 Performance of Barrier Type Cover System

Instead of having a reduced permeability layer (likewise enhanced store & release system), there exists a low permeability barrier layer ($\leq 1.0 \times 10^{-9}$ m/s) on the top of the WRD to limit net percolation into WRD (Figure 5.12). In this type of cover system, the thickness of topsoil could be increased, or a storage layer can be placed to prevent damage caused by surface runoff.

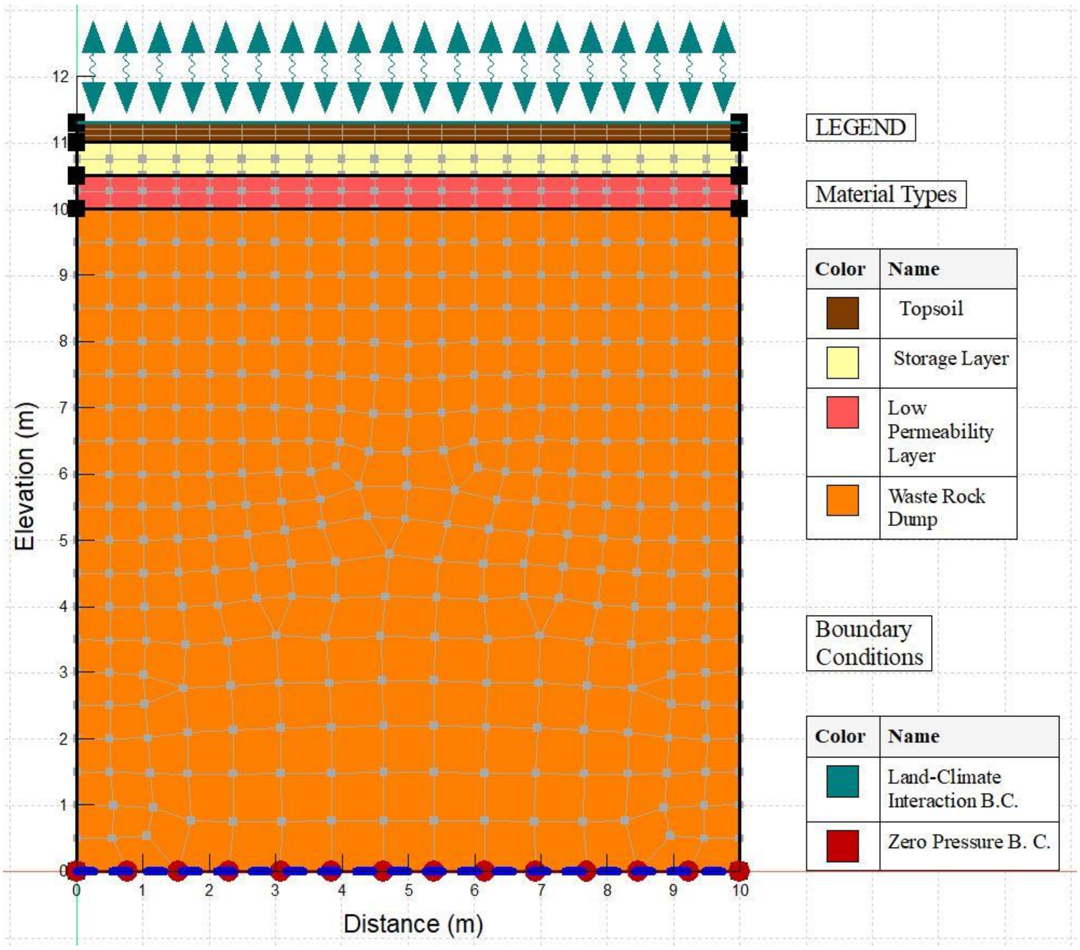


Figure 5.12. Cover System Alternative 4 – Barrier Type

The hydraulic parameters required for low permeability layer was also estimated from the pre-defined functions library of SEEP/W. Clay was used as a low permeability layer. Additional information regarding saturated VWC value of clay was gathered from unsaturated hydraulic functions table of UNSODA (1996). According to this table, saturated VWC value of clay was determined as 0.38. The saturated K value was assigned as 1.0x10^{-9} m/s as per minimum cover system requirement.

In addition to VWC functions of WRD and topsoil, VWC functions estimated using the pre-defined functions library of SEEP/W for low permeability layer, and storage layer are also presented in Figure 5.13.

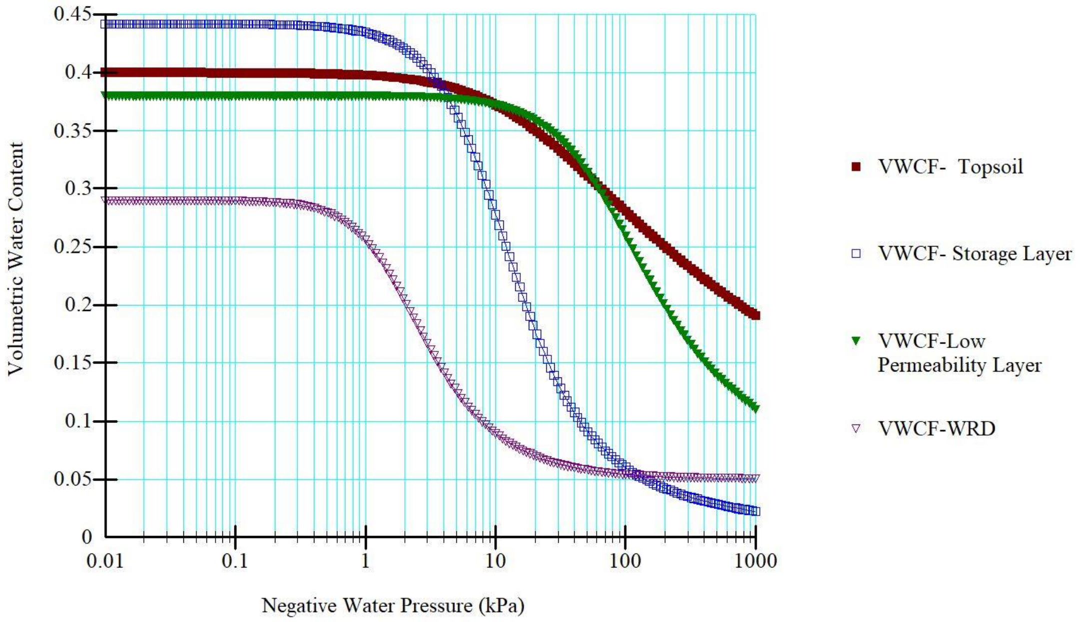


Figure 5.13. VWC function estimated for topsoil, storage layer, low permeability layer, and WRD

The graph of K functions estimated by Van Genuchten Method for WRD, low permeability layer, storage layer, and topsoil are given in Figure 5.14.

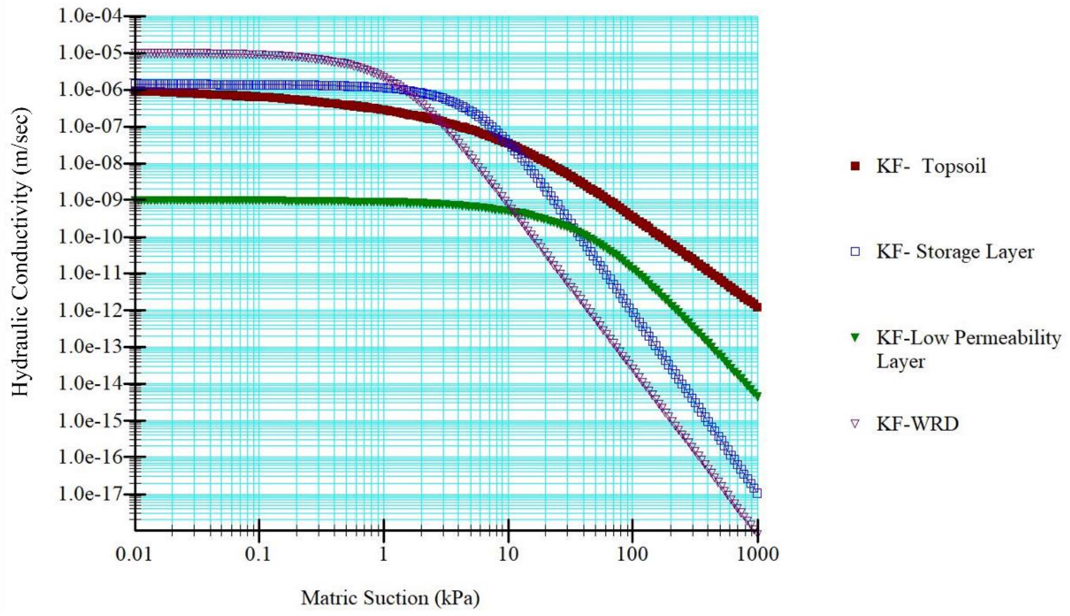


Figure 5.14. K function estimated for topsoil, storage layer, low permeability layer, and WRD

The transient seepage analysis for a duration of 10,957 days (or for 30 years) with a time increment 0.5 day was run for five (5) representative locations. The water balance results were given in Table 5.6.

Table 5.6 Water Balance Result for Cover System Alternative 4 – Barrier Type Cover System

Location-Climate Zone	Unit	Parameters						
		Rainfall	Snow melt*	Evapo-transpiration	Surface Runoff	Net Infiltration	Storage	Net Percolation
Iğdır – BS	mm/year	235.8	13.5	158.1	97.6	-6.4	-6.4	≈0.0
	mm/year	249.3		249.3			-6.4	
	%	94.6	5.4	63.4	39.2	-2.6	-2.6	**0.0**
Rize – Cf	mm/year	2188.0	35.7	842.3	1301.8	79.7	19.2	60.4
	mm/year	2223.8		2223.8			79.7	
	%	98.4	1.6	37.9	58.5	3.6	0.9	**2.7**
İzmir – Cs	mm/year	683.4	0.2	447.1	213.0	23.5	13.7	9.8
	mm/year	683.6		683.6			23.5	
	%	100.0	0.0	65.4	31.2	3.4	2.0	**1.4**
Sivas – Dc	mm/year	346.7	38.0	303.4	79.4	2.0	2.0	≈0.0
	mm/year	384.8		384.8			2.0	
	%	90.1	9.9	78.9	20.6	0.5	0.5	**0.0**
Balıkesir - Do	mm/year	501.5	4.7	352.2	136.7	17.4	10.2	7.2
	mm/year	506.2		506.2			17.4	
	%	99.1	0.9	69.6	27.0	3.4	2.0	**1.4**

*Water equivalent of snow melt.

At the end of 30 years, the water balance result revealed that the amounts of net percolations for all locations, except Iğdır, decreased dramatically. Iğdır has already the minimum percolation rates (almost 0.0%) for all alternatives. Similarly, almost 0.0% net percolation was also observed in Sivas for this type of cover system. The remaining locations, namely, Rize, İzmir, and Balıkesir have net percolation percentages of 2.7%, 1.4%, and 1.4%, respectively. It can be observed that evapotranspiration rates were increased for all locations compared to previous alternatives. Finally, very low (<5.0%) net percolation rates were achieved in all locations for Barrier Type Cover System. However, it is observed that the amount of surface runoff was elevated for Rize during the analysis due to limitation of net percolation using a barrier layer, and evapotranspiration capacity during wet days was insufficient.

5.2.5 Performance of TMWR Type Cover System

This type of cover system is required by Turkish Mining Waste Regulation (TMWR). From bottom to top, it has a buffer layer for final grading, a clay layer for reducing permeability, a drainage layer for discharging the water from the system, and a topsoil layer for growing vegetation (Figure 5.15), respectively. Layer thicknesses of clay layer and drainage layer are determined as 0.30m and 0.25m, respectively. These are the minimum lift thicknesses described in Technical Specifications of Filling Works published by State Hydraulic Works (DSI, 2014).

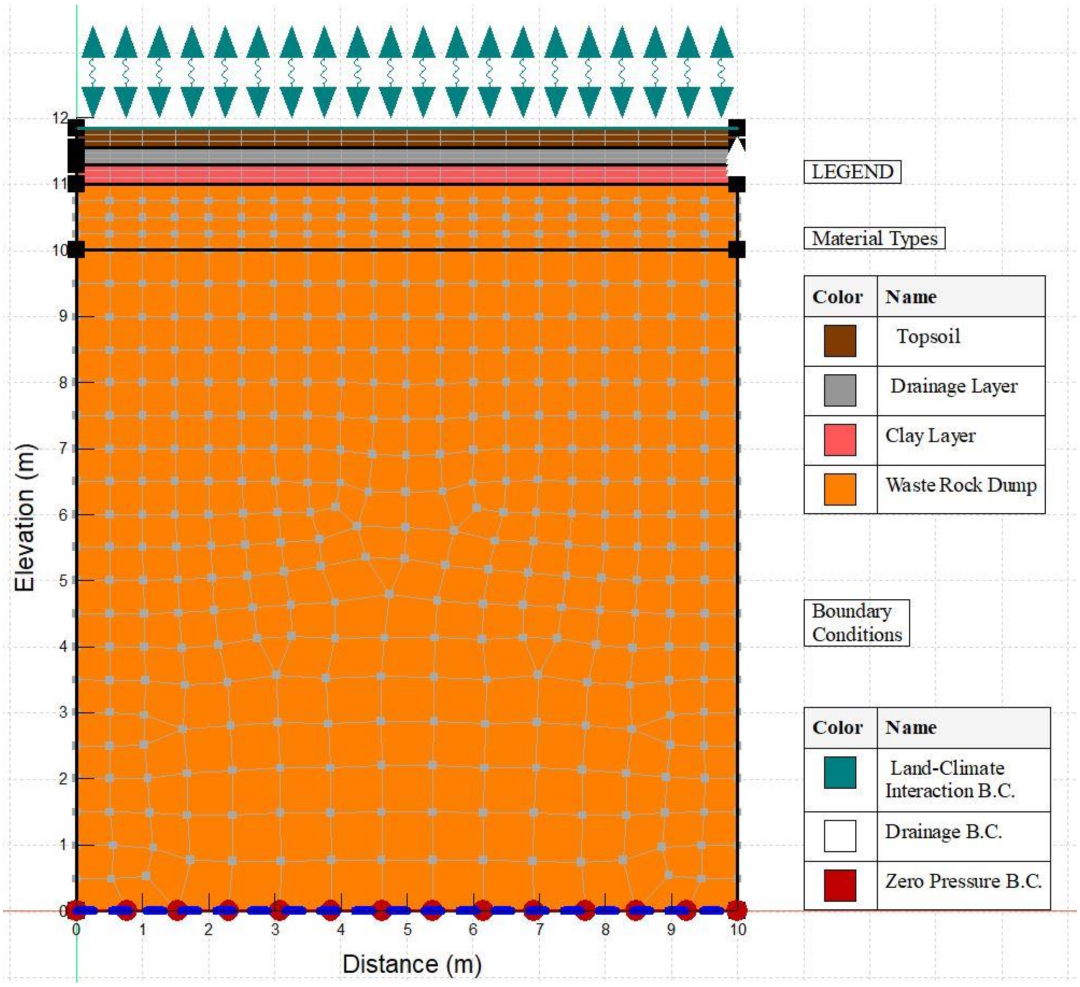


Figure 5.15. Cover System Alternative 5 – TMWR Type

It can be seen that there exists an additional type of boundary condition called as Drainage boundary condition for drainage layer (gravel). This type of boundary condition helps to discharge water from the cover system with the technical specification of assigned layer.

The hydraulic data required for clay layer and drainage layer were also estimated from the pre-defined functions library of SEEP/W. Clay and gravel type materials were used as clay layer and drainage layer. Additional information regarding saturated VWC value of clay was gathered from unsaturated hydraulic functions table of UNSODA (1996). According to this table, saturated VWC value of clay was determined as 0.38. The saturated K value was assigned as $1.0\text{x}10^{-9}$ m/s as per technical specifications of filling works document (DSI, 2014). On the other hand, VWC value of gravel was gathered from similar works of Dawood & Aubertin (2009) and Fala et. al. (2011). According to these studies, saturated VWC value and saturated K value of gravel were determined as 0.39 and $4.70\text{x}10^{-3}$ m/s, respectively. K_{sat} value used in aforementioned studies are also coherent with DSI (2014).

In addition to VWC functions of WRD and topsoil, VWC functions estimated using the pre-defined functions library of SEEP/W for clay layer, and drainage layer are also presented in Figure 5.16.

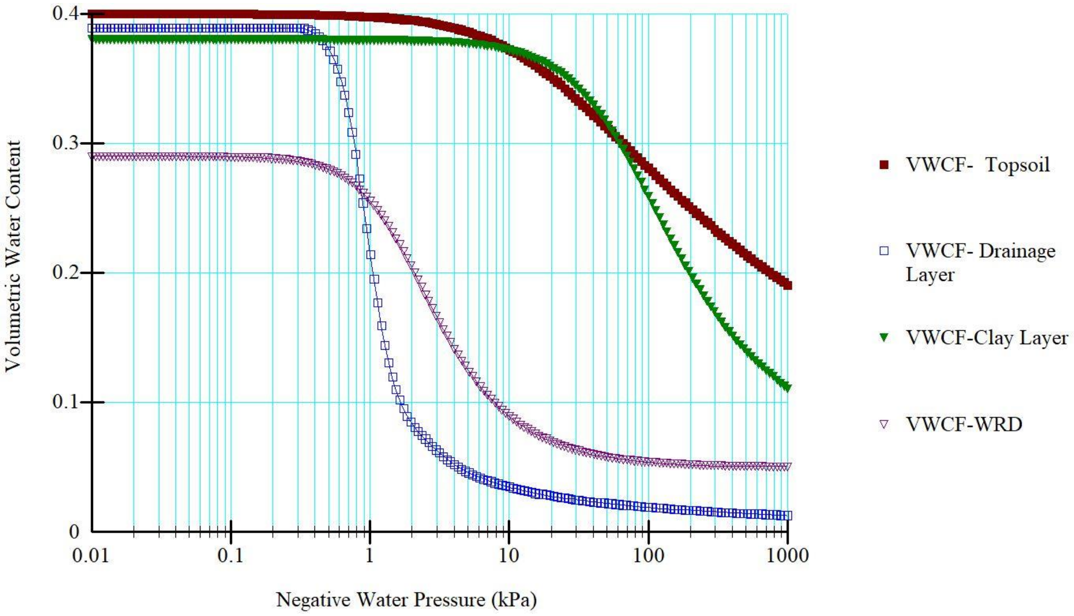


Figure 5.16. VWC function estimated for topsoil, drainage layer, clay layer, and WRD

The graph of K functions estimated by Van Genuchten Method for WRD, low permeability layer, storage layer, and topsoil are given in Figure 5.17.

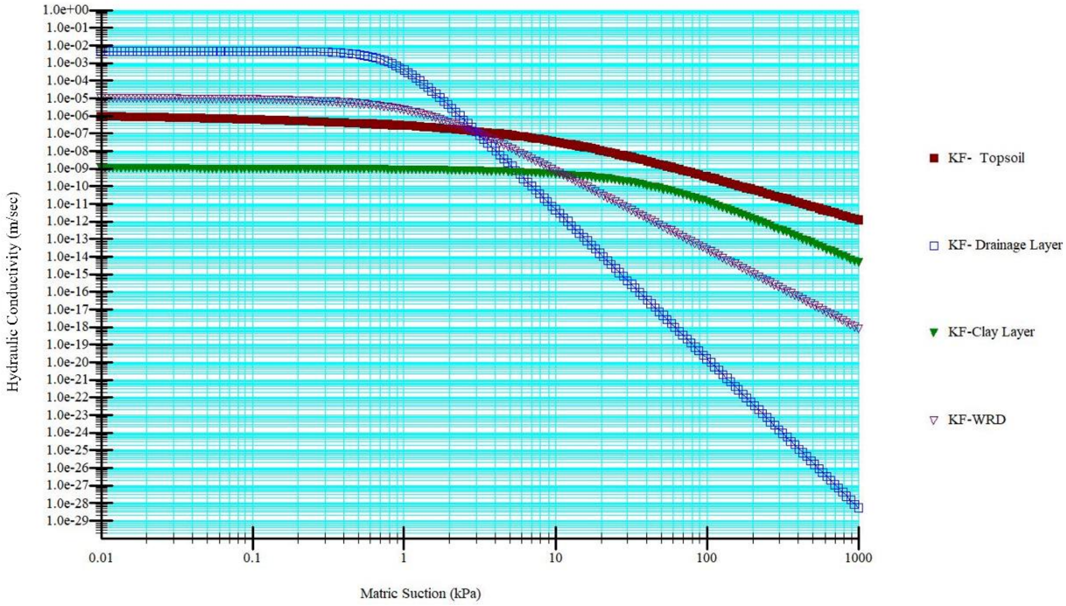


Figure 5.17. K function estimated for topsoil, drainage layer, clay layer, and WRD

The transient seepage analysis for a duration of 10,957 days (or for 30 years) with a time increment 0.5 day was run for five (5) representative locations. The water balance results were given in Table 5.7.

Table 5.7 Water Balance Result for Cover System Alternative 5 - TMWR Type Cover System

Locations	**Unit**	**Parameters**							
		Rainfall	**Snow melt*-**	**Evapo-transpiration**	**Surface Runoff**	**Net Infiltration**	**Storage**	**Drainage**	**Net Percolation**
Iğdır - BS	mm/year	235.8	13.5	158.1	96.9	-5.7	-5.7	0.0	0.0
	mm/year	249.3		249.3			-5.7		
	%	94.6	5.4	63.4	38.9	-2.3	-2.3	0.0	**0.0**
Rize - Cf	mm/year	2188.0	35.7	716.2	74.7	1432.9	15.7	1359.6	57.7
	mm/year	2223.8		2223.8			1432.9		
	%	98.4	1.6	32.2	3.4	64.4	0.7	61.1	**2.6**
İzmir - Cs	mm/year	683.4	0.2	351.8	158.6	173.2	10.5	153.9	8.8
	mm/year	683.6		683.6			173.2		
	%	100.0	0.0	51.5	23.2	25.3	1.5	22.5	**1.3**
Sivas - Dc	mm/year	346.7	38.0	280.4	97.3	7.0	-2.8	9.8	0.0
	mm/year	384.8		384.8			7.0		
	%	90.1	9.9	72.9	25.3	1.8	-0.7	2.5	**0.0**
Balıkesir - Do	mm/year	501.5	4.7	262.9	164.7	78.5	7.8	70.3	0.4
	mm/year	506.2		506.2			78.5		
	%	99.1	0.9	51.9	32.5	15.5	1.5	13.9	**0.1**

*Water equivalent of snow melt.

At the end of 30 years, the lowest amounts of net percolations for all locations were observed for TMWR type cover system. Similar to barrier type cover system, almost 0.0% net percolation was also observed in Iğdır, and Sivas for this type of cover system. The remaining locations, namely, Rize, İzmir, and Balıkesir have lower net percolation percentages as 2.6%, 1.3% and 0.1%, respectively. It can be observed that evapotranspiration rates were decreased for all locations compared to previous alternatives, except basic erosion protection cover system, since there is a drainage layer that discharge water out of the cover system. Thanks to drainage system, the amount of surface runoff calculated in Rize decreased dramatically compared to Barrier type cover system. Finally, very low (<5.0%) net percolation rates were achieved in all locations for TMWR type cover system.

5.3 Further Analysis for Verification of the Performances of Cover System Alternatives for a Selected Climate Type

A further analysis was performed to verify the performances of cover system alternatives for a selected climate type. One (1) climate type was selected from Köppen-Trewartha Climate Classification (KTCC) to evaluate the difference between cover performances of two (2) different provinces classified as the same climate type according to KTCC. This investigation is raised since some of the provinces, which area classified as in the same climate type in KTCC, are not classified as in the same climate type in other climate classification methods. Other climate classification methods used by Turkish State Meteorological Service (MGM) for Turkey are; Climate Classification of Turkey according to Aydeniz aridity index (Bölük, 2016a), Climate Classification of Turkey according to De Martonne aridity index (Bölük, 2016b), Climate Classification of Turkey according to Erinç precipitation effectiveness index (Bölük, 2016c), Climate Classification of Turkey according to Thornthwaite precipitation effectiveness index (Bölük, 2016d), and Köppen Climate Classification of Turkey (Bölük, 2016e). MGM generated climate classification maps for the aforementioned climate classification methods as they can be seen in Appendix B.

Dc-type oceanic temperate climate was selected for comparison purpose since it is the most common (47%) climate type in Turkey according to KTCC. Interestingly, although Bitlis is classified as oceanic temperate (Dc) type in KTCC (see Figure 3.1a), it is classified as either humid or very humid (like Rize) in some of the classification methods, namely Aydeniz, De Martonne, Erinç, and Thornthwaite (see Appendix B). Therefore, a station (Tatvan station) from Bitlis (Dc) was selected to compare with Sivas (Dc) to investigate the cover system performance variations in these two locations situated in the same climate class according to KTCC.

Tatvan station (elevation: 1665m) is situated at 371-meter higher altitude from Sivas station (elevation 1294m). Tatvan station is also located approximately 475 kilometers south-east of Sivas station. The information regarding both stations is given in Table 5.8 below.

Table 5.8 Information of Sivas (17090) and Tatvan (17205) Meteorological Stations

Köppen-Trewartha Climate Classification (KTCC) Type	Dc	
Climate Definition	Continental-temperate	
Province	Sivas	Bitlis
Station Name	Sivas	Tatvan
Station Number	17090	17205
Latitude	39.7437	38.5033
Longitude	37.0020	42.2808
Elevation (m)	1294	1665
Data from (d.m.y)	01.01.1981	01.01.1981
Data to (d.m.y)	31.12.2010	31.12.2010
Data length (Days)	10957	10957

Meteorological parameters of Bitlis (Tatvan) in comparison with Sivas were visualized in Appendix C to reflect meteorological conditions of the project areas. Similar to Sivas, Bitlis (Tatvan) is also classified as Type D according to KTCC (see section 3.1.4) since there exists six (6) months with an average temperature value of more than 10 °C. In addition to this, since the temperatures of the coldest months are less than 2 °C for both Sivas and Bitlis (Tatvan), they both classified as Dc type continental temperate climate according to criteria in KTCC. When the graphs in Appendix C are examined, it can be seen that very similar values were measured for temperature, relative humidity and wind speed at both Sivas and Tatvan stations. For 30 years between 1981 and 2010, the daily average temperature value of Sivas is 9.1 °C and Tatvan is 8.9 °C, the daily average relative humidity value of Sivas is 66.5% and Tatvan is 65.8%, and the daily wind speed value of Sivas is 1.2 m/s and Tatvan is 1.3 m/s. On the other hand, precipitation and snow depth values measured at Tatvan station is quite higher than the ones measured at Sivas station. While the average annual total precipitation value of Sivas is 451.7 mm, the average annual precipitation value as Tatvan station is measured as 819.0 mm. The average annual total snow depth values of Sivas station and Tatvan station are 686.2 cm and 1044.1 cm, respectively.

Performances of all cover system alternatives were also evaluated for Tatvan station of Bitlis (Dc type climate) as in Table 5.9. Rather than having similar results with Sivas (Dc type climate), it can be said that the performances of cover systems are similar the ones obtained for Rize (Cf type climate). Among all cover systems mentioned in this study, barrier type and TMWR type cover systems can achieve very low (<5%) net percolation rates for Tatvan station in Bitlis.

Table 5.9 Water Balance Results of Tatvan station (Bitlis) for all Cover System Alternatives

Cover Type	**Unit**	**Parameters**							
		Rainfall	**Snow melt***	**Evapo-transpiration**	**Surface Runoff**	**Net Infiltration**	**Storage**	**Drainage**	**Net Percolation**
Basic Erosion Protection	mm/year	582.5	97.8	234.4	102.8	343.1	11.0	-	332.1
	mm/year	680.3		680.3			343.1		
	%	85.6	14.4	34.5	15.1	50.4	1.6	-	48.8
Store & Release	mm/year	582.5	97.8	299.4	103.9	277.0	13.5	-	263.4
	mm/year	680.3		680.3			277.0		
	%	85.6	14.4	44.0	15.3	40.7	2.0	-	38.7
Enhanced Store & Release	mm/year	582.5	97.8	309.1	105.4	265.8	12.2	-	253.7
	mm/year	680.3		680.3			265.8		
	%	85.6	14.4	45.4	15.5	39.1	1.8	-	37.3
Barrier Type	mm/year	582.5	97.8	396.8	255.8	27.7	7.6	-	20.1
	mm/year	680.3		680.3			27.7		
	%	85.6	14.4	58.3	37.6	4.1	1.1	-	3.0
TMWR Type	mm/year	582.5	97.8	270.2	182.5	227.6	7.2	211.1	9.3
	mm/year	680.3		680.3			227.6		
	%	85.6	14.4	39.7	26.8	33.4	1.1	31.0	1.4

*Water equivalent of snow melt.

This investigation served as a prove in order not to rely on only one (1) climate classification method and only one location representative of a climate class in evaluating the performance of cover systems. It is suggested that a site-specific study utilizing local meteorological conditions as well as specific design criteria and parameters shall be conducted for each case since each study area is unique by its own hydroclimatic, hydrogeologic, and design characteristics.

5.4 Water Balance Errors of Cover System Alternatives

Water balance errors (WBE) calculated during the 30 years analysis were presented for thirty (30) different scenarios in Table 5.10. It can be said that water balance errors were recorded less than 2.00% for all alternatives. The maximum and the minimum WBEs were calculated for Basic Erosion Protection Cover System in Bitlis, and Barrier type cover system in Balıkesir as 1.94% and 0.04%, respectively. The difference between the water balance errors is due to the different iteration processes during each model run since both climatic parameters and the cover system types are different from each other.

Table 5.10 Water Balance Errors of Cover System Alternatives

Location – Climate type according to KTCC	**Water Balance Errors of Cover Systems**				
	Basic Erosion Protection	**Store & Release**	**Enhanced Store & Release**	**Barrier Type**	**TMWR Type**
Iğdır - BS	0.55%	0.55%	0.27%	0.34%	0.40%
Rize - Cf	0.80%	0.60%	0.48%	0.10%	0.23%
İzmir - Cs	1.47%	0.83%	0.67%	0.42%	0.39%
Sivas - Dc	0.79%	0.36%	0.26%	0.47%	0.55%
Balıkesir - Do	1.24%	1.15%	0.88%	0.04%	0.95%
Bitlis - Dc	1.94%	1.06%	1.18%	0.24%	1.13%

5.5 Cost Estimation

Since the cost of a work is very wide from one project to another, the unit prices were taken from the price lists published by government agencies and the cost estimation was calculated according to the amount of material that would be used for a cover system. The unit price book (for 2022/2) of State Hydraulic Works (DSI), which is affiliated to the Ministry of Agriculture and Forestry, the unit price list (for 2022/2) of General Directorate of Highways (KGM), which is affiliated to the Ministry of Transport and Infrastructure, and the unit prices list (for 2022/3) of the Higher Technical Board (YFKB), which is affiliated to the Ministry of Environment, Urbanization, and Climate Change, were used.

The type, availability, source and quantity of a specific material used in cover systems were given in the Table 5.11 below. While calculating the quantity of a material, thickness of a layer and "10m x 10m" hypothetical edges were considered.

Table 5.11 Information about the Material used in Cover Systems

Cover Type	Material	Availability	Source	Quantity Needed (m^3)
Basic Erosion Protection	Topsoil	On-site	Salvaged topsoil during earlier stages of mine construction	30
Store & Release	Topsoil	On-site	Salvaged topsoil during earlier stages of mine construction	30
	Storage Layer	On-site	Locally available well graded deposits	100
Enhanced Store & Release	Topsoil	On-site	Salvaged topsoil during earlier stages of mine construction	30
	Storage Layer	On-site	Locally available well graded deposits	50
	Reduced Permeability Layer	On-site	Locally available silt/clay deposits	50
Barrier Type	Topsoil	On-site	Salvaged topsoil during earlier stages of mine construction	30
	Storage Layer	On-site	Locally available well graded deposits	50
	Low Permeability Layer	Off-site	Clay mineral with specific hydraulic properties	50
TMWR Type	Topsoil	On-site	Salvaged topsoil during earlier stages of mine construction	30
	Drainage Layer	Off-site	Drainage material with specific hydraulic properties	25
	Clay Layer	Off-site	Clay mineral with specific hydraulic properties	30
	Buffer Layer	On-site	Non-Potential Acid Generating Waste Rock	100

A total number of four (4) main activities, namely excavation/stripping, production/sieving, transportation, and placement, were specified for the estimated cost calculation. The estimated costs for all operations are summarized in Table 5.12. Since materials for topsoil, storage layer, reduced permeability layer, and buffer layer can be supplied from on-site as per their descriptions, no production/sieving and transportation cost included for these materials. For this reason, excavation or stripping work could be performed to simply provide these materials. However, materials like low permeability layer, drainage layer, and clay layer shall be produced/sieved and transported from an external resource since they have very specific hydraulic properties. On the other hand, placement effort shall be carried out for all kind of materials.

As the excavation/stripping operation was priced by KGM (2022) according to hardness of the excavated material, two (2) different unit prices were used for two (2) different kind of materials as soft material (i.e., topsoil) and the remaining hard materials. Since the production prices were obtained from a confidential contract, no further information can be given for this item. The transportation price, including both loading and unloading, calculated only for off-site material using the price lists of KGM (2022), YFKB (2022), and DSI (2022). During the calculations, it is assumed that the production area is 10-kilometers away from the facility where the cover system will be placed. Finally, the placement effort was priced using the price lists of KGM (2022) and YFKB (2022). It is assumed that more placement effort shall be conducted for the materials containing clay, namely reduced permeability layer, low permeability layer, and clay layer, since there are specific hydraulic conductivity values aimed to be achieved for those materials.

Table 5.12 The Estimated Costs for Cover Systems

Cover Type	Material	Quantity Needed (m^3)	Cost (USD)*				
			Excavation or Stripping	Production and/or Sieving	Transportation (+Loading and Unloading)	Placement (+Moisture conditioning and compaction)	TOTAL
Basic Erosion Protection	Topsoil	30	53.33	-	-	108.05	161.37
Store & Release	Topsoil	30	53.33	-	-	108.05	722.38
	Storage Layer (Silty Sand)	100	200.86	-	-	360.15	
Enhanced Store & Release	Topsoil	30	53.33	-	-	108.05	780.66
	Storage Layer (Silty Sand)	50	100.43	-	-	180.08	
	Reduced Permeability Layer (Silty Clay)	50	100.43	-	-	238.35	
Barrier Type	Topsoil	30	53.33	-	-	108.05	1,115.64
	Storage Layer (Silty Sand)	50	100.43	-	-	180.08	
	Low Permeability Layer (Clay)	50	-	295.38	140.04	238.35	
TMWR Type	Topsoil	30	53.33	-	-	108.05	1,380.68
	Drainage Layer (Gravel)	25	-	93.98	70.02	90.04	
	Clay Layer	30	-	177.23	84.02	143.01	
	Buffer Layer	100	200.86	-	-	360.15	

*Cost (USD) was converted from cost (TRY) on 21 November 2022 when 1.00 USD was equal to 18.62 TRY.

As the cover system complexity increases, the cost also increases, as expected. It can be seen that the cost of the cover systems dramatically increases from 161.37 USD for basic erosion protection system to 1,380.68 TRY for TMWR system. By keeping the cover material thicknesses constant and expanding both hypothetical edges (“10m x 10m”) 10 times (“100m x 100m”) to define more representative area for a real WRD, the total cost would grow up to a value between 16,000.00 USD and 138,000.00 USD.

CHAPTER 6

DISCUSSION

Model results revealed that the performances of cover systems can change in different climate zones. While the technically simpler cover systems can also achieve very low net percolation rates in drier (more arid) climates, it is necessary to construct a more complex system for wetter (more humid) climates to achieve very low net percolation rates. The most importantly, a site-specific study shall be carried in order to better understand the performance of a cover system for a study area.

Results of this study show similarities between the previous studies in this field in terms of cover performances for some of the climates. For basic erosion protection type cover system, Birkham et. al. (2014) calculated very high (>40%) net percolation rates between 52% and 86% in humid climate. Similarly, 63% net percolation rate was calculated at Rize (Cf) in this study. For store and release type of cover system, Power et. al. (2018) indicated that high (15-40%) net percolation rate was achieved as 28% for a seasonally humid (dry summer) type of climate. In a similar way, the net percolation rate was calculated at İzmir (Cs) as 23.3% for store and release type cover system. For enhanced store and release type of cover system, Ayres et al. (2013) calculated high net percolation rate as 23% in semi-arid climate whereas Argunhan (2014) calculated very low (<5%) net percolation rate as 1.5% in Uşak (Do). In this study, moderate (10-15%) net percolation rate was calculated in between those values as 13.4% for Balıkesir (Do) for the same type of cover system. The net percolation rate calculated for barrier type of cover system by Williams et al. (2006) is 1% for semi-arid climate. Similarly, it is observed as 1.4% in this study for Balıkesir (Do). For cover systems with engineered layers, Hersey (2021) calculated very low net percolation rates as 0.4% in humid climates. Similarly, very low net percolation rate as 2.6% was achieved in Rize (Cf) in this study for TMWR type cover system. No comparison could be made for the study of SRK (2015) since the climate type of their project area is sub-arctic continental which is not comparable with the climates of Turkey. Therefore, it can be seen that mostly similar results were obtained in this study compared with the similar studies in the literature.

There are also some weaknesses of this study. One of the most important weak sides is that there is no real data to perform calibration of the model since this study is a hypothetical work that does not represent a real case scenario. In order to get more realistic results, calibration of the numerical model with site specific observations shall be performed for a real case scenario. Secondly, a simplified model geometry was applied to reduce simulation time. However, a large-scale model representing the site-specific design consideration may better reflect the real situation. On the other hand, the simplified model geometry provided an opportunity to model thirty (30) cases in a shorter time period under the same conditions except the climatic parameters.

Another topic that needs to be discussed is how climate change will affect Turkey’s climate and the performances of the cover system types correspondingly. In order to present how climate change will affect Turkey’s climate in the future, Turkish State Meteorological Service (MGM) has developed climate projections using three (3) different global circulation models (GCMs), namely HadGEM2-ES, MPI-ESM-MR, GFDL-ESM2M, for the period 2016-2099 (MGM, 2015). Projection results for Turkey with a reference period of 1971-2000 and a resolution of 20-km were obtained using the dynamic downscaling method of RegCM4.3.4 regional model according to RCP4.5 and RCP8.5 emission scenarios. According to the results obtained from the projections of three (3) GCMs, the average increase in the temperature throughout Turkey for the period 2016-2099 is between 1.5°C and 2.6°C for RCP4.5 scenario, and between 2.5°C and 3.7°C for RCP8.5 scenario (see graphs in Appendix D). On the other hand, it is expected to be a change in average precipitation values between -3% and -6% for RCP4.5 scenario, and +3% and -12% for RCP8.5 scenario (see graphs in Appendix D). Therefore, an increasing trend in temperature values can be expected for Turkey; however, there is no consistent increasing or decreasing trend in precipitation values although a general decreasing trend is expected. Besides, it can be seen that precipitation projections do not indicate any trend due to irregular distribution and high variability.

The climate change may have impact on the most important components of water balance. The increase in the temperature would directly affect the rate of evapotranspiration (Görgüner et. al., 2019), the time required for melting of snowpack (Yücel et. al., 2015), and the type of precipitation -snow or rainfall- (Demircan et. al., 2017) in Turkey. Besides, the irregularities in precipitation trend also tends to elevate the number of extreme anomalies (Bağçaci et. al., 2021 & Demircan et. al., 2017). Another outcome was obtained by Yücel et. al. (2015) regarding the timing of peak flows on Aras, Euphrates, Tigris, and Çoruh rivers of Turkey. It was stated that timing of the peak flows will be shifted to earlier days meaning that the fraction of the runoff will rise in winter and fall in spring. These kinds of changes related with the water balance components shall be investigated very carefully for the long-term performance of the cover systems. Since the effect of climate change can differ from a region to another, a site-specific study is crucial to get more realistic long-term model performances. Finally, different climate change scenarios should be investigated to identify the range of projected climate scenarios in design of cover systems.

CHAPTER 7

CONCLUSION & RECOMMENDATIONS

7.1 Conclusion

To conclude, cover systems could be successful to minimize water ingress (net percolation) rates into WRD. It would be very beneficial in terms of performance and budget to choose the most appropriate cover system for a mining facility, such as WRD. The results show that there is a strong relation between cover system performance and climate type (see Table 7.1).

It can be seen that the performance of the cover system is increasing from the simplest one to the most complex one. TMWR type cover system is the most successful cover system in terms of performance to minimize net percolation rates regardless of the climate type. The results indicated that even basic erosion protection type cover system can be successful at Iğdır or BS type dry climates. It should be noted that, negative net infiltration rates and thus negative storage values were observed in model results of Iğdır (BS type dry climate) due to the loss of in-situ water content. Once the residual water content is released from the system via evapotranspiration, the amount is calculated as negative net infiltration or negative storage in the model. Moreover, very low (< 5.0%) net percolation rates could be achieved for one of the selected provinces, namely Sivas, from continental temperate (Dc) climate by constructing store & release type cover system. Moderate, high, or very high net percolation rates were observed for the provinces selected from Do (oceanic temperate), subtropical dry-summer (Cs), and subtropical humid (Cf) type climates, unless barrier type or TMWR type cover systems are designed for these types of climates.

Although it is obvious that TMWR Type cover system, which is the most complex and costly one, achieved the maximum performance for all climate types in this study, simpler and less expensive ones can also be successful to achieve low net percolation rates (< 5%) in some of the climate types.

Table 7.1 Performances of Cover System Alternatives for studied climate types

Locations	**Climate Type according to KTCC**	**Net Percolation Rates**				
		Basic Erosion Protection	**Store & Release**	**Enhanced Store & Release**	**Barrier Type**	**TMWR Type**
Iğdır	BS	≈0.0%	≈0.0%	≈0.0%	≈0.0%	≈0.0%
Rize	Cf	63.2%	62.4%	52.6%	2.7%	2.6%
İzmir	Cs	34.5%	23.3%	22.3%	1.4%	1.3%
Sivas	Dc*	7.1%	0.6%	0.5%	≈0.0%	≈0.0%
Bitlis		48.8%	38.7%	37.3%	3.0%	1.4%
Balıkesir	Do	23.0%	14.1%	13.4%	1.4%	0.1%

Classification of Percolation Rates (MEND, 2012)

> 40 %	Very High Net Percolation Rates
15-40 %	High Net Percolation Rates
10-15 %	Moderate Net Percolation Rates
5-10 %	Low Net Percolation Rates
< 5 %	Very Low Net Percolation Rates

* Sivas and Bitlis were selected to compare the design performance at two (2) different locations within the same climate zone (Continental temperate / Dc) according to KTCC.

Another assessment was conducted in order not to rely on only one (1) climate classification method since some of the regions of Turkey are represented by different climate types by different classification methods (see section 5.3). Two (2) different study areas from Dc type (continental temperate according to KTCC) of climate was evaluated in terms of cover performances (see Table 7.1). As a result, quite different results were obtained especially for basic erosion protection, store and release, enhanced store and release type cover systems. Tatvan station from Bitlis (Dc) has similar outcomes as Rize (Cf) rather than Sivas (Dc) as some of the climate classifications, namely Aydeniz, De Martonne, Erinç, and Thornthwaite (see Appendix B), reported. Very low (< 5%) net percolation rates could be obtained for Tatvan/Bitlis if barrier type or TMWR type cover systems were constructed.

As a result, TMWR type cover system is the most successful cover type in terms of minimum net percolation rates for all study locations in this study. Although the climate has a huge impact on performance of a cover system, there is no pre-determined cover system suitable for a specific climate type since each study area has its own hydroclimatic, hydrogeologic, and design characteristics.

7.2 Recommendations

Recommendations of this study are sorted below:

- A site-specific study shall be conducted for any kind of cover performance modeling study. Although there is a relationship between climate type and cover systems, generalization is not always possible as shown in this study since criteria of climate classification methods do not group study areas using all climatic properties. In Turkey, land-sea distribution and topographic complexity result in high variability in climatic conditions even in short distances. Even if two (2) different study areas located at the same province or climate, site-specific meteorological station data shall be used for each. Therefore, it is recommended to treat each site unique in terms of climatic properties and perform site specific studies using local hydrometeorological characteristics in modeling and designing cover systems.
- TMWR type cover system is evaluated as the most successful system in terms of performance. Although TMWR type cover system has the maximum performance among all types of cover systems, the less complex and inexpensive cover systems are also successful to achieve very low (< 5.0%) net percolation rates in some of the selected sites. It is important to choose the optimum cover system for a study area in terms of engineering point of view.
- Barrier type cover system has a performance similar to TMWR type cover system for Rize (Cf), however, it created very high ratios of surface run-off compared to other cover system alternatives. The higher amounts of surface runoff may lead erosion on topsoil layer. Therefore, it would be beneficial to place a drainage layer to discharge water out of the system (as in the TMWR type cover system) for a long-term performance.
- Mostly lower evapotranspiration rates were observed for TMWR type cover system compared to store and release, enhanced store & release, and barrier type cover system because of the existence of a drainage layer which remove

water from the cover system by minimizing the time required for evapotranspiration. For a real project, the amount of water needed for the local species shall be considered for a sustainable vegetation.

- No stability concerns were taken into account in this study. However, stability calculations shall be made for a real case scenario.
- Material properties and regulation rules were applied using the minimum requirements, in order to create the most challenging cases in this study. However, it is possible to reduce net percolation rates more than as in this study by using thicker materials with lower hydraulic conductivity values.
- It is assumed that all materials used in this study are homogeneous in terms of particle distributions, hydraulic properties, and compaction ratio etc.; however, mostly heterogeneous conditions are valid in real cases. Therefore, it should be noted that the models do not exactly reflect the real situation in terms of homogeneity.
- In this study, plateau section of a WRD was modeled to create the worst-case scenario; however, slope section of the WRD, where lower net percolations can be achieved compared to plateau section, should also be modeled for a real case scenario. On the other hand, slope section of the WRD is more prone to erosion due to less infiltration and higher surface-runoff rates.
- No geological structure (i.e., fractures or faults) that can affect hydrogeological system is taken into account in this study since the subgrade is not included in the hypothetical model domain. However, in real case, geological structures may have major effects on hydrogeological systems. Thus, geological structures located at the project area shall be considered during the planning of the cover system design.
- It is also assumed that minimum vegetation conditions with constant properties of grass was applied in this study. In real life case, different kind of species would be growing with seasonality. Therefore, better model predictions would increase the accuracy of the model once the transpiration rates of local species are quantified.

- It should be noted that an additional watering could be performed to support healthy and sustainable vegetation growth in dry (BS) type climate (e.g., Iğdır). In this case, an additional water source should be taken into account during water balance calculations.
- In this study, it is assumed that sufficient amount of moisture conditioning and compaction was applied prior to material placement in the cover systems to obtain satisfactory material properties. In real life, that should also be the case.
- As mentioned before, the design considerations were hypothetical and hydraulic parameters of the cover system were taken from the literature. Therefore, a numerical model that is representing the design considerations and that is calibrated with site specific observations shall be implemented for a real case scenario to get realistic results.
- In this thesis, climatic parameters used in the model were measured between 1981 and 2010. Therefore, no climate change projection data used in this thesis. It would be beneficial to obtain additional models using data from climate change projections. Different climate change scenarios may be tried to investigate the impact of various climate change scenarios on designing cover systems.
- Test plots shall be constructed to examine study outcomes prior to construct a cover system in any kind of climate type. Monitoring of these kind of test plots by using the real material available on the site would be beneficial to understand the performance of the cover system under site-specific conditions.
- Finally, it is recommended that long term monitoring studies shall be conducted after construction of a cover system in order to monitor erosion, physical stability and vegetation success. Additionally, periodical sampling sessions shall be performed at nearby groundwater and surface-water resources to assess water quality against deterioration.

REFERENCES

Argunhan, Ç. 2014. Optimum Cover Design for Waste Rock Storage Areas. Master's Thesis. Middle East Technical University. Geological Engineering Dept.

Ayres, B. & O'Kane, M. & Barber, L. & Hiller, D. & Helps, D. 2013. Performance of an Engineered Cover System for a Uranium Mine Waste Rock Pile in Northern Saskatchewan After Six Years. In Proc. of Northern Latitudes Mining Reclamation Workshop and CLRA Conference, Whitehorse, YT, September 9-12.

Azam, S. & Wilson, G. W. & Herasymuik, G. & Nichol, C. & Barbour, L. S. 2007. Hydrogeological behavior of an unsaturated waste rock pile: A case study at the Golden Sunlight Mine, Montana, USA. Bulletin of Engineering Geology and the Environment (August 2007). 66:259–268. DOI: 10.1007/s10064-006-0077-7.

Bağçacı, S. C. & Yücel, İ. & Düzenli, E. & Yılmaz, M. T. 2021. Intercomparison of the expected change in the temperature and the precipitation retrieved from CMIP6 and CMIP5 climate projections: A Mediterranean hot spot case, Turkey. Atmospheric Research 256 (2021) 105576. https://doi.org/10.1016 /j.atmosres.2021.105576.

Belda, M. & Holtanová, E. & Halenka, T. & Kalvova, J. 2014. Climate classification revisited: From Köppen to Trewartha. Climate Research. 59. 1–13. 10.3354/cr01204.

Benson, C. H. & Bareither, C. A. 2012. Designing Water Balance Covers for Sustainable Waste Containment: Transitioning State-of-the-Art to State-of-the-Practice. Geotechnical Special Publication (May 2012). DOI: 10.1061/9780784412138.0001

Birkham, T. & O'Kane, M. & Goodbrand, A. & Barbour, S. L. & Carey, S. K. & Straker, J. & Baker, T. & Klein, R. 2014. Near-surface water balances of waste rock dumps. O'Kane Consultants Inc.

Blackmore, S. & Pedretti, D. & Mayer, K. U. & Smith, L. & Beckie, R. D. 2018. Evaluation of single- and dual-porosity models for reproducing the release of external and internal tracers from heterogeneous waste-rock piles. J. Cont. Hydrology. doi 10.1016/j.jconhyd.2018.05.007

Bölük, E. 2016a. Aydeniz İklim Siniflandirmasina Göre Türkiye İklimi (Climate of Turkey according to Aydeniz Climate Classification). Meteoroloji Genel Müdürlüğü. Araştırma Dairesi Başkanlığı, Klimatoloji Şube Müdürlüğü. Ankara. Available online: https://www.mgm.gov.tr/FILES/iklim/iklim_siniflandirmalari/aydeniz.pdf

Bölük, E. 2016b. De Martonne Kuraklık İndisine Göre Türkiye İklimi (Climate of Turkey according to De Martonne Aridity Index). Meteoroloji Genel Müdürlüğü. Araştırma Dairesi Başkanlığı, Klimatoloji Şube Müdürlüğü. Ankara. Available online: https://www.mgm.gov.tr/FILES/iklim/iklim_siniflandirmalari/Demartonne.pdf

Bölük, E. 2016c. Erinç İklim Siniflandirmasina Göre Türkiye İklimi (Climate of Turkey according to Erinç Climate Classification). Meteoroloji Genel Müdürlüğü. Araştırma Dairesi Başkanlığı, Klimatoloji Şube Müdürlüğü. Ankara. Available online: https://www.mgm.gov.tr/FILES/iklim/iklim_siniflandirmalari/erinc.pdf

Bölük, E. 2016d. Thornthwaite İklim Siniflandirmasina Göre Türkiye İklimi (Climate of Turkey according to Thornthwaite Climate Classification). Meteoroloji Genel Müdürlüğü. Araştırma Dairesi Başkanlığı, Klimatoloji Şube Müdürlüğü. Ankara. Available online: https://www.mgm.gov.tr/FILES/iklim/iklim_siniflandirmalari/Thornthwaite.pdf

Bölük, E. 2016e. Köppen İklim Siniflandirmasina Göre Türkiye İklimi (Climate of Turkey according to Köppen Climate Classification). Meteoroloji Genel Müdürlüğü. Araştırma Dairesi Başkanlığı, Klimatoloji Şube Müdürlüğü. Ankara. Available online: https://www.mgm.gov.tr/FILES/iklim/iklim_siniflandirmalari/koppen.pdf

Bölük, E. & Kömüşçü, A. Ü. 2018. Köppen-Trewartha İklim Siniflandirmasina Göre Türkiye İklimi (Climate of Turkey according to Köppen-Trewartha Climate Classification). Meteoroloji Genel Müdürlüğü. Araştırma Dairesi Başkanlığı, Klimatoloji Şube Müdürlüğü. Ankara. Available online:

https://www.mgm.gov.tr/FILES/iklim/iklim_siniflandirmalari/Köppen-Trewatha.pdf

Broda, S. & Aubertin, M. & Blessent, D. & Hirthe, E. & Graf, T. 2014. Improving control of contamination from waste rock piles. Journal of Environmental Geotechnics. DOI: 10.1680/envgeo.14.00023

Çevre ve Şehircilik Bakanlığı (Ministry of Environment and Urbanization). 2015. Maden Atıkları Yönetmeliği (Mining Waste Regulation). Available online: https://www.resmigazete.gov.tr/eskiler/2015/07/20150715-3.htm.

Childs, E.C. & Collis-George, N. 1950. The Permeability of Porous Materials. Proceedings of the Royal Society, pp. 392-405.

Darcy, H. 1856. Les fontaines publiques de la ville de Dijon. Paris: Dalmont.

Dawood, I. & Aubertin, M. 2009. A numerical investigation of the influence of internal structure on the unsaturated flow in a large waste rock pile. GeoHalifax2009.

Demircan, M. & Gürkan, H. & Eskioğlu, O. & Arabacı, H. & Coşkun, M. 2017. Climate Change Projections for Turkey: Three Models and Two Scenarios. Turkish Journal of Water Science & Management. Volume: 1 Issue: 1 Year: 2017.

Demers, I. & Molson, J. & Bussière, B. 2010. Numerical modelling of contaminated neutral drainage from a waste rock field test plot. GEO2010, in the new west, Calgary, Alberta.

DSI - Devlet Su İşleri (State Hydraulic Works) – Tarım Orman Bakanlığı (Ministry of Agriculture and Forestry). 2014. Dolgu İşleri Teknik Şartnamesi (Technical Specifications of Filling Works) R00_20061110. Available from https://www.dsi.gov.tr/Sayfa/ Detay/740.

DSI - Devlet Su İşleri (State Hydraulic Works) – Tarım Orman Bakanlığı (Ministry of Agriculture and Forestry). 2022. DSI 2022/2 Yılı Birim Fiyat Kitabı (Unit Price Book for the year 2022/2). Available from https://www.dsi.gov.tr/Sayfa/Detay/738.

Fala, O. & Molson, J. & Dawood, I. & Aubertin, M. & Buissière, B. & Chapuis, R. P. 2011. Simulating water flow and reactive transport in waste rock piles using stochastic properties (Rapport technique n° EPM-RT-2011-03).

Garneau, P. & Albano, K. & Moore, W. T. 2016. Cover system performance — using numerical modelling to optimize monitoring systems. Mine Closure 2016 – AB Fourie and M Tibbett (eds). Australian Centre for Geomechanics, Perth, ISBN 978-0-9924810-4-9.

Geoslope International Ltd. 2008. Vadose/W Tutorial 2D. Available online: http://downloads.geo-slope.com/geostudioresources/examples/7/Vadose%202D%20Tutorial.pdf.

Geoslope International Ltd. 2012. Seepage Modeling with SEEP/W (July 2012 Edition). Calgary, Alberta, Canada.

Geoslope International Ltd. 2014. Vadose Zone Modeling with VADOSE/W (April 2014 Edition). Calgary, Alberta, Canada.

Geoslope International Ltd. 2017a. Stability with perched water table. Available online: https://www.geoslope.com/solutions/groundwater.

Geoslope International Ltd. 2017b. Transpiration by root water uptake. Available online: http://www.geoslope.com/solutions/vadose-zone-hydrology.

Geoslope International Ltd. 2017c. Design of a Soil Vapor Barrier to Prevent Gas Diffusion from Waste Dumps. Available online: http://downloads.geo-slope.com/geostudioresources/examples/9/0/VadoseW/Design%20of%20a%20soil%20vapor%20barrier.pdf.

Geoslope International Ltd. 2021. Heat and mass transfer modeling with GeoStudio 2021. Calgary, Alberta, Canada.

Golder Associates Inc. 2006. Cover, Erosion, and Revegetation Test Plot Study. Tyrone Mine Stockpiles. As-built Report.

Gonzales, C. & Scheuermann, A. & Arnold, S. & Baumgartl, T. 2016. Application of spatial time domain reflectometry measurements in heterogeneous, rocky substrates. Journal of Geophysics and Engineering 13 (2016) 758–767. doi:10.1088/1742-2132/13/5/758

Google Earth. 2022. Location of Turkey. Retrieved on July 11, 2022 from http://www.google.com/earth/index.html.

Görgüner, M. & Kavvas, M. L. & Ishida, K. 2019. Assessing the impacts of future climate change on the hydroclimatology of the Gediz Basin in Turkey by using dynamically downscaled CMIP5 projections. Science of the Total Environment 648 (2019) 481–499. https://doi.org/10.1016/j.scitotenv.2018.08.167.

Hajizadeh, H. & Luo, M. & Li, S. 2014. Assessment of Unsaturated Flow for a Large Coal Mine Waste Rock Pile. Advanced Materials Research. DOI: 10.4028/www.scientific.net/AMR.955-959.1179.

Hersey, D. 2021. Long-term Field Performance of Geomembrane-Lined Cover Systems at Mine Waste Rock Piles. Electronic Thesis and Dissertation Repository. 8182. Available online: https://ir.lib.uwo.ca/etd/8182.

Hopp, L. & McDonnell, J.J. & Condon, P. 2011. Lateral Subsurface Flow in a Soil Cover over Waste Rock in a Humid Temperate Environment. Vadose Zone Journal, Vol. 10. doi:10.2136/vzj2010.0094.

ICMM (International Council on Mining & Metals). 2019. Integrated mine closure: good practice guide. 2nd edition.

INAP (International Network for Acid Prevention). 2014. Global Acid Rock Drainage Guide. November 2017.

INAP (International Network for Acid Prevention). 2017. Global Cover System Design - Technical Guidance Document. November 2017.

KGM – Karayolları Genel Müdürlüğü (General Directorate of Highways) – Ulaştırma ve Altyapı Bakanlığı (Ministry of Transport and Infrastructure). 2022. 2022 Yılı – 2 (Yol, Köprü, Tünel, Bitümlü Kaplamalar, Bakım ve Trafik İşlerineAit Birim Fiyat Listesi). Available from https://www.kgm.gov.tr/Sayfalar/KGM/SiteTr/Baskanliklar/BaskanliklarTeknikArastirma/BirimFiyatlar.aspx.

Köppen, W. 1936. Das geographische System der Klimate, Handbuch der Klimatologie (The Geographical System of the Climate, Handbook of Climatology). Borntraeger, Berlin, Bd. 1, Teil. C.

Lamontagne, A. & Fortin, S. & Poulin, R. & Tassé, N. & Lefebre, R. 2000. Layered co-mingling for the construction of waste rock piles as a method to mitigate acid mine drainage – laboratory investigations. ICARD 2000, Fifth International Conference on Acid Rock Drainage

MEND (The Canadian Mine Environment Neutral Drainage). 2004. Design, Construction and Performance Monitoring of Cover Systems for Waste Rock and Tailings. 2.21.4a. Volume 1. July 2004.

MEND (The Canadian Mine Environment Neutral Drainage). 2012. Cold regions cover system design technical guidance document. 1.61.5c. July 2012.

MGM – Meteoroloji Genel Müdürlüğü (Turkish State Meteorological Service). 2015. Yeni Senaryolar ile Türkiye İklim Projeksiyonlari ve İklim Değişikliği (Climate Projections of Turkey and Climate Change with new scenarios). Araştırma Dairesi Başkanlığı Klimatoloji Şube Müdürlüğü. Ankara – Nisan 2015.

MTA - Maden Tetkik ve Arama Genel Müdürlüğü (Mineral Research and Exploration General Directorate). 2019. Türkiye Maden Yatakları Haritaları (Mineral Deposits Maps of Turkey). Retrieved on July 12, 2022 from https://www.mta.gov.tr/v3.0/hizmetler/maden-yataklari.

Neuner, M. & Smith, L. & Blowes, D. W. & Sego, D. C. & Smith, L. J. D. & Fretz, N. & Gupton, M. 2013. The Diavik waste rock project: Water flow through mine waste rock in a permafrost terrain, Applied Geochemistry, Volume 36, Pages 222-233. ISSN 0883-2927.

Noël, M. M. & Rykaart, E. M. 2003. Comparative Study of Surface Flux Boundary Models to Design Soil Covers for Mine Waste Facilities. 6th ICARD. Cairns, QLD, 12 – 18 July 2003.

Nordstrom, D. K. & Alpers, C. N. 1999. Geochemistry of acid mine waters. In Plumlee, G. S. & Logsdon, M. J. (eds.), The Environmental Geochemistry of Mineral Deposits. Part A. Processes, Methods and Health Issues, Reviews in Economic Geology, Littleton, CO: Society of Economic Geology, Vol. 6A, pp. 133–160.

O'Kane, M. & Ayres, M. & Christensen, D. & Meiers, G. 2002. CANMET – CETEM Manual on Cover System Design for Reactive Mine Waste. OKC Report No. 689-01.

Patton, C. P. 1962. A note on the classification of dry climate in the Köppen system. California Geographer 3: 105−112.

Power, C. & Ramasamy, M. & Mkandawire, M. 2018. Performance assessment of a single-layer moisture store-and-release cover system at a mine waste rock pile in a seasonally humid region (Nova Scotia, Canada). Environ Monit Assess (2018) 190: 186. https://doi.org/10.1007/s10661-018-6555-0

Qui, Y. & Sego, D. C. 2000. Laboratory Properties of Mine Tailings. Canadian Geotechnical Journal (June 2000).

Raymond, K. E. & Seigneur, N. & Su, D. & Mayer, K. U. 2021. Investigating the Influence of Structure and Heterogeneity in Waste Rock Piles on Mass Loading Rates—A Reactive Transport Modeling Study. Front. Water 3:618418. doi: 10.3389/frwa.2021.618418

Richards, L. A. 1931. Capillary Conduction of Liquids Through Porous Mediums. Physics, Vol. 1.

SRK Consulting Inc. 2015. Minto Mine Closure Covers: Results of Numerical Modelling to Bracket Percolation Predictions. Technical Memorandum.

Stormont, J. C. & Morris, C. E. 1998. Method to estimate water storage capacity of capillary barriers. Journal of Geotechnical and Geoenvironmental Engineering, 124(4), 297-302.

Trewartha, G. T. & Horn, L. H. 1980. Introduction to climate, 5th edition. McGraw Hill, New York, NY.

UNSODA. 1996. The UNSODA Unsaturated Soil Hydraulic Database User's Manual Version 1.0. United States Environmental Protection Agency. Office of Research and Development. Washington DC 20460

USGS - United States Geological Survey. n. d.. Illustrations: Groundwater is the area underground where openings are full of water. Water Science School. Available from: https://www.usgs.gov/media/images/groundwater-area-underground-where-openings-are-full-water

van Genuchten, M. T. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal 44(5): 892-898.

Wang, H. F. & Anderson, M. P. 1982. Introduction to groundwater modeling: finite difference and finite element methods. Academic Press, Inc.

Williams, D. J. & Stolberg, D. J. & Currey, N. A. 2006. Long-Term Monitoring of Kidston's "Store/Release" Cover System over Potentially Acid Forming Waste Rock Piles. 7th International Conference on Acid Rock Drainage (ICARD), March 26-30, 2006, St. Louis MO. R.I. Barnhisel (ed.) Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502.

Wilson, G. W. 1990. Soil Evaporative Fluxes for Geotechnical Engineering Problems. Ph.D. Thesis, University of Saskatchewan, Saskatoon, Canada.

Wilson, G. W. & Fredlund, D. G. & Barbour, S. L. 1997. The effect of soil suction on evaporative fluxes from soil surfaces. Canadian Geotechnical Journal, 34: 145-155.

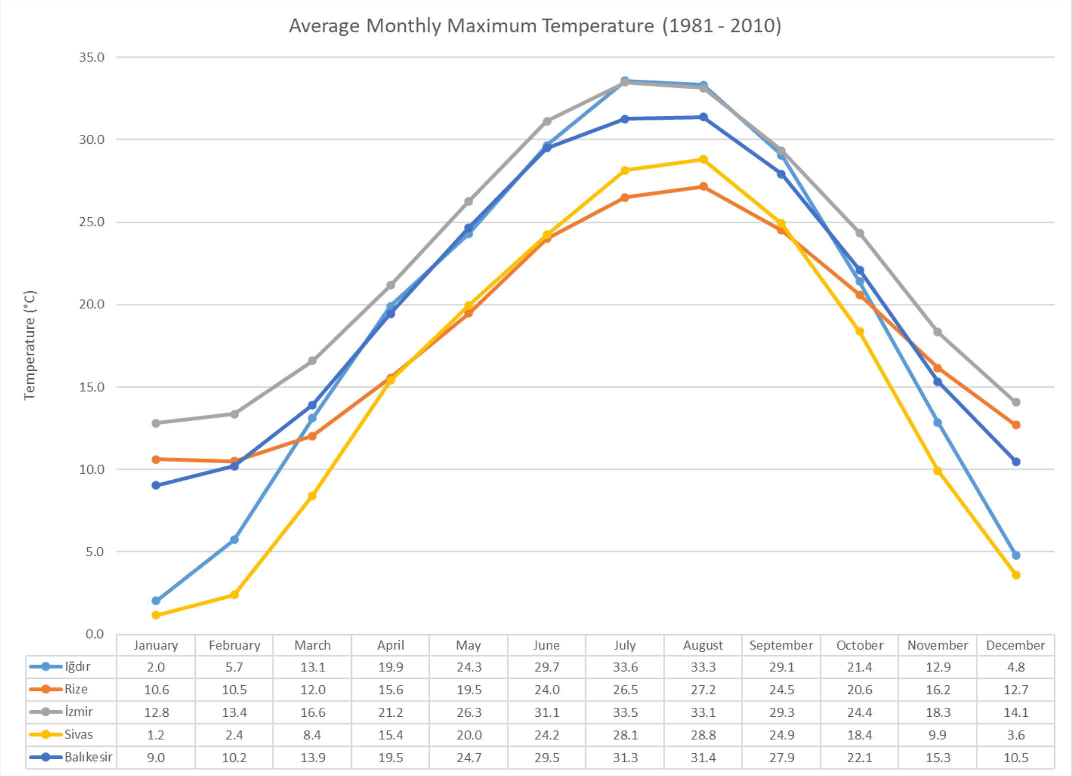
YFKB – Yüksek Fen Kurulu Başkanlığı (the Higher Technical Board) – Çevre, Şehircilik ve İklim Değişikliği Bakanlığı (Ministry of Environment, Urbanization, and Climate Change). 2022. 2022/3 İnşaat ve Tesisat Birim Fiyatları. Available from https://yfk.csb.gov.tr/birim-fiyatlar-i-100468.

Yılmaz, E. & Kesimal, A. & Erçıkdı, B. 2004. Evaluation of Acid Producing Sulphidic Mine Tailings as a Paste Backfill. İstanbul Üniv. Müh. Fak. Yerbilimleri Dergisi, C. 17, S. 1, SS. 11-19, Y. 2004.

Yücel, İ. & Güventürk, A. & Şen, Ö. L. 2015. Climate change impacts on snowmelt runoff for mountainous transboundary basins in eastern Turkey. International Journal of Climatology. 215–228 (2015). DOI: 10.1002/joc.3974

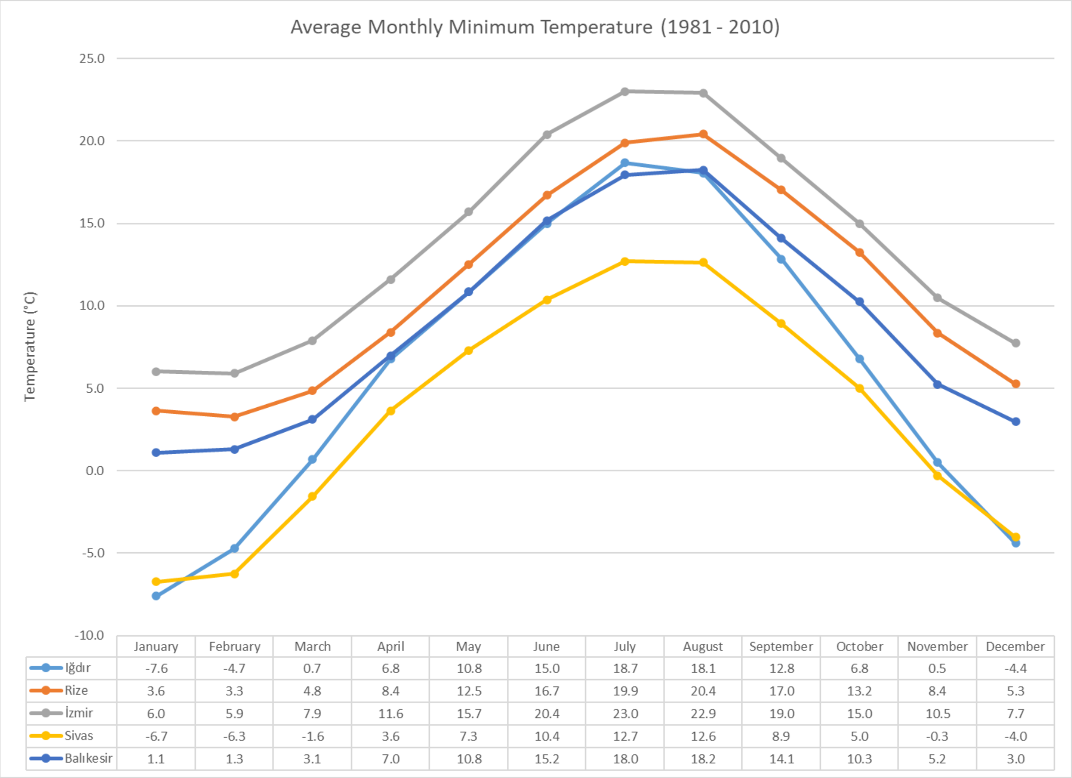
APPENDICES

A. Additional Graphs of Meteorological Parameters of Five (5) Main Provinces



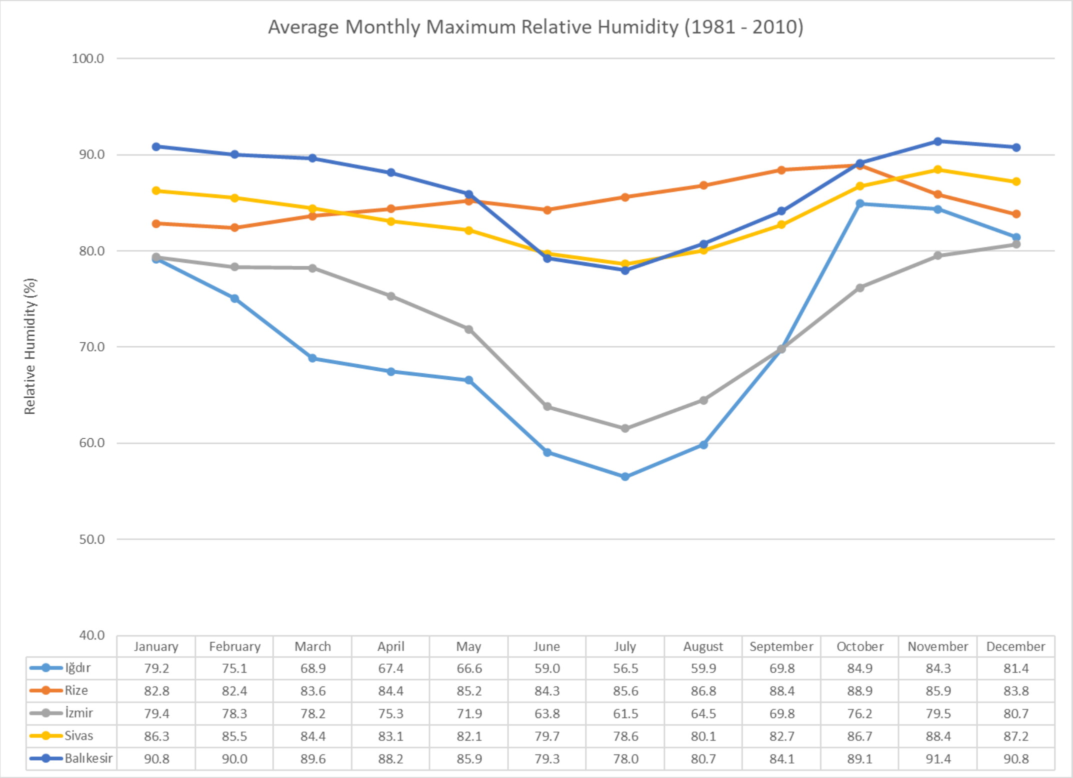
	January	February	March	April	May	June	July	August	September	October	November	December
Iğdır	2.0	5.7	13.1	19.9	24.3	29.7	33.6	33.3	29.1	21.4	12.9	4.8
Rize	10.6	10.5	12.0	15.6	19.5	24.0	26.5	27.2	24.5	20.6	16.2	12.7
İzmir	12.8	13.4	16.6	21.2	26.3	31.1	33.5	33.1	29.3	24.4	18.3	14.1
Sivas	1.2	2.4	8.4	15.4	20.0	24.2	28.1	28.8	24.9	18.4	9.9	3.6
Balıkesir	9.0	10.2	13.9	19.5	24.7	29.5	31.3	31.4	27.9	22.1	15.3	10.5

Figure A.1. Average monthly maximum temperature values measured at meteorological stations of five (5) provinces for 30 years between 1981-2010.



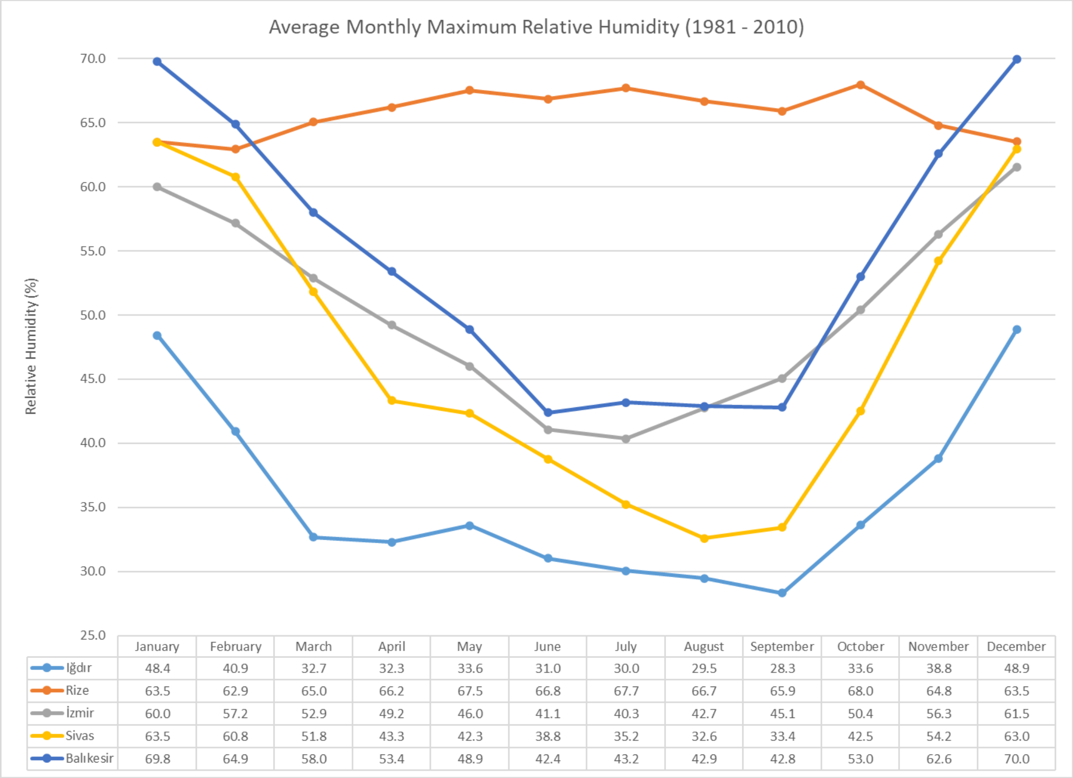
	January	February	March	April	May	June	July	August	September	October	November	December
Iğdır	-7.6	-4.7	0.7	6.8	10.8	15.0	18.7	18.1	12.8	6.8	0.5	-4.4
Rize	3.6	3.3	4.8	8.4	12.5	16.7	19.9	20.4	17.0	13.2	8.4	5.3
İzmir	6.0	5.9	7.9	11.6	15.7	20.4	23.0	22.9	19.0	15.0	10.5	7.7
Sivas	-6.7	-6.3	-1.6	3.6	7.3	10.4	12.7	12.6	8.9	5.0	-0.3	-4.0
Balıkesir	1.1	1.3	3.1	7.0	10.8	15.2	18.0	18.2	14.1	10.3	5.2	3.0

Figure A.2. Average monthly minimum temperature values measured at meteorological stations of five (5) provinces for 30 years between 1981-2010.



	January	February	March	April	May	June	July	August	September	October	November	December
Iğdır	79.2	75.1	68.9	67.4	66.6	59.0	56.5	59.9	69.8	84.9	84.3	81.4
Rize	82.8	82.4	83.6	84.4	85.2	84.3	85.6	86.8	88.4	88.9	85.9	83.8
İzmir	79.4	78.3	78.2	75.3	71.9	63.8	61.5	64.5	69.8	76.2	79.5	80.7
Sivas	86.3	85.5	84.4	83.1	82.1	79.7	78.6	80.1	82.7	86.7	88.4	87.2
Balıkesir	90.8	90.0	89.6	88.2	85.9	79.3	78.0	80.7	84.1	89.1	91.4	90.8

Figure A.3. Average monthly maximum relative humidity values measured at meteorological stations of five (5) provinces for 30 years between 1981-2010.



	January	February	March	April	May	June	July	August	September	October	November	December
Iğdır	48.4	40.9	32.7	32.3	33.6	31.0	30.0	29.5	28.3	33.6	38.8	48.9
Rize	63.5	62.9	65.0	66.2	67.5	66.8	67.7	66.7	65.9	68.0	64.8	63.5
İzmir	60.0	57.2	52.9	49.2	46.0	41.1	40.3	42.7	45.1	50.4	56.3	61.5
Sivas	63.5	60.8	51.8	43.3	42.3	38.8	35.2	32.6	33.4	42.5	54.2	63.0
Balıkesir	69.8	64.9	58.0	53.4	48.9	42.4	43.2	42.9	42.8	53.0	62.6	70.0

Figure A.4. Average monthly minimum relative humidity values measured at meteorological stations of five (5) provinces for 30 years between 1981-2010.

B. Additional Climate Classification Maps of Turkey

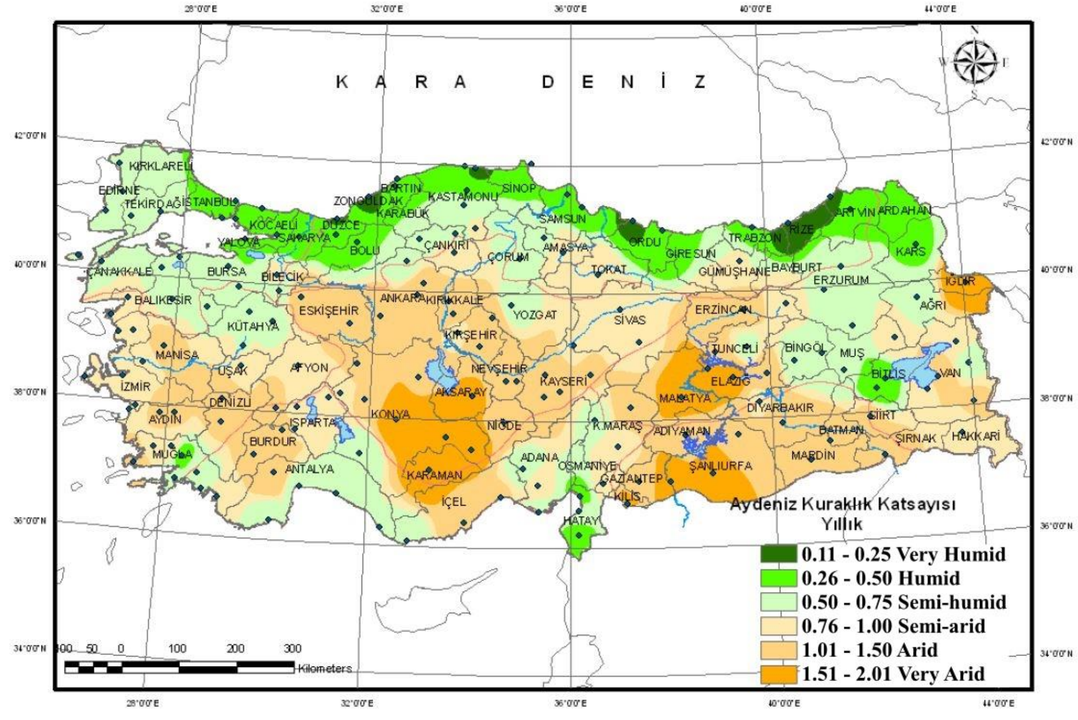


Figure A.5. Climate Classification Map of Turkey according to Aydeniz (Bölük, 2016a).

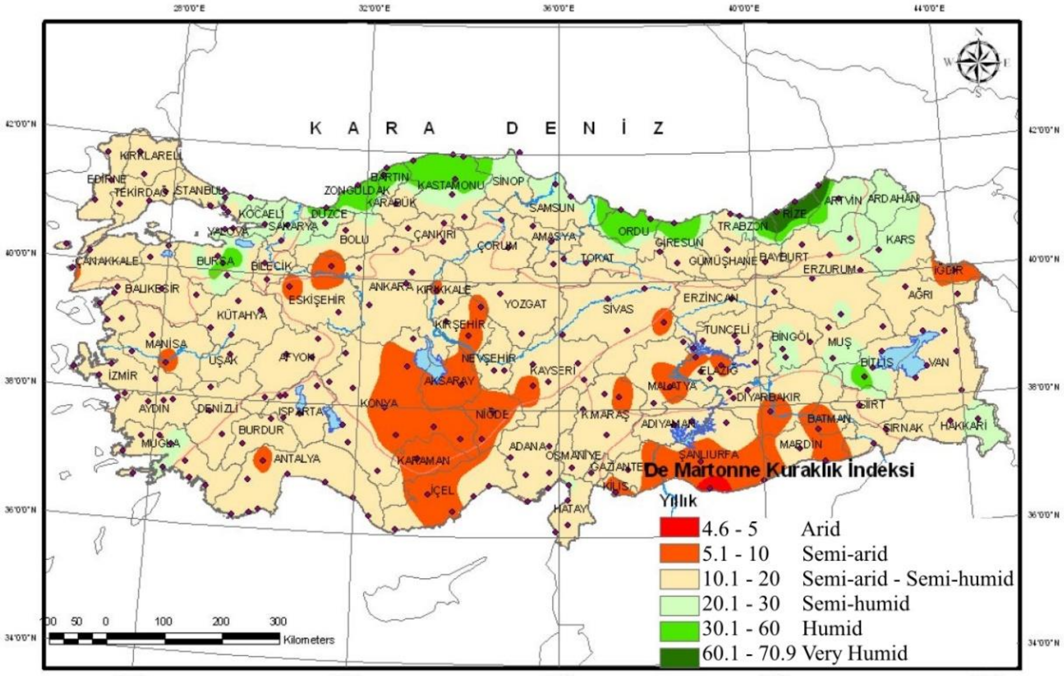


Figure A.6. Climate Classification Map of Turkey according to De Martonne (Bölük, 2016b).

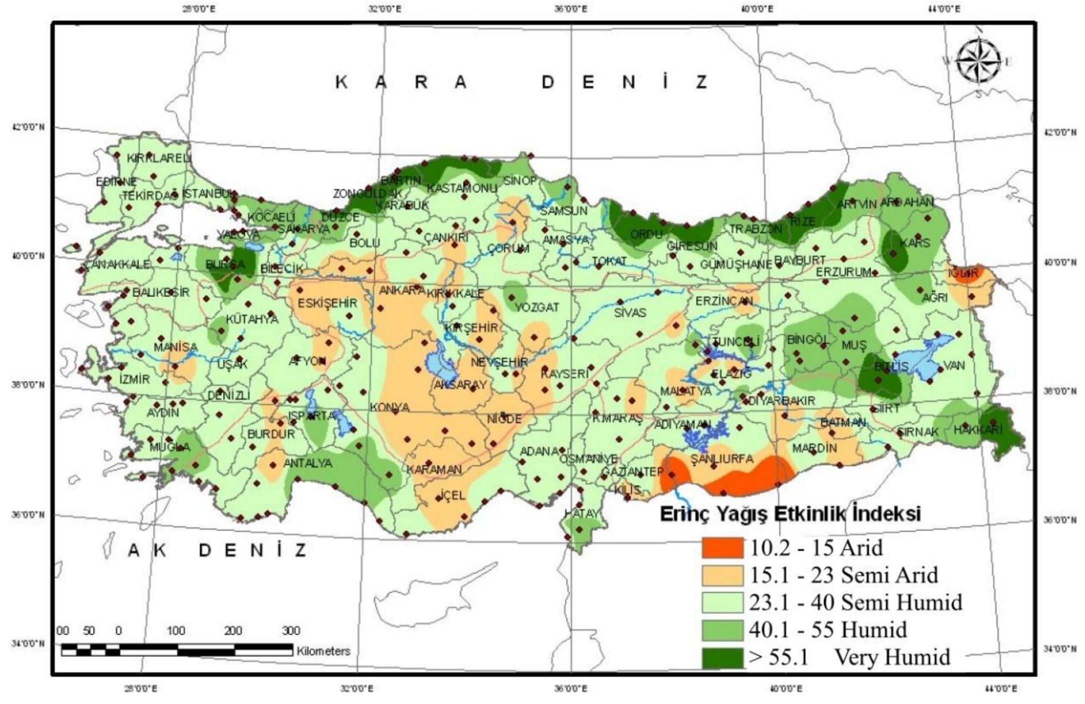


Figure A.7. Climate Classification Map of Turkey according to Erinç (Bölük, 2016c).

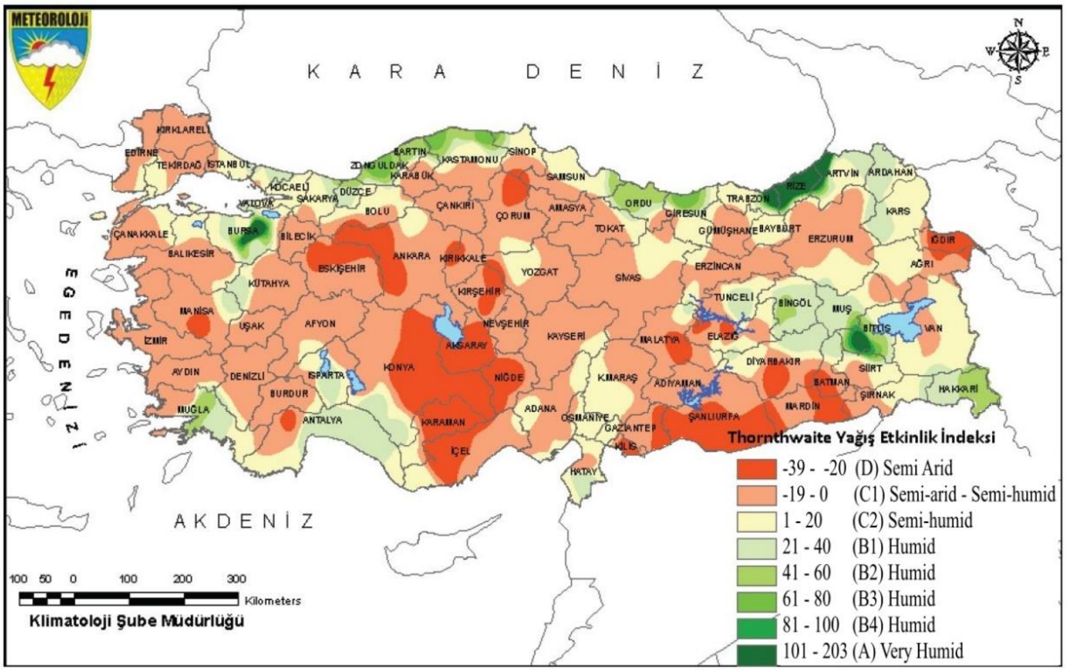


Figure A.8. Climate Classification Map of Turkey according to Thornthwaite (Bölük, 2016d).

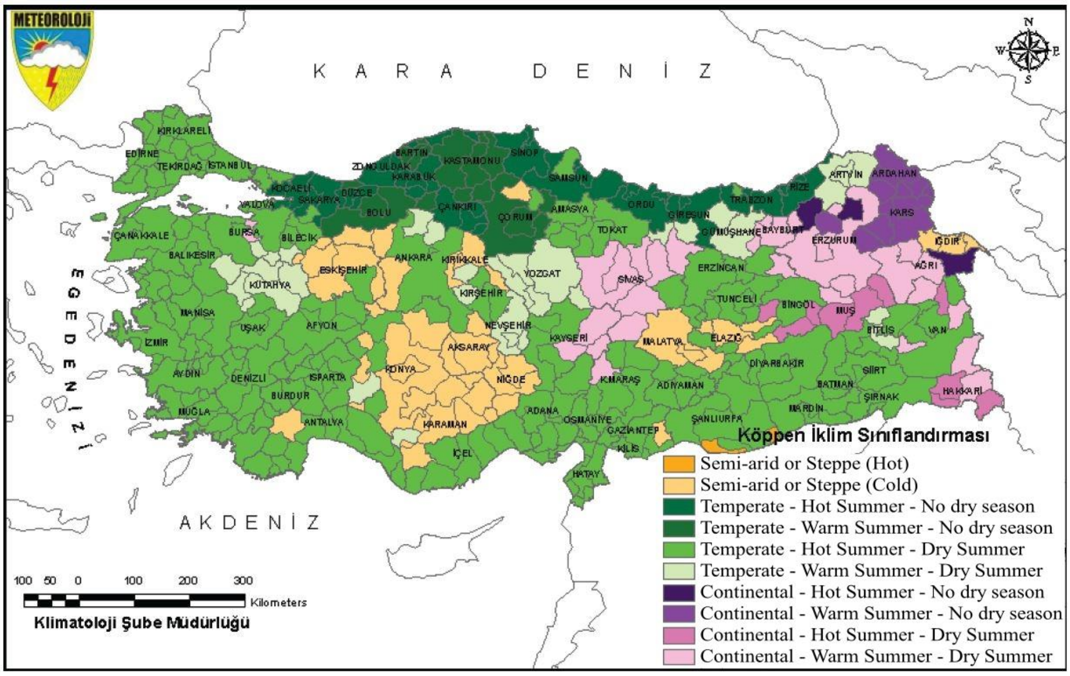
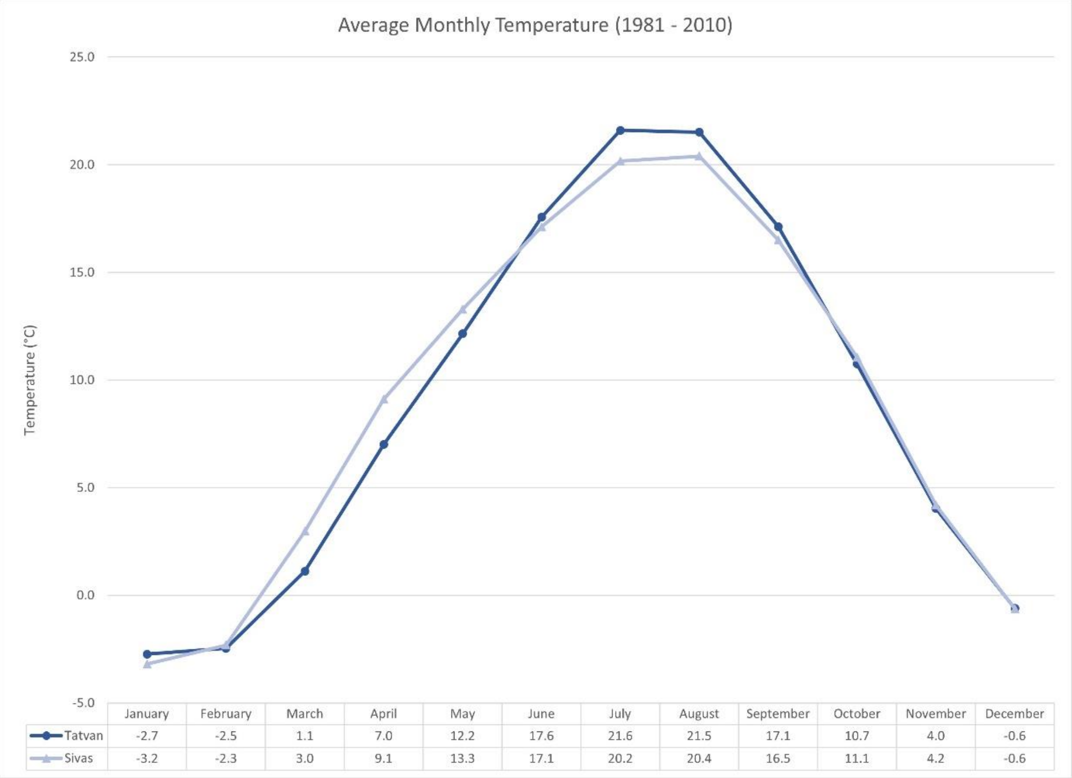


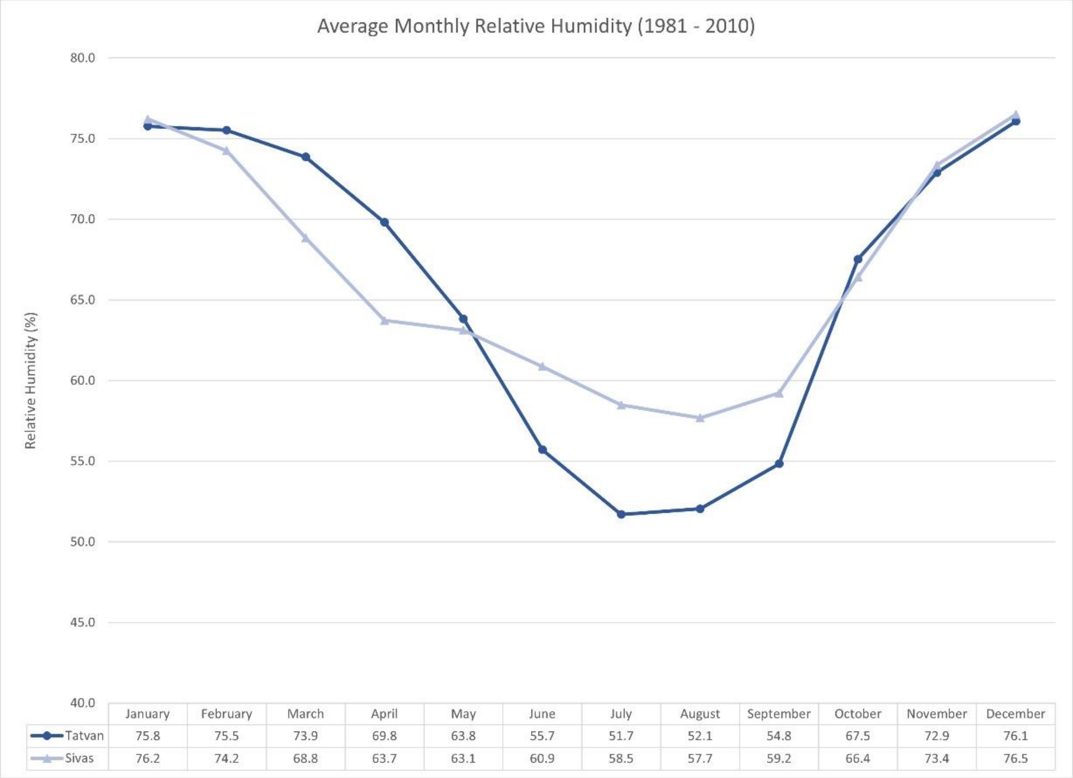
Figure A.9. Climate Classification Map of Turkey according to Köppen (Bölük, 2016e).

C. Graphs of Meteorological Parameters generated to compare Dc Type Provinces (Sivas and Bitlis (Tatvan)) according to KTCC



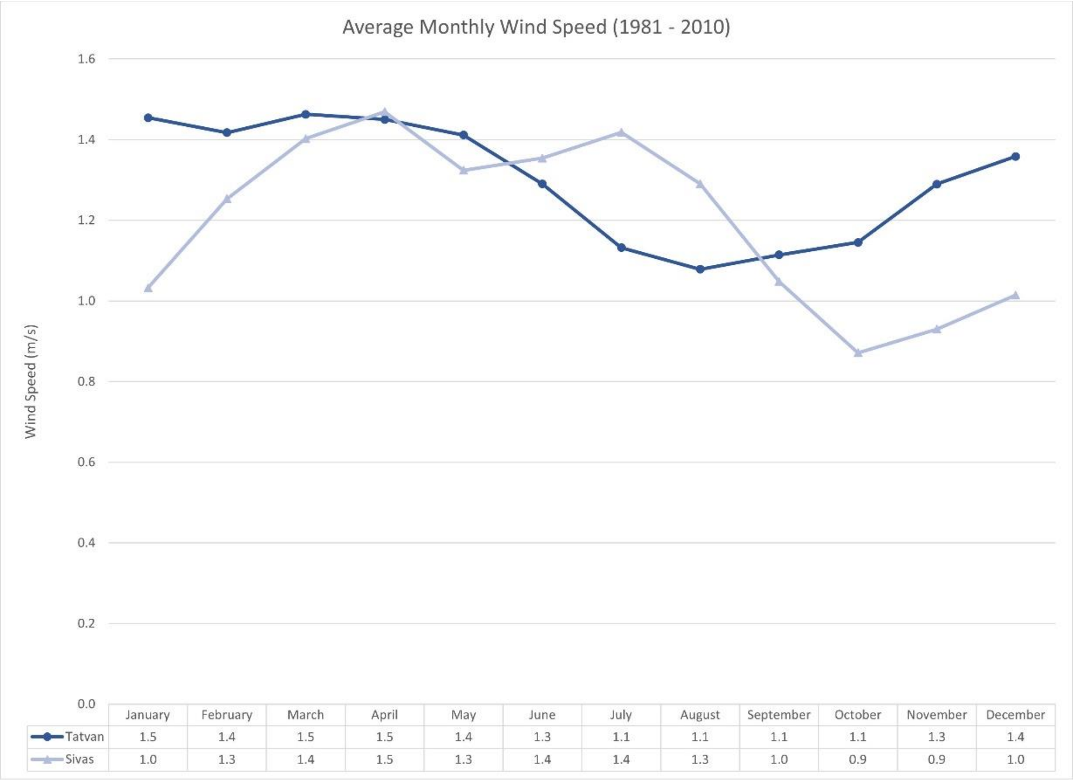
	January	February	March	April	May	June	July	August	September	October	November	December
Tatvan	-2.7	-2.5	1.1	7.0	12.2	17.6	21.6	21.5	17.1	10.7	4.0	-0.6
Sivas	-3.2	-2.3	3.0	9.1	13.3	17.1	20.2	20.4	16.5	11.1	4.2	-0.6

Figure A.10. Average monthly temperature values measured at meteorological stations of Sivas and Bitlis (Tatvan) for 30 years between 1981-2010.



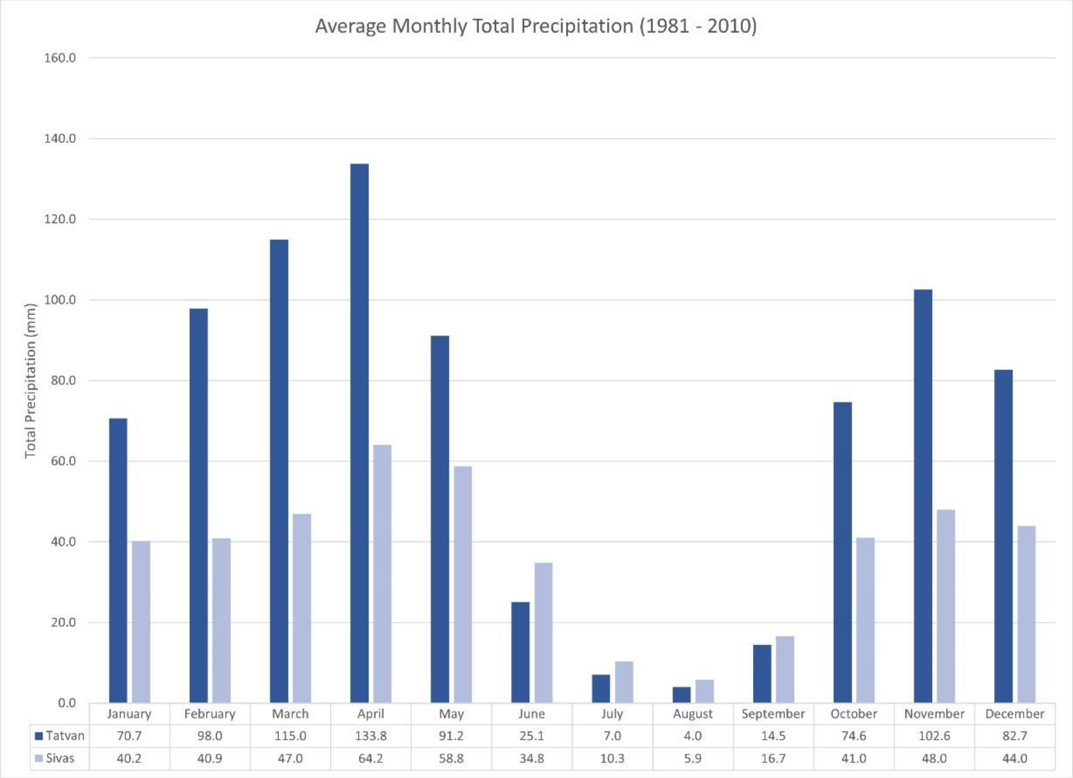
	January	February	March	April	May	June	July	August	September	October	November	December
Tatvan	75.8	75.5	73.9	69.8	63.8	55.7	51.7	52.1	54.8	67.5	72.9	76.1
Sivas	76.2	74.2	68.8	63.7	63.1	60.9	58.5	57.7	59.2	66.4	73.4	76.5

Figure A.11. Average monthly relative humidity values measured at meteorological stations of Sivas and Bitlis (Tatvan) for 30 years between 1981-2010.



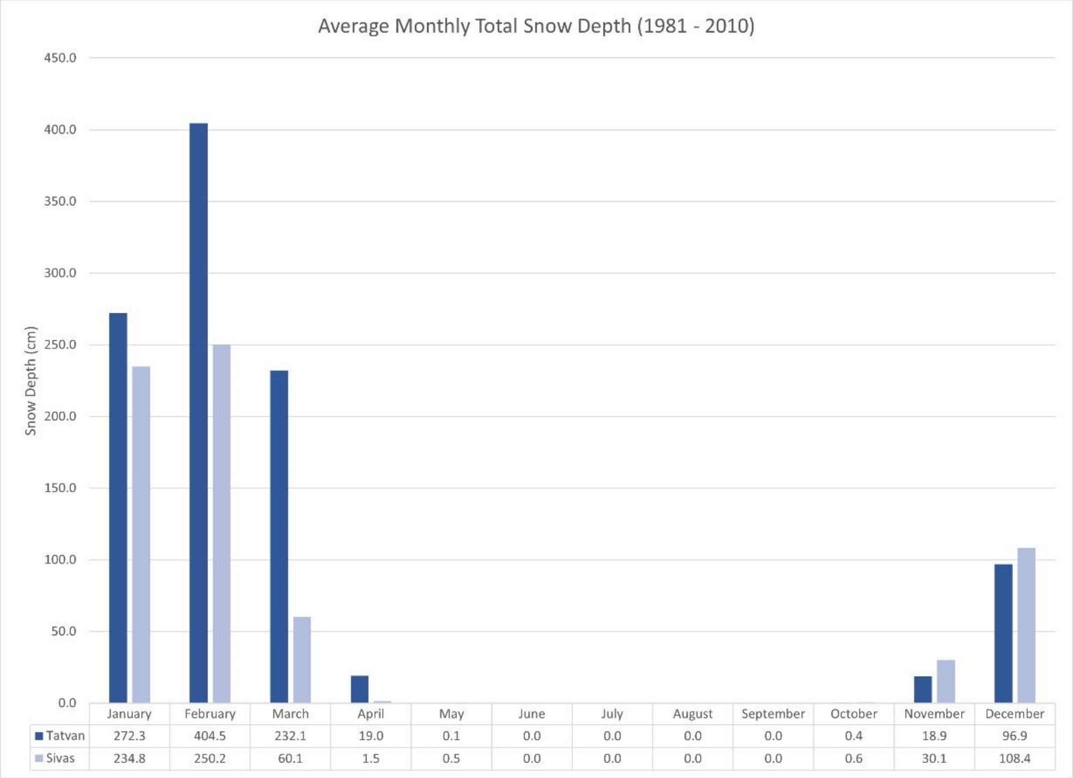
	January	February	March	April	May	June	July	August	September	October	November	December
Tatvan	1.5	1.4	1.5	1.5	1.4	1.3	1.1	1.1	1.1	1.1	1.3	1.4
Sivas	1.0	1.3	1.4	1.5	1.3	1.4	1.4	1.3	1.0	0.9	0.9	1.0

Figure A.12. Average monthly wind speed values measured at meteorological stations of Sivas and Bitlis (Tatvan) for 30 years between 1981-2010.



	January	February	March	April	May	June	July	August	September	October	November	December
■ Tatvan	70.7	98.0	115.0	133.8	91.2	25.1	7.0	4.0	14.5	74.6	102.6	82.7
■ Sivas	40.2	40.9	47.0	64.2	58.8	34.8	10.3	5.9	16.7	41.0	48.0	44.0

Figure A.13. Average monthly total precipitation values measured at meteorological stations of Sivas and Bitlis (Tatvan) for 30 years between 1981-2010.



	January	February	March	April	May	June	July	August	September	October	November	December
■ Tatvan	272.3	404.5	232.1	19.0	0.1	0.0	0.0	0.0	0.0	0.4	18.9	96.9
■ Sivas	234.8	250.2	60.1	1.5	0.5	0.0	0.0	0.0	0.0	0.6	30.1	108.4

Figure A.14. Average monthly total snow depth values measured at meteorological stations of Sivas and Bitlis (Tatvan) for 30 years between 1981-2010.

D. Climate Change Projections of Turkey for the period 2016-2099

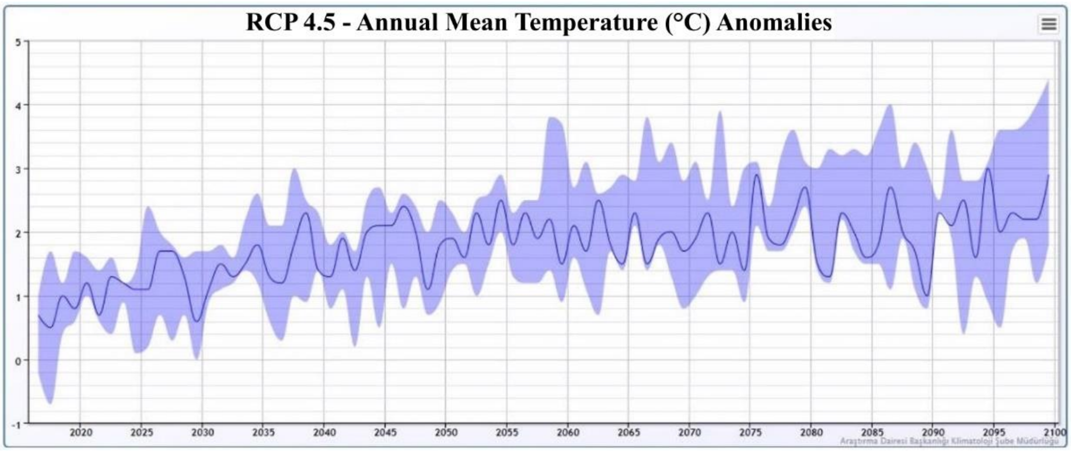


Figure A.15. RCP 4.5 - Temperature Anomaly Change Projection (MGM, 2015)

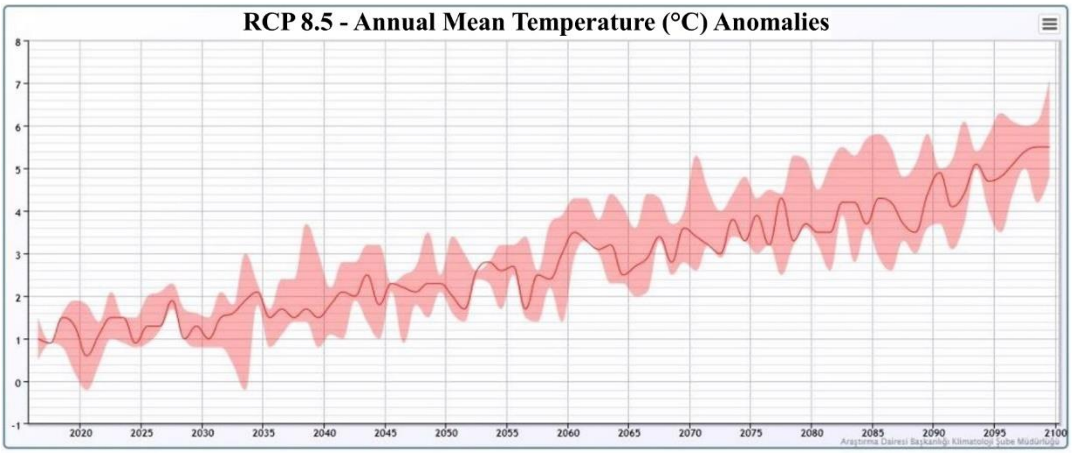


Figure A.16. RCP 8.5 - Temperature Anomaly Change Projection (MGM, 2015)

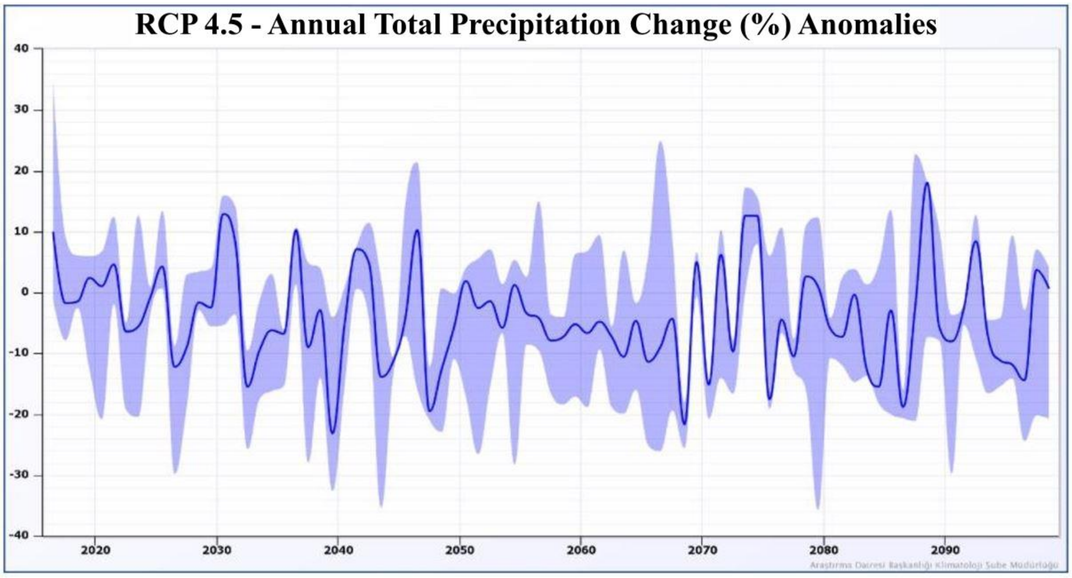


Figure A.17. RCP 4.5 - Total Precipitation Anomaly Change Projection (MGM, 2015)

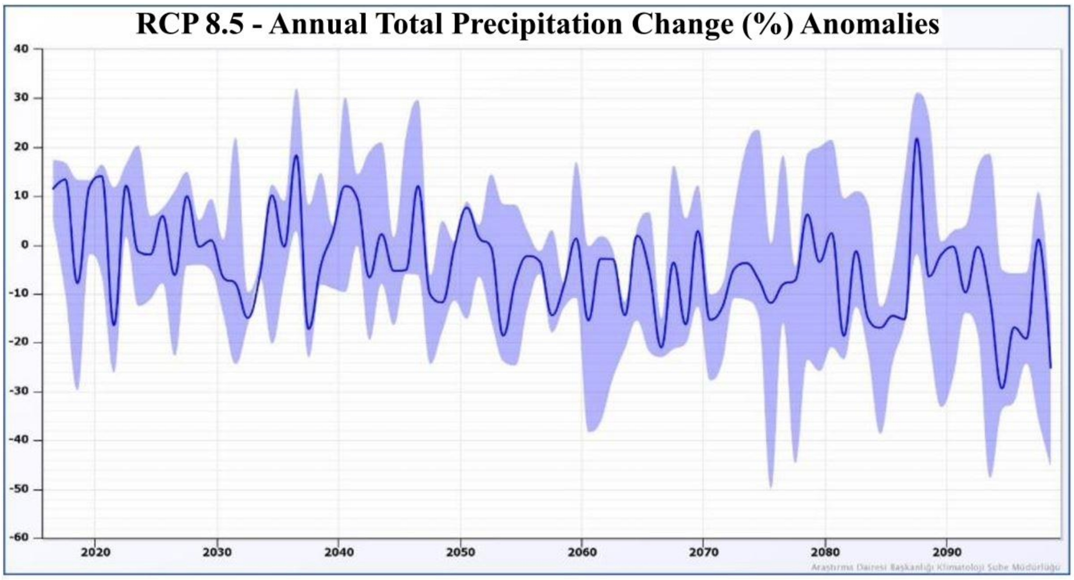


Figure A.18. RCP - 8.5 - Total Precipitation Anomaly Change Projection (MGM, 2015)