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TECHNICAL ARTICLE

Modeling and Performance Assessment of Alternative Cover Systems on a Waste Rock Storage Area

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Abstract The selection and design of an appropriate mine waste cover system for the local climatic conditions, unsaturated and saturated material properties, and available cover materials is important to mine waste management. We investigated the performance of various cover configurations for minimizing the ingress of water and oxygen into the northern waste rock storage area of the Kışladağ gold mine, in Uşak, Western Turkey. SEEP/W and VADOSE/W software were used to model the flow in unsaturated and saturated zones and to assess the performance of various cover systems. The accuracy of input data was checked during calibration for steady-state conditions with SEEP/W. Subsequently, bedrock, waste rock, and three different cover alternatives were modeled under transient conditions for 20 years using daily climatic data. All three alternatives (enhanced store-and-release, and double and single capillary barriers) were effective in limiting infiltration. However, capillary barrier covers were more effective in limiting oxygen ingress than enhanced store-and-release covers.

Keywords Acid rock drainage · Capillary barrier covers · Kışladağ Gold Mine · Soil covers · Store-and-release covers · Unsaturated flow

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Introduction

Soil cover systems are intended to isolate waste material from the atmosphere and biosphere, thus protecting environmental resources and public health (Hopp et al. 2011; McGuire et al. 2009; Nyhan 2005). The primary objective of most waste rock covers is to minimize net percolation and/or oxygen ingress into the underlying material (O'Kane et al. 1998). The long term performance of covers is an important issue because system failures can cause environmental damage due to acid rock drainage (ARD) and metal leaching. Numerical modeling of cover systems is a useful tool for long-term prediction of cover performance.

Soil covers vary depending on climate, types and volume of waste material, size and geometry of the waste storage facility, available cover materials in the field, etc. Commonly used types of soil covers are summarized as wet (water) covers, low hydraulic conductivity covers, capillary barriers, and store and release types (O'Kane and Wels 2003). Disposal of acid-generating materials below a water cover are very effective in preventing ARD because the maximum concentration of dissolved oxygen in water is approximately 30 times less than in the atmosphere and oxygen transport in water is seriously limited relative to transport in air because of advection and diffusion (INAP 2014). Low hydraulic conductivity covers are mainly composed of compacted clays with an attempt to construct a relatively impervious cover over the waste rock. However, desiccation can cause cracks in the clay layer and make it permeable, decreasing the efficiency of the cover (Fredlund and Stianson 2009).

Capillary barrier covers can be very effective in limiting both water and oxygen ingress. The capillary barrier effect occurs when a finer-textured material is placed over coarser material. The key point is the contrast between the hydraulic properties of the coarse and fine textured materials (Abdolahzadeh et al. 2011; Khire et al. 2000; Molson et al. 2008; Stormont and Anderson 1999). The concept is that the coarser material will drain to residual water content following an infiltration event, and suction is quite low at this water content for coarse material. As a result, the finer material will not drain due to this low suction and will remain in a tension-saturated condition. A capillary break will occur during drainage whenever the residual suction of the lower coarser material is less than the air entry value of the upper finer material. In addition, the performance of capillary barriers does not decrease due to desiccation or freezing and thawing, in contrast to low hydraulic conductivity barriers. Capillary barrier covers can be designed as either a single or double capillary layered system. A single capillary barrier design comprises a coarse layer overlain by a fine textured layer. In double capillary barriers, a second coarse textured layer overlies the fine textured layer to act as a drainage layer and limit the loss of water by evaporation from the moisture-retaining fine layer (MEND 2012).

Store and release covers (also referred to as evapotranspiration and water storage covers) depend on the moisture retention and storage characteristics of the cover material (Zhan et al. 2014; Zornberg et al. 2003). The key concept is that the cover material stores the infiltration during the rainy season and release the water during the dry season via evaporation and transpiration (Bosse et al. 2015; Eamus et al. 2012; O'Kane and Ayres 2012). A store and release cover can consist of one or more layers designed to maximize root penetration and soil moisture storage capacity. The multi-layered covers are referred to as enhanced store and release covers (Bosse et al. 2013; Christensen and O'Kane 2005; MEND 2012).

The local climate is important in determining the most appropriate cover type. Water covers, for example, is especially valid in humid areas since they need a high amount of precipitation to maintain a sufficient depth of water over the waste material. Store and release covers can be used under wet and dry climatic conditions but are more effective in semiarid climates (Schnabel et al. 2012). Although capillary barrier covers were initially used in arid and semi-arid climates, recent studies have shown their applicability in humid regions (Rahardjo et al. 2007). The study presented herein was conducted under semi-arid conditions, so only store and release and capillary barrier alternatives were considered. We compared the performance of both types of covers to determine which would minimize the ingress of water and oxygen following mine closure for the northern waste rock storage area of the Kışladağ gold mine, which is located in Uşak in western Turkey. The total storage capacity of the waste rock dump area is 928.6 million tons. The ultimate footprint of the facility will be approximately 477 ha. The scope of the work involved modeling the bedrock, waste rock, and various types of covers using SEEP/W and VADOSE/W software. Both of these are two-dimensional finite element programs that model unsaturated and saturated flow in porous media. The model parameters for the bedrock were obtained by conducting field tests and steady-state and transient model runs. The parameters for the waste rock and different covers were obtained from field tests and the literature. Finally, the long-term performance of each cover was evaluated.

Site Description

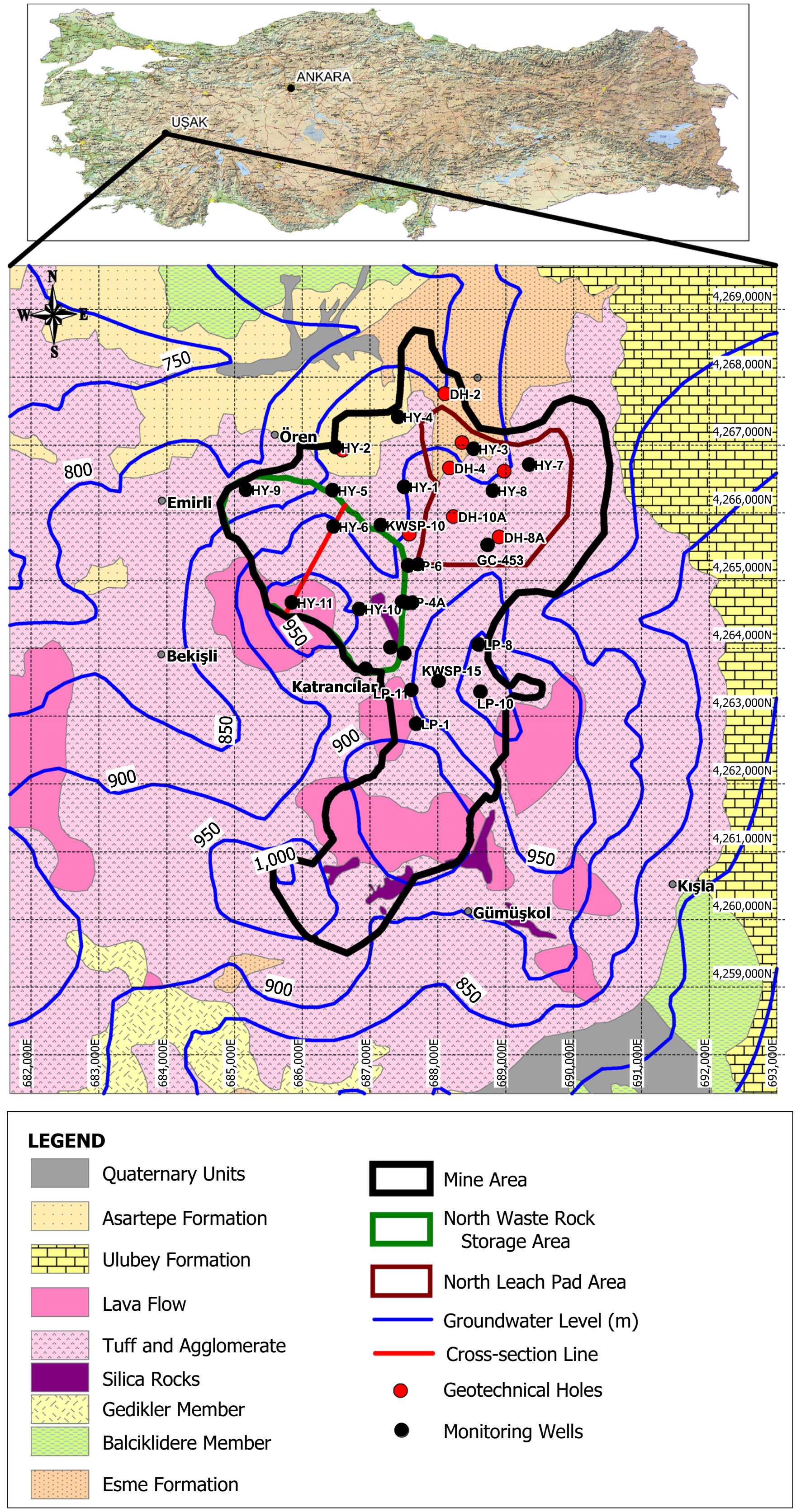
The Kışladağ gold mine is located approximately 30 km southwest of the city of Uşak (Fig. 1). The study area is located between the Aegean and Central Anatolian regions. The area has a mild winter and spring, which is the main characteristic of the area's Mediterranean transition climate (Türkeş 1996). Average annual precipitation was calculated as 493 mm for the mine site using long-term (1975–2012) precipitation data (Yazicigil et al. 2013). Long-term total annual evaporation is 1198 mm. Relative humidity is quite low in the summer months (≈38–50%), but ≈75% in the winter months.

The study area's regional geology has been described by Yazicigil et al. (2000, 2013) and mapped by MTA (2002; Fig. 1). The Eşme Formation, which is made up of schists and gneisses, comprises the crystalline basement in the study area. The Gedikler and Balçıklıdere members of the Ahmetler Formation lies unconformably above the basement, and consists of a fining-upward sequence of conglomerates, sandstone, tuffite, claystone, and marl. The Beydağı volcanics, which are made up of andesitic lava flow, agglomerates, and tuffites, have extensive outcrops in the area. The Ulubey Formation conformably overlies the Ahmetler Formation and is made up of intercalating siltstone, claystone, marl, and clayey limestones at the bottom and lacustrine limestones at the top. Deposits of this formation outcrop extensively, especially in the eastern and the northern parts of the area. The Asartepe Formation, overlying the older units unconformably, consists of alternating, weakly-cemented conglomerates, sandstones, and siltstones with local lenses of marl and claystone. Quaternary alluvial fan deposits, colluvium, and alluvium also occur in the study area.

Hydrogeology and Conceptual Model

The Kışladağ Mine is located on the groundwater divide between the Gediz and Küçük Menderes river basins. The northern waste rock dump area is located in the Gediz river basin. Both regional and local hydrogeology of the area

Fig. 1 Location and geological map of the study area



have been studied by others (SRK consulting 2005; Yazicigil et al. 2013). The groundwater level was drawn based on the drilled boreholes and monitoring wells data in the area (Fig. 1). The groundwater level is high in the southwestern part of the north waste rock storage area because of the high precipitation at the higher altitude. While the groundwater level is 960 m in the southwest, it decreases to 810 and 920 m towards the north and east, respectively. The groundwater divide occurs around well HY-11 (Fig. 1).

The Eşme Formation is overlain by Beydağı volcanics in the northern waste rock storage area. The saturated hydraulic properties of these formations are based on previous pumping and slug tests (Yazicigil et al. 2013). The Eşme Formation is generally considered to be a poor aquifer with low yields: around 2.5–3 L/s in the mine area and around the town of Eşme. The hydraulic conductivity of this formation ranges between 1.18×10^{-8} and 2.61×10^{-6} m/s, with a geometric mean of 1.81×10^{-7} m/s. The average specific capacity of wells in the Eşme Formation is 0.032 L/s/m.

The Beydağı volcanics also have low water potential. According to pumping and slug tests results, their hydraulic conductivity ranges between 4.56×10^{-9} and 1.62×10^{-6} m/s, with a geometric mean of 1.06×10^{-7} m/s. The average specific capacity of the wells in the volcanic sock is 0.002 L/s/m.

Numerical Modeling of Bedrock

Bedrock was modeled because it represents the lower boundary of the waste rock site. Modeling was completed in two stages: steady state runs followed by transient runs. The model calibration was first conducted under steady-state conditions because of the absence of long-term groundwater level data. The steady-state model results were then used as an initial head condition for the transient run. Model extents and grid properties were the same for both conditions, but boundary types changed.

A southwest to northeast cross section was used to develop a numerical model for the northern waste rock storage area (Fig. 1). This cross section was oriented to pass through the existing monitoring wells (HY-11 and HY-6) and parallel to the study area's groundwater flow direction. The Beydağı volcanics, and Eşme Formation were modeled as two different zones due to their different hydraulic properties (Fig. 2). The model domain was 1750 m in length with a unit width; however, the thickness varied due to

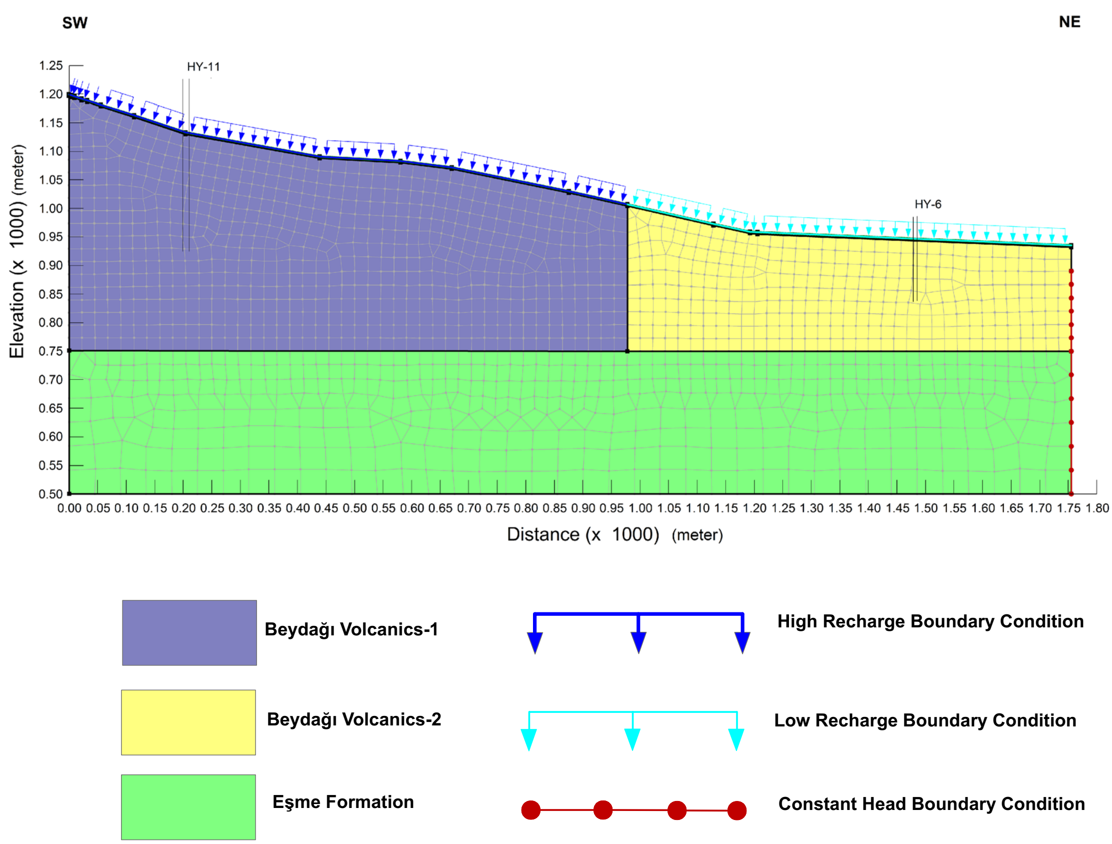


Fig. 2 Discretized model domain

topography. The Eşme Formation was modeled with a constant thickness of 250 m, while the Beydağı volcanic rocks were modeled with a thickness that varied between 446 and 183 m. Groundwater levels in the HY-6 and HY-11 wells and a groundwater level map (Yazicigil et al. 2013) were used for the steady state calibration. A finite element grid was designed based on the model geometry and the aim of the study. Quads and triangular elements were used. An element size of 22.5 m was selected for the Beydağı volcanics, while the element size of the Eşme Formation was set at 45 m due to its greater saturated thickness. The bedrock model contained 3484 nodes and 3411 elements.

Next, boundary conditions were defined. For the steady-state analysis, the groundwater head condition at the northeastern part of the model was assigned a constant head boundary of 890 m. An impervious boundary condition was assigned to the southwestern part of the model to represent the groundwater divide. A boundary condition for the upper border of the model domain was assigned as two different recharge zones (Unsal and Yazicigil 2016). The southwestern part of the model domain, which is at a higher elevation and receives more recharge, is referred to as the highland recharge zone and was initially assigned a recharge rate of 76 mm/year. The lower recharge zone in the northeast, referred to as the lowland recharge zone, was assigned a recharge rate of 29 mm/year. Both values were changed within reasonable limits during calibration.

For the transient analysis, the upper boundary was assigned as a climate boundary. For the bedrock transient run, the northeastern boundary was no longer kept as constant head. A unit flux boundary was assigned to the northeastern boundary where the assigned unit flux amount was obtained from the steady state calibrated model. The seepage boundary condition was assigned above the unit flux boundary condition to remove the excess water.

Model Parameters

Volumetric Water Content Function [Soil Water (or Moisture) Characteristic Curve]

The volumetric water content function or soil water characteristic curve (SWCC) defines how much water will be held in the system depending on matric suction. The volumetric water content curve can be determined by grain size analysis, and laboratory and in situ analysis. Additionally, in the absence of data, the volumetric water content curve can be estimated from the literature. Both SEEP/W (Geo-Slope 2007) and VADOSE/W (Geo-Slope 2007) use the Van Genuchten estimation method to calculate the SWCC. The Van Genuchten estimation formula uses saturated and residual water contents and curve fitting parameters (air entry value and slope) to obtain the change in water volume with respect to changes in matric suction.

Saturated water content was taken to be 2% for both the Beydağı volcanic rocks and the Eşme schists. To determine Van Genuchten parameters for these bedrock units, both the fine grained soil and matrix part of the fractured rocks were considered (Benson et al. 2007; Rasmussen 2001; Parent and Cabral 2006; Stormont and Morris 1998). Figure 3 shows the resulting SWCC.

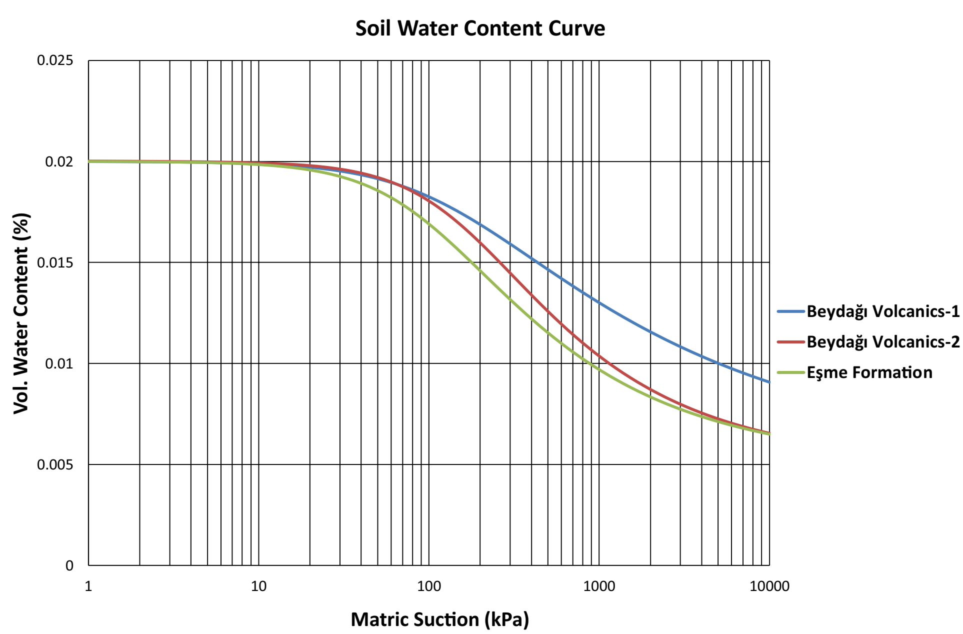


Fig. 3 Soil water content curve for the bedrock model

Unsaturated Hydraulic Conductivity

The hydraulic conductivity for the unsaturated zone changes with water content. In the absence of field and/or laboratory methods to derive these curves, estimation methods, such as those of Van Genuchten (1980) and Fredlund and Xing (1994), can be used. In this study, the Van Genuchten method was used. The unsaturated hydraulic conductivity curves used in the bedrock model after calibration are shown in Fig. 4. The ratio of anisotropy, i.e. the ratio of vertical conductivity to the horizontal conductivity, was assumed to be 0.1 (Unsal and Yazicigil 2016).

Vegetation Parameters

Vegetation data is required by VADOSE/W to model cover design alternatives. Grasses are generally preferred for soil covers because they minimize erosion, transpire stored water, and have thin roots that do not create preferential flow paths. Three components were used as input for the vegetation data: leaf area index (LAI), plant moisture limiting point, and root depth. In order to determine LAI, grass quality and growth season are necessary. The growth season is between April 15 and Oct. 10 (Yazicigil et al. 2013). The vegetation can be defined as being of poor, good, or excellent quality, while root depth can be measured in the field or an average grass depth can be assigned. In this study, the grass was of poor quality and root depths in the cover designs were taken to be 30 cm by comparing precipitation, growth season, and actual evaporation to other similar studies (Adu-Wusu et al. 2007; Christensen and O'Kane 2005).

Climate Parameters

Input for climate data in VADOSE/W is daily minimum and maximum temperature, minimum and maximum relative humidity, wind speed, and precipitation. Daily climate data obtained from the on-site meteorological station for the period between 2008 and 2012 was used in the model. Precipitation was distributed for 24 h because runoff is predicted more accurately when the precipitation is applied uniformly throughout the day (Bohnhoff et al. 2009).

Modeling Methodology

Steady-state Calibration

The bedrock model was calibrated under steady-state conditions due to the absence of long-term groundwater level data at the waste rock storage area. During calibration, a trial and error method was used to modify parameters such as saturated hydraulic conductivity, flux amount, and volumetric water content functions. These parameters were adjusted within reasonable limits until there was a good match between measured and simulated groundwater levels across the cross section shown in Fig. 1. The goodness of the fit was checked by comparing the simulated and measured groundwater levels (Supplemental Fig. 1). The model was calibrated with a root mean square error (RMSE) value of 0.93 m and a normalized root mean square error (NRMSE) value of 1.37%. These statistics are acceptable considering the homogeneity of the parameters used in the model.

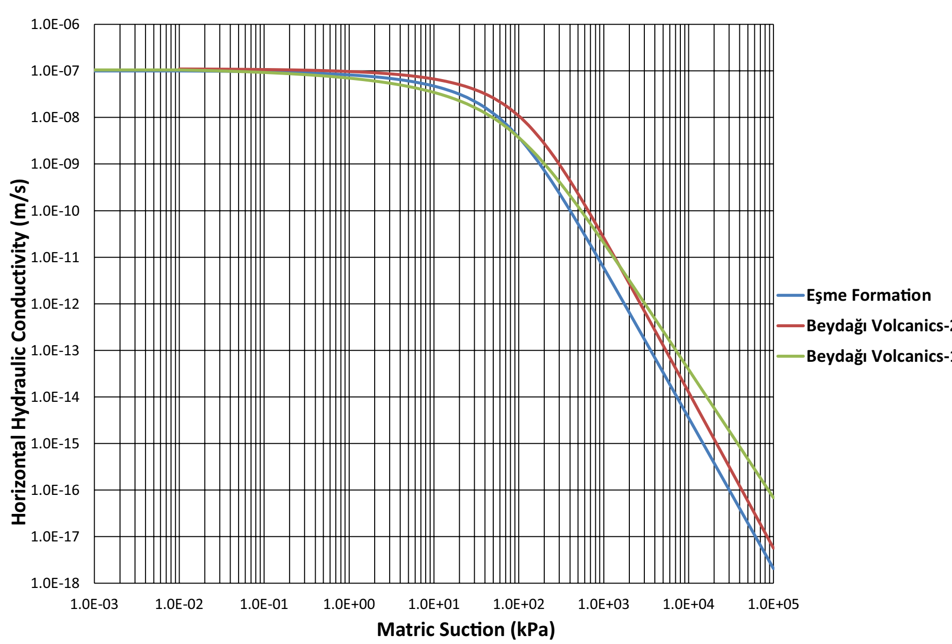


Fig. 4 Unsaturated hydraulic conductivity curves for the bedrock model

A sensitivity analysis was performed to evaluate the effects of variations in saturated hydraulic conductivity, recharge values, constant head boundary, and Van Genuchten parameters (α and n). The resulting NRMSE value from the sensitivity analysis was compared with the NRMSE obtained from the calibration. Among the evaluated parameters, the model showed the highest sensitivity to highland recharge. The model was not sensitive to SWCC parameters under steady-state conditions. However, the model was quite sensitive to SWCC parameters under transient analysis because SWCC controls storativity. In order to assign reasonable curve parameters, these parameters were checked under transient conditions. Since long-term measured water level data were not available, it was not possible to conduct a transient calibration. While curve parameters were evaluated, water levels at HY-6 and HY-11 monitoring wells were checked to see if simulated and measured water levels were similar, despite the short period of record (6 months for HY-6 and 15 days for HY-11). Furthermore, the infiltration amount was also checked to see if the calculated value was similar to the amount used in the steady-state model.

Transient Analysis

In the transient analysis of the bedrock, water levels at the HY-6 and HY-11 monitoring wells and water budget were evaluated. A transient analysis of the bedrock was started from Jan. 2008 and was run for 20 years. For the climate parameter, 5 year daily climate data (2008–2012) measured in the Kışladağ gold mine's AWOS meteorological station was sequentially repeated 4 times. Supplemental Fig. 2 shows the simulated and measured water levels for the HY-6 monitoring well. The groundwater level at this well was close to (about 22.5 m below) the ground surface. Therefore, any changes in the precipitation had a rapid response in the groundwater level. The groundwater levels at HY-6 were monitored from June 1, 2012 to Dec. 12, 2012, during which measured levels fluctuated between 913.62 and 913.12 m. The simulated values oscillated between 914.28 and 913.93 m, with a similar pattern.

Supplemental Fig. 3 shows the simulated ground water level for HY-11. There is no oscillation of the ground water level for HY-11, unlike HY-6. The groundwater level is quite deep around the HY-11 well, so changes in precipitation do not immediately affect the water level there during the short period of observation. Additionally, the modeled groundwater level at HY-11 generally decreases. VADOSE/W can overestimate the runoff value resulting in less water entering the system (Bohnhoff et al. 2009). This could explain the simulated decrease. The first four columns in Table 1 shows the average water budget components obtained from the transient model run for the bedrock system. Results are given as an annual average.

The fourth column in Table 1 shows the percentage of water budget components due to precipitation. 38.22% of the precipitation was lost due to evaporation and 54.66% due to runoff. The remainder was calculated as infiltration from the surface. After that, infiltrated water is either lost due to boundary flux or kept in the system as a storage amount. This means the sum of the storage and boundary flux equals the infiltration. The average infiltration value was calculated as 39 mm over 20 years (Table 1). This value is divided into 45 and 27.5 mm for the highland and lowland areas, respectively. After steady-state model calibration, recharge values of 60 and 27 mm were selected for the highland and lowland, respectively.

Alternative Cover Scenarios

Four different models were evaluated: a no cover alternative (bare waste rock), an enhanced store and release alternative, a single capillary barrier alternative, and a double capillary barrier alternative (Fig. 5). All models were run for 20 years under transient conditions in two dimensions in VADOSE/W. To increase runoff and minimize ponding, the surface of the site (model) was assumed to be graded at 5%. The sides of the models were sloped at 20%. The soil water content curve (Fig. 6) and unsaturated hydraulic conductivity curves were input to the models. The SWCC parameters were taken from field tests for oxidized rocks and literature for cover layers (Benson et al. 2007; Bussiere et al. 2003; Hopp et al. 2011; Khire et al. 2000; Mbonimpa et al. 2008; Noel and Rykaart 2003; Stormont and Morris 1998). VADOSE/W used the Van Genuchten estimation method to draw the unsaturated hydraulic conductivity curve (Fig. 7), which is derived from the saturated hydraulic conductivity value and SWCC. The climate boundary was assigned as an upper boundary condition in all models. No vegetation function was assigned to the no-cover alternative because waste rock generally consists of coarse material on which it is nearly impossible to grow vegetation. However, the vegetation function was included in the other three models. The other boundary conditions were kept the same as in the bedrock transient analysis.

The water budget components, especially the infiltration amount into the waste rock and the oxygen content percentage in the waste were evaluated in order to compare the performance of the various cover types. To limit oxygen migration, the overlying storage layer must be at least 85% saturated (Adu-Wusu et al. 2007; Yanful 1993). In all cover alternatives, saturation is enhanced by including a fine grained layer that behaves as a storage layer. The average saturation at five different points in the middle of the

Table 1 Average water budget components for bedrock and alternative covers

Bedrock				No cover alternative (bare waste rock)			Enhanced store and release alternative				Single capillary barrier alternative			Double capillary barrier alternative		
Water budget component	m^3/year	mm/year	Percentage due to precipitation (%)	m^3/year	mm/year	Percentage due to precipitation (%)	Water budget component	m^3/year	mm/year	Percentage due to precipitation (%)	m^3/year	mm/year	Percentage due to precipitation (%)	m^3/year	mm/year	Percentage due to precipitation (%)
Precipitation	969.00	543.16		993.00	543.16		Precipitation	993.00	543.16		993.00	543.16		993.00	543.16	
Actual evaporation	366.00	205.20	38.22	673.00	368.00	67.75	Actual evaporation	561.32	307.00	56.52	556.83	304.58	56.10	623.80	340.80	62.74
Runoff	534.00	299.30	54.66	160.00	87.40	16.10	Runoff	370.00	203.38	37.44	389.25	212.91	39.20	305.45	167.00	30.75
Infiltration	69.00	38.68	7.12	160.00	87.40	16.10	Infiltration from top of surface layer	61.70	33.70	6.20	46.92	25.60	4.71	63.75	34.87	6.42
Transpiration	0.00	0.00	0.00	0.00	0.00	0.00	Transpiration	44.30	24.21	4.46	35.65	19.50	3.60	32.94	18.00	3.31
							Infiltration into waste rock	15.32	8.37	1.54	5.55	3.00	0.55	6.00	3.30	0.60
Boundary flux	89.00	48.7	8.97	89.00	48.7	8.97	Boundary flux	89.00	48.7	8.97	89.00	48.70	8.97	89.00	48.7	8.97
Storage	−20.00	−10.00	−1.85	71.00	38.83	7.15	Storage	−71.60	−39.20	−7.22	−77.73	−42.50	−7.83	−58.19	−31.80	−5.85

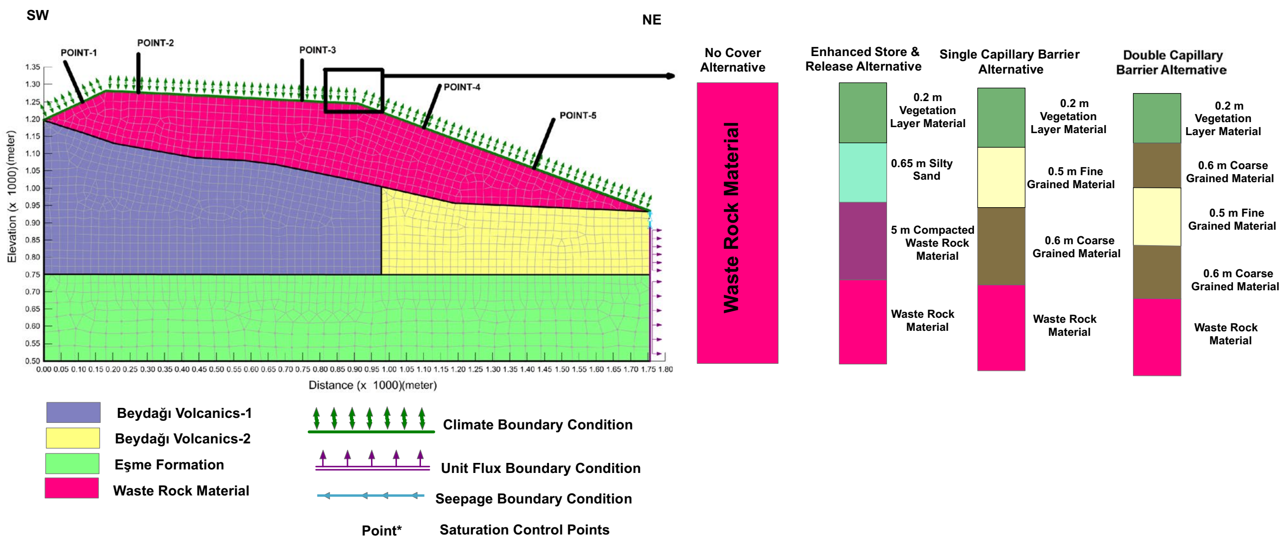
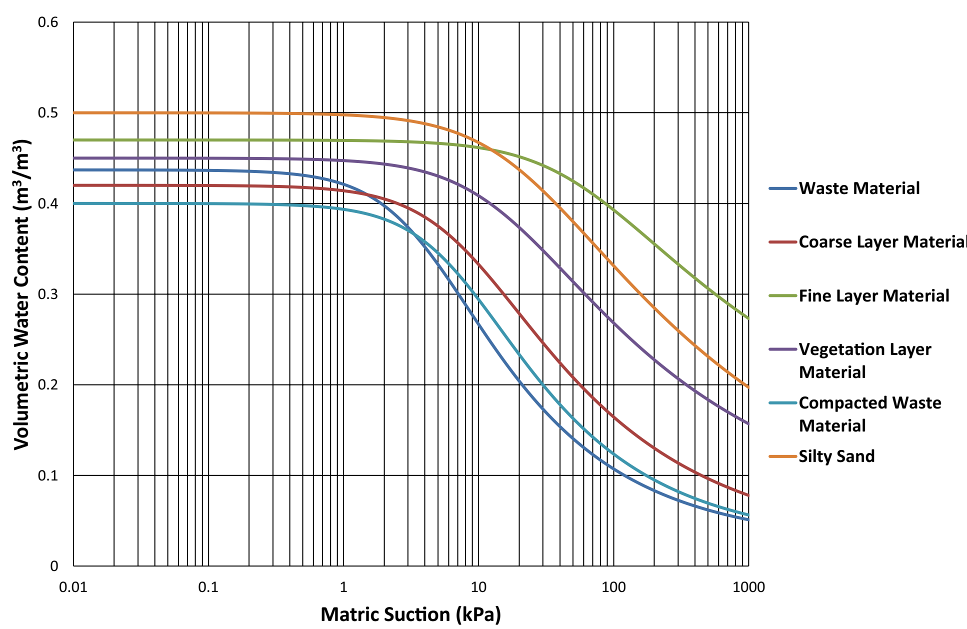


Fig. 5 Alternative cover designs

Fig. 6 SWCC for the alternatives



storage layer was graphed (Fig. 5). Additionally, in order to see the amount of oxygen in the waste rock, a cross section was taken from the ground surface into the waste rock. The ground surface elevation is different for various cover alternatives since the covers in this study have different thicknesses. Thus, in order to compare the oxygen content percentage, a reference elevation of 1258 m was selected.

No Cover Alternative

This alternative consisted of modeling the bare waste rock. Test results from the waste show that the sulphide waste rock material has acid rock drainage (ARD) potential (Encon 2013). Modeling the bare waste rock gives information on the amount of water infiltration and oxygen ingress. The saturated hydraulic conductivity (2.32×10^{-4} m/s), saturated water content (θ_s; 0.437) and residual water content (θ_r; 0.025) values used for the waste rock material were taken from the report prepared by Encon (2013) for the Kışladağ Gold Mine. The soil water content curve fitting parameters, which are the air-entry value and slope of curve, were also taken from the same report, but the parameters were slightly modified, according to Hopp et al. (2011).

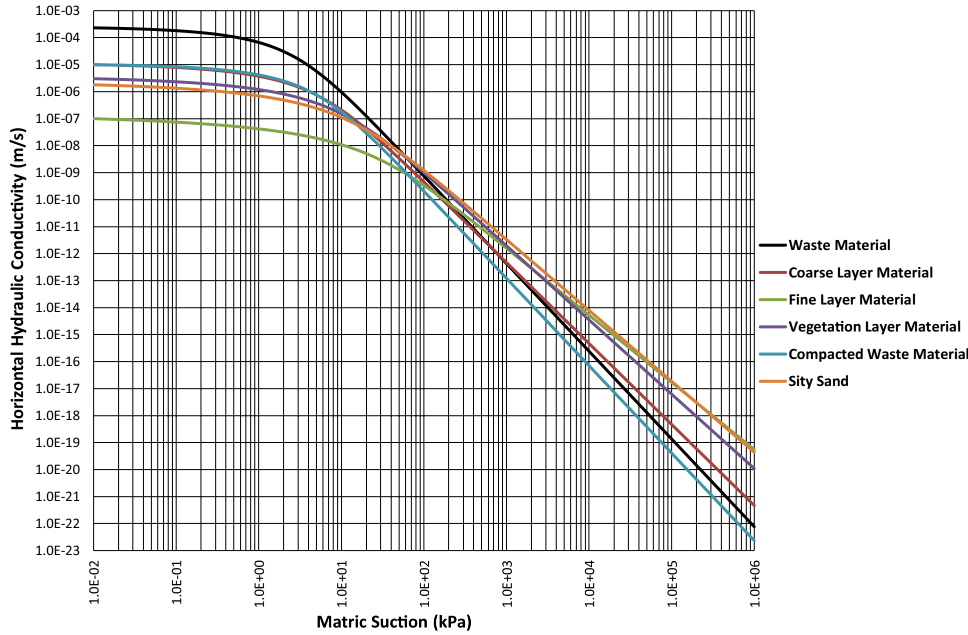


Fig. 7 Unsaturated hydraulic conductivity curve for the alternatives

Enhanced Store and Release Alternative

Store and release type covers may consist of one or several layers, with the latter referred to as enhanced store and release covers. In this study, three layers were used, making good use of on-site materials. The modeled cover included 0.65 m of silty sand (storage layer) underlain by 5 m of compacted waste rock to create a capillary break. The compacted waste rock kept the storage layer saturated and limited downward percolation. A 0.2 m thick vegetated layer was added on top of the system.

SWCC for the compacted waste material was modified from the waste material SWCC curve. When the material is compacted, the air-entry value increases and the porosity and saturated hydraulic conductivity decreases, although the SWCC slope is similar (Ayres et al. 2003; Heshmati and Motahari 2012). According to the unified soil classification system, the saturated hydraulic conductivity for silty sand ranges between 1×10^{-5} and 1×10^{-8} m/s; a value of 1.8×10^{-6} m/s was used, based on literature (Benson et al. 2007; Parent and Cabral 2006; Stormont and Morris 1998). The vegetated layer was designated a sandy loam with a saturated hydraulic conductivity of 3.29×10^{-6} m/s, referring to similar studies (Hopp et al. 2011; Stormont and Morris 1998).

Single Capillary Barrier Alternative

When they are properly constructed, capillary barriers are effective in limiting water migration in semi-arid areas (Fala et al. 2005; Parent and Cabral 2006). However, it can be difficult to design a cover that contains a layer that stays 85% saturated for prolonged dry periods. The single capillary barrier cover selected for this study had three layers: a 0.6 m thick coarse grained capillary break layer placed under a 0.5 m thick fine-grained moisture-retaining layer, with a 0.2 m thick vegetated layer for erosion protection. Layer thicknesses were selected based on Khire et al. (2000) and Parent and Cabral (2006). The latter showed that when the thickness of the lower coarse-grained layer is less than 0.60 m, there can be a decrease in suction value at the interface, inducing seepage from the fine-grained layer. Khire et al. showed that storage layers thicker than 0.45 m do not transmit significant amounts of percolation water. The fine-grained layer was selected to be a silty material with a hydraulic conductivity of 1×10^{-8} m/s, while the coarse-grained layer was selected to be a sandy gravel mixture with a hydraulic conductivity of 1×10^{-5} m/s.

Double Capillary Barrier Alternative

In this alternative, the cover is designed by considering material properties, optimum thickness, and fine and coarse layer alternation to keep the fine layer 85% saturated. This alternative uses a double capillary barrier to limit oxygen ingress into the waste rock (Fig. 5). The design consists of four layers and is similar to a single capillary barrier design except that a coarse grained layer is placed over the fine grained soil to act as a drainage layer and limit the loss of water by evaporation from the moisture-retaining fine layer.

Results and Discussion

Table 1 shows the results of the average annual water budget components for the bedrock and all the cover alternatives that were obtained from transient run models over 20 years with daily time steps. All models used the same annual precipitation sequence. As expected, the calculated runoff in the bare waste rock model was quite low. Since more water infiltrates into the waste rock, the calculated evaporation rate was also higher in the waste rock model.

In the enhanced store and release alternative, about 60% of the precipitation was removed by evaporation and transpiration. This is quite consistent with the purpose of store and release covers.

When the water budgets of capillary barrier alternatives were evaluated, the double capillary barrier alternative had more infiltration but less runoff due to the additional coarse-grained layer. In the single capillary barrier alternative, however, evaporation was less because of its lower water content. In both capillary barrier alternatives, infiltration into the waste rock was significantly reduced (i.e. 0.55 and 0.6% of precipitation in the single and double capillary barrier alternatives, respectively). In short, all three cover models effectively limited infiltration into the waste rock.

VADOSE/W assumes oxygen concentrations of 280 g/m^3, which is a typical concentration in air at the ground surface. Hence oxygen content at the ground surface is accepted as 100%; the changes in oxygen content in storage layers after 20 years are given in Fig. 8. In the no cover alternative, oxygen content was 96% at the reference point (1258 m). Oxygen content was only slightly lower (86–90%) in the store and release alternative. The capillary barrier alternatives had 30–40% oxygen content at the reference elevation, with the double capillary barrier alternative being more effective in limiting oxygen ingress. Oxygen ingress is controlled by the water saturation percentage of the storage layer; increased saturation reduces oxygen ingress.

The saturation percentage in the storage layers for the various cover alternatives over the 20 years simulation period is shown (Fig. 9). The store and release cover alternative had significantly less saturation than the capillary barrier alternatives. In the dry season, saturation in the store and release cover decreases 40–50%, while the capillary barriers had significantly higher saturation percentages, even in the dry season.

In the single capillary barrier, saturation varied from 75 to 95%, depending on the season, but was generally less than 85%, and decreased to 70% on the side slopes. On the other hand, the double capillary barrier alternative had a saturation percentage that exceeded 85% most of the time, even on the side slopes. Thus, both capillary barrier models produced low amounts of oxygen ingress due to higher water saturation in the storage layers, with the double capillary barrier being the most effective in limiting oxygen ingress on side slopes.

Summary and Conclusions

We compared the performance of different modeled waste rock covers for the planned northern waste rock storage area of the Kışladağ Gold Mine using two-dimensional finite element models, SEEP/W and VADOSE/W. Modeling was completed in connected stages. First, site-specific and literature-estimated data were used to assign material properties. The first modeling step was bedrock calibration under steady-state conditions with SEEP/W until a good

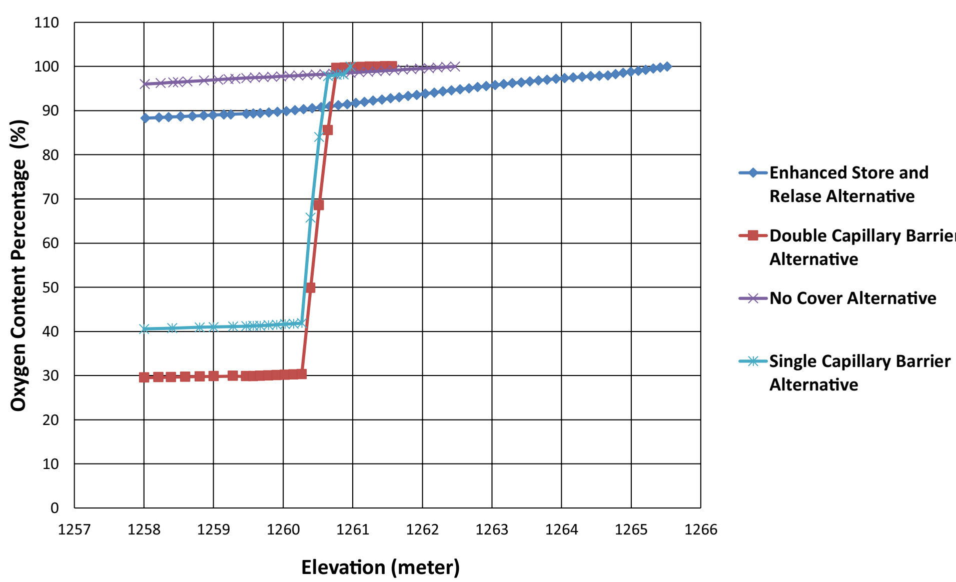


Fig. 8 Oxygen content percentage at the end of 20 years for cover alternatives

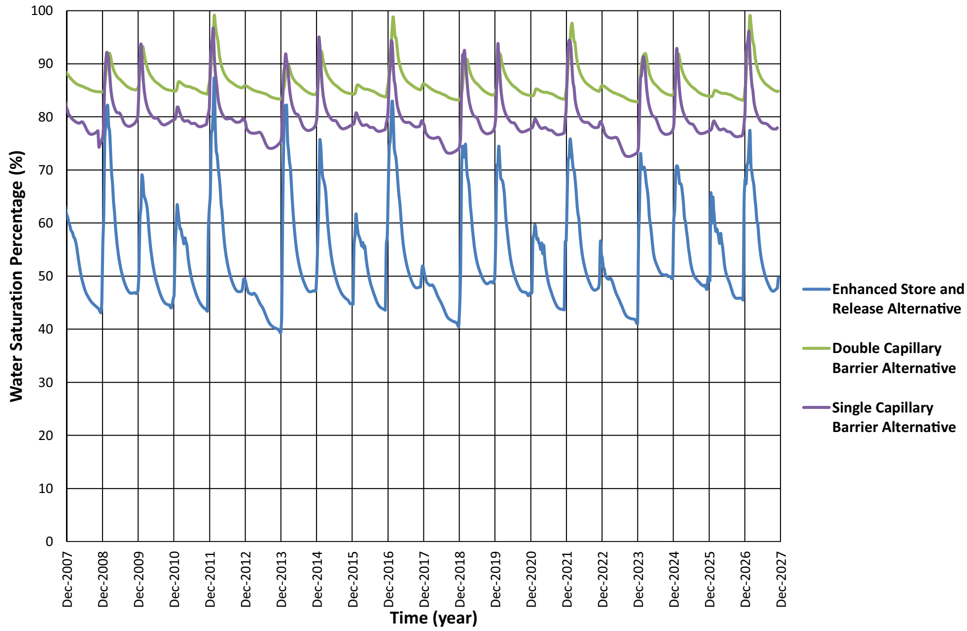


Fig. 9 Water saturation percentage in the storage layers of cover alternatives throughout the 20 years

match was obtained between the measured and simulated groundwater levels. Then, the bedrock was modeled under transient conditions with VADOSE/W for a 20 years period using daily time steps. The result of the calibrated steady-state model was used as an initial head distribution for transient analysis of the bedrock system. Waste rock was then placed on the bedrock and they were modeled together. The waste rock was initially modeled without a cover and the results showed that there were significant amounts of water infiltration and oxygen migration into the waste rock. Three soil cover options were then modeled; the results showed that all three were quite effective in limiting water infiltration into the waste rock, with a consequent decrease into the groundwater system.

The choice of a particular cover over waste rocks depends not only on the ARD potential of the waste rock but also on the cost and availability of the local materials. The enhanced store and release alternative made the best use of on-site materials. The capillary barrier alternatives would require external sourcing or processing of materials; however, the capillary barriers had greater saturation percentages in the storage layer, even in a semi-arid study area. Additional field testing would need to be done to identify a store and release configuration where the storage layer remains at least 85% saturated at all times. Among the three alternatives tested, the double capillary barrier maintained saturation the best, thereby limiting oxygen ingress into the waste rock.

Numerical modeling can provide initial screening of the various cover types, even if a full set of parameter values are not available. After viable alternatives are determined, test plots can be constructed in the field to evaluate the effectiveness of the soil covers in reducing ARD, with the goal of choosing the best option for final closure.

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