

Cold desert evapotranspiration cover system design

L Bunting *GeoSystems Analysis, Inc., USA*

J Keller *GeoSystems Analysis, Inc., USA*

M Milczarek *GeoSystems Analysis, Inc., USA*

C Jim *Round Mountain Gold Corp., USA*

K Bansah *Round Mountain Gold Corp., USA*

Abstract

*Round Mountain Gold Corporation (RMGC) mine is located in central Nevada, USA at an elevation varying between 1,770 m and 2,070 m above mean sea level. The climate is characteristic of a cold desert climate, with cold winters and hot summers. Average annual precipitation is 11.8 cm, approximately 13 times less than the calculated average annual potential evapotranspiration (PET) of 159 cm. RMGC constructed evapotranspiration (ET) cover system test plots in 2012 to evaluate the effectiveness of 0.3 m, 0.9 m, and 1.5 m thick monolayer ET cover systems in minimizing net percolation of precipitation into underlying potential acid generating waste rock which may result in poor water quality seepage outflow. Each test plot is approximately 200 m² and includes three cover system performance monitoring stations consisting of sensors placed at approximately 0.6 m intervals along a vertical profile in the cover and waste rock to a maximum depth of 2.4 m. The sensors measure soil matric potential, temperature, water content, and direct net percolation water flux. Soil water content and matric potential data are used to evaluate the cover systems' capacity to store infiltrated precipitation and to remove water via ET. Direct net percolation flux measurements are collected below the estimated depth of ET and these measurements provide a point estimate of net percolation flux into the waste rock. The site-specific seed mix applied to the test plots did not establish, thus test plot vegetation is primarily comprised of invasive annuals Russian Thistle (*Salsola tragus*) and Halogeton (*Halogeton glomeratus*).*

Annual precipitation from 2012 through 2021 was representative of long-term average precipitation conditions. Wetting was observed to a maximum depth of 1.2 m at the 0.3 m and 1.5 m ET cover system test plots. The deepest wetting (1.8 m) was observed in the 0.9 m ET cover system test plot due to focused run-on at the location of two of the three monitoring stations. At all test plots, drying of the soil profile occurred in late spring and early summer in response to decreased precipitation and increased ET. The average annual net percolation flux over the monitoring period was zero for the 0.3 and 1.5 m ET cover systems and 0.1% of precipitation for the 0.9 m cover system, most likely due to run-on to the test plot. Results to date indicate no difference in the effectiveness of 0.3 m, 0.9 m, and 1.5 m ET cover system thicknesses in minimizing net percolation of precipitation into underlying waste rock.

Keywords: *ET cover system, net percolation, monitoring, modelling*

1 Introduction

Excluding water from acid-generating material is a feasible alternative to control acid mine drainage in arid and semi-arid environments (Scanlon et al. 2005; Zhan et al. 2014). Consequently, mine closure plans in these types of environments generally focus on minimizing infiltration and net percolation (i.e., seepage) resulting from precipitation on waste rock, spent leach ore, or tailings. The amount of long-term steady-state seepage is a function of climatic conditions, plant species rooting depth and water consumption, and waste material and cover system hydrologic properties. In arid and semi-arid environments where annual potential evaporation and transpiration is much greater than precipitation, evapotranspiration (ET) cover systems are often placed over mine waste material to minimize net percolation of precipitation. ET cover systems reduce

net percolation by storing infiltrated water in soil or waste until vegetation can transpire or atmospheric demand can evaporate the stored water.

Cold desert climates, as defined by the Köppen-Geiger climate classification system (Kottek et al. 2006) experience hot, dry summers and cold, dry winters. In North America, the cold desert climate occurs in the Great Basin Desert of Nevada, Utah, California, Oregon and Idaho. In these environments, annual potential evapotranspiration (PET) may be five times or more than precipitation; however, the majority (e.g., more than 75 percent) of PET occurs during the spring/summer (April through September) and 25 percent in the fall winter (October through March) whereas precipitation is typically evenly distributed through the year. As a result, approximately 50 percent of the precipitation occurs during the time of the year when PET is low, requiring sufficient ET cover system storage during this period.

The long-term performance of ET cover systems in arid and semi-arid environments is often difficult to quantify due to low unsaturated flow rates and highly variable hydrologic properties (Milczarek et al. 2000). Furthermore, net percolation can be expected to result primarily from episodic periods of higher than average precipitation (i.e. during El Niño years), such that net percolation between these periods may not exist or be extremely difficult to measure. Thus long term-monitoring to capture climatic variability is necessary.

The objective of this study was to quantify long term ET cover system performance in the cold desert climate of Nevada and to assess the optimum ET cover thickness to reduce net percolation into potential acid generating waste rock.

2 Methods

Round Mountain Gold Corporation (RMGC) operates the Round Mountain gold mine located in central Nevada, USA, 72 km north of Tonopah, Nevada (Figure 1). Round Mountain uses conventional open-pit mining methods and processes ore by mill and heap leach. Current life of mine is through 2027, with 2.2 million oz of estimated proven and probable gold reserves. Mine site elevations vary between 1,770 m and 2,070 m above mean sea level (amsl), with the mine waste repositories located on the valley floor between the Toiyabe and Toquima mountain ranges.

The climate is characteristic of a cold desert climate, with cold winters and hot summers. Average monthly temperatures (1950 through 2021) range from -1°C in December to 22°C in July. Average annual precipitation (2012 through 2021) is 11.8 cm, approximately 13 times less than the Penman-Monteith method (Allen et al. 1998) calculated average annual PET of 159 cm. On average, approximately half of precipitation falls during the fall/winter season (October through March) when 25% of PET is predicted to occur and half of precipitation falls in the spring/summer season (April through September) when 75% of estimated PET is predicted. Snowfall at the site is negligible.

ET cover system trials have been initiated by RMGC to evaluate the efficacy of 0.3-, 0.9, and 1.5-m mono-layer ET cover system thicknesses in minimizing net percolation of precipitation into potentially acid generating (PAG) waste repositories at Round Mountain. Large-scale test plots have been constructed over waste rock and instrumented with sensors to evaluate the cover systems' capacity to store infiltrated precipitation and to remove water via ET. In this paper we examine the performance of the ET cover systems in reducing net percolation.

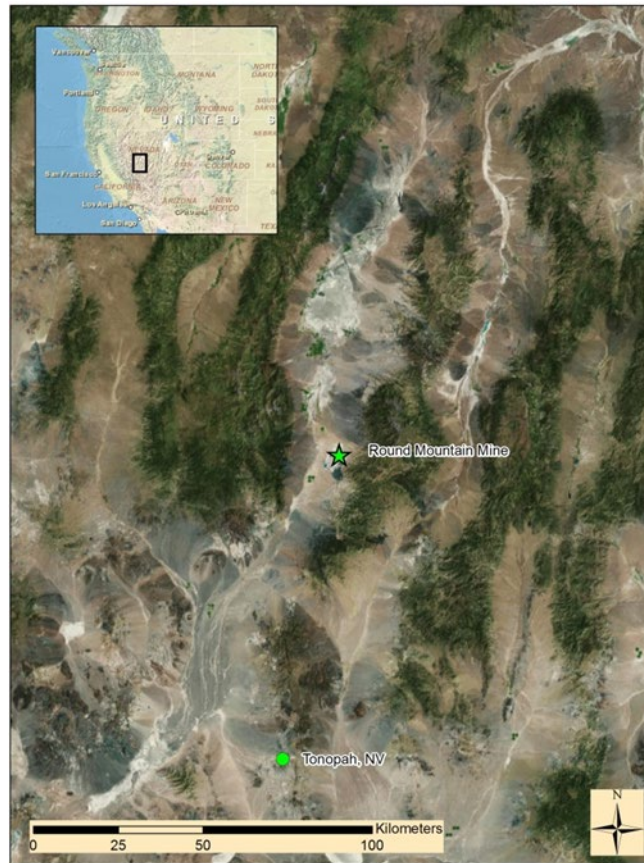


Figure 1 Round mountain mine location map

2.1 Test plot monitoring

In December of 2012 RMGC constructed mono-layer ET cover system test plots consisting of 0.3-, 0.9-, and 1.5-m alluvium cover material over PAG waste rock. Each test plot is approximately 200 m² and includes three cover system performance monitoring stations spaced approximately 7 m apart and consisting of sensors placed at intervals along a vertical profile in the cover and waste rock to a maximum depth of 2.4 m (Figure 2). The cover material is on average 34% gravel (>4.75 mm), 52% sand (4.75 mm – 0.075 mm) and 14% fines (<0.75 mm). Waste rock particle size distribution is slightly finer textured than the cover material, on average containing 28% gravel, 50% sand and 22% fines.

The three principal soil water parameters monitored are: 1) soil water potential, 2) water content, and 3) direct net percolation flux. Soil water potential and water content are used to evaluate the cover systems' water storage capacity and observed hydraulic gradients determine the direction of soil water movement. Net percolation flux describes the rate of water movement beyond the ET depth (zero flux plane) that will eventually become groundwater recharge.

To monitor these three variables the following sensors are included at each monitoring station at various depth intervals (Figure 2):

- Four heat dissipation sensors to measure soil water potential and temperature under moderately wet to dry soil conditions and to provide data for the potential-based soil water net percolation flux model.
- Four capacitance sensors to measure water content.
- Two advanced tensiometers to measure soil water potential under wet soil conditions and to provide data for the potential-based soil water net percolation flux model.
- One passive capillary water flux meter (WFM) to directly measure net percolation flux.

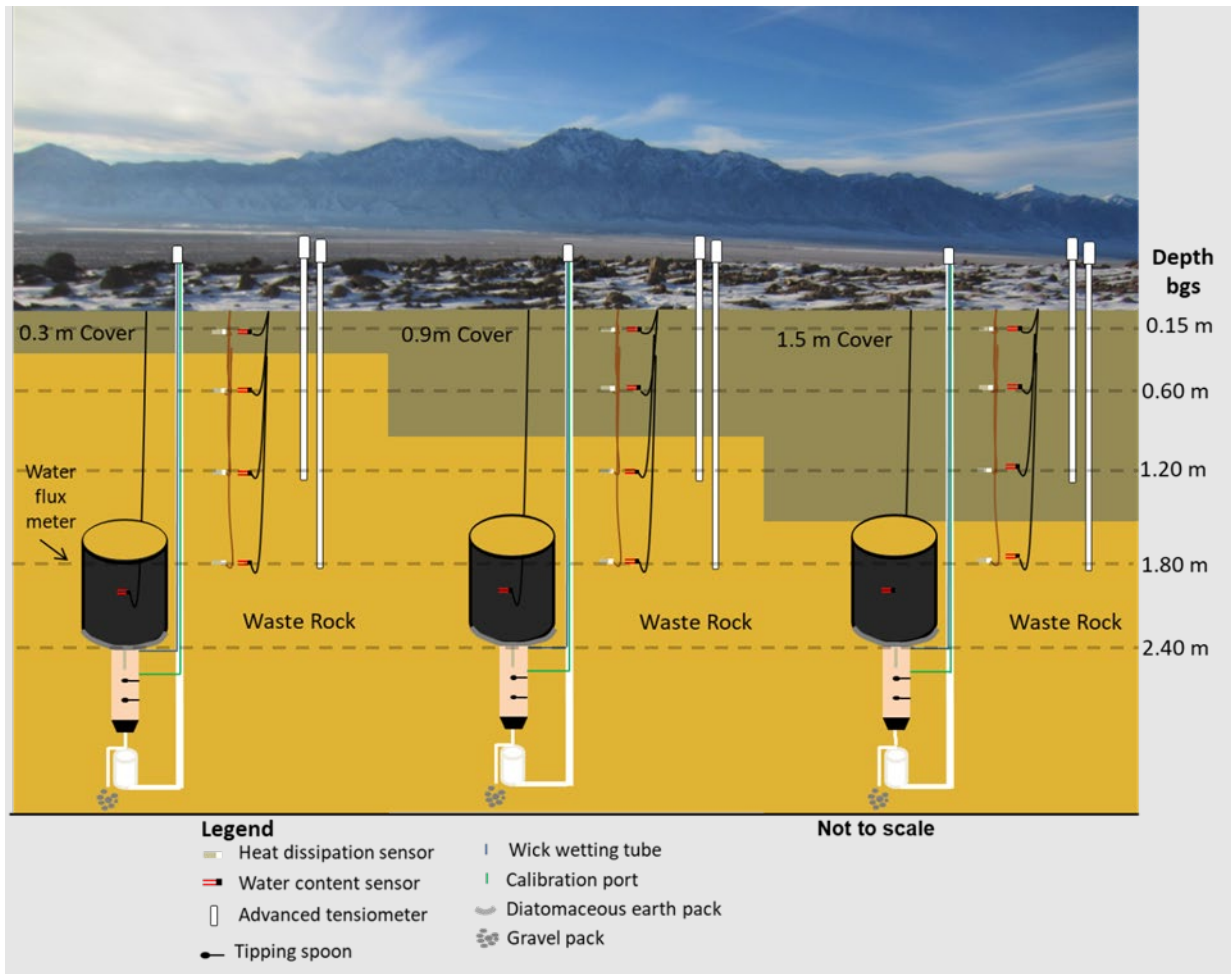


Figure 2 Cross-section of cover performance monitoring station with 0.3-, 0.9-, and 1.5-m cover thickness

Additionally, a precipitation gauge was installed to measure precipitation at the test plots. All sensors are connected to a datalogger which controls the sensors and stores sensor data for retrieval via telemetry.

In the spring 2013 the ET cover system test plots were partially seeded using a site-specific seed mix; however, none of the seeded plants established and vegetation is primarily comprised of invasive annuals Russian Thistle (*Salsola tragus*) and Halogeton (*Halogeton glomeratus*) (Figure 3).



Figure 3 Cover test plot surface conditions (July 2014)

2.2 Calculated net percolation flux

Net percolation flux was calculated from sensor data at each monitoring station by calculating the one-dimensional vertical flux from Darcy's Law for steady-state equilibrium as modified by Buckingham (1907) for unsaturated flow, and van Genuchten's (1980) analytical solution to Mualem's (1976) theoretical model of the relationship between unsaturated hydraulic conductivity and matric potential. Flux rates were calculated from soil water potential data and the measured hydraulic gradient between the two deepest soil water potential sensors located at each station, together with van Genuchten parameters determined from laboratory measurements of moisture retention characteristics and in-situ measurements of saturated hydraulic conductivity using a Wooding's infiltrometer (Wooding 1968) (Table 1). At the 0.3- and 0.9-m cover stations, these sensors are both installed in waste rock. At the 1.5-m cover stations, the sensor installed at 1.20 m bgs is in cover material and the sensor at 1.80 m bgs is in waste rock (Figure 2).

Table 1 Hydraulic properties used for calculated net percolation

Material	Saturated hydraulic conductivity (cm/sec)	van Genuchten Parameters				
		Saturated water content (cm ³ /cm ³)	Residual water content (cm ³ /cm ³)	alpha (1/cm)	n (-)	l (-)
Waste Rock	8.30E-04	0.459	0.005	0.086	1.252	0.5
Cover	3.03E-04	0.375	0.011	0.021	1.251	0.5

3 Results

Data are presented and analysed by water year (WY), defined as the 12-month period from October 1 to September 30. For example, WY 2021 is the period from October 1, 2020 through September 30, 2021. The monitoring period reported here includes partial WY 2013 (December 21, 2012 through September 30, 2013) and complete WYs 2014 through 2021.

3.1 Precipitation

Long-term precipitation data (1950 to 2021) from the Smokey Valley-Carvers weather station located approximately 7 km west of the cover test plots were used to define WYs and seasons as average, wet, or

dry. Average annual precipitation is 15.7 cm, with a standard deviation of 5.8 cm. A wet year is defined as one with a precipitation total greater than the annual mean plus the standard deviation (21.5 cm) and a dry year as one with a precipitation total less than the mean minus the standard deviation (9.9 cm). Fall/winter (October – March) and spring/summer (April – September) were similarly defined. By this definition, a wet year occurs approximately every 7 years and a dry year approximately every 8 years.

Table 2 provides cover test plot precipitation for the monitoring period by WY and season and designates these data as average, wet or dry. In general, 50% or more of the WY precipitation occurred in spring/summer (April – September). WYs 2014 through 2019 were average precipitation years based on the historic seasonal averages. WYs 2020 and 2021 were drier than average.

Table 2 Cover test plot precipitation

Water year (October 1 - September 30)	Water year precipitation (cm)	Water year wet, dry, average²	Fall/ winter (October – March) precipitation (cm)	Fall/ winter Season wet, dry, average	Spring/ summer (April – September) precipitation (cm)	Spring/ summer season wet, dry, average
2013 (partial)	8.0	NA	0.9	NA	7.1	Average
2014	11.9	Average	3.0	Dry	8.9	Average
2015	10.7	Average	3.2	Dry	7.5	Average
2016	16.9	Average	12.2	Average	4.7	Average
2017	13.1	Average	6.1	Average	7.0	Average
2018	12.9	Average	4.4	Average	8.4	Average
2019	16.4	Average	9.8	Average	6.6	Average
2020	6.0	Dry	3.4	Dry	2.6	Dry
2021	6.9	Dry	2	Dry	4.8	Average
Mean	11.8	NA	5.5	NA	6.3	NA

3.2 Soil water potential and water content

Measured soil water potential and water content for the 0.3-, 0.9-, and 1.5-m cover monitoring stations are presented in Figure 3 and Figure 4, respectively. Monitoring station data from one of the three stations in each test plot is presented; similar results were observed between the three monitoring stations within each test plot. Seasonal wetting and drying are generally observed, with wetting in the later fall, winter and early spring when PET is low and drying during other times of the year. Soil/waste rock began drying slightly later at deeper depths as moisture was removed by ET starting from the soil surface and progressing down through the soil profile. For all WYs, wetting is observed in all test plots to a depth of 0.6 m bgs. Deeper wetting and longer wet conditions were observed in WY 2016 than other WYs due to increased precipitation relative to other years and specifically 12.2 cm of precipitation occurring in the fall/winter season (Table 2).

Wetting into the waste rock at the 0.3-m cover test plot was measured in all WYs; however measured wetting was limited to 1.2 m bgs and shallower depths. Wetting into the waste rock at the 0.9-m cover test plot was minor in WYs 2014, 2015, and 2018 through 2021, with greater wetting observed to depths of 1.8 m bgs in WY 2016 and 1.2 m bgs in WY 2017. Minor wetting, though still dry conditions, was observed at the 1.8 m depth in the 1.5-m cover test plot in WYs 2014 through 2016, though no wetting was observed at this depth in WY 2017 through 2021.

A topographic survey conducted in March 2015 identified settlement depressions around all stations that may create surface ponding and/or areas of focused infiltration. Cover material was added by RMGC in July 2015 to fill in these depressions. A November 2016 topographic survey indicated that major depressions near the stations had been alleviated; however, based on sensor response and visual observations, small depressions still existed in the 0.9 m cover. These depressions likely serve as locations of focused infiltration, resulting in greater wetting depth in the 0.9 m cover.

The zero-flux plane is a hypothetical depth that separates upward movement of soil water (due to ET) from downward movement to the water table. The depth of the zero-flux plane changes through the year, being shallower in the winter months and increasing in depth in the summer months as ET increases. Measured soil water potential gradients between the 1.2 m and 1.8 m bgs sensors, calculated as the difference in measured soil water potential divided by the difference in depth, indicates whether water is moving upward or downward over the 1.2 m to 1.8 m depth interval. In WY 2016, which observed the greatest wetting at the 0.9 m cover monitoring stations, the soil water potential gradients generally specified downward movement of water in the winter and spring. In summer through early fall, the hydraulic gradients indicated predominately upward movement of water, such that water below this depth could still move upward to ET.

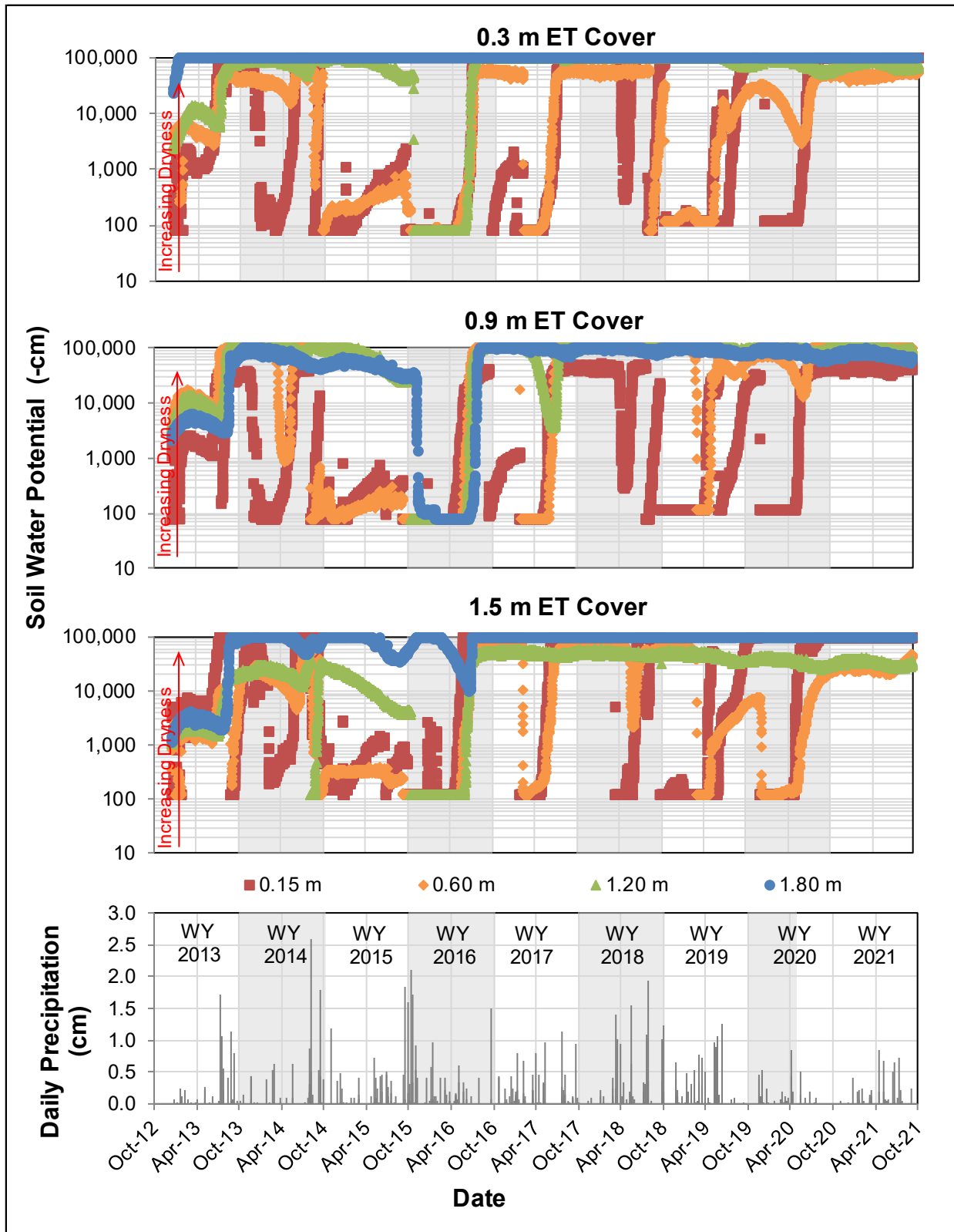


Figure 4 Test plot soil water potential

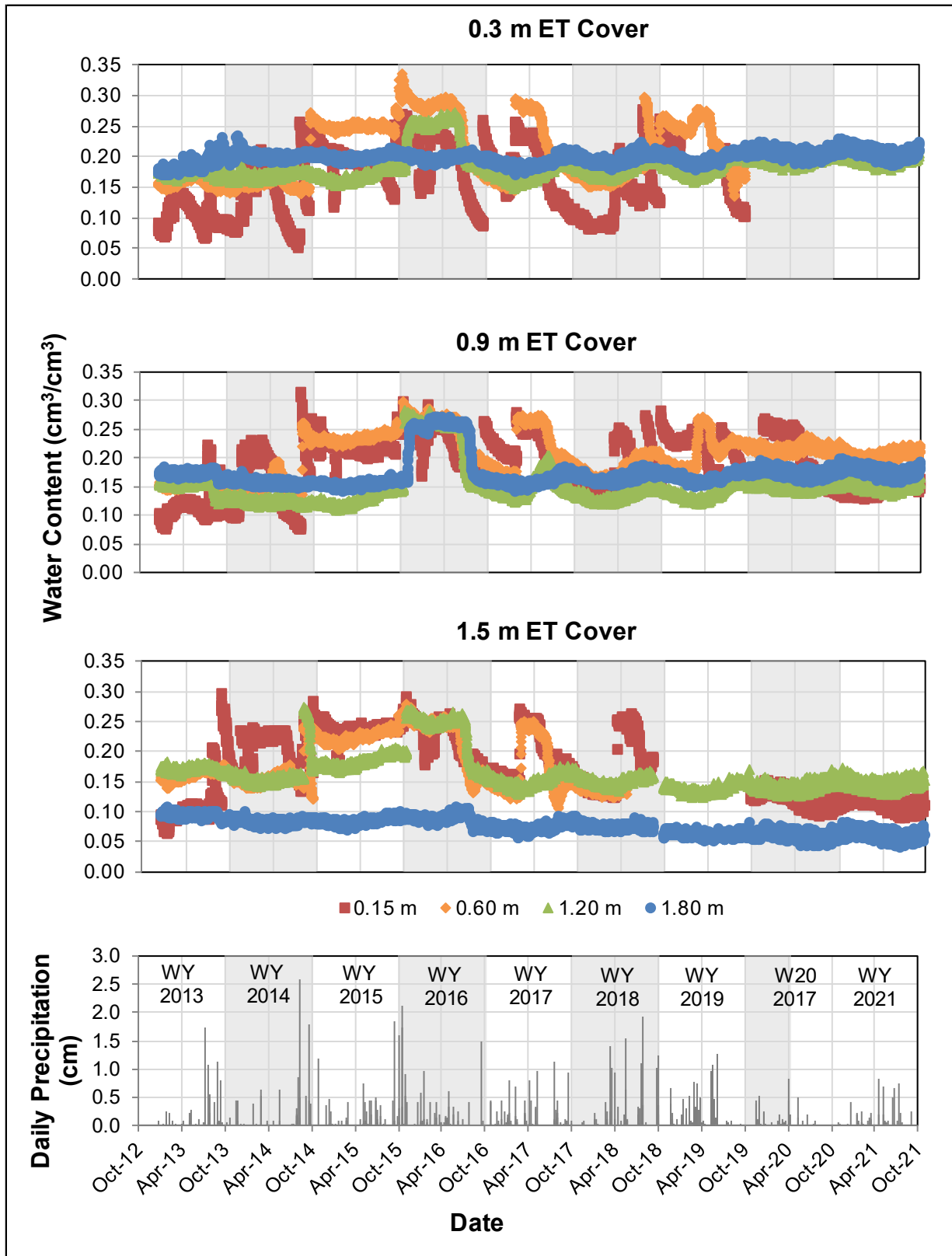


Figure 5 Test plot water content

3.3 Cover material water storage

Cover material water storage is the total quantity of water that is in the cover. It is calculated by integrating the measured water content over the cover thickness with the following equation:

$$\text{Water Storage} = \int_0^L \theta(z, t) dz \quad (1)$$

where:

L = the cover thickness, θ is the volumetric water content

z = the depth of measurement

t = time.

Calculated cover material water storage over time, as averaged over the three sensor stations in each test plot is shown in Figure 5. Data are only presented through WY 2020 due to failure of sensors used to calculate cover water storage in the 0.3-m and 0.9-m covers in WY 2021.

Cover material water storage increases in response to winter and spring precipitation and declines with increased ET in summer and fall. Cover material water storage in the 0.9-m and 1.5-m cover material was greater in WY 2016 than other WYs due to greater precipitation in WY 2016. WY 2016 cover material water storage in the 0.3-m cover material was similar to WYs 2015, 2017, and 2018, indicating at least 0.3-m of cover is needed to store an average precipitation WY.

Material storage capacity is traditionally defined as the water content level below which water drainage becomes negligible (Hillel 1980). By this definition, net percolation is negligible below the water content storage capacity. Storage capacity of the cover material was estimated from laboratory derived van Genuchten-Mualem model parameters (Table 1) and the van Genuchten-Mualem model (van Genuchten 1980). Water storage capacity was assumed to be equal to the water content when the drainage flux from the cover material reaches a value of 1.0×10^{-7} cm/s or less (Meyer et al. 1997). This water content value ($0.223 \text{ cm}^3/\text{cm}^3$) was then multiplied by the cover thickness, resulting in an estimated cover material field capacity of 6.8 cm, 20.4 cm, and 33.9 cm for the 0.3-, 0.9-, and 1.5 m cover, respectively.

At various times during WYs 2014 through 2018, the cover material water storage for the 0.3-m and 0.9-m covers exceeded the estimated storage capacity, indicating the additional water observed in excess of storage capacity percolated into the waste rock (Figure 5). Cover material storage for the 1.5-m cover exceeded the estimated cover material storage capacity near the end of WY 2014 and in WY 2016. Percolation of water into the waste rock during these time periods is supported by measured increased soil water potential and water content in the waste rock sensors (Figure 3, Figure 4). Water that percolates into the waste rock may report as net percolation flux or may be transported in the future to the surface via ET, depending on the depth of the zero-flux plane.

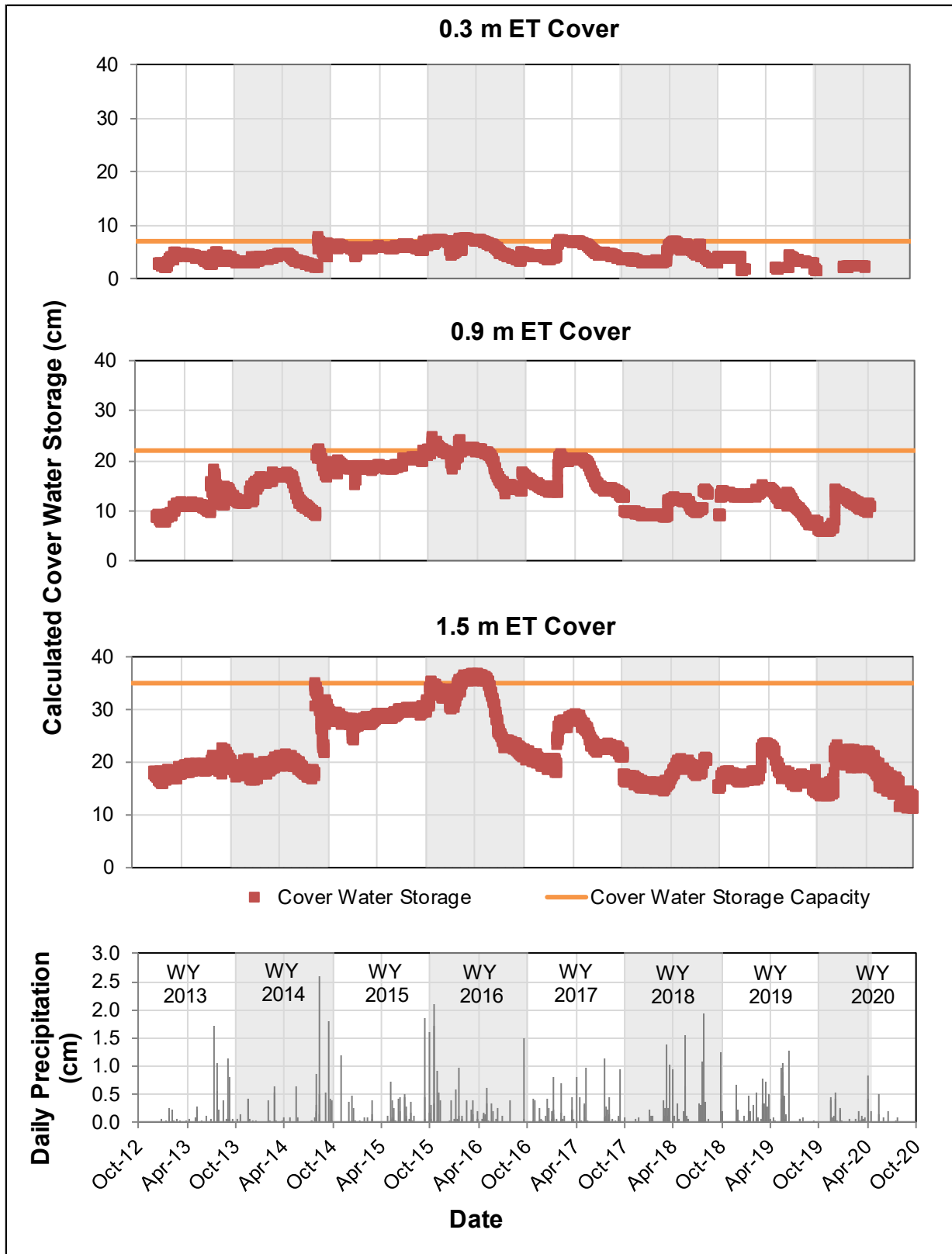


Figure 6 Cover water storage

3.4 Net percolation flux

Annual average calculated net percolation flux values are presented in Table 3. Zero net percolation flux values were calculated for the 0.3- and 1.5-m covers, indicating no downward movement of water at this depth during the monitoring period. Zero net percolation flux was calculated for the 0.9 m cover except for WY 2016, where 0.68 cm (4.0% of precipitation) net flux reflected the wet conditions during the winter and spring to a depth of 1.8 m bgs. Over the monitoring period the average annual calculated net percolation flux was 0.07 cm (0.4% of precipitation) for the 0.9-m cover test plot.

Table 3 Water year 2013-2021 average soil potential-based and water flux meter-based flux

Monitoring station	Soil potential-based flux		Water flux meter-based flux	
	Annual average flux (cm)	Flux as % of precipitation	Annual average flux (cm)	Flux as % of precipitation
0.3-m Cover	0.00	0.0%	0.00	0.0%
0.9-m Cover	0.07	0.4%	0.02	0.1%
1.5-m Cover	0.00	0.0%	0.00	0.0%

Measured annual average net percolation flux is presented in Table 3 for each cover test plot. Excepting the 0.9-m cover, all monitoring stations measured 0.00 cm of flux over the monitoring period. Measured cumulative flux at the 0.9-m cover was 0.14 cm (0.8% of precipitation) in WY 2016 and 0.00 cm for all other WYs. Average annual measured net percolation flux for the monitoring period was 0.02 cm (0.1% of precipitation) for the 0.9-m cover test plot.

Average annual measured net percolation flux values at the 0.9-m cover were less than the calculated net percolation flux using soil water potential data (0.02 cm versus 0.07 cm). The discrepancy between measured and calculated net flux may be due to the base of the WFM being approximately 0.60 m deeper than the deepest soil water potential sensor (Figure 2). These data indicate that water percolating to 1.8 m bgs may still be removed from the soil profile by ET as indicated by the measured upward gradients between 1.2 m and 1.8 m bgs and rapid drying measured at the 1.8 m sensors (Figure 3, Figure 4). Thus, the calculated net percolation flux may serve as an upper estimate of net percolation while measured net percolation flux may be more representative of deeper net percolation.

As noted previously, the observed deeper wetting and net percolation flux in the 0.9-m cover test plot is most likely associated with surface depressions and ponding at the monitoring stations. An irregular surface and ponding in surface depressions can be expected in future reclamation at Round Mountain. Thus, the observed net percolation in the 0.9-m cover also can be expected to occur in the 0.3-m and 1.5-m cover systems; the sensor stations in these cover test plots happen to not be in depressions.

Net percolation flux values for all locations represent poor vegetation conditions primarily consisting of invasive annuals. The establishment of native vegetation, particularly deeper rooting shrub type vegetation, can be expected to decrease the amount of net percolation flux during average and wet precipitation years.

4 Conclusion

During the slightly above average precipitation WY 2016, wetting was observed to a maximum depth of 1.2 m at the 0.3 m and 1.5 m ET cover system test plots. The deepest wetting (1.8 m) was observed in the 0.9 m ET cover system test plot due to focused run-on at the location of the monitoring stations. At all test plots, drying of the soil profile occurred in late spring and early summer in response to decreased precipitation and increased ET. The average annual calculated and measured net percolation flux over the monitoring period was zero for the 0.3 and 1.5 m ET cover systems and 0.4% and 0.1% of precipitation for the 0.9 m cover system. ET depths appeared to be at least 1.8 m bgs, consequently, the measured net percolation flux (0.1%

of precipitation) for the 0.9 m cover system is most likely representative. The establishment of native vegetation, particularly deeper rooting shrub type vegetation, is expected to decrease the amount of net percolation that may exist during wet water years. Results to date indicate no difference in the effectiveness of 0.3 m, 0.9 m, and 1.5 m ET cover system thicknesses in minimizing net percolation of precipitation into underlying waste rock. As a result of this work, RMGC has shown that a thinner cover than previously bonded for will sufficiently limit net percolation, and this has significantly reduced RMGC's bonding requirements.

Acknowledgement

We thank staff and management at RMGC for their support of this project and for permitting the presentation of this work.

References

- Allen, RG, Pereira, LS, Raes, D & Smith, M 1998, 'Crop Evaporation – Guidelines for Computing Crop Water Requirements', *Food and Agriculture Organization of the United Nations Irrigation and Drainage Paper 56*, Rome, Italy, 1998.
- Buckingham, E 1907. 'Studies on the movement of soil moisture', *Bulletin 28*, United States Department of Agriculture, Bureau of Soils, Washington D.C., 61 pages.
- Hillel, D 1980, *Applications of Soil Physics*. Academic Press, San Diego.
- Kottek, M, Grieser, J, Beck, C, Rudolf, B, & Rubel, F 2006. 'World Map of the Koppen-Geiger Climate Classification Updated' *Meteorologische Zeitschrift*, Vol. 15, pp. 259-263.
- Meyer, PD, Rockhold, ML & Gee, GW 1997, 'Uncertainty Analyses of Infiltration and Subsurface Flow and Transport for SDMP Sites (NUREG/CR-6565, PNNL-11705)', *U.S. Nuclear Regulatory Commission, Washington, D.C.*
- Mualem, Y 1976, 'A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media', *Water Resources Research*, vol. 12, pp. 513-522.
- Milczarek, M, Hammermeister, D & Vinson, J 2000. 'Myths, Models, and Realities, Infiltration and Seepage Control in Mine Reclamation Cover in the U.S. Southwest' In *Proceedings of the 5th International Conference on Acid Rock Drainage*, The Society, United States.
- Scanlon, R, Reedy, RC, Keese, KE, & Dwyer, SF 2005, 'Evaluation of Evapotranspiration Covers for Waste Containment in Arid and Semiarid Regions in the Southwestern USA', *Vadose Zone Journal*, vol. 4, pp. 55-71.
- van Genuchten, MTh 1980. 'A closed Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils', *Soil Science Society of America Journal*, vol. 44, pp. 892-898.
- Wooding, RA 1968. 'Steady infiltration from a shallow circular pond', *Water Resources Research*, vol. 4, pp. 1259-1273.
- Zhan, G, Keller, J, Milczarek, M, & Giraudo, J 2014. '11 Years of Evapotranspiration Cover Performance at the AA Leach Pad at Barrick Goldstrike Mines'. *Mine Water and the Environment*, vol. 33, pp. 195-205.