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Cold Desert Evapotranspiration Cover System Design Evaluation

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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 cool winters and hot summers. Average annual precipitation is 16.1 cm, approximately 10 times less than the calculated average annual potential evapotranspiration (PET) of 160 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 waste rock. Each test plot is approximately 200 m^2 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 become established, thus test plot vegetation is primarily comprised of the invasive annuals Russian Thistle (*Salsola tragus*) and Halogeton (*Halogeton glomeratus*).

Annual precipitation from 2012 through 2017 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. Net

percolation flux into the waste rock was calculated based on measured soil water matric potential data and also directly measured via water flux meters. 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 0.8% and 0.2% of precipitation for the 0.9 m cover system, most likely due to run-on to the test plot. The establishment of native vegetation, particularly deeper rooting shrub type vegetation, is expected to decrease the amount of net percolation. 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.

Introduction

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. The current life of mine is through 2027, with 3.1 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, with the mine waste repositories located on the valley floor between the Toiyabe and Toquima mountain ranges.

Figure 1: Round Mountain Mine location map

The climate is characteristic of a cold desert climate, with cool winters and hot summers. Average monthly temperatures (1950 through 2017) ranged from –1°C in December to 22°C in July. Average annual precipitation (1950 through 2017) was 16.1 cm, approximately 10 times less than the Penman-Monteith method (Allen et al., 1998) calculated average annual potential evapotranspiration (PET) of 160 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.

Evapotranspiration (ET) cover system trials have been initiated by RMGC in order 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.

Methods

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 m^2 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 principle 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.

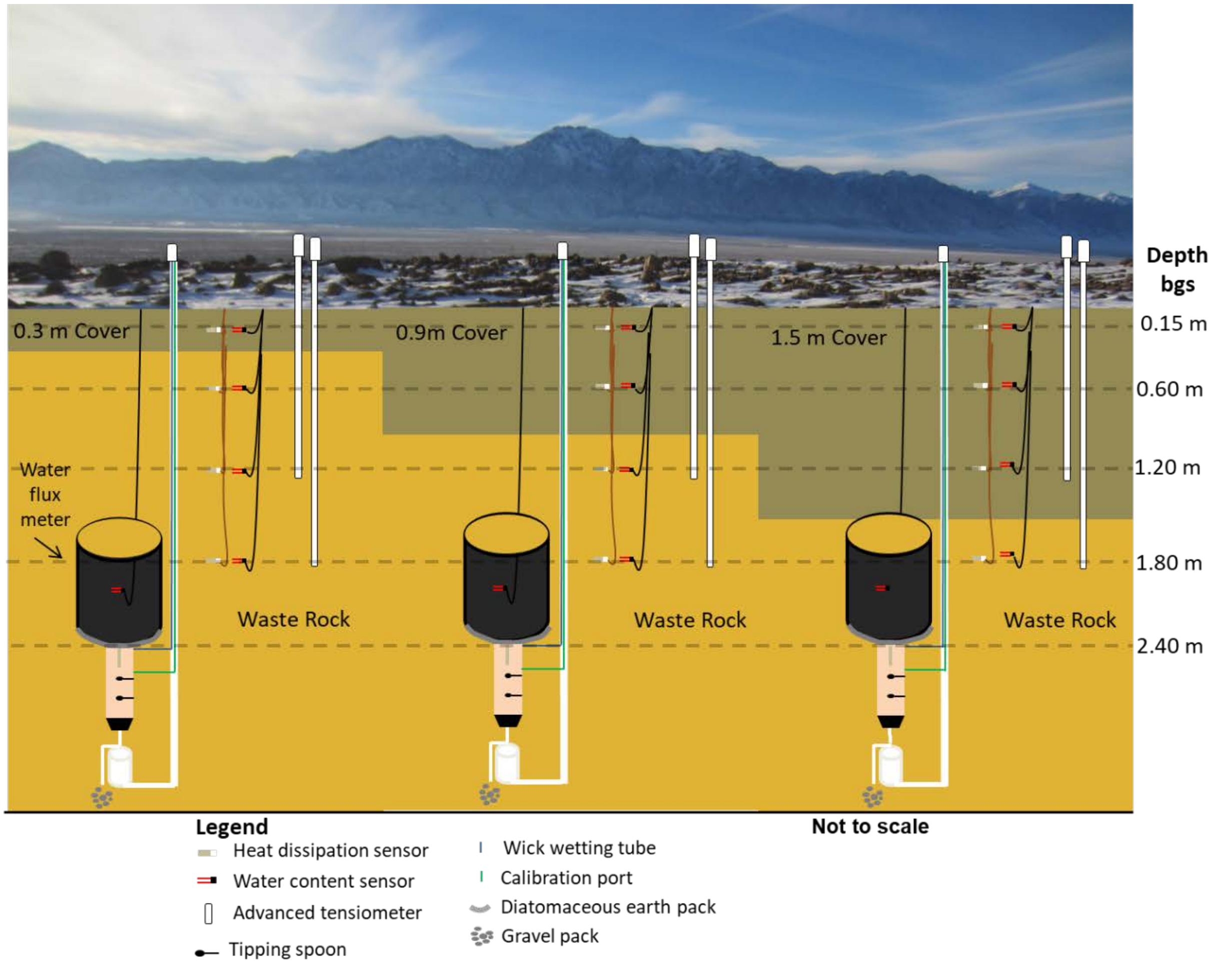

Figure 2: Cross-section of cover performance monitoring station with 0.3-, 0.9-, and 1.5-m cover thickness

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

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

Figure 3: Cover test plot surface conditions (July 2014)

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).

Results

Data are presented and analyzed by water year (WY), defined as the 12-month period from October 1 to September 30. For example, WY 2017 is the period from October 1, 2016 through September 30, 2017. The monitoring period reported here includes partial WY 2013 (December 21, 2012 through September 30, 2013) and complete WYs 2014 through 2017.

Table 1: Hydraulic properties used for calculated net percolation

Material	Saturated hydraulic conductivity[1]	Saturated water content	van Genuchten Parameters[2] Residual water content	alpha	n	l
	(cm/sec)	(cm^3/cm^3)	(cm^3/cm^3)	(1/cm)	(–)	(–)
Waste rock	8.30E-04	0.459	0.005	0.086	1.252	–1
cover	3.03E-04	0.375	0.011	0.021	1.251	0.5

1 – waste rock n = 6; cover material n = 10

2 – waste rock n = 2; cover material n = 2

Precipitation

Long-term precipitation data (1950 to 2017) 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 16.1 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 (21.8 cm), and a dry year as one with a precipitation total less than the mean minus the standard deviation (10.3 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. Seventy percent or more of the WY precipitation occurred in spring/summer (April – September) in the 2014 and 2015 WYs; in WY 2016, more than 70% of the precipitation occurred in fall/winter (October – March). WY 2017 precipitation was similar between spring/summer and fall/winter. WYs 2014 through 2017 were average precipitation years based on the historic seasonal averages. Fall/winter precipitation in WY 2014 and WY 2015 was drier than average. All other seasonal precipitation was average.

Table 2: Cover test plot precipitation

Water year (October 1 – September 30)	Water year precipitation (cm)	Water year wet, dry, average[2]	Fall/winter (October – March) precipitation (cm)	Fall/winter season wet, dry, average[3]	Spring/summer (April – September) precipitation (cm)	Spring/ summer season wet, dry, average[4]
2013[1]	8.0	n/a	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

n/a: Not applicable due to being a partial water year of data;

[1] Partial water year: 12/22/2012 – 9/30/2012;

[2] Wet > mean + std dev (21.8 cm), Dry < mean – std dev (10.3 cm);

[3] Wet > mean + std dev (12.9 cm), Dry < mean – std dev (3.5 cm);

[4] Wet > mean + std dev (11.9 cm), Dry < mean – std dev (4.5 cm)

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 Figures 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 is 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 was 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 and 2015, 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.

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 exist 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.

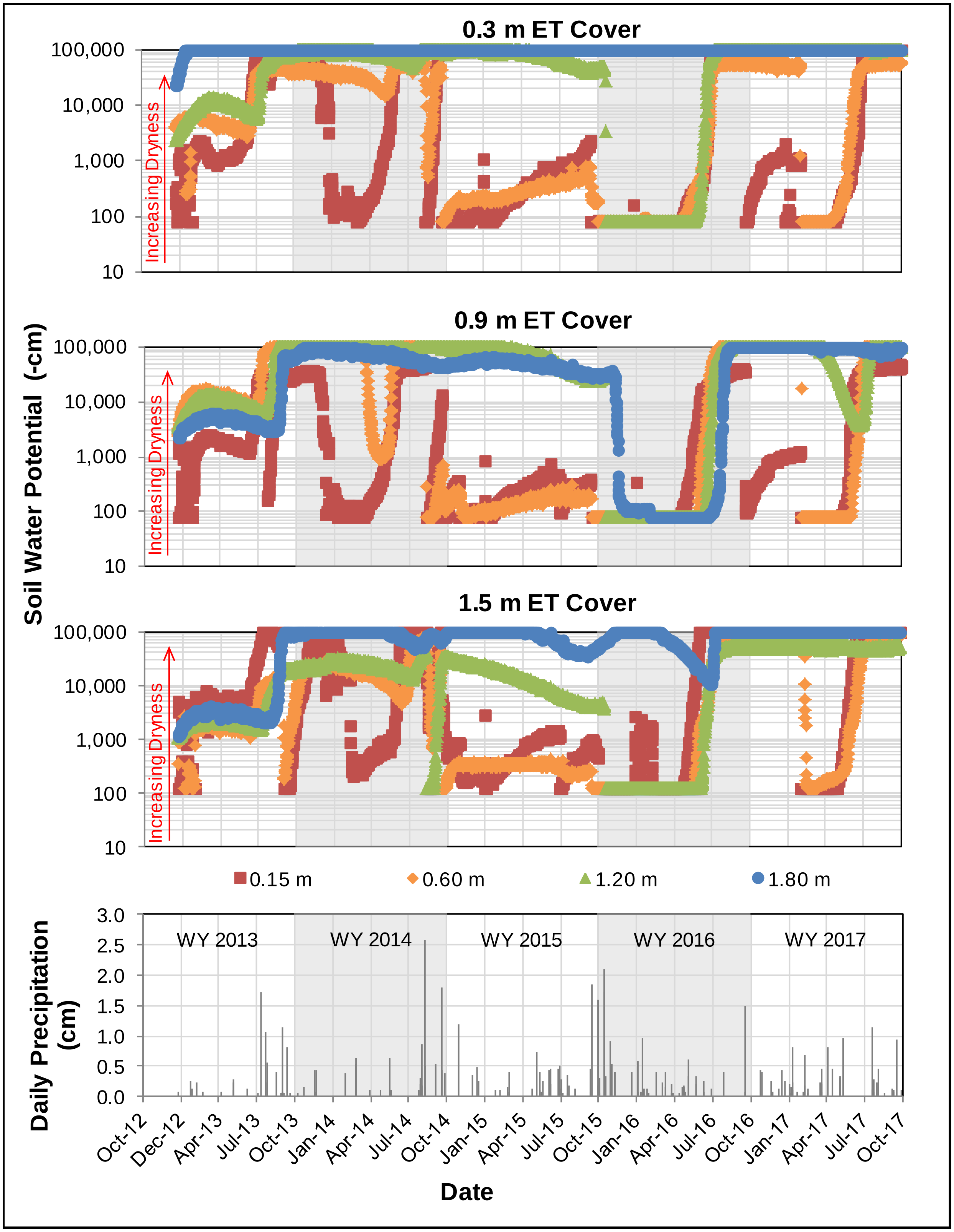

Figure 3: Test plot soil water potential

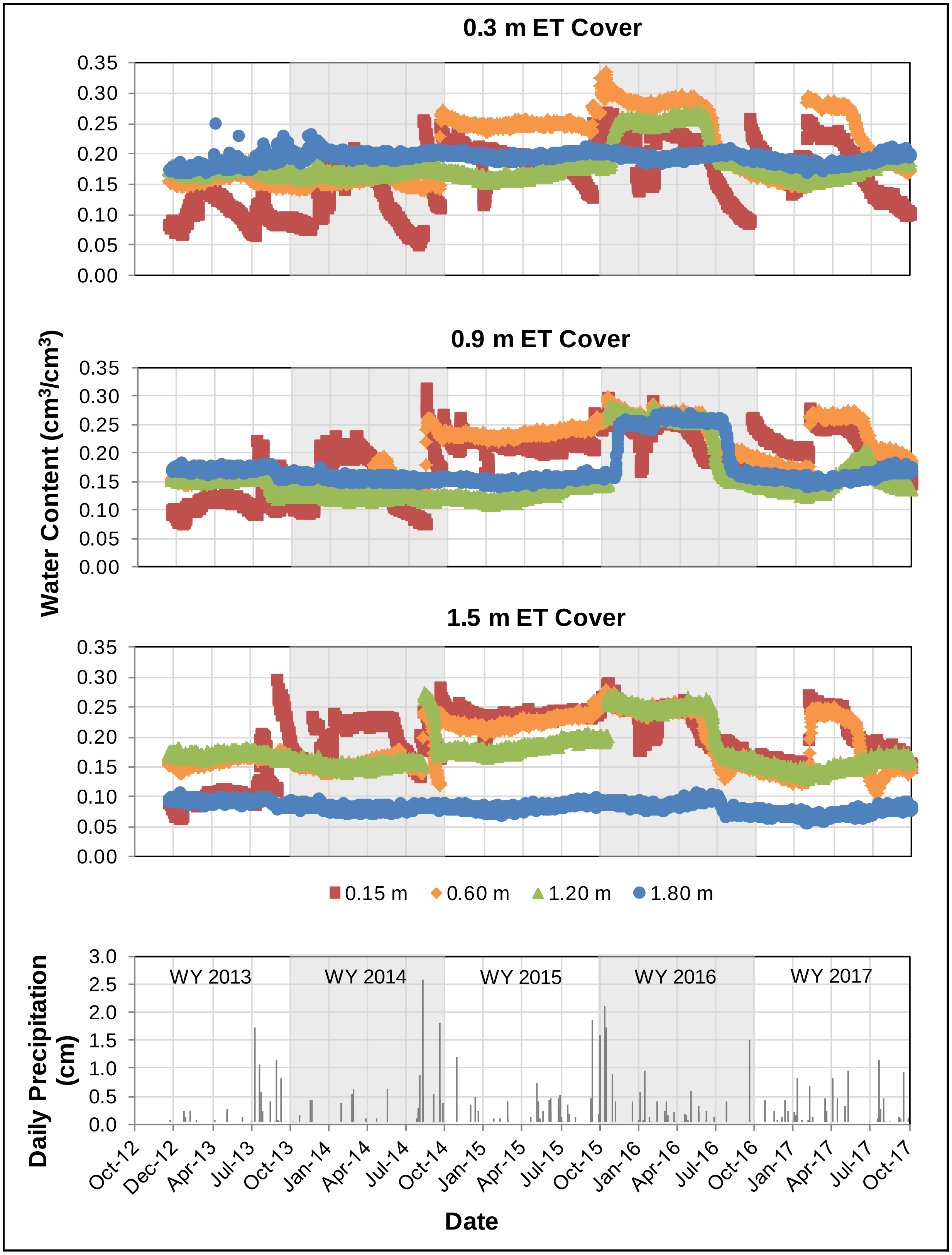

Figure 4: Test plot water content

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:

$$Water\ Storage = \int_0^L \theta(z,t)dz$$

where:

L is the cover thickness,

θ is the volumetric water content,

z is the depth of measurement, and

t is time.

Calculated cover material water storage over time, as averaged over the three sensor stations in each test plot, is shown in Figure 5.

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 0.30-m cover material was similar to WYs 2015 and 2017, indicating at least 0.30-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 x 10^{-7} cm/s or less (Meyer et al., 1997). This water content value (0.223 cm^3/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 0.30-, 0.90-, and 1.5-m cover, respectively.

At various times during WYs 2014 through 2017, 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.

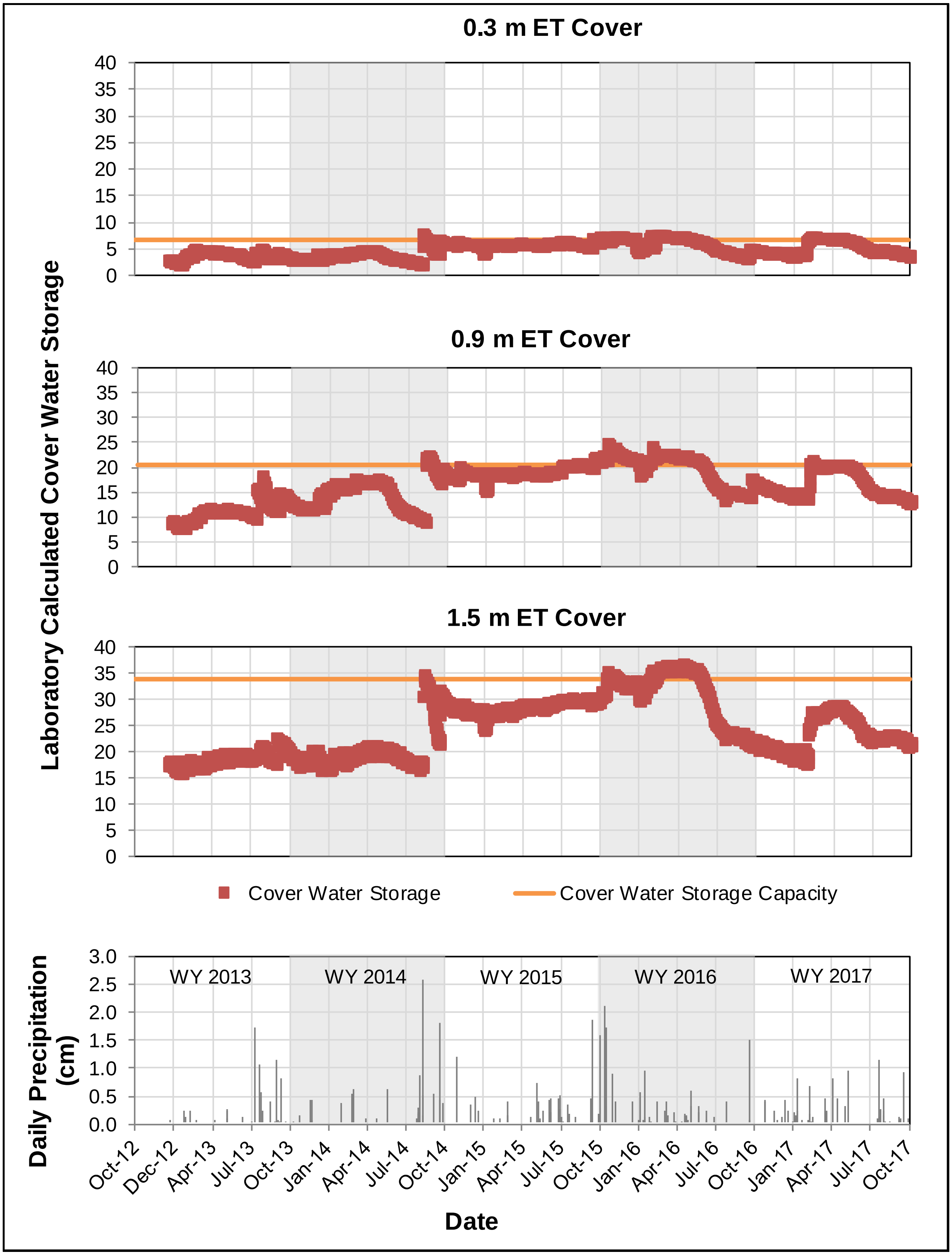

Figure 5: Cover water storage

Net Percolation Flux

Cumulative annual calculated net percolation flux values are presented in Table 3. Zero cumulative net percolation flux values were calculated for the 0.3- and 1.5-m covers for all WYs, indicating no downward movement of water at this depth during these time periods. Zero net percolation flux was also 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. The average annual calculated net percolation flux for WYs 2013 through 2017 is 0.13 cm (0.8% of precipitation) for the 0.9-m cover and 0.00 cm for the 0.3- and 1.5-m covers.

Table 3: Calculated net percolation flux

Test plot	WY 2013 Flux		WY 2014 Flux		WY 2015 Flux		WY 2016 Flux		WY 2017 Flux		WY 2013 – 2017 Average flux	
	Total (cm)	% of Precip	Total (cm)	% of Precip	Total (cm)	% of Precip	Total (cm)	% of Precip	Total (cm)	% of Precip	Total (cm)	% of Precip
0.3-m Cover	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%
0.9-m Cover	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.68	4.0%	0.00	0.0%	0.13	0.8%
1.5-m Cover	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%

Measured cumulative annual net percolation flux is presented in Table 4 for each cover test plot. With the exception of the 0.9-m cover, all monitoring stations measured 0.00 cm of WY cumulative flux in WYs 2013 through 2017. 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 WYs 2013 through 2017 was 0.03 cm (0.2% of precipitation) for the 0.9-m cover and 0.00 cm for the 0.3- and 1.5-m test plots.

Table 4: Water flux meter-measured flux

Test plot	WY 2013 Flux		WY 2014 Flux		WY 2015 Flux		WY 2016 Flux		WY 2017 Flux		WY 2013 – 2017 Average flux	
	Total (cm)	% of Precip	Total (cm)	% of Precip	Total (cm)	% of Precip	Total (cm)	% of Precip	Total (cm)	% of Precip	Total (cm)	% of Precip
0.3-m Cover	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%
0.9-m Cover	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.14	0.8%	0.00	0.0%	0.03	0.2%
1.5-m Cover	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%	0.00	0.0%

Average annual measured net percolation flux values at the 0.9-m cover was less than the calculated net percolation flux using soil water potential data (0.03 cm versus 0.13 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 located 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.

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 0.8% and 0.2% 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 (0.2% 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. 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.

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