APPENDIX D, Oxide Stockpile Full-Scale Cover System 2010-11 Annual Performance Monitoring Report

Teck Resources – Red Dog Mine

Oxide Stockpile Full-Scale Cover System

2010-11 Annual Performance Monitoring Report

Report No. 694/4-01

Prepared for:

Teck Alaska

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EXECUTIVE SUMMARY

O'Kane Consultants Inc. (OKC) was retained by Teck Alaska – Red Dog Mine to design and install a performance monitoring system for the Oxide Stockpile cover system. Two automated monitoring stations were installed on the west-facing slopes and plateau of the Oxide Stockpile. Collected field data include *in* situ matric suction, temperature, and water content, rainfall, net radiation, snowpack thickness, and net percolation.

The 20010-11 monitoring period represents the third year of monitoring for the overburden cover system constructed on the Oxide Stockpile. From examination of the meteorological and *in situ* soil temperature and water content measurements, net percolation in 2010-11 was approximately 16% (Plateau) and 17%-24% (West) of annual site specific precipitation. Percolation rates for the Plateau and West Slope sites are designed to be a direct measurement from a lysimeter; unfortunately data at both sites was compromised due to wire and tipping bucket failure. Net percolation values for the 2010-11 were calculated using the hydraulic head gradients at the cover/waste interface, as well as changes in moisture storage in the base of the cover. Hydraulic head gradients represent the direction and magnitude of water flowing through the covers, and were used to determine if net percolation through the cover was recognized.

Previous predictive numerical modeling (OKC, 2004) that estimated 15% net percolation over a four-year simulation period. The net percolation result for the Plateau is similar to previous years. The 2010-11 higher net percolation value for the West is attributed the loss of direct measurement from the lysimeters. It is OKC's opinion that net percolation rates measured in 2010-11 represent the higher boundary of possible West percolation rates station.

<u>Recommendations:</u>

OKC recommends the completion of a snow survey before the onset of spring melt as described in the Field Reference Manual (OKC, 2009a). OKC suggests a site visit during the early part of the 2012 field season in May or June 2012. This will allow OKC personnel to complete regular annual maintenance and ensure all components of the monitoring system including the lysimeter tipping buckets are operational following the winter and spring season.

<u>Summary of Performance Monitoring Report:</u>

This performance monitoring report presents field data collected from October 2010 to September 2011. The overall data capture rate for all the monitoring systems was 89%. The following is a summary of key data and trends in the performance of the overburden cover system for the 2010-11 monitoring period.

- Total precipitation measured at the Airport weather station during the monitoring period was 15.3 inches (389 mm), which was approximately 9% less than the 16.9 inch (429mm) eight-year average at the site.
- Total precipitation estimated for Plateau and West stations (rainfall + snow water equivalent) was 9.4 inches (238 mm) and 22.5 inches (571mm), respectively.
- The depth of freezing at the Plateau monitoring location was similar in 2009-10 with the freezing front penetrating deeper than the deepest installed sensor (98 in). However the freezing front did not penetrate the sensors in the waste rock material at the West Slope site due to the large amount of insulative snowpack received during the 2010-11 season. Temperatures at the base of the overburden cover system did not increase above 0°C until late July 2011 at the Plateau. Temperatures at the base of the cover system increased above 0°C in early June 2011 at the West station.
- Automated volumetric water content measurements show wetting and drying fronts develop at all stations in response to the seasonal climatic events. Each station showed distinct wetting fronts reaching the base of the overburden cover system from the rainfall events in July, August, and September.
- Matrix potential suction measurements responded in a similar manner as volumetric water content measurements. Matric suction values near the surface at Plateau station ranged up to 600 kPa during the dry spring / early summer period, but decreased to near saturated conditions for the remainder of the monitoring period after substantial rainfall events.
- Matric suction values near the overburden cover / waste rock interface were examined to determine the magnitude and direction of flow gradients throughout the monitoring period. While timing was slightly varied due to the influence of frozen conditions, each station showed a downward flow gradient at the conclusion of the spring melt period, small downward or upward gradients (low flow) during the early summer season, and downward gradients in late July, August and September.
- Total net percolation calculated at Plateau and West stations were 2.5 inches (63 mm) and 3.6 inches (92 mm) respectfully. This equates to 16% and 24% of total airport precipitation, for the Plateau and West station, respectively. The West Slope lysimeter wire became disconnected in late 2010 and was not discovered until the site visit in September 2011. The Plateau lysimeter tipping bucket was also found to have stopped recording data in late June 2011. The water balance methodology may have affected results, and the West station net percolation is believed to range from 17% to 24% of airport precipitation.
- A water balance was used to estimate the actual evapotranspiration (AET) at each station during the monitoring period. AET ranged from 137 mm at Plateau station to 133 mm at West station.

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1 INTRODUCTION

O'Kane Consultants Inc. (OKC) was retained by Teck Alaska – Red Dog Mine to design and install a performance monitoring system for the Oxide Stockpile cover system at the Red Dog mine. The instrumentation, which was installed and commissioned in October 2008, allows performance of the cover system to be evaluated over time under site-specific climate conditions. Two automated monitoring stations were installed on the west-facing slopes and plateau of the Oxide Stockpile. Complete as-built details for the Oxide Stockpile performance monitoring systems can be found in OKC (2009b).

1.1 Report Organization

Section 2 of this report discusses data collection and maintenance issues for the various automated and manual components of the performance monitoring system. Field data collected during the monitoring period are presented and discussed in Section 3, while a summary of the field monitoring data is provided in Section 4. In this report precipitation and net percolation values will be reported in inches; however, metric units will be used to report all other values.

2 DATA COLLECTION IN 2010-11

2.1 Data Capture Rates

Data capture rates for various components of the performance monitoring system are summarized in Table 2.1. The overall data capture rate for the October 2010 to September 2011 period is 89%. Data capture rates for automated sensors are based on the number of sensors operating compared to the total number of sensors installed.

Table 2.1
Performance monitoring system data capture rates for the 2010-11 monitoring period.

Component	No. of Automated Sensors Installed	No. of Automated Sensors Operating	% of Sensors Operating
Meteorological Monitoring			
Tipping bucket rainfall gauge	1	1	100%
Sonic snow depth gauge	2	2	100%
Air temperature	1	1	100%
Net radiation	1	0	0%
Plateau Station			
Thermal conductivity sensor	10	9	90%
Water content sensor	10	10	100%
Lysimeter tipping bucket gauge	1	0	0%
West Slope Station			
Thermal conductivity sensor	10	10	100%
Water content sensor	10	9	90%
Lysimeter tipping bucket gauge	1	0	0%
Totals	***47***	***42***	***89%***

2.2 Maintenance Notes for the Oxide Stockpile Monitoring Systems

The data capture rate decreased from 96% in 2009-10 to 89% during the 2010-11 monitoring period. The decrease was due to tipping bucket failure at both lysimeters, and the detachment of the net radiation sensor. Therefore, data from both tipping buckets and the net radiometer was lost during the 2010-11 monitoring period.

The West Slope station performance monitoring system was buried by snow through the 2010-11 winter season. The wind and heavy snow fall caused the net radiation sensor to break off from the station mount. Battery power was sufficient to operate the system during the winter months when there was limited sunlight hours to recharge the batteries through the solar panels. The snow depth sensor became buried in snow; while total snow depth was not measured, the snow depth sensor continued to function.

OKC completed a site visit to Red Dog operations in September 2011. The main objectives of the site visit were to replace the damaged West Slope station fiberglass enclosure, install new lysimeter

tipping buckets, replace the snow depth sensor transducers, collect Diviner moisture content readings, and raise the West Slope station net radiometer.

2.2.1 Erection of West Slope Tower and Cross arm

Due to the large amount of snowfall during the 2010-2011 winter, the enclosure mounting flanges were cracked and disconnected from the West slope data collection system. The solar panel barely remained above the snow and the solar radiation and snow depth sensors were covered and the mounts damaged.

In addition to affecting snow depth and net radiation readings, the previous winter's snow buried the enclosure box, making data downloads nearly impossible. A modified aluminum tower was used to achieve the desired height for the station, allowing the snow depth sensor, net radiometer and solar panel to be located at a height expected to be above future snow depths. A steel cross arm was fabricated on site and attached to the tower, approximately ten feet from the ground, serving as a mount for the snow depth and net radiometer sensors (see Figure 2.2). The enclosure box could not be raised because of the limited length of sensor cables; therefore, the new enclosure box was attached to the tower at its previous height. For winter download capability, a weatherized data cable was connected to the datalogger and routed outside the enclosure box; a new smaller secondary enclosure was attached by TAK at a higher point on the tower to house the opposite end of the weatherized download cable (not shown in Figure 2.2).

Figure 2.1 West slope station before repairs, person is holding up the net radiometer original location.

Figure 2.2 West slope station with repaired enclosure box and newly erected tower and cross arm.

3 PRESENTATION AND DISCUSSION OF FIELD DATA

Substantial amounts of data are collected from the monitoring stations on the Oxide Stockpile. The key sets of data are presented in this section to evaluate the performance of the overburden cover system over the 2010-11 monitoring period.

3.1 Meteorology

A complete meteorological weather station is operated and maintained at the Red Dog airport. The instrumentation includes a heated precipitation gauge and air temperature, relative humidity and wind speed sensors.

3.1.1 Precipitation

Figure 3.1 shows the cumulative precipitation recorded at the airport precipitation gauge from October 2010 to September 2011. A total of 15.3 inches (389 mm) of precipitation was recorded, which is slightly less than the eight-year average annual precipitation (2003-11) of 16.9 inches (429 mm). Precipitation increased by 16% from the previous year, which recorded the lowest rainfall in the previous seven years (12.8 in). The daily precipitation shows the majority of precipitation occurred in July, August, and September. There were several rainfall events larger than 0.5 inches (13 mm) including February 23rd, July 2nd, August 12th and September 9th and10th. The greatest rainfall events occurred in mid-August with 2.4 inches (60 mm) of rainfall recorded between August 3rd and August 14th.

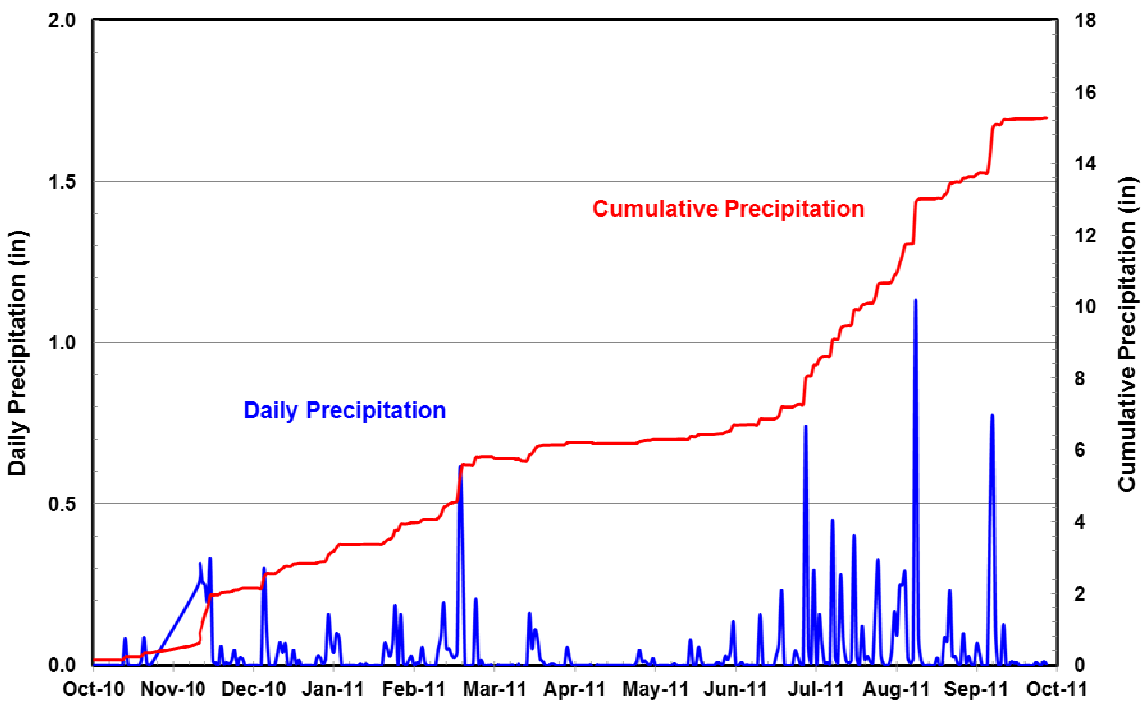

Figure 3.1 Precipitation measured at the Airport weather station during the 2010-11 period.

Figure 3.2 compares the annual monthly precipitation to the 2003-11 average monthly precipitation. Precipitation for the first eight months of the monitoring period varied greatly above and below the average with the exception of December, January and March. Rainfall in the frost-free months spanning July to September was normal within 0.5 inches of the eight-year average value for the month.

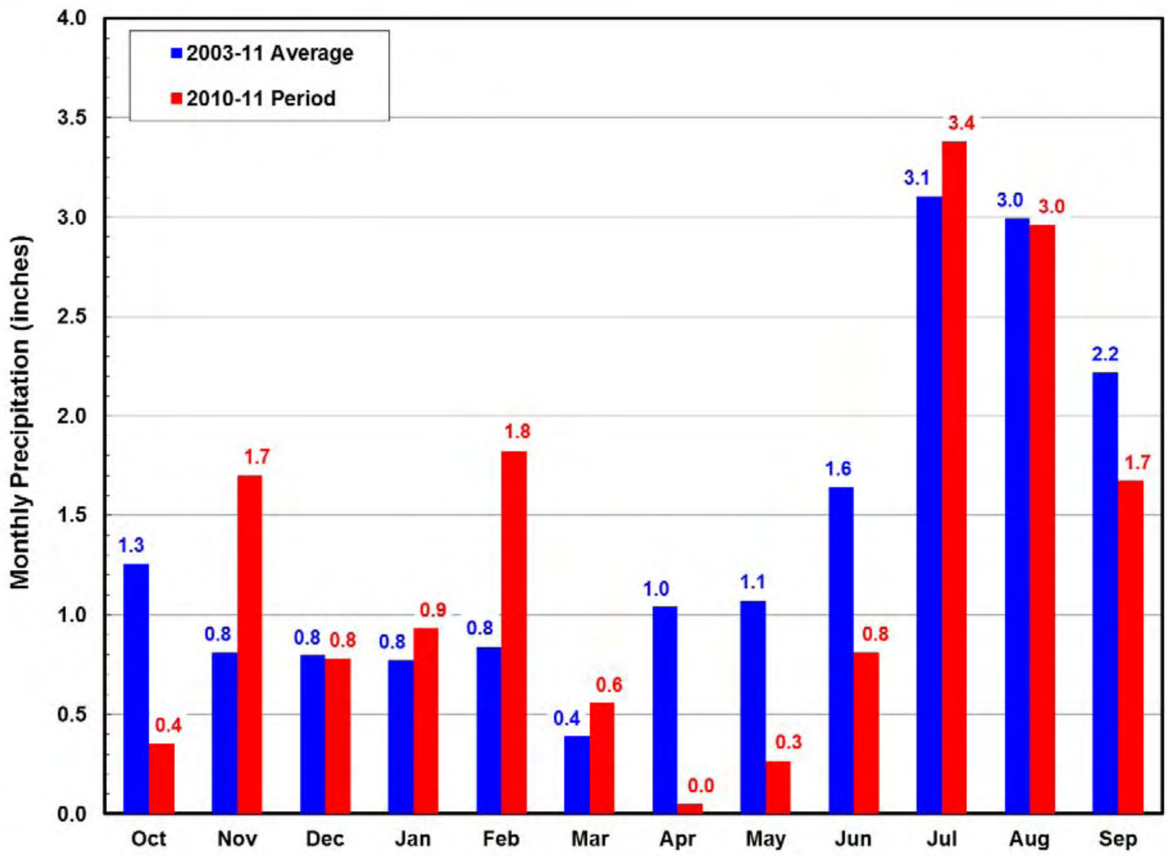

Figure 3.2 Comparison to 2010-11 monthly precipitation to the seven-year (2003-11) monthly averages.

3.1.2 Snow Measurements (Snowfall Equivalent)

The heated precipitation gauge at the Red Dog airport station provides an accurate measurement of the annual snowfall. The total snowpack that developed at the Plateau station and the West slope station greatly differed from the measured snowfall due to loss of moisture through sublimation over the winter period and drifting or redistribution of snow across the landscape. Sonic snow depth sensors monitored the development of snowpack at Plateau and West stations.

A substantial snowpack developed at West station during the winter period as shown in Figure 3.3. The flat-line section of the figure is a result of the snow depth sensor buried under the snowpack. The snowpack reached a maximum of 58 inches (1.5 m) until the snow depth sensor was buried in mid-January. The West station lies within a snow deposition area as West station measured snowpack has exceeded total airport snowfall over all project monitoring periods. The snowpack thickness and corresponding snow-water equivalent (SWE) were estimated to be 69 inches (1750 mm) and 23 inches (588 mm), respectively. The cumulative precipitation (rainfall + SWE) estimated for West station was 32.5 inches (825 mm) for the monitoring period.

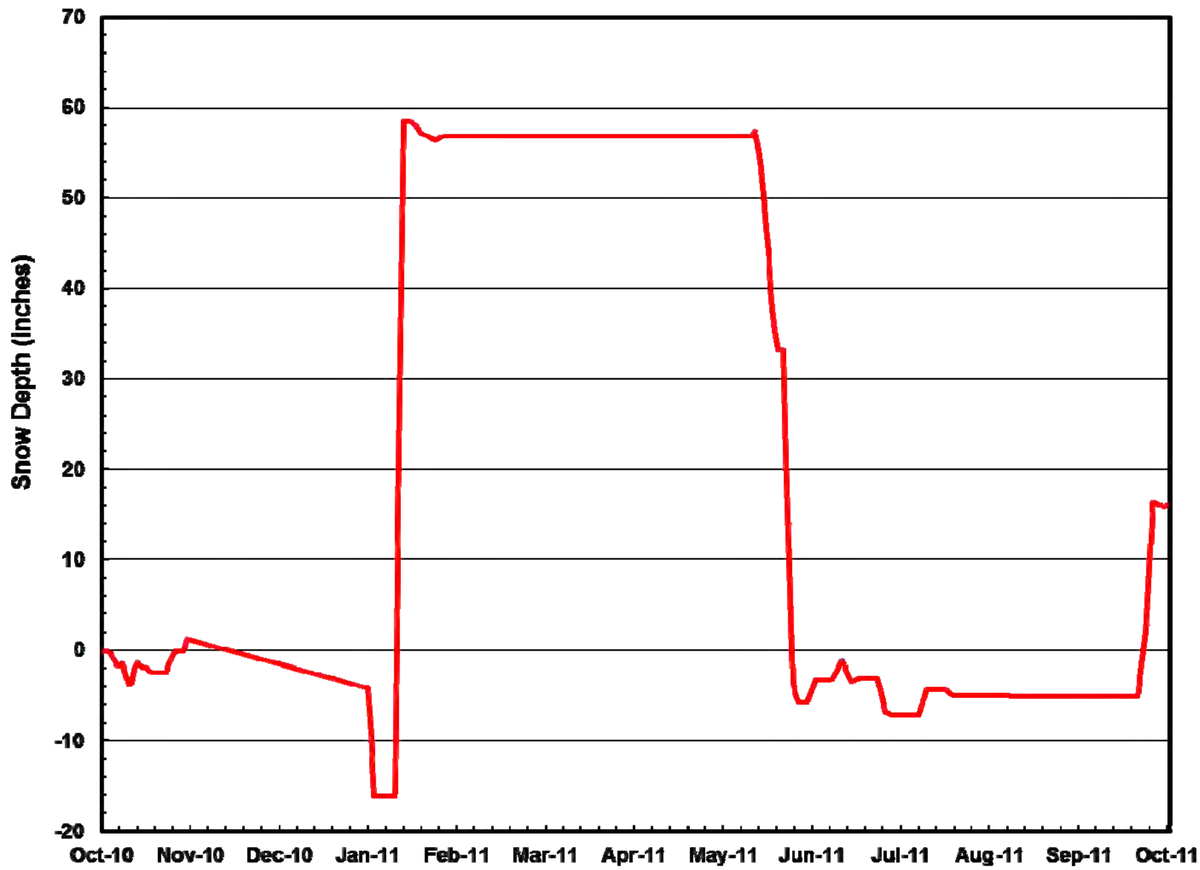

Figure 3.3 Total snowpack measured by snow depth sensor at West station.

Snowpack measured by the sonic sensor was never greater than 6-7 inches at Plateau station during the winter season. The Oxide Stockpile plateau is exposed to wind, which redistributes snowfall. The snowpack fluctuated between 4 and 7 inches during the winter months before the above freezing temperatures in mid-April began the snowmelt; it is assumed that no snow was present to contribute to Plateau cover moisture. Figure 3.4 summarizes the total precipitation at Plateau station. Due to the absence of a substantial snowpack, the estimated precipitation (rainfall + SWE) at Plateau station is 9.4 inches (239 mm).

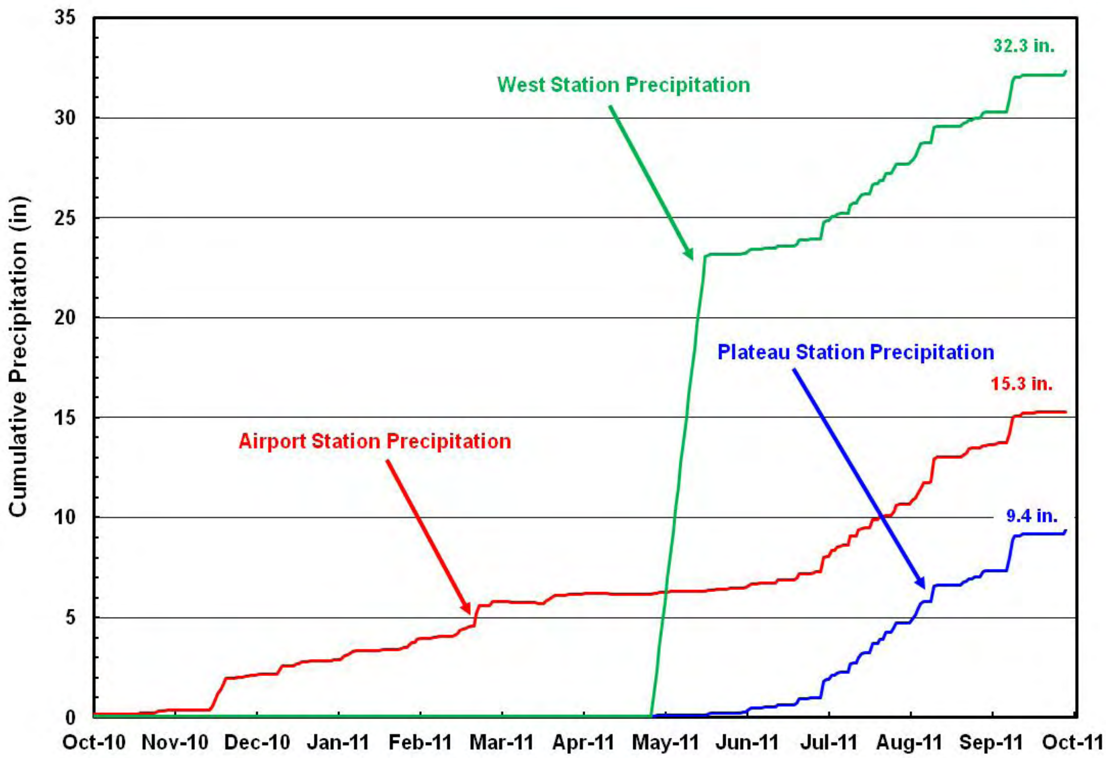

Figure 3.4 Comparison of precipitation measured at the Airport station and that estimated for Plateau station and West station during the monitoring period.

3.1.3 Potential Evaporation

The principal drivers of cover system performance are precipitation and energy available for evaporation. Potential evaporation (PE), which is a theoretical maximum assuming free water on the surface at all times, was estimated based on the pan evaporation data collected at the site. OKC traditionally estimates PE using the Penman (1948) method and meteorological data. However, the net radiation sensor detached from the station mount due to heavy snowfall. Insufficient data was recorded until a new sensor mount was installed September 2011. Actual evapotranspiration (AET) represents the actual water lost to the atmosphere, either through surface evaporation or plant transpiration, as a result of PE. In general, when plants are very active and surface soils are near saturation, AET and PE rates will be similar (AET/PE ~ 1). As plant activity declines and the soil surface dries out, more energy is required to evaporate water resulting in lower AET/PE rates.

Pan evaporation data was collected at the Airport station from May 24, 2011 to September 30, 2011 during which 9.4 inches (239 mm) of pan evaporation was recorded. This data was used in place of Penman-derived PE in the water balance calculations due to the loss of net radiation data. Missing August pan evaporation was replaced with the average daily 2010 pan evaporation rate.

Figure 3.5 compares the monthly potential evaporation estimated in 2010-11 to precipitation. PE was much greater than precipitation in May and June as a result of the below average spring rainfall at the site. When PE is greater than precipitation, the capacity for the cover system to store precipitation and release it back to the atmosphere during non-rainy periods is greatly improved, thereby improving the performance of the cover system. However, PE was slightly less than rainfall in September and substantially less than rainfall in July and August. During these periods, infiltration into the cover system profile is expected as total precipitation is greater than the potential evaporative energy to remove it.

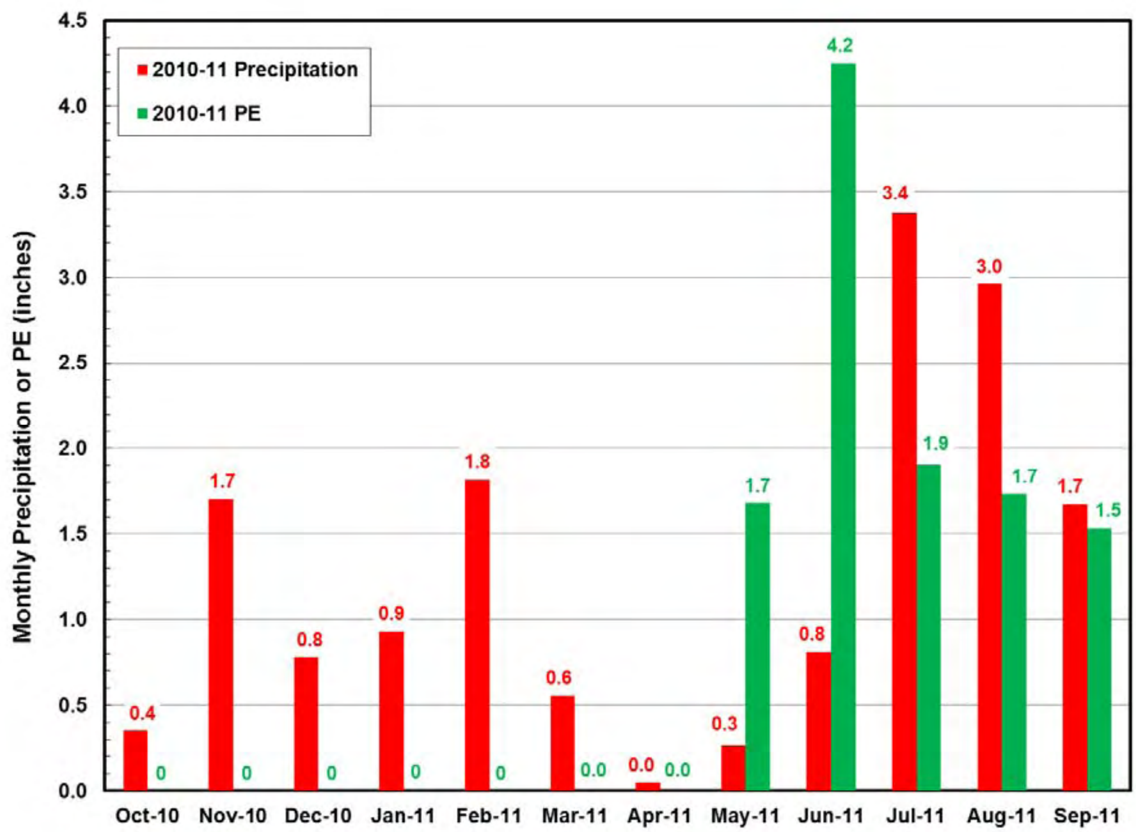

Figure 3.5 Monthly PE and precipitation measured during the monitoring period.

3.2 In Situ Temperature

In situ temperatures are continuously monitored with a profile of thermal conductivity (TC) sensors within each monitoring location. Figure 3.6 shows *in situ* temperatures measured to a maximum depth of 250 cm at Plateau station within the waste rock and overburden cover system profile. *In situ* temperature near the surface changes with season, ranging from -16°C in winter to 20°C in the summer. Deeper within the cover profile, *in situ* temperature is less influenced by seasonal surface temperatures. For example, slightly below the overburden/waste rock interface(130 cm) at a depth of 150 cm, the *in situ* temperature ranged from -7°C to 10°C.

The freezing front developed to a considerable depth at Plateau station during the winter season due to lack of snow. Temperature at the deepest sensor within the waste rock material (depth = 250 cm) was below 0°C from mid-January to the later part of July 2011. The blank area in the plot represents missing data for an inoperable sensor at 80 cm. In situ temperatures and freezing front depths recorded in the 2010-11 monitoring period were similar to measurements from the 2009-10 monitoring period.

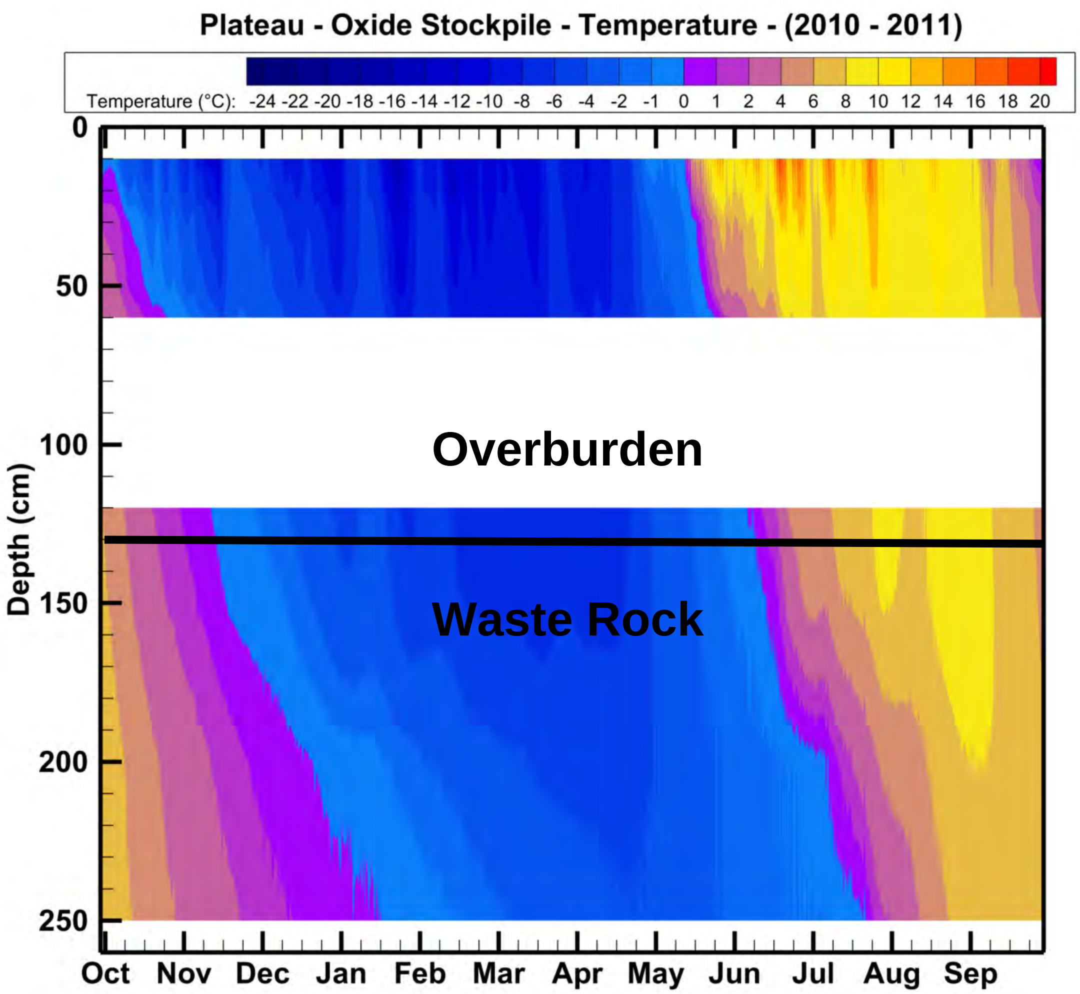

Figure 3.6 *In situ* temperature measured within Plateau station waste rock and overburden cover profile during the monitoring period.

Figure 3.7 shows *in situ* temperatures measured to a maximum depth of 240 cm at West Slope station within the waste rock and overburden cover system profile. *In situ* temperatures within the overburden and waste rock were colder in 2009-10 than compared to 2010-11. Maximum depth of freezing was approximately 130 cm in 2010-11. Temperatures at the overburden / waste rock interface ranged between -.2°C and 11°C in 2010-11. The large amount of snow pack at the West station provided insulation from the freezing air temperatures and produced a shallower freezing front.

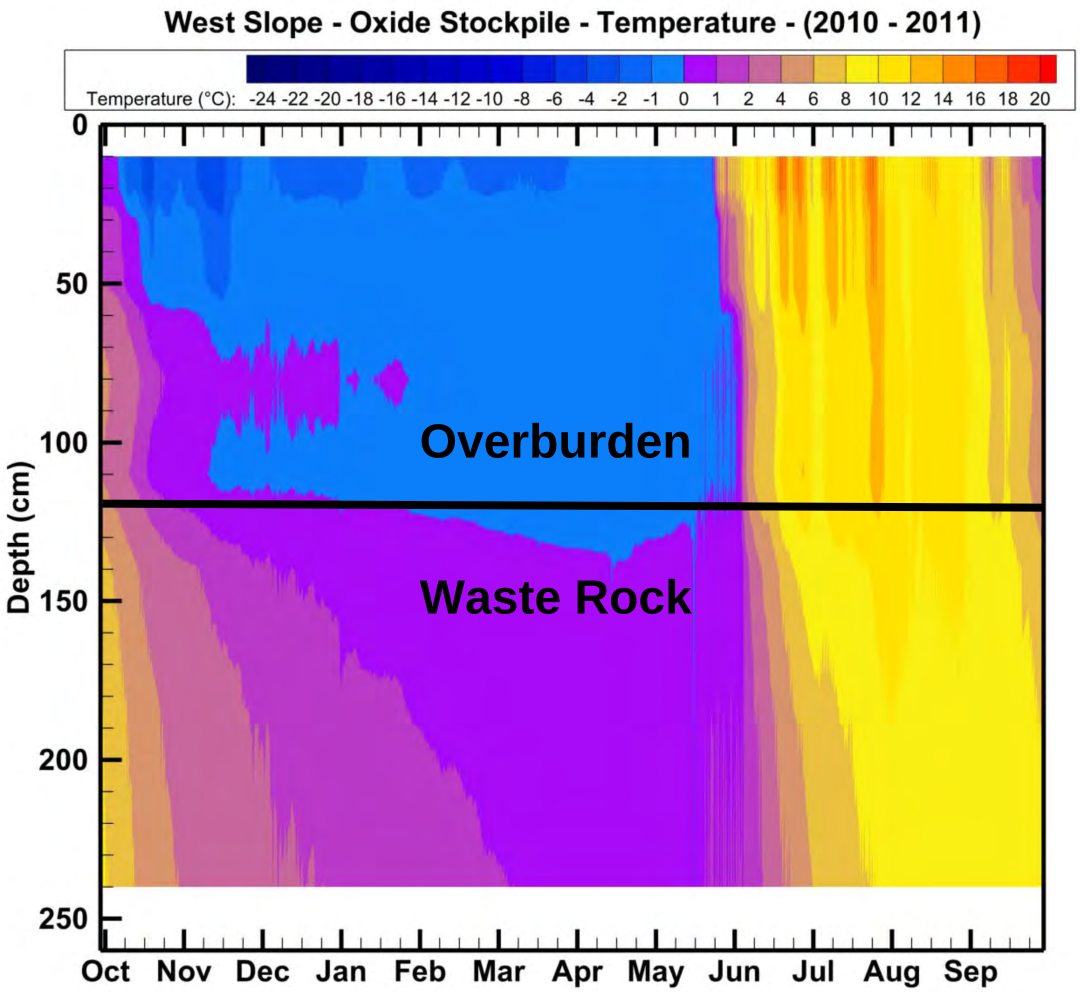

Figure 3.7 *In situ* temperature measured within West station waste rock and overburden cover profile during the monitoring period.

3.3 Cover System Water Dynamics

Matric suction and volumetric water content are indirectly measured using the CSI Model CS229 thermal conductivity (TC) sensors and CSI Model CS616 time domain reflectometry (TDR) sensors, respectively. Material-specific calibration curves are used to convert frequency readings obtained from each TDR sensor into volumetric water content values, while a sensor-specific calibration curve was developed for each CS229 sensor. At Plateau station, the sensor nest consists of 10 pairs of CS616 and CS229 sensors installed to a maximum depth of 250 cm. At West station, the sensor nest consists of 10 pairs of sensors installed to a depth of 240 cm. Depths of each sensor vary according to the depth of the overburden cover material / waste rock interface and are summarized in the record of installation report (OKC, 2009c).

3.3.1 Summary of Moisture Conditions Measured with TDR Sensors

Volumetric water content profiles were examined at both monitoring stations on the Oxide stockpile. This section presents the water contents observed within the profiles during the monitoring period and the change in moisture storage within the overburden cover system.

Figure 3.8 shows the water content profile for Plateau station during the monitoring period. The blank areas within the figure indicate that the sensors are frozen and therefore not providing accurate measurement. Saturation levels were high within the overburden cover during the 2011 frost-free period. Water contents ranged from 0.11 cm^3/cm^3 and 0.35 cm^3/cm^3 in the overburden material where porosity is approximately 0.35 cm^3/cm^3. Distinct wetting fronts are visible due to rainfall events in July, August, and September. There were decreases in the near-surface water content after the rainfall events likely due to evapotranspiration of moisture from the surface and water drainage to deeper areas of the cover profile.

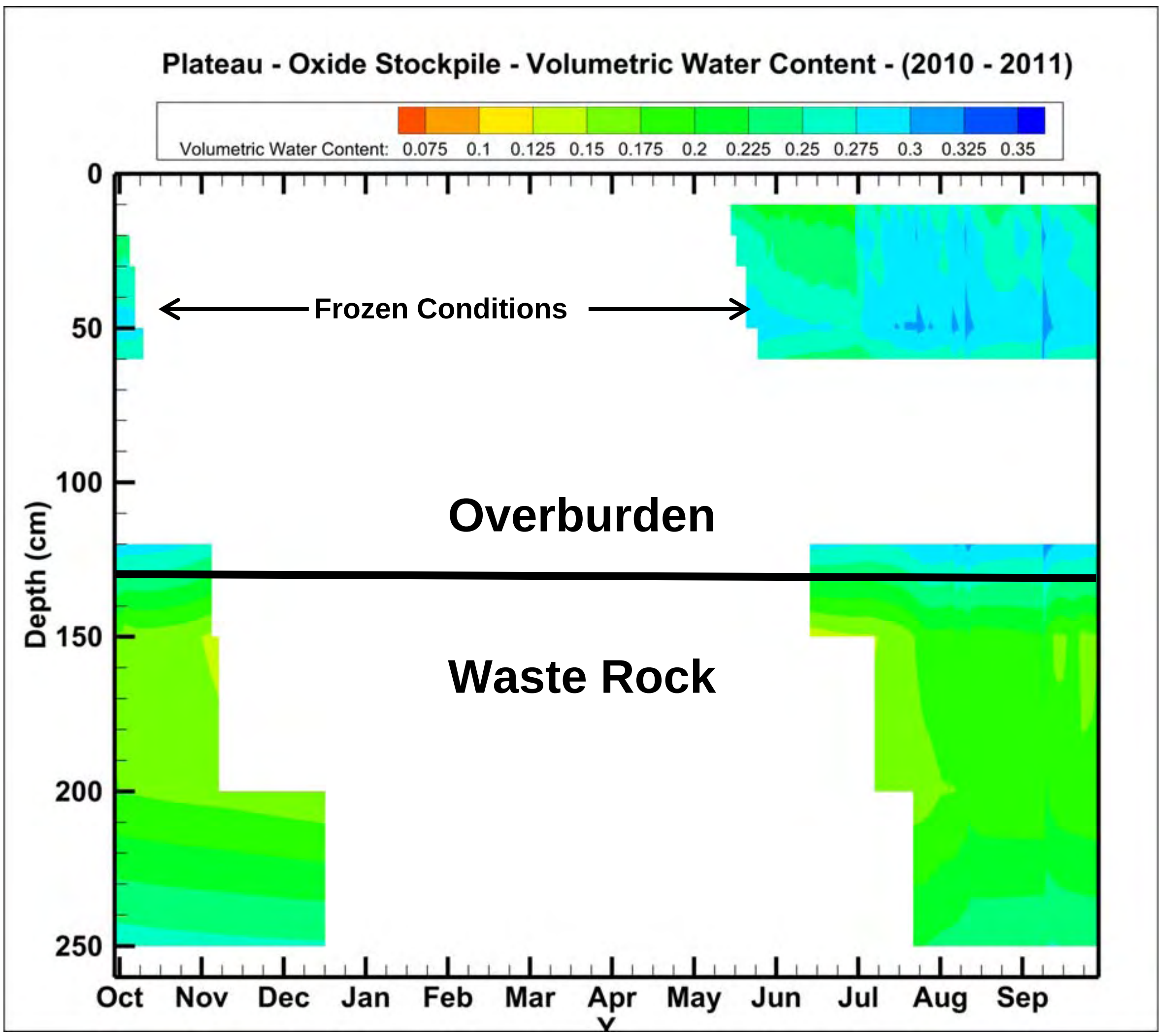

Figure 3.8 *In situ* volumetric water content measured at Plateau station during the monitoring period.

Figure 3.9 shows the response of water content sensors at West station. The *in situ* water content within the overburden profile increased to approximately 0.23 cm^3/cm^3 after spring thaw with water contents increasing to 0.27 cm^3/cm^3 in response to the July, August, and September rainfall events. Similar to Plateau station, wetting fronts developed within the cover profile due to the rainfall events and water contents within the waste rock increased accordingly.

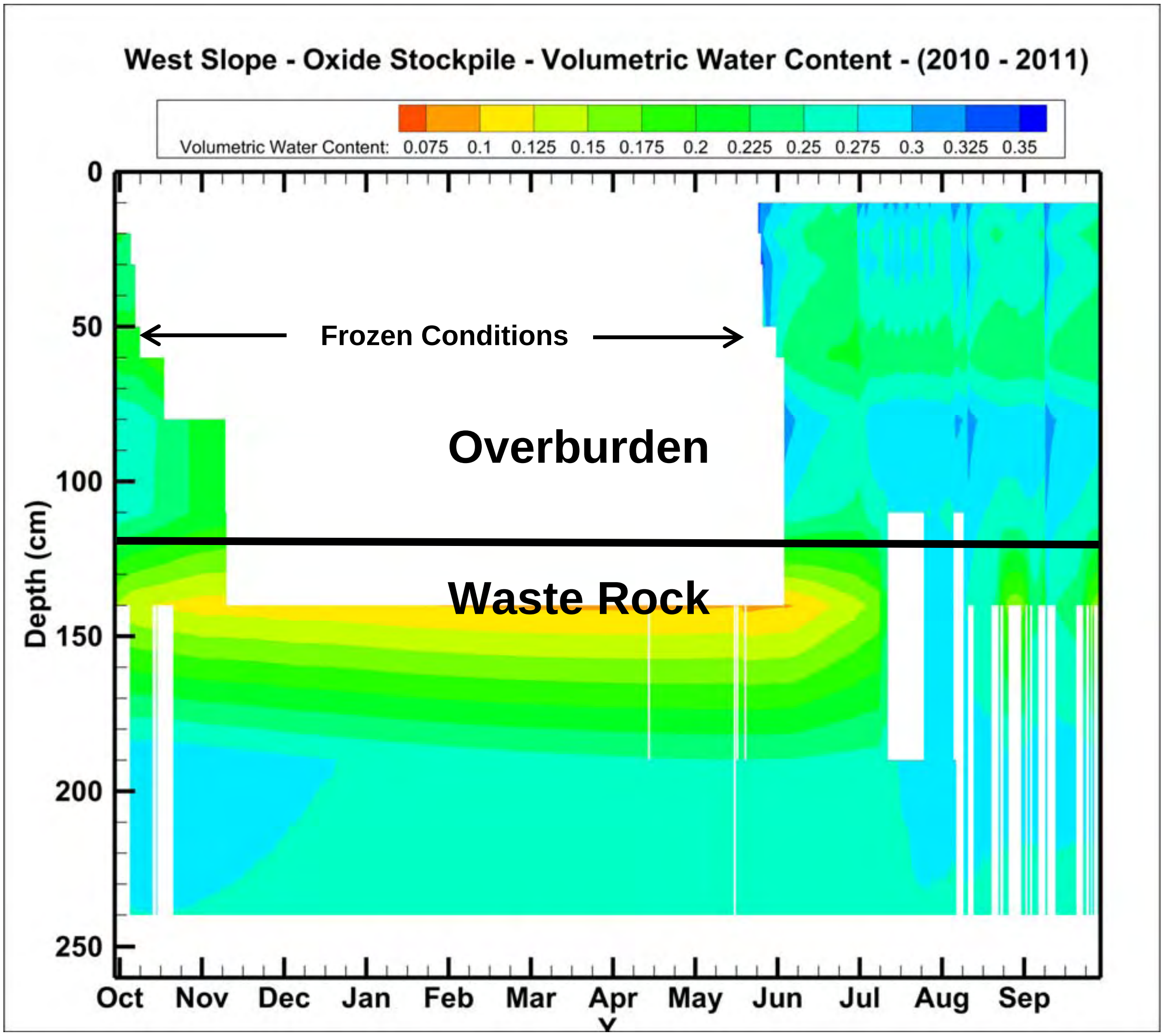

Figure 3.9 *In situ* volumetric water content measured at West station during the monitoring period.

Figure 3.10 presents the change in water storage within the overburden cover system for the monitoring locations for the 2008-09, 2009-10 and 2010-11 monitoring periods. The volume of water stored within the overburden cover system is estimated by discretizing the cover profile into multiple layers each with a CS616 sensor at its center. The total volume of water within the cover profile is calculated by summing the product of the volumetric water content and its elemental thickness. The change in water storage from the initial total water volume is presented to allow comparison between the Plateau and West Slope stations over the three-year span.

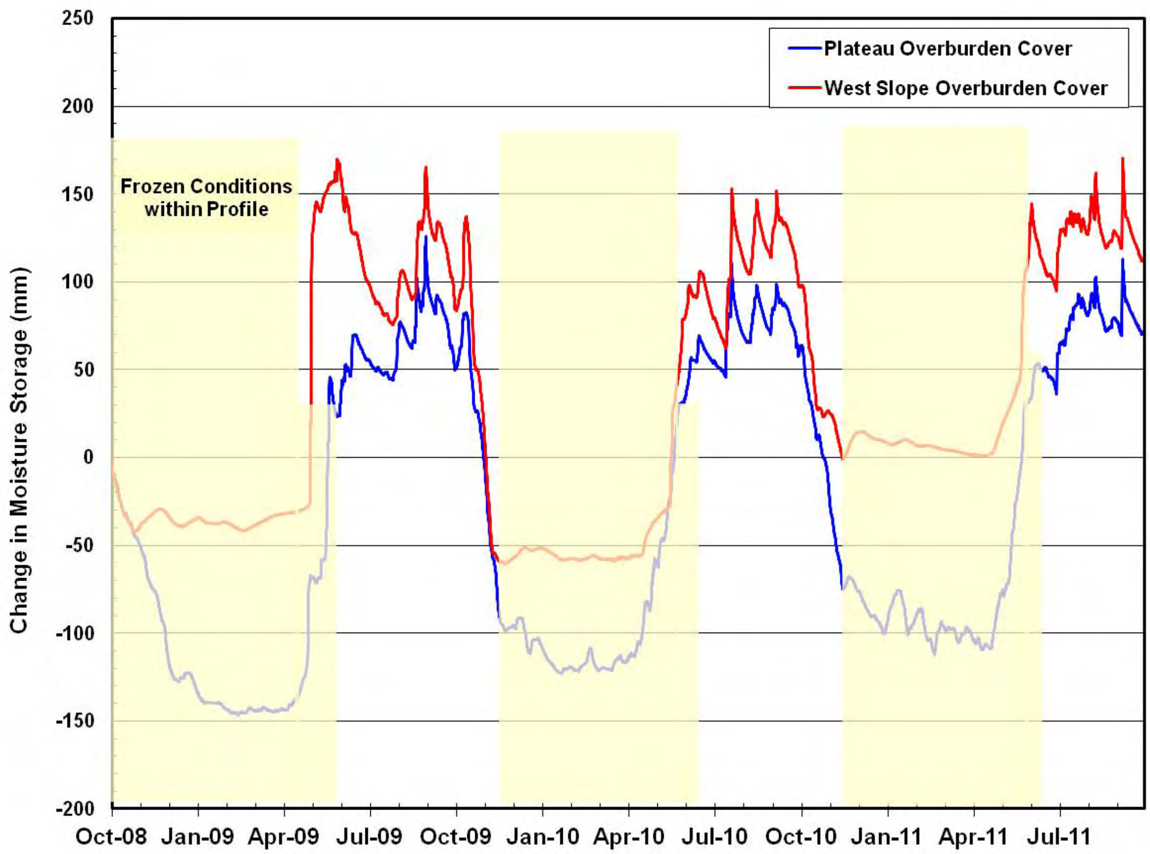

Figure 3.10 Change in water storage within the overburden cover profile at Plateau and West stations.

In the 2011 frost-free period, the responses of the overburden cover system to climatic conditions at the stations were similar, which indicates both sets of sensors are providing consistent water content measurements (i.e – responding to rainfall events and drying periods at the same time with similar magnitude. This is to be expected as the monitoring stations are only 100 m apart and likely receive similar rainfall and evaporative conditions.

The water content sensors showed strong responses to storm events on July 2nd, August 12th and September 10th. Moisture storage decreased between the rainfall events due to evapotranspiration at the cover system surface and deep drainage from the base of the cover system to the waste rock below.

3.3.2 Summary of Moisture Conditions Measured with TC Sensors

Matric suction data measured by the CS229 sensors at Plateau station are shown in Figure 3.11. The blank areas within the figure indicate that the sensors are frozen or inoperable (80 cm depth) and therefore not providing accurate measurement. During the 2011 frost-free period, the near surface sensor (10 cm) responded to rainfall events with sharp drops in matric suction and the subsequent gradual increase in suction was due to the drying effects of surface evaporation and vegetation transpiration. During the June dry period, suction increased to approximately 150 kPa at a 30 cm depth below ground surface and suction was 6 – 12 kPa at the cover system / waste rock interface. After the large rainfall event late June, *in situ* moisture conditions within the cover system remained close to saturation through mid-August. Suction near the cover system surface increased during the short drying periods between large rainfall events.

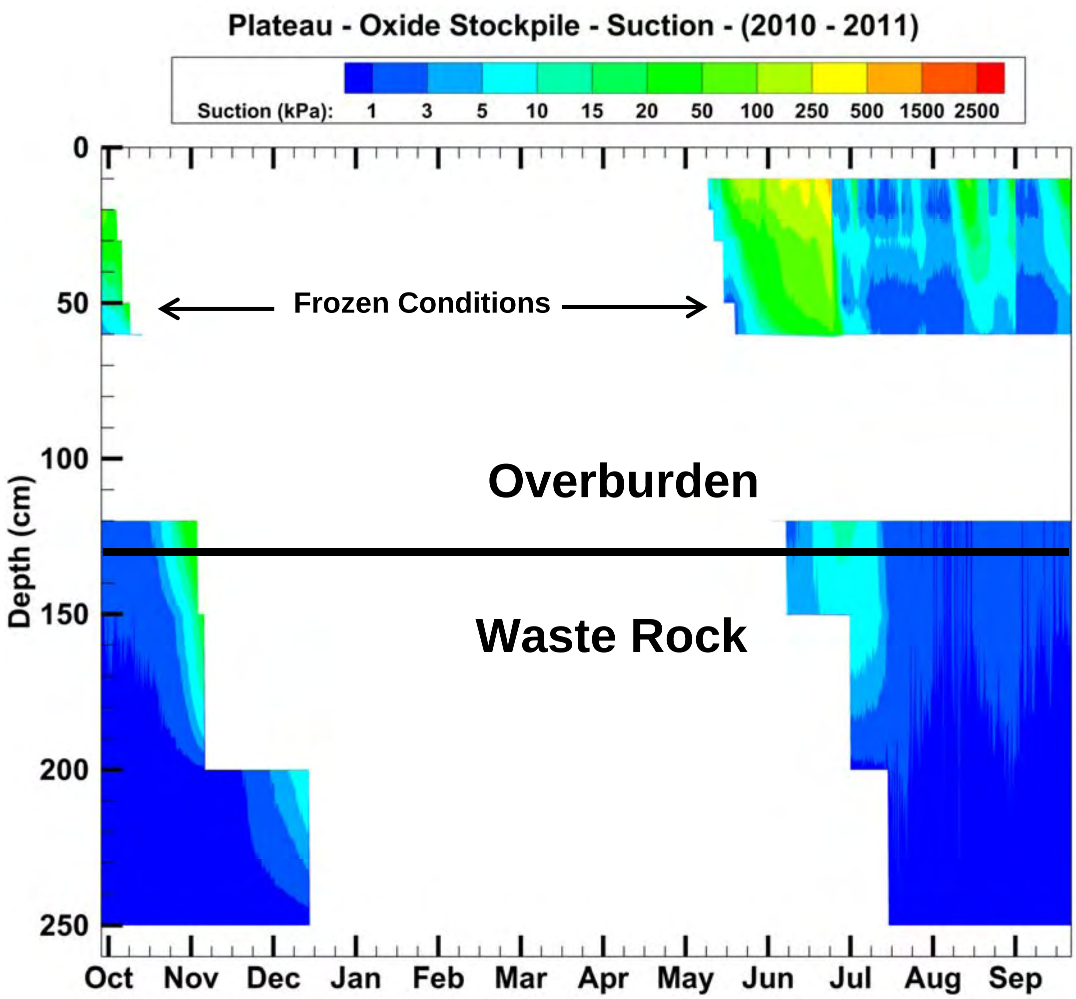

Figure 3.11 Matric suction measured within the overburden cover system and waste rock profile at Plateau station.

Figure 3.12 presents the matric suction measured at 120 cm and 150 cm depth at Plateau station as well as the calculated hydraulic gradient across the overburden cover / waste rock interface. The calculated gradient became positive (indicating downward flow) immediately after spring thaw in mid-June 2011. The calculated gradient remained positive until decreasing to a negative value (indicating upward flow gradient) in response to the drying period in late June and early July. The calculated hydraulic gradient increased to approximately 1 m/m due to the mid-July rainfall events and remained until the end of the monitoring period in September. The gradient data indicates that downward movement of water (i.e. net percolation) occurred during the frost-free period of 2011 at Plateau station.

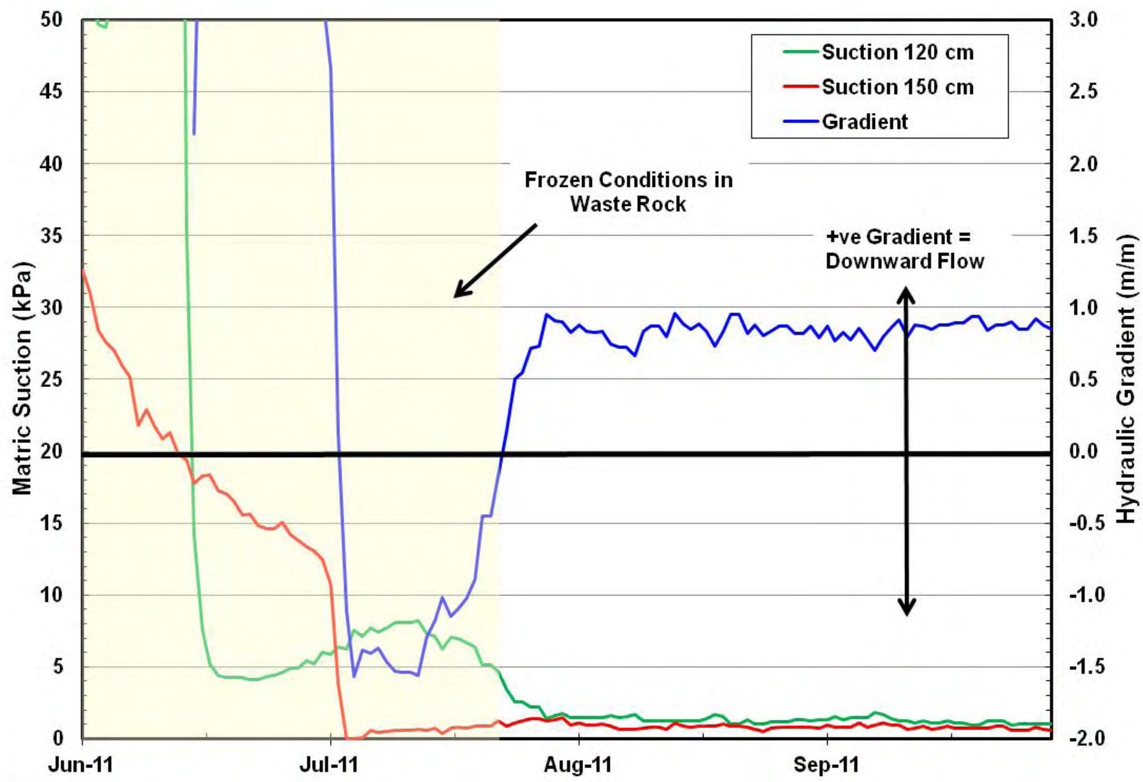

Figure 3.12 Matric suction measured at depths of 120 cm (overburden) and 150 cm (waste rock) and hydraulic gradient calculated at the overburden / waste rock interface at Plateau station.

Figure 3.13 shows the hydraulic gradient calculated at the overburden cover system / waste rock interface at Plateau and West stations. As discussed previously, hydraulic gradient at Plateau station rapidly decreased after the spring thaw, slowly increased during July, and increased to be consistently near 1 m/m for the remainder of the monitoring period. Hydraulic gradient at West station stayed at a consistent positive value in response to snowmelt and early-July rainfall events and remained between .1 and 1 m/m remainder of the period, briefly interrupted by small increase and decrease due to the late September rainfall event.

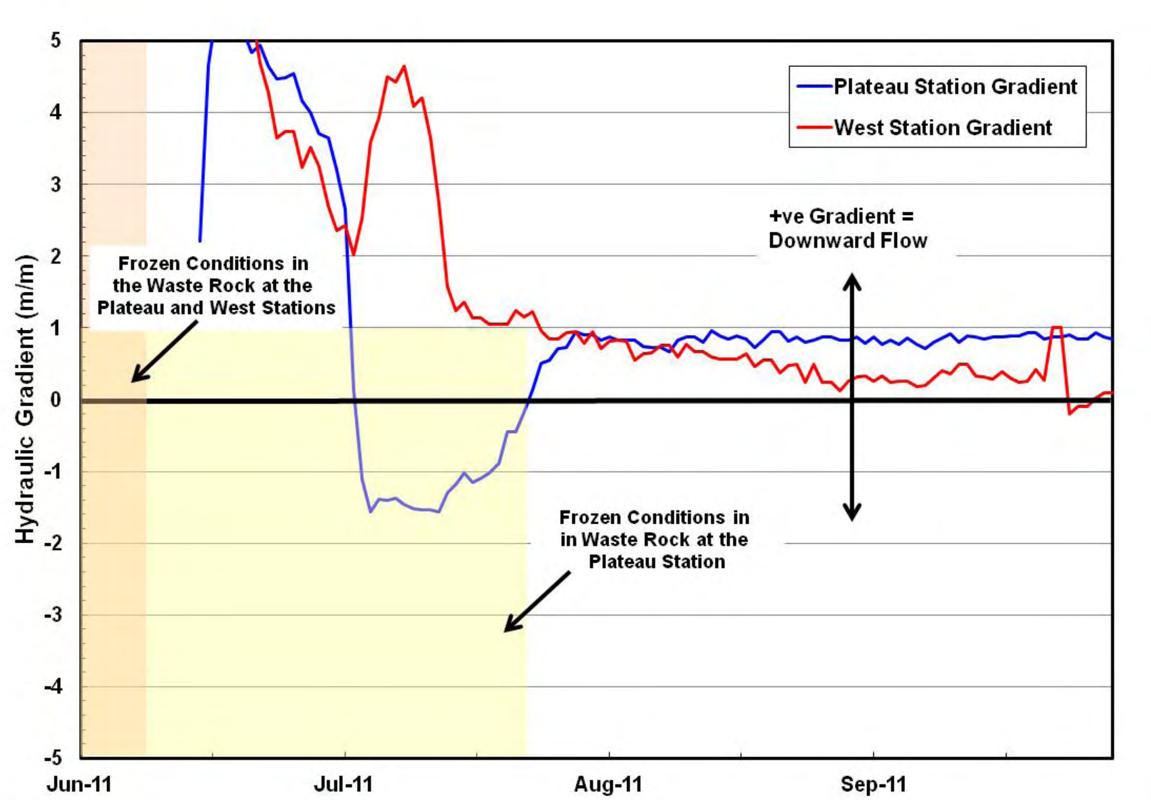

Figure 3.13 Hydraulic gradient calculated at the overburden / waste rock interface at the monitoring locations.

3.3.3 Net Percolation

Net percolation is set up to be measured by the automated monitoring system from the lysimeters installed at both Plateau and West stations. An automated tipping bucket gauge provides measurement of the total volume of percolation that passes through the lysimeter. During the 2010-11 monitoring period the West Slope lysimeter wire became disconnected in late 2010 and was repaired during the site visit in September 2011. Furthermore, after reviewing the Plateau tipping bucket data, it was determined the initial tipping bucket stopped recording data in late June 2011. Data from both the Plateau and West Slope lysimeters was incomplete for the 2010-11 monitoring period therefore net percolation values were estimated using hydraulic head gradients, and changes in moisture storage.

The total net percolation calculated at Plateau station was 2.5 inches (63.5 mm), which is approximately 27% of the 9.4 inches (389 mm) of rainfall precipitation recorded at the Plateau station. Net percolation at West station was calculated to be 3.6 inches (91.7 mm) which is approximately 16% of 22.5 inches (572mm) rainfall and SWE precipitation estimated at the West station. Both measurements reference the total liquid precipitation that was released to each site. These measurements are substantially more than measured in the 2009-10 field season and are attributed to the loss of direct measurement from the lysimeters tipping buckets as well as the increase in precipitation. Both lysimeter tipping buckets were replaced and tested during the September 2011 site visit to ready the stations for the 2012 field season.

3.4 Water Balance

A water balance was completed for the cover system field trials to quantify the volume of water percolating through the cover system in the 2010-11 monitoring period. A water balance was completed for both monitoring locations based on field measurements and solving the water balance equation on a daily basis during the frost-free period.

The water balance for a sloping cover system consists of the following components (expressed in mm):

$$PPT = RO + AET + NP + \Delta S + ITF \quad [1]$$

where:

PPT = precipitation (rainfall plus snow water equivalent (SWE)),

RO = runoff,

AET = actual evapotranspiration,

NP = net percolation,

ΔS = change in moisture storage, and

ITF = interflow or lateral drainage within the cover profile.

The estimation and application of each of these components in calculating the water balance is discussed briefly below.

Precipitation is measured at the Plateau site with a tipping bucket gauge to measure rainfall precipitation. The depth of the snowpack, and therefore snow water equivalent, was estimated with a sonic ranger at Plateau and West stations.

Runoff (RO) is not measured at the site but was estimated for the snowmelt and summer rainfall events. At the sloping West station, the snowmelt runoff coefficient was assumed to be 100% and the rainfall runoff coefficient increased with rainfall intensity but averaged approximately 20% for rainfall events greater than 5 mm. The assumed coefficients were lower at Plateau station due to its relatively flat surface and high winds; no snowmelt present to melt and the rainfall coefficient averaged 15% for rainfall greater than 5 mm. The selected runoff coefficients are based on OKC's experience at sites with similar climates and slopes.

Actual evapotranspiration (AET) was estimated based on rates of potential evaporation (PE) and climate data from the stations. Different AET:PE ratios were applied at five (5) day intervals of the frost-free period to arrive at reasonable AET rates. Also, a different AET/PE ratio was applied depending on precipitation occurrence on that day. This is an approximation as AET/PE ratios would likely change more frequently based on vegetation, available soil water, and other conditions. The ratio was then adjusted to match the calculated versus measured change in soil moisture storage as closely as possible.

Due to tipping bucket failure, net percolation (NP) values were determined based on hydraulic head gradients and changes in moisture content at the base of the cover. Hydraulic head gradients define the direction and magnitude of water flowing through the covers, and were used to determine if net percolation through the cover was realized. When the gradient was negative, there was an upward flux caused by evapotranspiration drawing water toward the surface. If the gradient was positive, indicating a downward flux, any loss of water in the lower layer of the cover profile was assumed to be net percolation.

Generally, interflow, or lateral flow (ITF), can be assumed to be negligible if the infiltration and percolation of water is limited to vertical 1D flow. This assumption was made for both Plateau and West stations.

The measured change in moisture storage (ΔS) in the cover profile was calculated using volumetric water content data recorded at each monitoring station, as described in Section 3.3.1 and shown in Figure 3.10.

3.4.1 Water Balance Calculation

Net percolation, AET/PE ratios, and runoff were manipulated in order to provide a calculated change in moisture storage value that best matched the measured change in storage using Equation 2:

$$\Delta S_{calc} = PPT - AET - ITF - RO - NP \approx \Delta S_{meas} \qquad [2]$$

The completed water balances presented in Figures 3.14 and 3.15 show a reasonable match between the measured change in storage (“Measured ΔS”), which is based on volumetric water content readings, and calculated change in storage (“Calculated ΔS”), which is based on solving the water balance equation for each monitoring site.

For the Plateau, shown in Figure 3.14, there was a good match between the measured and calculated change in storage for the frost-free monitoring period. The measured change in storage increased sharply due to the high rainfall events in July, August, and September and the calculated change in storage matched well during those periods which indicates the estimations of AET, runoff, and net percolation are reasonable. Total runoff during the monitoring period was 22 mm (0.9 inches) or approximately 9% of the total precipitation. The average AET/PE ratio for the monitoring location was 0.59 and the net percolation (calculated from the gradients and moisture storage) for the 2010-11 period was approximately 63.5 mm (2.5 inches), or 27% of the 9.4 inches of total precipitation measured at the Plateau station. Snow is not included in the Plateau precipitation total because it is not present to melt and contribute liquid water to the site.

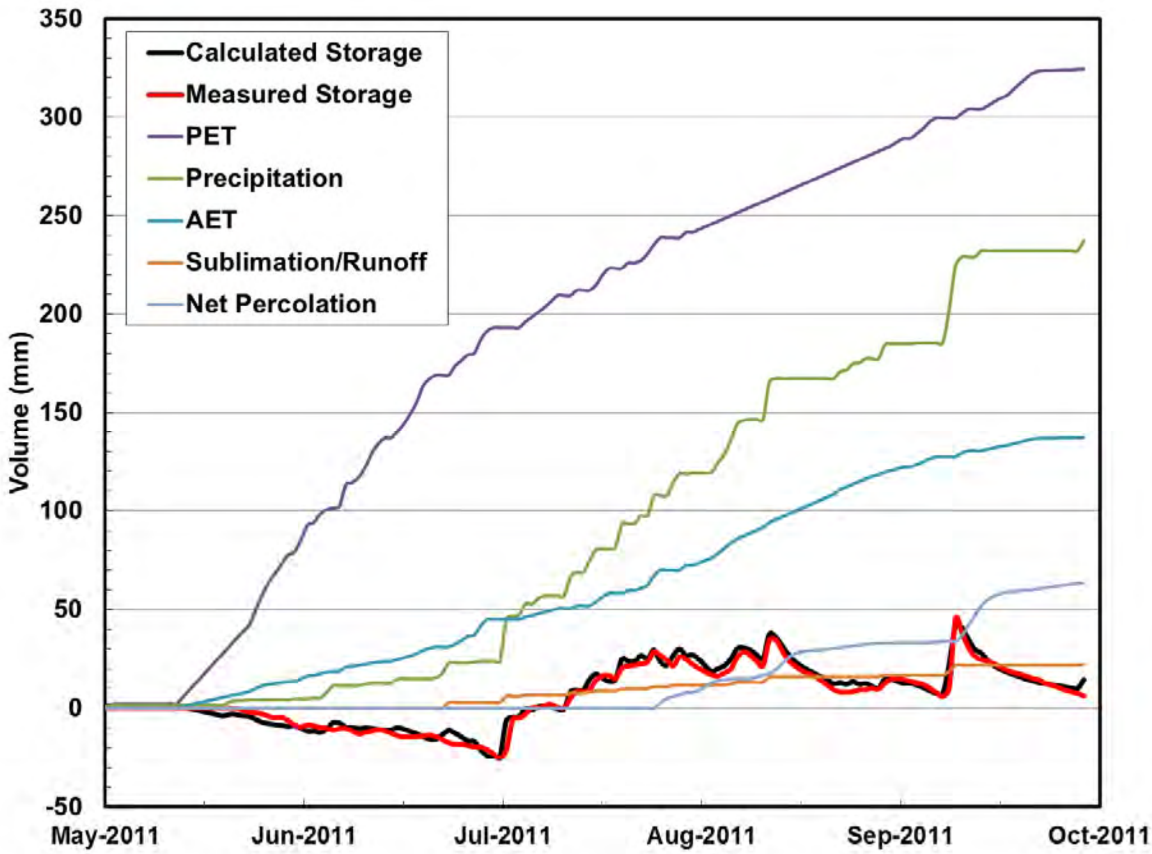

Figure 3.14 Cumulative water balance fluxes for Plateau station in the 2011 frost-free period.

The water balance completed for West station is shown in Figure 3.15. Similar to Plateau station, there was a good match between the measured and calculated change in storage for the majority of the period. The total precipitation at West station was greater than at Plateau station due to SWE. The total runoff estimated for the slope (615 mm) was also greater than estimated for the Plateau area due to the larger snowpack. It was assumed that 100% of SWE was released as runoff. The average AET/PE ratio for this monitoring location was 0.60. The estimated net percolation for the 2010-11 period was approximately 92 mm (3.6 inches), or 16% of the 22.5 inches of total precipitation measured at the West station.

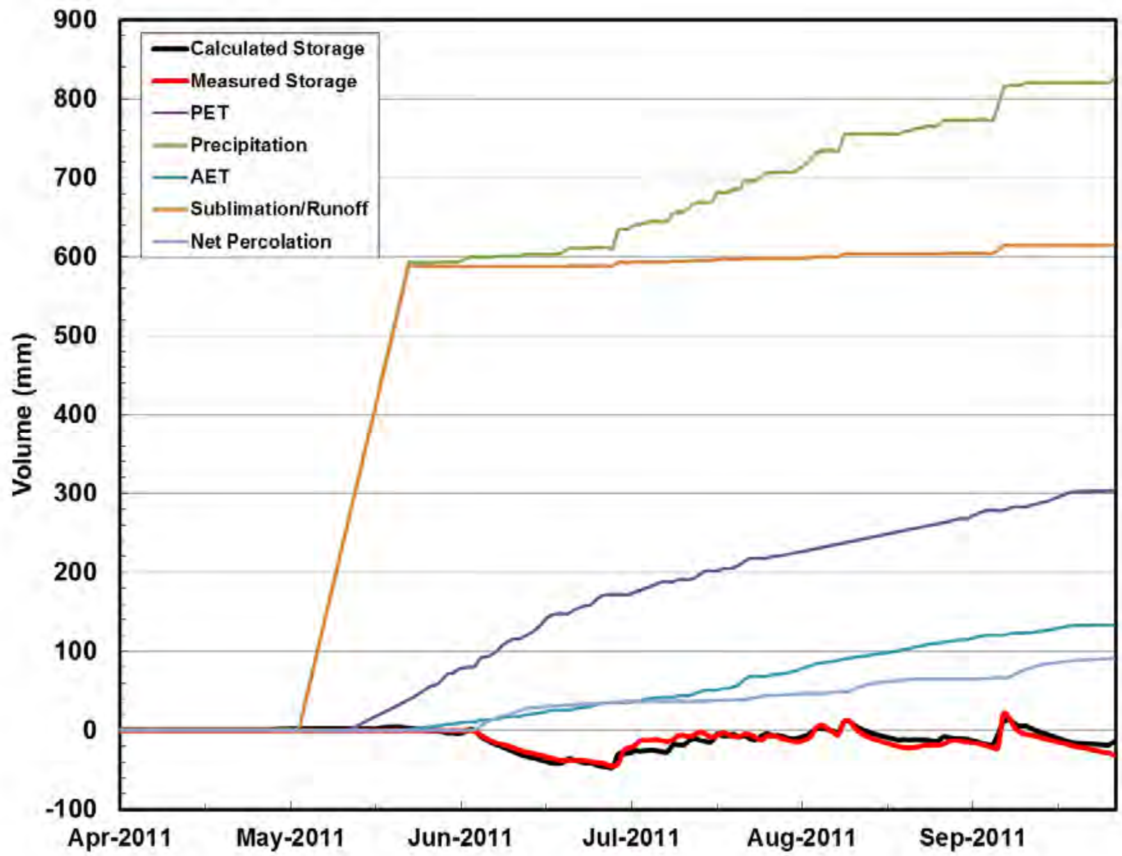

Figure 3.15 Cumulative water balance fluxes for West station in the 2011 frost-free period.

Table 3.1 summarizes the water balance precipitation at Plateau and West stations. The airport station precipitation is considered representative of precipitation that falls across the entire Red Dog mine area, both rain and snow. Changes in the distribution of snow, caused by sublimation, blowing and drifting, results in station specific precipitation totals for the Plateau and West stations. The Plateau loses all its snow from the water balance, a reduction of 39%. The West station gains 112% of total precipitation due to drifting, which implies that the additional snow is from an area larger than the west slope (it is assumed that the West station snow depth is indicative of the entire west slope area).

Table 3.1
Summary of the water balance precipitation.

Water Balance Parameter	Plateau Station	West Station
Precipitation (Airport Station)	389 mm (15.3 inches)	389 mm (15.3 inches)
Loss / gain SWE (due to sublimation, blowing and drifting)	- 152 mm (-39%)	+ 436 mm (+112%)
Station Precipitation (Rainfall + SWE)	237 mm (9.4 inches)	825 mm (32.5 inches)

Table 3.2 summarizes the components of the water balance at Plateau and West stations. The percentages shown in the table are based on the site specific precipitation at each location.

Table 3.2
Summary of the key parameters of the water balance for Plateau and West stations.

Water Balance Parameter	Plateau Station	West Station
Station Precipitation (Rainfall + SWE)	237 mm (9.4 inches)	825 mm (32.5 inches)
Runoff	22 mm (9%)	615 mm (75%)
Actual Evaporation	137 mm (58%)	133 mm (16%)
Net Percolation	63 mm (27%)	92 mm (11%)
Change in Storage	15 mm (6%)	-15 mm (-2%)

The locations of both Plateau and West stations have an effect on their water balance results. The Plateau station is located on the top of the waste dump where the wind prevents snow pack from accumulating. As a result, it is assumed, no runoff is attributed from snow. Due to little to no snow pack accumulation, the freezing conditions penetrate to the deepest sensors (250 cm). Therefore the waste rock remains frozen until late July, which prevents net percolation until the waste rock has thawed.

Unlike the Plateau station, the West Slope station accumulates additional snow pack during the winter. The snow pack acts as insulation and largely prevents freezing conditions in the waste rock. This allows net percolation to begin in early June resulting in a higher value than the Plateau station. However, it is assumed that all of the snow pack accumulated at the West station is released as runoff because the ground had not yet thawed.

Table 3.3 presents a summary of net percolation results as a percentage of precipitation for the two stations. Consistent with previous reports the net percolation is shown as a percentage of the airport precipitation, while the percentage of actual station precipitation is shown for the most recent monitoring period.

Year 1 and Year 3 results are very similar. The Year 1 Airport precipitation was 394 mm, compared to 389 mm in Year 3. The SWE of the airport precipitation appears very similar; in Year 1, 120 mm was removed from the Plateau water balance by blowing, compared to 150 mm in Year 3. While the Plateau shows an apparent identical response in net percolation, the West station net percolation increases from 17% to 24%

This increase in West net percolation could be attributed to two items: SWE equivalent water balance contribution and water balance methodology. The Year 3 water balance assumed that 100% of SWE equivalent reported as runoff; while it is not reflected in automated volumetric water content measurement, it is possible that some portion of the West SWE did infiltrate and contribute to net percolation, possibly by flow through frozen ground. The explanation deemed most likely responsible for the West Year 3 increase in net percolation (relative to Year 1) is the water balance methodology, which relied not on actual net percolation measurements, but rather an estimate utilizing suction gradients and changes in water content. The 24% is therefore viewed as the upper range of possible net percolation results, as may be as low as the 17% seen in Year 1.

Table 3.3
Net percolation summary.

	Airport Precipitation			**Station Precipitation**
Station	**Year 1 2008-2009**	**Year 2 2009-2010**	**Year 3 2010-2011**	**2010-2011**
Plateau	16%	11%	16%	27%
West	17%	10%	24%	16%

3.5 Comparison of 2010-11 Period to Short-Term Monitoring Record

In order to characterize the performance of the cover systems in the 2010-11 monitoring period, it is useful to examine their response within the context of the short-term monitoring record from 2003-04 to 2010-11. Figure 3.16 presents the precipitation recorded in each monitoring period at the Airport weather station.

In 2008-09, net percolation rates were approximately 17% and precipitation was closer to the short-term average similar to the 2010-11 period. Net percolation rates calculated in 2010-11 represent the higher boundary of percolation rates for the Plateau station (27%) but the net percolation rate calculated for the West Slope station (16%) is within the expected boundary for this site. Due to the loss of tipping bucket data, measured net percolation data could not be used in the water balance as had been done in the previous monitoring years.

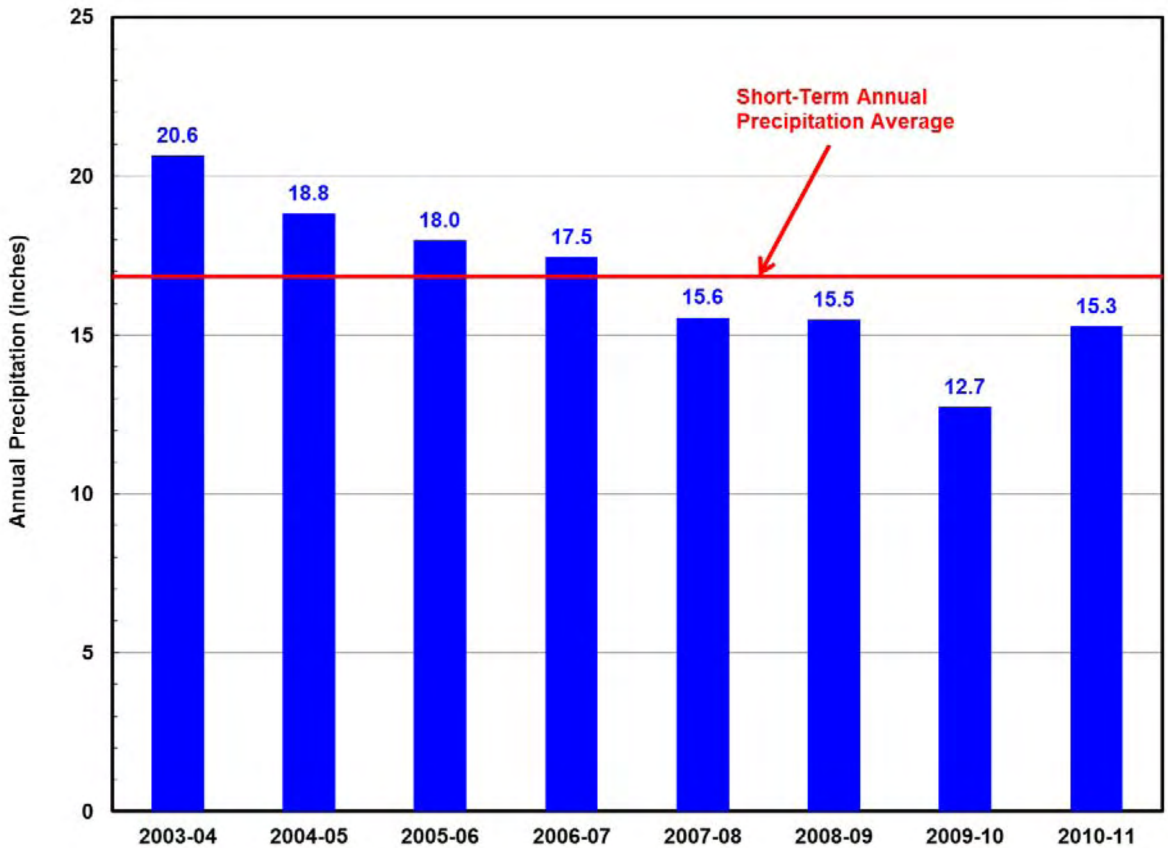

Figure 3.16 Rainfall recorded during each monitoring period since the onset of monitoring.

4 RECOMMENDATIONS

The following recommendations are made for the Oxide Stockpile monitoring system:

1. Re-establish the collection of water content data from the Diviner access tubes. This includes ensuring that the Diviner sensor and display unit are functional (this is currently being investigated). In addition, replacing the few cracked Diviner tubes would return the monitoring to the original scope.
2. Move the Plateau flume and install it in a newly constructed runoff channel below the West Slope station. Due mainly to the lack of snow accumulation, runoff is not being channelled through the flume at its current location. Placing the flume on the West Slope would result in runoff measurements, most likely from both snowmelt and rain. If the flume is moved, the OTT PLS water level sensor and a CR800 Campbell Scientific datalogger are recommended for water level and temperature measurements.

5 REFERENCES

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