Near-Surface Water Balances of Waste Rock Dumps

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ABSTRACT

The near-surface water balance of mine impacted landscapes is a key control on re-vegetation performance, and on the hydrologic and water quality impact at the watershed scale. As part of Teck Resources Limited's applied research and development program focused on managing water quality in mine-affected watersheds, 12 sites in western Canada (southeastern British Columbia and western Alberta) representing a range of waste rock dump reclamation surface management options (i.e. soil cover, surficial mounding) were instrumented in 2012 to measure meteorological and soil water response and to quantify the near-surface water balances with a focal objective to improve estimates of ranges of net percolation into waste rock dumps under a range of scenarios.

Subsurface water and meteorological conditions varied substantially, as expected for the range of elevation, slope aspects, vegetation, soil covers, geographic location and surface preparation of the selected sites. Patterns in water balance trends emerged in the first year of analysis with net percolation (NP) into underlying waste rock typically decreasing for increased vegetation and soil cover, as well as for decreases in rainfall or snowmelt. Increased vegetation cover resulted in a greater volume of water removed from near-surface through evapotranspiration. The lowest NP (as % of water input) was estimated for a mature, reclaimed conifer forest site and a dense agronomic grass/alfalfa covered site. Net percolation estimated for a soil covered waste rock slope was approximately 15% (of water inputs) less than an adjacent bare waste rock slope. Decreased NP was partly attributed to greater water storage in the finer-textured soil cover. Net percolation through the soil cover is expected to further decrease with time as vegetation establishes relative to the bare waste rock slope. Net percolation for a mounded, bare waste rock slope was less than estimated for an adjacent smooth slope. Net percolation below a trough was similar to the smooth slope, but decreased at the crest and mounded mid-slope positions due to thinner snowpack (less snowmelt) from wind scouring. Additional monitoring and analysis of site-specific water balances will help define the shift in the relative proportions of water entering the deposits as vegetation matures.

INTRODUCTION

Mining activities undertaken by Teck Resources Limited (Teck) to access the metallurgical coal resource in the Elk Valley of southeastern British Columbia and in northwestern Alberta result in waste rock dumps with material susceptible to long term weathering and erosion processes. The waste rock is known to increase concentrations of some constituents of interest (CIs) in downstream surface water and groundwater systems. Post-depositional weathering of the waste rock is accelerated by oxygen ingress and weathering products can be transported with infiltrating water. These two processes are both controlled by the degree of saturation of the unsaturated waste rock.

The amount of water that infiltrates into waste rock landforms is a function of the near-surface water balance. This surface water balance is a key control on vegetation establishment and its long term performance and will affect the hydrology, hydrogeology and geochemistry of affected watersheds. For example, selenium (Se) concentrations in mine-affected rivers are reported to have increased over the last three decades (Lussier, Veiga & Baldwin, 2003; Chapman, Berdusco & Jones, 2007) and the understanding of Se release and transport from waste rock dumps is still developing. Research has indicated that Se is more readily transported in the soluble form of selenate suggesting a strong link to water movement (Chapman, Berdusco & Jones, 2007).

Controls on the movement of water through and out of waste rock dumps include the volume, rate, and flow path of net percolation (NP) waters. The term 'net percolation' is defined as water that migrates into and downward in the material profile to depths not influenced by atmospheric processes (i.e. evapotranspiration). This water may eventually be released from waste rock to adjacent groundwater or surface water. Important aspects of NP include:

- Volume: NP volumes are a primary control on water volumes reporting as basal and toe seepage from waste rock dumps and have important implications for mine-affected watershed water balances and water management strategies. NP volumes may be an important control on solute loadings in basal and toe seepage;
- Rate: The flow velocity of NP through mine wastes, as well as the height of the waste deposit, will control the residence time of pore-water in the waste rock profile. Residence time may be an important consideration on the dissolution of CIs; and
- Flow Path: Water may move via preferential pathways (i.e. macro-pore flow) or via matrix flow, which is more distributed. Preferential flow through waste rock will decrease the surface area contacted by NP and residence time of NP in waste rock dumps, which are opposite to the trends for matrix dominated flow. Preferential flow paths will increase the time required to flush CIs from a waste rock dump compared to matrix dominated flow as NP following preferential flow paths bypasses and does not flush oxidation products from all of the waste rock.

As part of Teck's applied research and development program focused on managing water quality in mine-affected watersheds, 12 sites representing different waste rock dump reclamation surface management options were instrumented in 2012 to measure meteorological and soil water dynamics. Data from these sites was used to quantify the near-surface water balances with a focal objective to improve estimates of ranges of NP into waste rock dumps for a variety of conditions.

METHODOLOGY

The study sites are located at four coal mining operations in the Elk Valley, BC and one in northwestern Alberta: Line Creek (LC); Greenhills (GH); Elkview (EV); Fording River (FR); and Cardinal River (CR; Figure 1). The climate at all of the study sites is humid continental. Climate normals data (1981-2010, Environment Canada, Sparwood station at 1140 m asl) indicate the Elk Valley mines are located in a region with mean annual precipitation of 613 mm (411 mm as rainfall, 202 mm as snow). Mean annual precipitation from climate normals data (1981 – 2010, Environment Canada, Jasper East Gate at 1003 m asl) for the Cardinal River area is 599 mm (448 as rainfall, 151 mm as snow). The study sites monitoring instruments were commissioned in the summer and fall of 2012 and have been collecting data since. This paper reports on data for each site over one hydrologic year starting October 1st, 2012 through September 30th, 2013. A large rainfall event in the Elk Valley from June 18th – 21st, 2013 largely influenced the amount of precipitation observed in the first year of monitoring as this event resulted in 81% more rain in June than the monthly climate normal for that month.

General Site Descriptions

The study sites were chosen to investigate the effect of elevation, surface soil placement, re-vegetation types, site orientation (slope/aspect) and microtopography on the near-surface water balance (Table 1). The study site locations include two instrumented sites at Greenhills Operation North Thompson mine area that are part of a paired cover trial with a uniform sloped soil cover (GH_NTC) and bare waste rock (GH_NTW) slope. A soil cover was also placed on the Turn Creek dump (FR_TCR) at Fording River Operation. Three sites (LC_BHE, LC_RHE and LC_RME) were installed on benched plateaus of the West Line Creek dump at the Line Creek Operation at different elevations and with varying degrees of vegetation cover. A reclaimed mature forest site (FR_CSP) at the Fording River Operation provided an optimal scenario to understand the effect of mature tree re-vegetation on near-surface water retention and net percolation. Data collected on a south-facing, vegetated slope of the Bodie Dump (EV_BRD) at the Elkview Operation allow quantification of the effect of a thick grass-legume vegetation cover and slope aspect. Similarly, instruments installed at the Cardinal River Operation north-facing (CR_B5D) and south-facing (CR_B4D) slopes were used to observe differences due to aspect and soil placement. The sloped surface in the Greenhills Rosebowl mine area (GH_RMS) and Cardinal River Cheviot area (CR_CMS) have been prepared using a mounding technique creating crests, mid-slopes and troughs, which help evaluate the effect of mounding on re-vegetation success and overall NP rates.

Performance Monitoring Instrumentation

All sites were instrumented with both soil profile monitoring (suction, temperature and water content) and meteorological stations with the exception of CR_B4D, which was installed with only a net radiation sensor. Components of a soil monitoring station included one primary *in situ* water content monitoring station consisting of eight thermal conductivity (pore-water suction) and eight time-domain reflectometry (TDR, water content) sensors, and four secondary *in situ* water content monitoring stations, each consisting of four TDR sensors. Meteorological stations measured rainfall (CS700 Tipping Bucket Rain Gauge), air temperature and relative humidity (HC2-S3 Probe), wind speed/direction (R.M. Young Model 05103AP-10 Wind Monitor), net radiation (Net Radiation Kipp & Zonen model NR-LITE2 Net Radiometer), and snow depth (Sonic Ranger 50A). Eddy covariance stations were installed at LC_RHE, LC_BHE, FR_CSP, and GH_NTW, and included a gas analyzer (either LICOR Li-7200 closed-path for forest and grasses, or a Li-7700 open-path CO_2/H_2O analyzers for bare waste rock), an ultrasonic anemometer (Windmaster, Gill Instruments), an air temperature and relative humidity sensor (HMP45 sensor, Vaisala), and a net radiometer (CNR4, Kipp & Zonen). Nine Gee lysimeters were installed under the trough, crest, and slope areas of the GH_RMS study to directly measure net percolation rates. Lastly, 24 sap flow sensors were installed in 12 trees at FR_CSP to measure sap flow velocity and estimate water uptake rates by each tree.

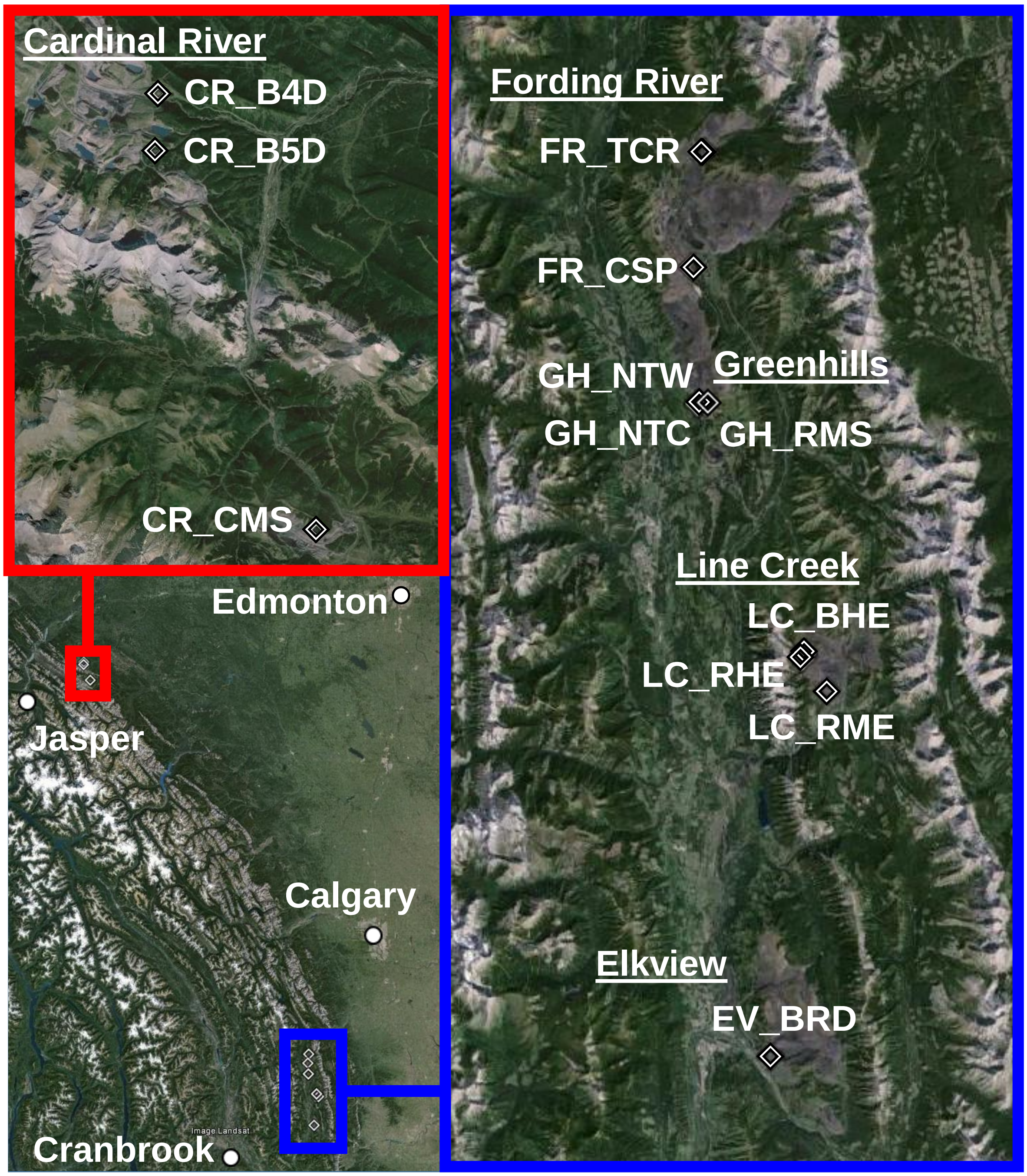

Figure 1 Aerial map showing locations of study sites.

Table 1 Summary of characteristics at study sites located in southeast BC and northwest AB

Site	Easting	Northing	Mine Area	Elevation (m asl)	Cover Soil	Surface	Slope (°)	Aspect	Topographic Shading	Vegetation
GH_NTW	5550564	651834.7	N Thompson Ck	1800	No	Smooth	26	W	No	Planted Seedlings
GH_NTC	5550651	651875	N Thompson Ck	1800	2-Lift Surface Soil	Smooth	26	W	No	Planted Seedlings/ Natural Regeneration
GH_RMS	5550429	652172.1	Rosebowl	1920	No	Mounds	26	SW	No	Planted Seedlings
LC_BHE	5535363	658257.9	West Line Ck	2150	No	Smooth/ Harrow	-	Level	No	Planted Seedlings
LC_RHE	5535020	658138.9	West Line Ck	2075	No	Smooth/ Harrow	-	Level	No	Agronomic Grasses/ Legumes
LC_RME	5533016	659655.7	West Line Ck	1790	No	Smooth/ Harrow	-	Level	No	Agronomic Grasses/ Legumes
FR_CSP	5559029	348453.1	C Spoil	1690	No	Smooth	26	E	No	~25 Year Old Regenerating Conifer Forest
FR_TCR	652279	5566138	Turn Creek	1800	Salvaged Soil/ Overburden	Smooth/ Harrow	-	Level	Yes	Planted Seedlings
EV_BRD	5510559	343964.9	Bodie Rock Drain	1470	No	Smooth	26	SW	No	Agronomic Grasses/ Legumes
CR_B5D	5879971	475328.5	Luscar B5	1630	Regolith	Smooth	26	NE	No	Agronomic Grasses/ Legumes
CR_B4D	5878010	474278.7	Luscar B4	1690	No	Smooth	26	S	Partial Winter	Agronomic Grasses/ Legumes
CR_CMS	5864953	479802.9	Cheviot 1930	1930	Salvaged Soil (Till)	Mounds	26	S	No	Planted Seedlings/ Natural Regeneration

*Substrate for all sites was waste rock.

Water Balance Analysis

Water balances were developed for each site over one hydrologic year starting October 1st, 2012 through September 30th, 2013. For these snow-dominated sites, water input was defined as the sum of rainfall minus rainfall interception, plus snowmelt (hereafter referred to as effective precipitation, P_{eff}). The following components of the water balance were measured or estimated to calculate daily changes in storage (ΔS) in the top ~1 m of material at the primary station profiles:

$$\Delta S = R + M - AE(T) - RO - NP \tag{1}$$

where: R is rainfall, M is snowmelt, $AE(T)$ is actual evaporation or evapotranspiration where appropriate, RO is surface runoff, and NP is net percolation (all units are mm d^{-1}). Runoff at all sites was assumed to be zero as a result of the high hydraulic conductivity of the waste rock and cover soils.

Precipitation

Rainfall (volume and intensity) was measured with a tipping bucket rain gauge (TBRG, Campbell Scientific 700). Precipitation was verified by comparing multiple TBRG records at sites with similar elevation, the precipitation record from the Sparwood, BC climate station (1140 masl, Environment Canada) and other total precipitation gauges operated by McMaster University and Teck. Precipitation was assumed to be rain if the mean daily air temperature was greater than 2°C.

Daily average snow depth was measured continuously using an automated Sonic Ranger 50A (SR50) sensor. Snow surveys completed at the end of March 2013 provided snow depth and density data to calculate a transect-average snow-water equivalent (SWE) across each site. A continuous record of snowpack SWE was estimated with snow density equations (Bartlett, MacKay & Verseghy, 2006).

Melt

Point-based daily snow ablation amounts for each site were estimated using the energy balance equation and daily averages of meteorological data using the approach reported by Dingman (2002) and Burles & Boon (2011). The energy fluxes from ground heat flux and rain were assumed to be zero. Sensible heat was calculated as a function of measured wind speed and air temperature. Sublimation and evaporation were accounted for by the latent heat term which was a function of the vapour pressure gradient between the air and snow surface. The melt period was initialized with peak SWE and run to complete snowpack removal. The SR50 snow depth record in combination with field observations (including time-lapse photos) were used to determine the timing of snowpack disappearance.

Evapotranspiration

Potential evaporation was estimated using the Penman (1948) or Penman-Monteith combination method (Monteith, 1965) for sites with well-established vegetation. Canopy conductance (C_{can}) was estimated using leaf area index data collected in 2013 (Integral Ecology, 2013). A relationship between evapotranspiration (E(T)) and soil water deficits was used to relate potential evapotranspiration (PE(T)) to actual E(T) via the following equations:

$$AE(T) = PE(T) \cdot Available\ Water\ Ratio \tag{2a}$$

$$Available\ Water\ Ratio = (VWC - WP)/(FC - WP) \tag{2b}$$

where: VWC is the volumetric water content of the surficial soil profile (average of top 15 to 30 cm depending on vegetation and expected depth range accessible to evapotranspiration), WP is the wilting point and FC is the field capacity. WP and FC are defined as the volumetric water contents at 1500 and 10 kPa of suction, respectively. The available water ratio approached 1 at FC and declined as the availability of water decreased to the WP for plants (available water ratio = 0). Eddy covariance estimates of AE(T) were found to positively correlate with measured leaf area index (LAI) (Integral Ecology, 2013); therefore, AE(T) estimates calculated using Eq. 3a and 3b were constrained using the developed LAI-AE(T) relationship for conditions ranging from bare to vegetated ground.

Interception

Rainfall intercepted was assumed to be evaporated daily and estimated using a modified version of the forest rainfall interception model in Rutter and Morton (1977). Daily maximum rainfall interception was set equal to the canopy storage capacity for conifers (1 mm; Schmidt & Gluns, 1991). Intercepted snowfall in the trees at Fording River C-spoil was not considered during the first year of analysis due to the complexity in quantifying this process and scope of the study.

Storage

Changes in water storage (ΔS) through the soil profile were calculated using the volumetric water content (CS616 Time Domain Reflectometry Sensors) measured at the primary monitoring station. The volume of water was weighted for sensor depth and summed over the entire profile.

Net Percolation

It was assumed that NP occurred when there was a downward vertical hydraulic gradient as calculated from the soil suction values between 75 and 100 cm depth and if there was a net loss in storage within the bottom half of the instrumented profile. For this case, NP was assumed to be equal to the net loss in storage from the bottom half of the profile, as it was assumed AE(T) fluxes would not affect water storage at that depth. This assumption was supported by matric suction depth profiles (not presented) which exhibited the greatest changes with time and occurrence of upward gradients in the upper 50 cm.

If the water storage capacity of the bottom soil profile exceeded the field capacity (FC; 10 kPa of suction) during snowmelt infiltration or rainfall events, then NP was estimated via the water balance in Eq. 1. This NP estimation method was used during snowmelt infiltration and rainfall events as there was often a surplus of water during melt and rainfall events if the gradient / storage method for calculating NP described above was used. It was assumed that seepage rates could be near steady-state during melt and rainfall events and that NP could be occurring even if there was not a measured decrease in storage.

Analytical Model Calibration

Water retention curves (WRC) were developed using the water content and suction monitoring data. These were then used to estimate values of FC and WP. Water retention curves, however, are difficult to develop for heterogeneous, coarse-textured materials. Estimates of AE(T) were most sensitive to FC and WP parameters; therefore, sensitivity of water balance estimates were assessed by varying the FC and WP values ± 2 to 10%. Measured water content and the match of measured and calculated water storage was used to inform FC and WP estimates and constrain AE(T) values. Assuming no runoff, water input that was not removed by AE(T) was then assumed to eventually report to NP.

RESULTS AND DISCUSSION

The soil water contents and meteorological conditions were variable, which was expected given the range of elevation, slope aspects, vegetation, soil covers, geographic location and surface preparation of the selected sites. Meteorological conditions at the various sites were similar but with key differences that can be attributed to elevation, geographic location, and slope aspect. Precipitation increased with increasing elevation. LC_BHE, the highest elevation site (2,150 m asl) had the greatest measured total annual precipitation (1,210 mm). For sites in the 1,500 to 1,800 m asl elevation range, total annual precipitation ranged from approximately 800 to 950 mm. Sites located at the Cardinal River Operation were greatly influenced by the dry, warm winds blowing down the eastern slopes of the Rocky mountains. Data records indicate snowpack disappearance occurred earlier on the south-facing CR_B4D slope compared to north-facing B5D likely due to higher solar energy input received on the south-facing slope. Earlier snowmelt and snowpack disappearance was also observed on other south-facing slopes including EV_BRD and CR_CMS.

Patterns in water balance trends emerged in the first year of analysis with NP into underlying waste rock typically decreasing for increased vegetation and soil cover, as well as for decreases in rainfall or snowmelt. The highest NP occurred at LC_BHE due to greater P_{eff}, low AE(T), and less water holding capacity in the coarse waste rock compared to other monitored sites (Table 2). Increased vegetation cover resulted in a greater volume of water removed from the near-surface through AE(T), that would have otherwise resulted in NP. For example, the lowest NP (as % P_{eff}) calculated was for the mature, reclaimed conifer forest site (FR_CSP) and the dense agronomic grass/alfalfa covered site (EV_BRD). Lower NP at EV_BRD compared to FR_CSP was attributed to a higher water holding capacity in the material underlying the thick grass cover combined with lower P_{eff} on a south-facing slope. As the individual site cover systems evolve, vegetation communities mature, and water balance trends become more apparent the mechanisms having the largest impact on controlling net percolation through waste rock dumps and achieving re-vegetation objectives can be identified, quantified and evaluated as potential watershed management tools.

Net percolation estimated for a soil covered, waste rock slope (GH_NTC) was approximately 15% (of P_{eff}) less than an adjacent bare waste rock slope (GH_NTW). Research has shown that cover systems have the potential to limit infiltrating water (i.e. NP) through a waste rock dump (MEND, 2012). Water storage in the shallow subsurface was greater in the finer-texture soil cover at GH_NTC compared to GH_NTW (Figure 2). NP through the soil cover is expected to further decrease in future years as vegetation establishes, thus more available soil water will be removed through AE(T) (Integral Ecology, 2012).

The water balances for the covered sites at FR_TCR and GH_NTC, and the mature forest site at FR_CSP, were analyzed over a shorter period than other sites as data was not available until later in the fall. NP estimates (as a % of P_{eff}) are likely slightly over-estimated for these sites as heavy rainfall in early October prior to the first day of the water balance estimations were not included in the P_{eff} values but may have been contributing to NP during the analysis period.

The weighted net percolation for a mounded, bare waste rock slope (GH_RMS), considering the overall effect of troughs and crests, was lower than that calculated for an adjacent smooth slope (GH_NTW) (Table 2). Net percolation estimates at the GH_RMS were corroborated by direct measurement of NP by lysimeters. Net percolation in a trough at GH_RMS was similar to the smooth slope at GH_NTW, but decreased at the crest and mounded mid-slope positions due to thinner snowpack (less snowmelt) from wind redistribution. Increased water availability in the troughs, as well as wind and sun shading, are expected to increase vegetation productivity over time in the troughs relative to the crests which will increase AE(T) and further decrease NP at GH_RMS.

CONCLUSION

Patterns in near-surface water balances have begun to emerge in the first year of monitoring of a range of waste rock dump reclamation surface management options. Net percolation as estimated from data collected from field moisture and climate instruments decreased with increasing vegetation cover and the addition of a surficial soil cover. Overall NP at a mounded waste rock site was estimated to be less than for an adjacent smooth waste rock slope. The effect of mounding on NP should be considered on a site-specific basis, however, as differences in precipitation, depth of troughs, slope aspect and prevailing wind direction will influence the results.

Table 2 Cumulative annual water balance fluxes for all 12 study sites. All fluxes are presented in millimeters. Net percolation values are presented as a percentage of effective water inputs (rainfall plus snowmelt).

Site		Elev m asl	Description	Rain	Melt	Effective Precipitation (P_{eff})	Actual E(T)	Net Percolation (NP)	Meas ΔS	Calc ΔS	NP as % of P_{eff}	Sensitivity of NP (as % of P_{eff})
LC_BHE		2150	Bare, plateau	530	640	1170	**150**	970	60	50	**83%**	**79 – 85%**
LC_RHE		2075	Grass/legume, plateau	530	590	1120	**280**	780	65	65	**70%**	**68 – 71%**
LC_RME		1790	Grass/legume, plateau	630	270	900	**170**	640	90	85	**71%**	**68 – 73%**
GH_NTW		1800	Seedlings, bare, slope	510	430	940	**150**	750	30	35	**80%**	**77 – 83%**
GH_NTC[1]		1800	Seedlings, soil cover, slope	480	340	820	**180**	550	80	90	**67%**	**65 – 71%**
GH_ RMS	**Trough**	1920	Seedlings, bare, mounded, slope	510	470	980	**150**	810[4]	10	15	**83%**	**79 – 85%**
	Crest	1920	Seedlings, bare, mounded, slope	510	130	640	**150**	450[5]	55	45	**70%**	**63 – 77%**
FR_CSP[2]		1690	Trees, bare, slope	620	350	970	**380**[6]	560	40	35	**58%**	**55 – 61%**
FR_TCR[3]		1800	Seedlings, soil cover, plateau	600	250	850	**150**	730	-30	-30	**86%**	**82 – 89%**
EV_BRD		1470	Grass/legume, slope	690	190	880	**320**	460	100	100	**52%**	**49 – 55%**
CR_B5D		1630	Grass/legume, slope	460	420	880	**330**	590	-45	-40	**67%**	**64 – 70%**
CR_B4D		1690	Grass, legume, slope	460	400	860	**250**	650	-45	-40	**76%**	**72 – 79%**
CR_CMS		1930	Seedlings, cover, mounded, slope	450	300	750	**200**	570	-20	-20	**76%**	**72 – 79%**

* Runoff assumed to be zero for all sites.

1 Water balance period starting 18 Oct 2012

2 Water balance period starting 15 Oct 2012

3 Water balance period starting 25 Oct 2012

4 Drainage measured using Gee lysimeters was 780 mm

5 Drainage measured using Gee lysimeters was 65 mm

6 Rainfall canopy interception was estimated to be 70 mm of AE(T)

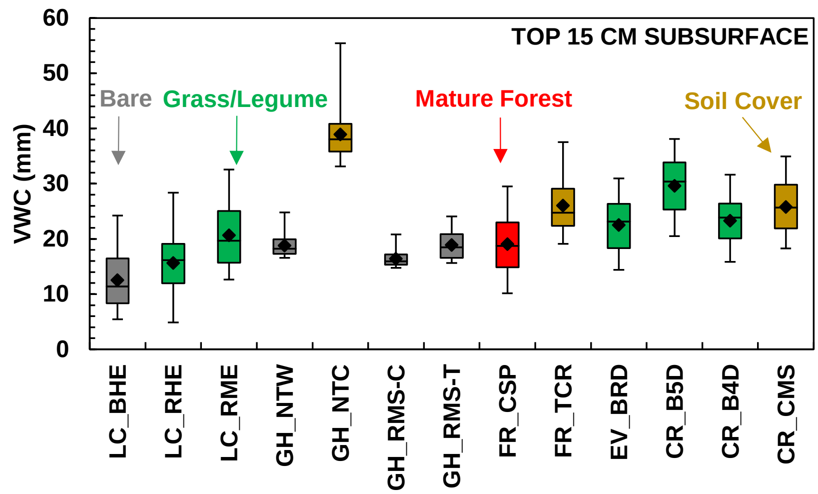

Figure 2 Box and whisker plot showing inter-site variability in mean daily VWC for the top 15 cm of material during the non-frozen period (May 1st to September 30th, 2013). Whiskers indicate the maximum and minimum values, the box represents the 25th and 75th percentiles, while the median values are represented by the mid-range lines. Mean values are presented as black diamonds to indicate the skew in the distribution of the data set.

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