TOWARDS AN ECOHYDROLOGIC CLASSIFICATION OF RECLAIMED WATERSHEDS: METHODS FOR ESTIMATING SOIL WATER REGIME ON RECLAIMED MINE WASTE MATERIALS; AND RELATIONSHIPS BETWEEN RECLAMATION AND SURFACE WATER BALANCES IN TECK'S RECLAIMED COAL-MINING WATERSHEDS

J. Straker[1]
M. O'Kane[2]
S. Carey[3]
T. Baker[1]
D. Charest[4]
R. Shurniak[2]

[1]Integral Ecology Group Ltd., Duncan, B.C. jstraker@iegconsulting.com
[2]O'Kane Consultants Inc., Calgary, AB
[3]McMaster University, Hamilton, ON
[4]Teck Resources Limited

ABSTRACT

The concept of a "soil moisture regime" or soil water regime is used worldwide to understand edaphic conditions, plant communities, and water balances. In particular, in western and northern Canada, Biogeoclimatic Ecosystem Classification ("BEC", B.C. and Yukon) and Ecological Land Classification ("ELC", AB and SK) use soil moisture regime as one of two primary variables in edaphic or edaptopic grids used to describe ranges of soil conditions and naturally occurring plant communities characteristics of these conditions. In most applications, soil moisture regime is a relative or unquantified parameter estimated from the presence of indicator plants, or from dichotomous keys using surficial material/soil properties observed in natural ecosystems. Applications of these estimation approaches to post-mining landforms and watersheds is challenging, because a) there are often few or no indicator plants and plant communities, and b) soils and surficial materials are reconstructed. Some quantitative approaches to estimation of properties that influence soil moisture regime (e.g., available water storage capacity) have been developed, but these are generally based on broad textural categories, and ignore the effects on water retention of all particles >2 mm. These approaches have limited utility to many post-mining materials, where the majority of particles may be >2 mm.

Methods for estimating soil moisture regime on reconstructed post-mining landscapes were developed using concepts from land-capability and biogeoclimatic-ecosystem classification systems combined with new analyses of effects of particle-size distribution on soil water retention. These methods are both quantified and objective, in that they provide consistent results when applied by different users. This paper discusses methods development, application, and testing of this estimation approach.

INTRODUCTION

One of the principal knowledge gaps in mine reclamation is that of the retention of water by and movement of water through surficial materials, and how this mediation of surface water balances influences both ecosystem development and watershed performance. This understanding is critical for better reclamation planning and projection of long-term characteristics of reclaimed ecosystems. It is also critical for improving understanding of hydrologic behaviour of reconstructed mine-affected watersheds and fate and transport of constituents of interest (CIs) in these watersheds. To date, most approaches to

addressing this gap, where it has been addressed at all, have been borrowed from ecosystem classification systems, and are limited by some or all of the following factors:

1. they are qualitative or semi-quantitative, and there is limited attempt to evaluate and demonstrate their hydrologic validity;
2. they rely substantially on the presence of vegetation communities to provide information on edaphic conditions – in mine-reclamation settings where these communities are absent or introduced, there is insufficient information for application of these approaches; and/or
3. they have a narrow focus on a single aspect of the surface water balance, e.g., estimating water retention for revegetation planning. In these approaches, there is no attempt to provide a more comprehensive understanding of surface water balances, and how water retention and use by vegetation may influence deeper percolation and the water balance of the underlying mine-waste landform.

This paper presents some advances in this field that propose a quantitative basis for understanding reclamation surface water balances and their effects on both reclamation ecosystem development and the hydrologic behaviour of mine-affected watersheds.

BACKGROUND

Biogeoclimatic ecosystem classification

The foundation of ecological classification in British Columbia is "biogeoclimatic" ecosystem classification (BEC), in which biogeoclimatic units ("zones") represent broad geographic areas of similar macroclimate, and are recognized as influencing biological characteristics of resulting ecosystems (Meidinger and Pojar, 1991). Development of biogeoclimatic classification of the province began in 1949 with the immigration of Vladimir Krajina. From 1950-1975, ecosystem studies undertaken by Dr. Krajina and his students at the University of British Columbia resulted in the development of the BEC system for B.C., based primarily on climate, soils, and vegetation data. This work still forms the basis of the current BEC system and mapping of the province.

In the BEC system, biogeoclimatic zones are subdivided into subzones, which are in turn subdivided into variants, with each subdivision representing a reduction in climatic variability and geographic area (Lloyd et al., 1990). Within each subzone or variant, there are sequences of distinct ecosystems or "site series", with associated vegetation communities reflecting differences in topography and soil depth, texture, drainage, moisture regime, and nutrient regime. In this system, soil water availability is believed to have the greatest influence on ecosystem development. This availability is influenced by climate, but since climate is relatively uniform within a biogeoclimatic subzone or variant, variation in soil water availability at this level of classification results from influences of soil and topography on surface water balances (Lloyd et al., 1990). These influences are manifested in resulting plant associations, i.e., each site series has an assemblage of plants that are adapted to its edaphic conditions – a fundamental principle of the BEC system is that sites with similar physical properties have similar vegetation potential (Meidinger and Pojar, 1990). A subset of plants on a site – "indicator plants" – are diagnostic of edaphic conditions due to their adaptation to narrow ranges of conditions, e.g., soil water availability.

Biogeoclimatic classification as developed in B.C. is a unique system substantially informed by the Russian concept of phytoassociations across ecological gradients (e.g., Sukachev, 1928), and by the classification work of the phytosociologist Braun-Blanquet (e.g., 1932) in southern Europe. Its concepts have been adopted elsewhere in Canada, particularly in western and northern Canada (e.g., Alberta, Saskatchewan, Yukon), and in the western U.S. and Japan (e.g., Kojima, 1991). In North America, the BEC system shares similarities with the site-classification systems of Ontario and with Daubenmire's habitat-type system in the western United States (Pojar et al., 1987).

Soil water availability

In B.C., soil water availability is estimated using a concept called "soil moisture regime" (SMR), which conceptually reflects "the average amount of soil water annually available for evapotranspiration by vascular plants over an extended period of time (several years)" (Pojar et al., 1985). Krajina's classification work incorporated nine SMR classes ranging from driest (Class 0, or very xeric) to wettest (Class 8, or hydric) – this spectrum is sometimes referred to as a "hygrotope" (Pojar et al., 1985; Meidinger and Pojar, 1990; Klinka et al., 1984). The most common classifications of hygrotope – and those that are used in the BEC system – are classifications of *potential* hygrotope based on subjective inferences from site and/or vegetation features, and represent relative ranking of sites or factors in terms of potential soil water availability. A common example of this approach, although more complex and semi-quantified examples exist in the BEC system (e.g., Lloyd et al., 1990), is shown in Table 1.

Quantified and objective approaches to estimation of both potential and actual hygrotope or soil moisture regime are uncommon, and those that exist are limited in their application to specific places and/or ecosystems (e.g., Waring and Major, 1964). In B.C., Green et al. (1984, and summarized in Pojar et al., 1985) used a water-balance approach to develop an actual hygrotope, but it is based on intra-annual duration of water deficits and on presence of water tables, and although the authors provide defining features for their classes, methods for classifying sites according to this system are not provided.

Various land capability classification systems in Canada – beginning with agricultural land capability systems – have used available water storage capacity (AWSC, sometimes called available water holding capacity, or AWHC) as an index of soil water availability. Available water storage capacity is defined as the difference between the volumetric water content at field capacity (FC) and permanent wilting point (PWP), where:

- field capacity is the state at which rapid downward movement of water due to gravitational drainage has become negligible relative to removal through evaporation or evapotranspiration – typically occurring at tensions of 10-33 kPa, depending on soil texture; and
- permanent wilting point is the water content at which soil water is no longer available for plant uptake – although this content varies by plant species (and even within species), by convention PWP is defined as occurring at a tension of 1500 kPa.

AWSC can be expressed as a volumetric water content (%), as a depth of water (mm), or as a depth of water per unit depth of soil/surficial material (mm water/cm soil). A common practice has been to assign AWSC values based on soil texture: for example, B.C.'s *Land capability classification for agriculture in British Columbia* (B.C. Environment, 1983) provides AWSC values in mm water/cm of soil depth for soils of different textural classes. However, these systems, being initially focussed on agriculture, do not

link AWSC to soil moisture regime, and to occurrence of typical natural ecosystems and/or larger hydrologic performance.

In northeast Alberta, the *Land capability classification system for forest ecosystems in the oil sands (*LCCS – Cumulative Environmental Management Association, 2006; first published in 1996) attempted to use earlier concepts (and values) of assigning AWSC to textural classes for application to mine-reclamation and forest-ecosystem settings. The LCCS equates a potential hygrotope very similar to that shown in Table 1 to numeric values calculated from texture-class-based AWSC, and some topography and surficial-material-depth modifiers. This approach represents an advancement in producing an objective and quantified potential hygrotope, but still has a number of limitations for broader application:

1. Consistent with conventional soil-science principles, calculation of AWSC in the LCCS is based solely on <2-mm particle-size fraction, with particles greater than 2 mm discounted on a volume basis (e.g., a material with 50% coarse fragments [>2 mm] and a fine-fraction [<2 mm] AWSC value of 1.0 mm/cm would have an aggregate AWSC of 50 mm). This has not been a substantial limitation in oil sands applications, because coarse-fragment contents are relatively insignificant, but it limits application of the LCCS approach to high-coarse-fragment-content settings like hard- and soft-rock mine wastes. Waring and Major (1964) state that evaluation of soil water in soils with coarse-fragment contents >10% must include some consideration of water stored in the coarse fraction, and report that in their study, disregarding water storage of the coarse fraction would have led to errors of up to 300% in determination of water storage.
2. Texture-based AWSC values in the LCCS apply uniformly across texture or material classes, and do not recognize or account for variation in particle-size distributions within these classes. For instance, the LCCS applies an AWSC value of 1.0 mm/cm to oil sands tailings, regardless of whether these tailings are complete, or are cyclone overflow or underflow products.
3. Although there has been substantial investigation and validation of the LCCS AWSC values (e.g., Barbour et al., 2010), and thus of their use as a potential hygrotope, there has been limited evaluation of the relationship between these values and actual soil water contents (the actual hygrotope), and of the relationship between these values and ecosystem development and landscape/watershed hydrologic performance.

The concept of soil moisture regime has been applied globally, based on duration or magnitude of growing-season water deficits, but typically involves relatively broad classes that can be mapped at a continental scale (e.g., Soil Survey Staff, 1999), versus local application to differentiate between ecosystems and hydrologic behaviours.

Table 1. Relative soil moisture regime classes and characteristics (after Meidinger and Pojar, 1991)

MOISTURE REGIME	DEFINING CHARACTERISTICS		FIELD RECOGNITION CHARACTERISTICS						SLOPE GRADIENT
			SOIL PROPERTIES						
	DESCRIPTION	PRIMARY WATER SOURCE	SLOPE POSITION	TEXTURE	DRAINAGE	DEPTH TO IMPERMEABLE LAYER	HUMUS FORM DEPTH	AVAILABLE WATER STOR. CAP.	
VERY XERIC 0	Water removed extremely rapidly in relation to supply; soil is moist for a negligible time after ppt	precipitation	ridge crests, shedding	very coarse (gravelly-S), abundant coarse fragments	very rapid	very shallow (<0.5m)	very shallow	extremely low	very steep
XERIC 1	Water removed very rapidly in relation to supply; soil is moist for brief periods following ppt	precipitation			rapid				
SUBXERIC 2	Water removed rapidly in relation to supply; soil is moist for short periods following ppt	precipitation	upper slopes, shedding	coarse to mod. coarse (LS-SL), mod. coarse frag.	rapid to well	shallow (<1m)	shallow	very low	steep
SUBMESIC 3	Water removed rapidly in relation to supply; water available for moderately short periods following ppt	precipitation						low	moderate
MESIC 4	Water removed somewhat slowly in relation to supply; soil may remain moist for a significant, but sometime short, period of the year. Available soil moisture reflects climatic inputs	precipitation in moderately to fine-textured soils & limited seepage in coarse -textured soils	mid-slope, normal, rolling to level	moderate to fine (L-SiL), few coarse fragments	well to moderately well	moderately deep (1-2m)	moderately deep	moderate	
SUBHYGRIC 5	Water removed slowly enough to keep the soil wet for a significant part of the growing season; some temporary seepage and possibly mottling below 20 cm	precipitation and seepage	lower slopes, receiving	variable, depending on seepage	moderately well to imperfect	deep (>2m)	deep	high	slight
HYGRIC 6	Water removed slowly enough to keep the soil wet for most of the growing season; permanent seepage and mottling present; possible weak gleying	seepage			imperfect to poor	variable, depending on seepage		variable, depending on seepage	
SUBHYDRIC 7	Water removed slowly enough to keep the water table at or near the surface for most of the year; gleyed mineral or organic soils; permanent seepage less than 30 cm below the surface	seepage or permanent water table	depressions, receiving	variable, depending on seepage	poor to very poor		very deep		
HYDRIC 8	Water removed so slowly that the water table is at or above the soil surface all year; gleyed mineral or organic soils	permanent water table			very poor	variable, depending on seepage		variable, depending on seepage	flat

METHODS DEVELOPMENT

Objectives of the proposed classification system

All of the classification systems described above – biogeoclimatic, hygrotope/SMR, and land-capability classifications – have substantially informed the classification system proposed here. However, the goals of this proposed system differ from these predecessors, in that it is intended to:

1. be broadly applicable to a range of climatic, physiographic, and surficial-material conditions (e.g., globally), yet have sufficient resolution to differentiate ecosystem characteristics and hydrologic performance at a local scale;
2. be capable of derivation solely from information on material particle-size distributions and topography, and not rely on observations of intact above-ground ecosystems for diagnosis;
3. be objective, quantitative, repeatable, and easily applied;
4. be capable of evaluation and validation or adjustment through analysis of related empirical observations, including relationships with non-mine ecosystems classified through standard BEC methods; and
5. provide useful interpretations for a range of mine-planning and reclamation-management considerations, including both cover placement/revegetation and understanding hydrologic behaviour at the mine landform-landscape-watershed scale.

Determination of AWSC

A standard particle-size distribution (PSD) ternary diagram for engineering interpretations was used as a framework for generating PSD-based AWSC values. This framework (based on the Unified System of Soil Classification) was used both to allow evaluation of the contribution of particles >2 mm (as opposed to conventional soil-science approaches), and to facilitate communication between mine planners/engineers and reclamation specialists. AWSC values were estimated from two databases of material characteristics[1] for all materials with measured particle-size distributions and water-retention curves. The materials were separated into 100 textural groups corresponding to subdivisions of the PSD ternary diagram, based on gravimetric proportions of coarse (>4.75-mm), sand (0.075-4.75 mm), and fine (<0.075-mm) particles. The average AWSC for each group was used to populate the ternary subdivision position. If a textural group had minimal or no AWSC data then an estimate was made from interpolation and/or extrapolation from surrounding positions. The resulting AWSC-populated ternary diagram is presented in Figure 1, where AWSC values are in mm water/cm material depth, and represent the centre point of each subdivision. Values in this table are preliminary, in that they provide a framework and enable testing of the proposed system, but it is recognized that they require further refinement prior to broad application. In order to allow consistent and repeatable use of this tool, software has been developed that will take input PSD information and consistently interpolate an AWSC value from the centre-point values, based on standard GIS interpolation algorithms. Input PSD information is based on all particles <100 mm. To facilitate more cost effective and reliable classification, low-technology field equipment has also been developed to allow rapid determination of the cobble-and-gravel separate (>4.75

[1] Databases included an internal database from O'Kane Consultants Inc. (OKC), based on properties of mine-waste and cover materials observed by OKC at different client mining sites around the world, and the other internal to SoilVision Systems Ltd.'s numerical modelling software (www.soilvision.com).

mm) based on a large volume of material, with subsequent determination of the sand and clay-and-silt separates (0.05-4.75 mm and <0.05 mm, respectively) based on laboratory analyses of smaller collected samples.

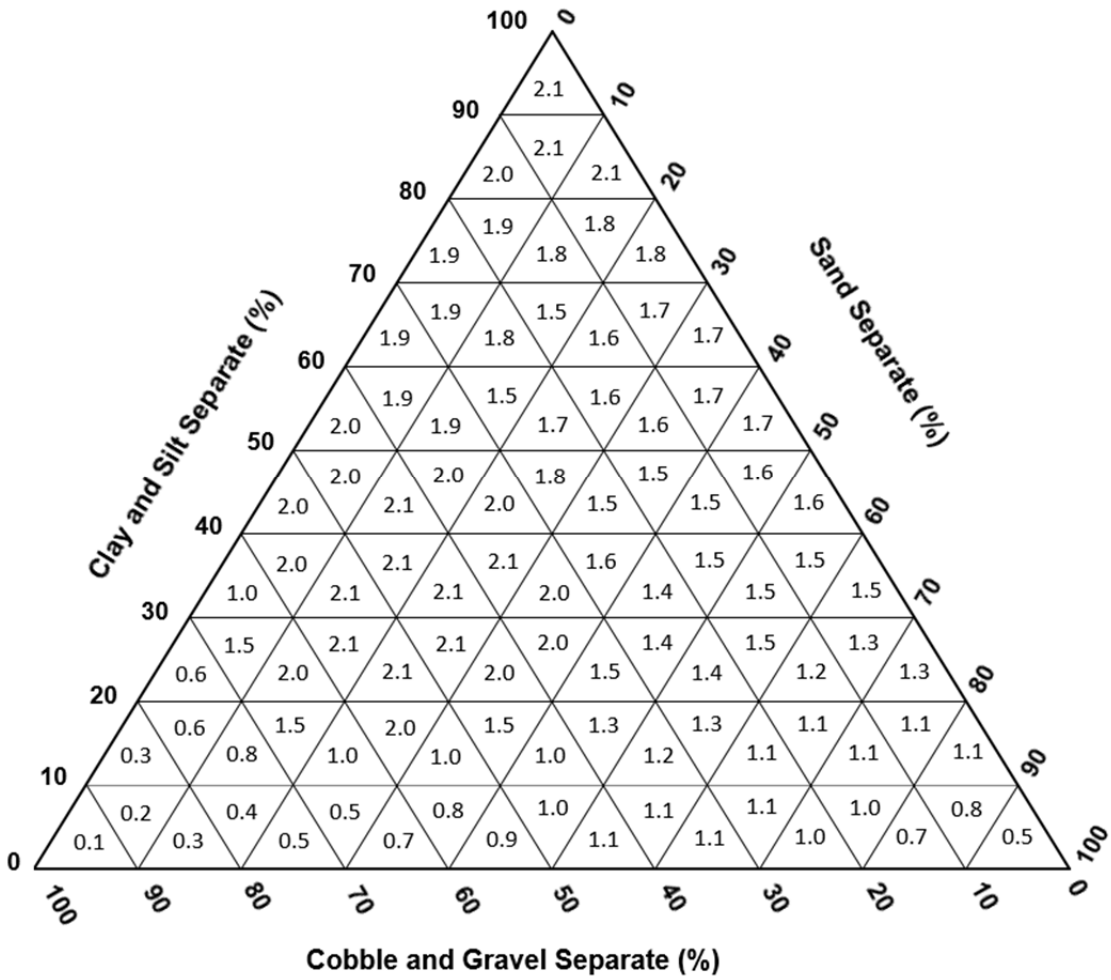

Figure 1. AWSC ternary diagram. AWSC values are in mm available water storage per cm of material depth, and represent the centre point of each subdivision of the diagram.

Values derived from Figure 1 are intended to represent a single material, and to be aggregated across a standard material profile or control section (typically 100 cm, but lesser sections could be used if stipulated). For instance, if a 50-cm soil cover were placed on mining waste rock or tailings, then one AWSC value would be calculated for the cover material, another would be calculated for the mine-waste material, and an aggregate AWSC would be generated by summing the values. If multiple layers were present within the soil cover (or mine waste), then an AWSC value would be calculated for each layer corresponding to depth and PSD data. For natural soils, calculation is based on horizon depths and characteristics. In the case of shallow soils over non-rooting-zone materials, the AWSC for the control section would be based only on the depth of the soil material, and thus would be reduced compared to a 1-m rooting zone.

Modification of AWSC values for energy regime

In B.C.'s BEC-based Terrestrial Ecosystem Mapping (TEM) system, the topographic effect on energy is recognized through "warm" and "cool" site modifiers. These modifiers are applied to slope angles >25% (14°; or >35% in coastal forest regions), with warm aspects being southerly or westerly (135°-285°), and cool aspects being northerly to easterly (285°-135°; Resources Inventory Committee, 1998). This TEM approach was modified for the current classification system as presented below in Table 2 to include a neutral energy regime on southeast and southwest slopes. This modification is based on two considerations:

1. the shift in energy regime on slopes as aspects change is more accurately a gradient of change rather than a categorical shift – the modified classification still uses categories, but incorporates a more gradual shift than an immediate shift from cool to warm as implied by the TEM system; and
2. evaluation of data on field-measured soil water-content profiles versus in comparison to AWSC indicates a better fit when southeast and southwest aspects are categorized as neutral than when they are classified as cool (southeast) or warm (southwest).

Table 2. AWSC energy modifiers

Energy class	Class definition	AWSC modifier
Neutral	Slopes <25% (<14°)	none
	Slope >25% (>14°); aspects 085-135° and 235-285°	
Warm	Slope >25% (>14°); aspect 135-235°	Calculated AWSC – 30 mm
Cool	Slope >25% (>14°); aspect 285°-085°	Calculated AWSC + 30 mm

Equation of modified AWSC values to soil moisture regime[2]

Adjusted AWSC values (PSD-based AWSC from Figure 1 plus any applicable energy modifiers from Table 2) were used to determine soil moisture regime, as outlined in Table 3. This table uses the classes of Krajina's potential hygrotope outlined in Table 1, but replaces the relative ranking of various criteria with ranges of adjusted AWSC. AWSC ranges for each SMR class are modified from the oil sands LCCS. The AWSC method for SMR determination applies only to upland (very xeric – mesic) SMRs, as wetter SMRs require input of seepage water or the presence of a water table within 100 cm of the soil surface, and are not dependent on soil storage. Thus determination of SMRs wetter than mesic in this system is based on observations of shallow groundwater seepage and/or the presence of a water table within the top 1 m of surficial materials.

[2] The term "soil moisture regime" is applied in this paper both to soils and to surficial materials in reclamation landscapes due to its history of use and understood meaning. However, in mine reclamation, many of the materials for which SMR can be estimated are not soils, but are mine wastes and/or salvaged parent materials. Thus SMR should more properly be understood as a soil or surficial-material moisture regime.

Table 3. Determination of SMR from adjusted AWSC.

SMR	Primary water source	Water-table depth (cm below ground surface)	Available water storage, surface 1 m (mm)
Very Xeric (0)	Precipitation and soil storage	>100	<60
Xeric (1)	Precipitation and soil storage	>100	60-89
Subxeric (2)	Precipitation and soil storage	>100	90-119
Submesic (3)	Precipitation and soil storage	>100	120-149
Mesic (4)	Precipitation and soil storage	>100	>150
Subhygric (5)	Precipitation and seepage	>100	>150, seepage contributes to supply
Hygric (6)	Seepage	30-100	n/a
Subhydric (7)	Seepage or permanent water table	0-30	n/a
Hydric (8)	Permanent water table	Water table permanently at or above soil surface	n/a

METHODS TESTING

The methods discussed above were developed and tested at reclamation-monitoring sites at seven mining operations in 2012-2014: Teck Resources Limited's (Teck) Elkview (EVO), Fording River (FRO), Greenhills (GHO), and Line Creek (LCO) metallurgical coal operations in southeastern B.C. and the Cardinal River (CRO) operations in west-central Alberta; at the Teck Highland Valley Copper Partnership's Highland Valley Copper mine in south-central B.C., and at Thompson Creek Metals' Endako mine in central B.C. Of particular relevance to testing are the five Teck coal mines, as in 2011, Teck commenced development of an integrated, multi-year and multi-disciplinary applied research & development program focused on managing water quality in mining-affected watersheds. In 2012-13, this program included installation of soil and meteorological instrumentation and soils and vegetation assessments at 12 reclamation sites at the above coal mines, to meet various research objectives including provision of updated data on reclamation conditions co-located and concurrent with information on meteorological and soil-moisture variables at each study site. This instrumented-site network and the data it provides supports increased understanding of how surface water balances and soil moisture regimes are affecting reclamation responses over time, and *vice versa*, as well as how reclamation approaches affect reconstructed landform water balances, and hence watershed hydrology.

The approach to estimation of soil moisture regimes discussed above was applied to these testing sites, and included adjustment of methods in response to interpretation of collected data.

AWSC estimates for different mine waste materials and reference sites

Figure 2 presents plotted PSD data from 65 mine-reclamation and non-mine reference sites on the AWSC ternary diagram. These data show both separation and similarities between different material types, as follows:

- Coal waste rock – sampled coal waste rocks generally have a cobble and gravel content from 50-80% of the entire sample, and a clay and silt content of ~5-20%. Their AWSC values range from approximately 0.4-1.5 mm/cm.
- Metal-mine waste rock – metal-mine waste rock in this study had a slightly lower cobble and gravel content than the coal waste-rock samples. These materials have a similar overall range of AWSC values, but slightly higher average AWSC. These differences between metal and coal waste-rock may be an artefact of differing physical-property sampling methods. Revised field sampling methods are under development to ensure consistent data collection across all study sites in future.
- Metals tailing – are composed entirely of fines, with approximately 5-20% clay and silt content.
- Cover materials – there is substantial variation in these materials, due to a range of source locations and material types, but they are generally finer than both metal and coal waste rocks. Their AWSC values range from 0.7-2.1 mm/cm, with a higher average AWSC than both waste rocks and tailings.
- Reference sites – these sites are similar to the mining cover materials (as most cover materials are sourced from sites like these), and generally have higher AWSC values than the mine wastes, for both ranges and averages.

Actual versus potential hygrotope

AWSC values calculated from the PSD ternary diagram provide quantification of the potential hygrotope, as they indicate the *capacity* for soil water storage (and eventual release as evapotranspiration, interflow, and/or net percolation), not actual storage. Actual storage is a product of the interaction between the potential hygrotope and local climate, which delivers precipitation for storage and energy for evaporation and transpiration. To evaluate the relationship between potential (calculated) and actual hygrotope, analyzed volumetric-water-content (VWC) and matric-potential (φ_m) data collected by O'Kane Consultants from the Teck instrumented study sites (metallurgical coal operations) were analyzed to derive mean growing-season *available* volumetric water contents (AWC) for each site. To do so, the VWC at permanent wilting point (PWP) was calculated for each material type (cover material, waste rock) from interpolated plots of VWC against φ_m for each sensor pairing. This gave each VWC sensor a VWC-at-PWP value, which was then subtracted from each of its VWC measurements to calculate AWC (water content above PWP) for all sensors. To calculate mean AWC from all sensors, each sensor's AWC was mathematically weighted according to rooting patterns observed at vegetated sites, with weight assigned for both root abundance and root size. Where rooting data did not exist, mean root patterns from all other sites have been applied. Reported AWC values are means of all daily measurements made during the 2013 growing season, which was defined by site-specific meteorological data using the criteria of five

consecutive days of average daily temperatures over and under 5°C as the beginning and end[3] of the growing season (Alberta Agriculture and Rural Development, 2009).

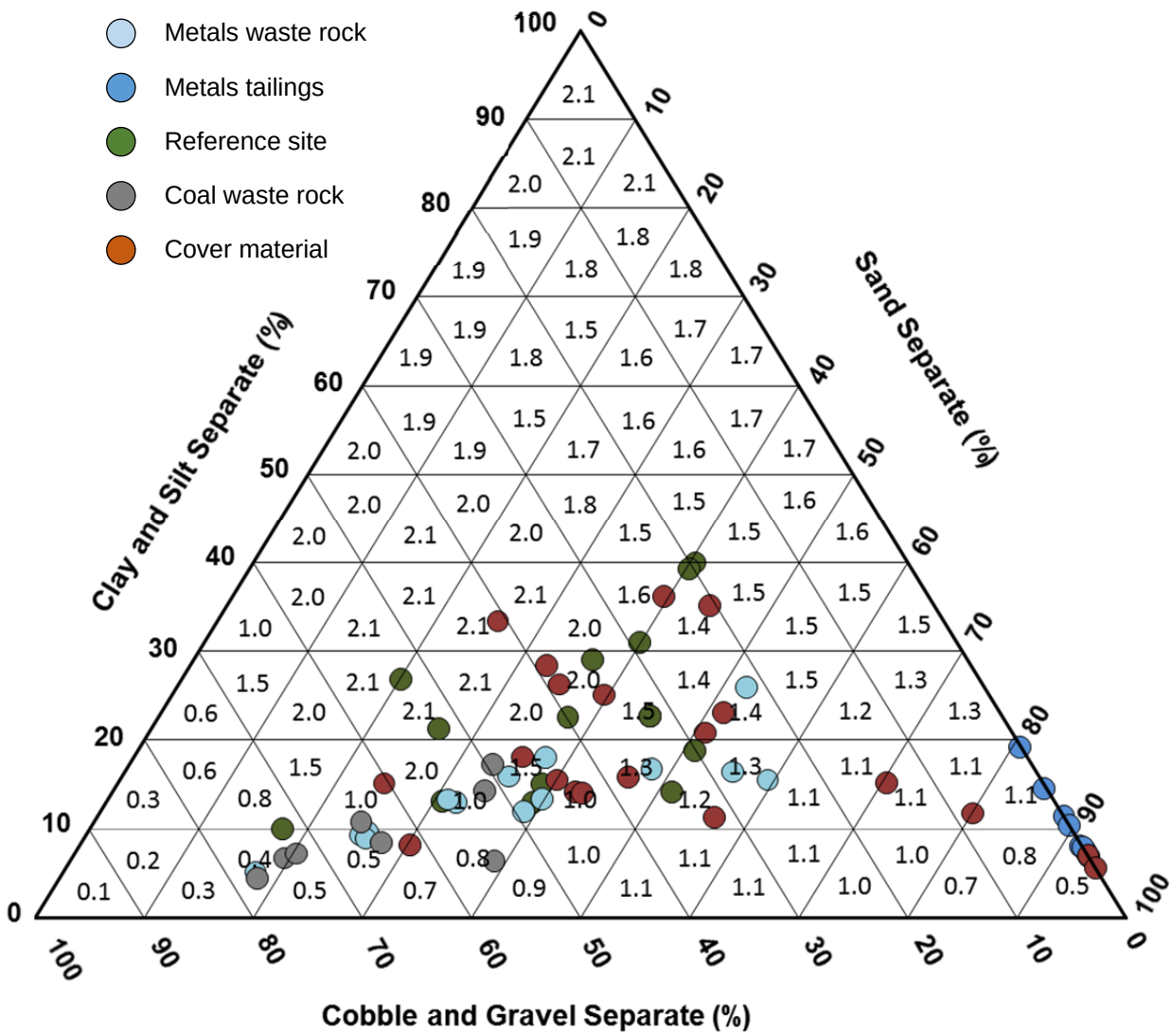

Figure 2. Plot of PSD-based AWSC values for mine-waste and cover-system materials, and non-mine reference sites.

<u>Data-based adjustment of AWSC modifiers</u>

The relationship between modified AWSC and mean AWC for the instrumented Teck coal study sites was usedto adjust energy modifiers (adjusted modifiers are presented in Table 2). Initial graphing of these data with the original (unadjusted TEM-based) energy modifiers yielded an R^2 value of 0.39, and showed one site in particular (the upper "x" in Figure 3) with a large fitting error. It was reasoned that the categorical nature of the original TEM-based energy correction – where sites transition from a 30-mm AWSC deduction on western aspects to a 30-mm AWSC addition on northwestern aspects – was too

[3] The end of the growing season cannot occur before August 1 regardless of temperature.

abrupt, and didn't recognize that, in fact, radiation is a continuous variable that is gradually declining over this range of aspects. Therefore, energy modifiers were adjusted to restrict the warm-aspect deduction to southeast to southwest aspects only, and to create a steep, southwest to west-northwest category with no modifier (neutral energy regime - Table 2). This adjustment produced the improved fit shown in Figure 3 ($R^2 = 0.45$).

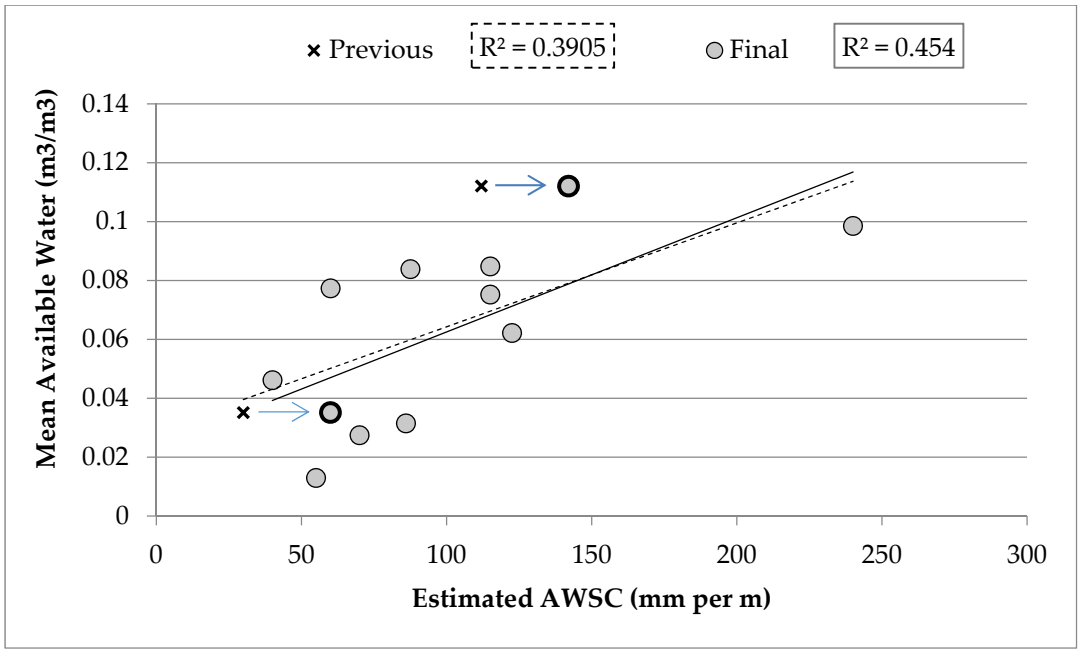

Figure 3. Mean available volumetric water content (AWC) by AWSC. Development of energy corrections was an iterative process based partially on agreement with soil moisture patterns. This figure depicts the alteration of energy corrections for two sites, where original AWSC values are plotted with crosses and have been shifted as indicated by blue arrows, which yields an improved correlation between modelled AWSC and actual AWC.

Analysis of fitting errors from the regression line in Figure 3 indicate that much of the observed deviation from the linear fit is attributable to differences in site vegetation: sites below the regression line show lower AWC than expected, primarily due to the presence of robust vegetation covers that are removing water through transpiration; whereas sites above the line are generally non-vegetated or sparsely vegetated, and thus have higher-than-expected AWC values, as water removal through evaporation alone cannot reduce VWC below field capacity through most of the profile.

Predicted AWSC and SMR

SMR was assigned for each of the 65 study sites using the PSD-based AWSC estimates with energy modifiers as described above. For the Teck coal research sites where AWC data is available, the AWSC-based SMR classification was evaluated using mean growing-season AWC (Figure 4). These data show general support for the current system, with mean growing-season AWC increasing for every SMR class, despite differences in vegetation development across these sites. On average, very xeric sites have less than 30% of the plant-available water that mesic sites have during the growing season, while xeric sites have approximately 50% of the plant-available water of mesic sites. Research sites at Endako and Teck

Highland Valley Copper lack continuous measurement of soil water contents, and so cannot be added to this database, but reference sites in these studies provide some ability to evaluate system fit, as predicted SMR using methods proposed in this paper can be related to potential hygrotope classification using standard subjective keys and the presence of indicator plants. All reference sites studied to date are zonal site series (in the SBSdw3 [Endako] and MSxk2 [Highland Valley Copper] biogeoclimatic variants) with mesic SMR – mean AWSC for these sites estimated with the proposed methods is 159 mm, which places them in the mesic SMR category according to the criteria presented in Table 3.

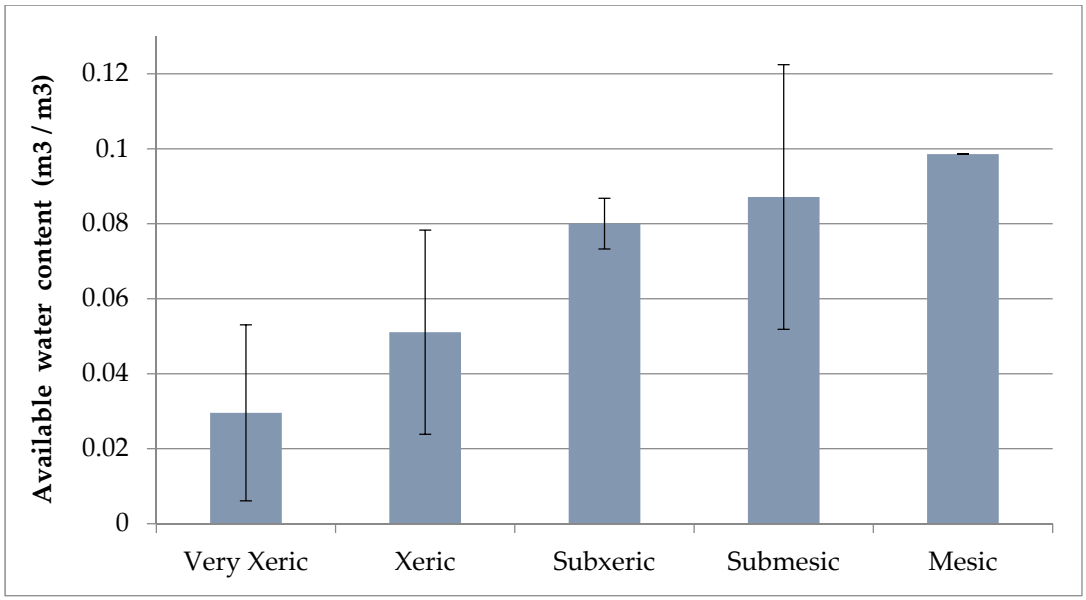

Figure 4. Mean AWC during the 2013 growing season at all sites classified by soil moisture regime. Error bars show one standard deviation of the mean.

APPLICATIONS

Reclamation and revegetation planning

The methods described above can be applied to both existing reclamation sites or planned future landscapes, using either measured or assumed PSD and topographic data. For instance, for an existing reclamation site, slope and aspect can be measured, and PSD data can be derived through field and lab measurements; for reclamation planning, projected post-mine topographies and assumed PSD characteristics can be used to estimate PSD-based AWSC, energy modifiers, and resulting SMR. BEC classification to the subzone-variant level using available mapping and elevation will then allow equation of calculated SMR to non-mine site series[4] – e.g., a site with a calculated AWSC value of 165 mm has a mesic SMR, which is hygrotopically equivalent to a zonal (frequently 01) non-mine site series. It is necessary to emphasize that numerical equivalency with respect to AWSC or surface-profile water supply does not equate to equivalency between reclaimed-mine site series and non-mine site series: although

[4] Equation of an estimated SMR using proposed methods to a site series also requires estimation of tropotophic position, or soil nutrient regime. Current data is insufficient to support determination of SNR through quantitative methods. Thus, the current proposed approach is to assume a very poor-poor nutrient regime (A-B) for reclaimed mine waste with no soil cover, and a medium nutrient regime (C) for sites with a soil cover.

sites with similar hygrotopic position have similar *capability* with respect to soil water supply, these sites have many other differences (e.g., soil biota, vegetation propagules), and their degree of actual similarity will depend on reclamation actions and stochastic events (e.g., climatic patterns during early reclamation establishment). To emphasize this distinction, the following nomenclature is proposed: non-mine sites are designated as per convention, e.g., "MSxk2 01" would indicate a zonal site series in the South Thompson Uplands Very Dry Cool Montane Spruce Variant, while a similar reclaimed site would be designated "MSxk2 RY_{01}", where "RY" is the TEM code for "reclaimed mine", and the RY subscript designates the reclamation site series[5].

Following designation of BEC subzone-variant and site series, knowledge of vegetation ecology can then be used for revegetation planning, with candidate revegetation species drawn from lists of species adapted to growth in the edaphic conditions of the site series, and tolerant of early successional conditions such as exposed mineral soil and full light. An example of this approach is shown in

Table *4*.

Assessment of equivalent capability

The approach discussed above can also be used as the basis of assessment of equivalent land capability, where land capability is defined as the potential for a site to achieve a specified land use(s) as a result of climatic, topographic, and soils/surficial-material-based limitations (B.C. Ministry of Energy, Mines and Petroleum Resources, 2008). Capability should not be confused with realized vegetation or ecosystem conditions, which, as discussed above, are based on capability but influenced by reclamation treatments and stochastic events. Given pre-development BEC mapping and the approach outlined in this paper, mapping and tabular data on relative areas can be produced, allowing comparison of pre-development and post-closure site series, which provides the basis for a comparison of pre- and post-mining capability with respect to hectares of target vegetation communities or habitat potential. An example of post-closure mapping allowing this capability-comparison approach is shown in Figure 5.

[5] In some cases it may be useful to group non-mine site series for creation of reclamation site series, where there is insufficient resolution to distinguish between two site series based solely on hygrotope. For instance, $RY_{02/03}$ could be used to designate a reclamation site series that spans the hygrotopic range of the 02 and 03 non-mine site series.

Table 4. Candidate revegetation species for the MSdk1 $RY_{102/103}$ reclamation site series. Species in bold font are those that are early-seral species characteristic of the analogous non-mine site series and commonly found in plots in these ecosystems.

Trees	**Douglas-fir**	Herbs	**Bluebunch wheatgrass**
	Lodgepole pine		**Fireweed**
	Hybrid white spruce		**Pearly everlasting**
	Trembling aspen		**Pinegrass**
	Western larch		**Ross's sedge**
Shrubs	**Birch-leaved spirea**		**Round-leaved alumroot**
	Common juniper		**Showy aster**
	Common snowberry		**Wild strawberry**
	Kinnikinnick		**Yarrow**
	Prickly rose		**Yellow penstemon**
	Saskatoon		Common horsetail
	Soopolallie		Fern-leaved desert-parsley
	Douglas maple		Junegrass
	Grouseberry		Lance-leaved stonecrop
	Low bilberry		Northern bedstraw
	Oregon grape		Purple-leaved willowherb
	Prairie rose		Sedges (terrestrial)
	Willows (terrestrial)		Sulphur buckwheat
			Yellow hedysarum
			Yellow penstemon

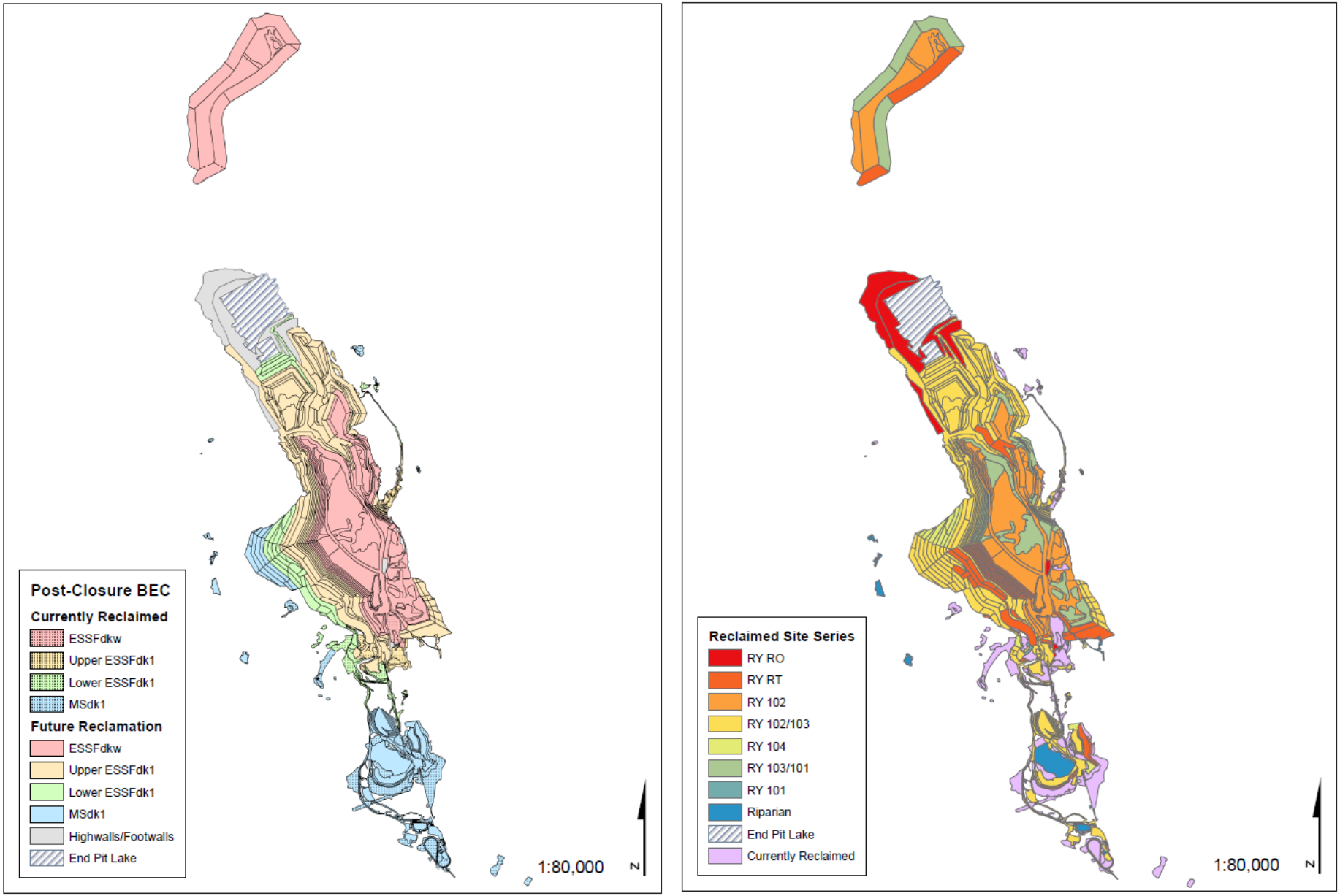

Figure 5. Example of post-closure BEC zone-subzone-variant and reclamation site series classification using methods proposed in this paper applied to a hypothetical post-closure topography.

Quantifying effects of mine-waste covers on surface water balances and ecosystem development

The final energy-corrected AWSC values for the Teck coal instrumented sites are plotted by cover type in Figure 6. This information shows that, while there are ranges in estimated AWSC by cover category, sites with salvaged soil or overburden covers have substantially higher AWSC than sites comprised of revegetated bare waste rock – the median SMR for sites with a salvaged soil or overburden cover is submesic, while the median SMR for vegetated waste rock is xeric. This information indicates that some form of salvaged-material cover is likely a necessary component of reclamation where reclamation goals include re-creation of submesic and mesic upland sites. This finding has implications for both mine planning/materials balances and assessment of equivalent capability, especially where capability and/or biodiversity goals indicate the need for replacement of wetter upland site series.

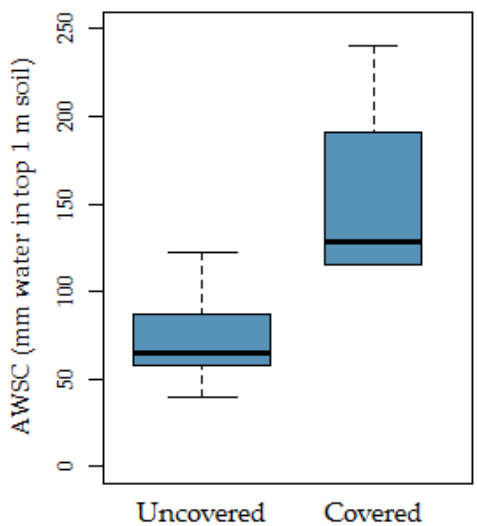

Figure 6. Modified AWSC by presence or absence of soil/overburden cover.

Net percolation and soil moisture regime

As discussed above, a primary goal of the proposed classification system is to not only provide information for reclamation planning, but also to contribute to the hydrologic understanding of how water is mediated by, and moves through, reclaimed landscapes and watersheds. In order to advance this objective, relationships between the proposed classification system and surface water-balance terms were evaluated. Preliminary water-balance estimates for a one-year period beginning October 1, 2012 were generated by O'Kane Consultants for the Teck coal instrumented sites, and are discussed in a companion paper by Birkham et al. (2014). Estimates of net percolation (NP) by estimated SMR class are presented in Figure 7. In general, the conceptual model is that net percolation decreases as SMR increases (i.e., from very xeric to mesic), as it is expected that the greater water storage associated with wetter moisture regimes would attenuate vertical movement of water (net percolation) and allow for more water removal through evapotranspiration. This is partially reflected in the fact that all moisture regimes other than very xeric have NP values approximately 30% lower than the very xeric class, but the conceptual model is not supported by the observed equivalence of NP data in the xeric to mesic classes. This is likely due to

confounding influences of vegetation at these sites, as many sites with wetter SMR are also very recent soil-covered reclamation areas, and thus lack vegetation. Therefore, there is no transpiration removal of water from these sites, soil water contents remain at field capacity or higher throughout the majority of the profile, allowing near-continuous drainage, and as a result NP is high. Evidence from reclamation research in other jurisdictions confirms that as vegetation develops, evapotranspiration increases (e.g., Carey, 2011), with a corresponding decrease in net percolation. Continued collection of surface water-balance and vegetation community-evolution data will enable development of improved SMR-NP relationships for each stage of the reclamation trajectory. It is also recognized that the fit of the SMR-NP relationship may be limited by a current potential conflict in the classification system in which two primary factors lead to classification of sites as drier: 1) limited soil storage; and 2) higher insolation. The first of these factors tends to lead to increased NP, as precipitation moves quickly through the system and is removed as NP, while the second tends to lead to decreased NP, as winter precipitation (P_{snow}) is reduced through sublimation and evapotranspiration is increased. Work is underway to further develop the classification system to address this conflict.

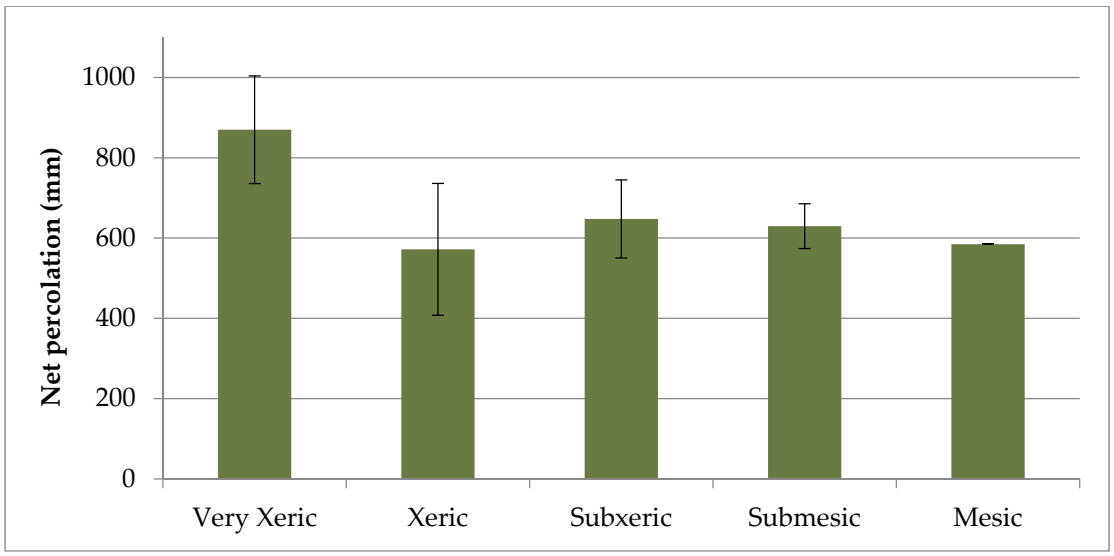

Figure 7. Net percolation values classified by SMR classes.

Relationships between soil and vegetation variables and net percolation

It was hypothesized that a large portion of the variation observed in net percolation can be explained by two key soil and vegetation variables: 1) AWSC (soil); and 2) leaf-area index (LAI – vegetation), with higher AWSC associated with higher LAI and lower NP, due to increasing ability to support vegetation (higher LAI), and increasing removal of water through transpiration (lower NP). Testing of this hypothesis through multiple-regression techniques indicated a significant negative relationship between LAI and NP, but no significant relationship between AWSC and NP. This result can be at least partially attributed to the low number of instrumented study sites, and to the fact that the high-AWSC sites are currently young and sparsely vegetated, and thus generally have high water contents and NP. In contrast, the two lowest-NP sites are low-AWSC mature vegetated coal waste rock with higher LAI values – thus, given current data, vegetation effects overwhelm any effects of AWSC. This effect is illustrated in Figure

8, which presents LAI and NP data, with a curvilinear (polynomial) regression line fit to the data. This relationship is statistically compromised by the fact that in these data, LAI and NP are not independent[6]. Thus R^2 or fitting-error information is not presented for this regression. Nevertheless, it is useful to present these data for conceptual reasons, as they illustrate the following:

1. On unvegetated or sparsely vegetated sites (LAI <1.5), approximately 70-85% of precipitation is transmitted through the upper 1 m of the reclamation cover and enters underlying waste as net percolation. Three unvegetated sites have NP over 80% of precipitation.
2. On moderately vegetated sites (LAI of 1.5-2.5), approximately 60-70% of precipitation is transmitted through the upper 1 m of the reclamation cover as net percolation;
3. On well-vegetated sites (LAI >3.5), approximately 35-55% of precipitation is transmitted through the upper 1 m of the reclamation cover as net percolation, a reduction in net percolation of 15-50% from the poorly or non-vegetated covers. The substantial differences in NP between these two high-LAI sites may reflect the influence of aspect (energy regime) on surface water balances – the lowest-NP value is from a south-facing site whose snowpack depth is approximately 30 cm towards the end of the growing season, and thus whose delivered winter

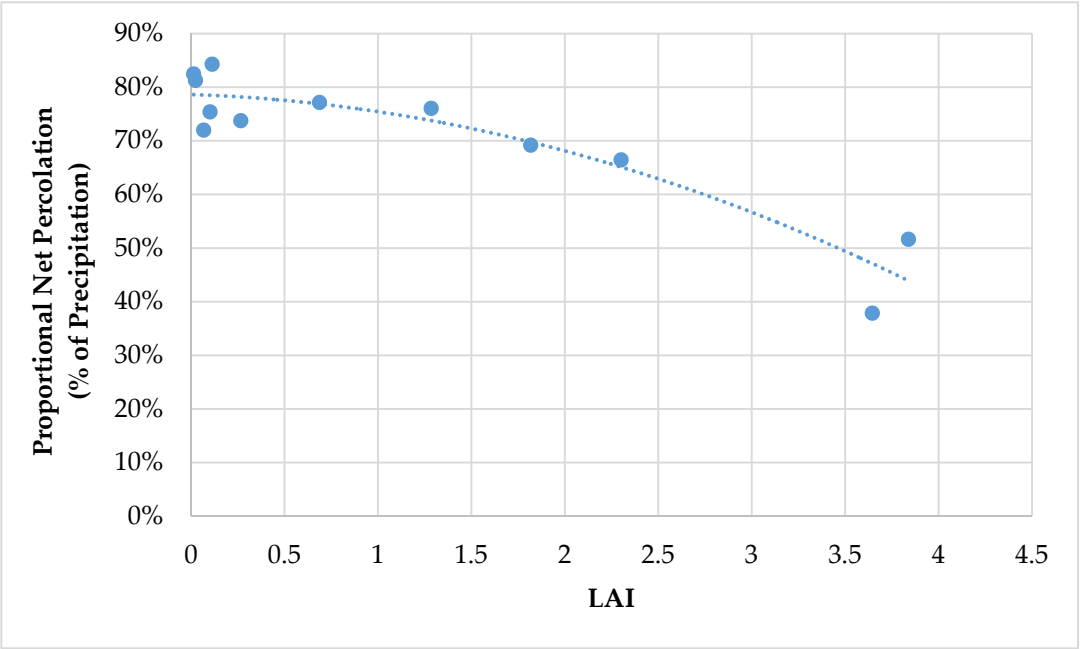

Figure 8. Net percolation as a proportion of precipitation by LAI.

precipitation (P_{snox}) is approximately 30 mm, resulting in reduced NP. In contrast, the higher-NP value of the pair is from an east-facing slope with less radiation and sublimation, giving it a winter/spring snowpack of approximately 60 cm, and thus higher delivered P_{snow} and higher NP, despite substantial removal of water through transpiration.

[6] A relationship between LAI and actual evapotranspiration (AET) was used to adjust NP values from O'Kane Consultants.

The soil moisture and climate data used to develop these relationships was collected in the period of October 2012-September 2013, which was a relatively wet year, and thus the NP values presented above represent the higher end of the expected range for these sites. Additional years of data will provide ranges

of NP for sites under varying precipitation levels. These values also primarily reflect NP achieved (in a wet year) with varying degrees of vegetation established directly on waste rock. As the vegetation communities on soil covers continues to establish and mature, it is anticipated that these points will shift right and down (higher LAI and lower NP) on the diagram (Figure 8), and these sites should regularly achieve NP values <40% of precipitation, due to enhanced removal of water through transpiration.

SUMMARY

This paper proposes a quantified and objective hygrotopic classification system that is broadly applicable to a range of ecosystems, including mine-waste-based landforms and mine-affected watersheds. The classification system is informed by the B.C. biogeoclimatic ecosystem classification system, and by various land capability classification systems, including the system used for mine reclamation in Alberta's oil sands. Although the proposed classification system is initially based on potential hygrotope, the use of regional and local biogeoclimatic ecosystem classifications allows its translation into actual hygrotopes, based on regional and local climatic conditions. This translation from potential to actual hygrotope has been tested in two regions of western Canada on instrumented reclamation study sites. Initial results show promising relationships between predicted SMR using the proposed classification system and mean growing-season available water contents calculated from continuous measurement by *in situ* sensors, with increasing observed available water contents as SMRs predicted by the classification model progress from drier to wetter sites. In addition, the proposed classification system shows concordance with traditional ecosystem classification of non-mine reference sites where classification is based on indicator-plant presence and topographic/soil relationships.

The potential management applications of the classification system include reclamation and revegetation planning, assessment of equivalent capability, and quantification of the effects of surficial-materials management on landform surface water balances. A synthesis of data on reclamation variables (topography, surficial-material particle-size distribution, and vegetation cover) indicates strong relationships between these variables and surface water-balance terms (evapotranspiration and NP). These relationships demonstrate the importance of landform, surficial-material, and vegetation management for achieving reclamation objectives and simultaneously contributing to landform and landscape water management. Landform, cover and vegetation treatments designed to increase SMR and vegetation establishment and growth will lead to measurable reductions in net percolation in comparison to sites with less surface water storage and vegetation cover.

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