10thICARDIMWA2015 | 10th International Conference on Acid Rock Drainage & IMWA Annual Conference

Mine Water Management for Closure – Mine Reclamation and Surface Water Balances

Justin Straker[1], Mike O'Kane[2], Sean Carey[3], Dan Charest[4], and Lee Barbour[5]

1. *Integral Ecology Group, Canada*
2. *O'Kane Consultants, Canada*
3. *McMaster University, Canada*
4. *Teck Resources Limited, Canada*
5. *University of Saskatchewan, Canada*

ABSTRACT

Understanding reclamation effects on surface water balances in mine-affected watersheds is critical to both prediction of, and design for, water movement through the post-closure landscape, and for development of appropriate reclamation and revegetation treatments for mine closure. Substantial effort has been invested in increasing knowledge of the effects of mine-waste cover systems on key water-balance terms such as net percolation, but there is a lack of tools to extend that knowledge to effects of cover systems on vegetation establishment, and the subsequent effects of these vegetation-substrate interactions on water-balance terms. The concept of a "soil moisture regime" is used worldwide to understand edaphic conditions and plant communities. However, in most applications, soil moisture regime is a relative or unquantified parameter estimated from the presence of indicator plants or soil properties observed in natural ecosystems. Applications of these approaches to post-mining landscapes are challenging, because soils/surficial materials are reconstructed, and often reference plant communities are not fully re-established. 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 agricultural soil science, and have limited utility to many post-mining materials.

The authors propose new methods for estimating soil moisture regime on post-closure landscapes, using concepts from existing biogeoclimatic-ecosystem classification systems and new analyses of effects of particle-size distribution on soil water retention. Key variables in the proposed estimation model include regional and local climate, material particle-size distributions (including distributions typical of mine-waste materials) and organic-matter accumulation, and topography. This paper discusses methods development, application, and testing of this estimation approach across a number of mines, and presents suggestions for broader application of the approach for quantifying surface-water-balance components (e.g., net percolation) and for reclamation planning (e.g., revegetation species selection) in closure landscapes.

Keywords: reclamation, soil, moisture, regime, water

INTRODUCTION

One of the principal knowledge gaps in mine reclamation is that of characterizing soil water dynamics within surficial materials used in reclamation cover systems. The concomitant water balance in these materials is a dominant control on both ecosystem development and watershed performance, and better understanding of these water balances is critical for improved reclamation planning and projection of long-term characteristics of reclaimed ecosystems. It is also critical for improving our understanding of the hydrologic behavior of reconstructed mine-affected watersheds, including the role of net percolation on flushing of constituents of interest (CIs) from the mine wastes within these watersheds. Although substantial effort has been invested from an engineering perspective in investigating the effects of cover systems on rates of net percolation, this effort has generally not been coupled with understanding soil water dynamics within the same cover systems for the purposes of reclamation planning and execution. To date most ecological approaches used to address the above knowledge 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:

- they are qualitative or semi-quantitative, and there is limited attempt to evaluate and demonstrate their hydrologic validity;
- they rely substantially on the presence of existing natural vegetation communities to provide information on edaphic conditions – these techniques are not applicable to mine-reclamation settings where vegetation communities are absent or introduced; and/or
- 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 of how water retention and use by vegetation may influence deeper percolation and the water balance of the underlying mine-waste landform.

This paper presents a quantitative method to relate the properties of landforms and cover-system materials to plant-available water and surface water balances, based on particle-size distributions and biogeoclimatic ecosystem classification.

BACKGROUND

Biogeoclimatic ecosystem classification

Biogeoclimatic ecosystem classification (BEC) is an ecological classification system developed primarily in the western Canadian province of British Columbia (B.C.) 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). In the BEC system, biogeoclimatic zones can be subdivided into subzones, which can in turn be 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 (“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 in part determined 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.

Soil water availability

In the BEC system, soil water availability is estimated using a concept termed "soil moisture regime" (SMR), which reflects "the average amount of soil water annually available for evapotranspiration by vascular plants over an extended period of time (several years)" (Pojar, Klinka & Meidinger, 1985). The BEC system incorporates nine SMR classes ranging from driest (Class 0, or very xeric) to wettest (Class 8, or hydric) – this spectrum is referred to as a hygrotope (Pojar, Klinka & Meidinger, 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 (e.g., source of water, rate of water removal, slope position, soil textural class), and represent relative ranking of sites in terms of potential soil water availability. A common example of this approach is provided by Meidinger and Pojar (1991), although more complex and semi-quantified examples exist in the BEC system (e.g., Lloyd et al., 1990). Actual hygrotopes integrate the above information with climate and surface-water-balance inputs and losses such as precipitation and evapotranspiration to provide estimates of absolute rather than relative water availability.

Quantified estimates of both potential and actual hygrotope or soil moisture regime are uncommon, and those that exist are limited in their application to specific geographic regions and/or ecosystems (e.g., Waring and Major, 1964). In B.C., Green et al. (1984, and summarized in Pojar, Klinka & Meidinger, 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) as an index of potential soil-water availability. Available water storage capacity is defined as the volume of water per unit area held within the active or rooting zone of the soil profile between the volumetric water content at field capacity (FC) and the permanent wilting point (PWP). The field capacity is the volumetric water content at which the rate of gravitational drainage becomes negligible relative to the current rate of evaporation or evapotranspiration (Zettl, 2014). This water content is often taken to be the water content at negative pore-water pressures of 10-33 kPa, depending on soil texture. The permanent wilting point is the volumetric water content at which soil water is no longer available for plant uptake. Although this water content varies by plant species, by convention it is defined as the water content at a negative pore-water pressure of 1500 kPa.

AWSC is generally expressed as a depth of water (mm) over a specified soil depth, or as a depth of water per unit depth of soil (mm water/cm soil). A common practice has been to assign AWSC values based on soil texture: for example, the document *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 focused 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* (or "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 to numeric values calculated from texture-class-based AWSC, and some topography and surficial-material-depth modifiers such as slope position and depth to impermeable layers. This approach represents an advancement in producing an objective and quantified relative hygrotope, but still has a number of limitations for broader application. 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. This has not been a substantial limitation in oil-sands reclamation applications due to relatively insignificant coarse-fragment contents, but it limits application of the LCCS approach to higher-coarse-fragment-content settings like hard- and soft-rock mine wastes. In addition, 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 actual particle-size distribution and whether these tailings are complete, or are cyclone overflow or underflow products. Finally, 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 relative hygrotope, there has been limited evaluation of the relationship between these values and actual soil water contents (i.e., 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 application to differentiate between ecosystems and hydrologic behaviors at a local or regional scale.

METHODS DEVELOPMENT

Objectives of the proposed classification system

The classification system proposed here is substantially informed by the biogeoclimatic, hygrotope/SMR, and land-capability classifications described above, but is intended to derive estimates of plant-available water, surface-water-balance performance, and associated ecosystem characteristics from landscape, landform and surficial-material properties, using objective and quantified methods that can be consistently and easily applied. Further, the proposed system is designed to 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. Additional goals for the classification system are that it:

- be capable of derivation solely from information on material properties, topography and climate, and not rely on observations of intact above-ground ecosystems for diagnosis;

- 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
- provide useful interpretations for a range of mine-planning and reclamation-management considerations, including both cover placement/revegetation and understanding hydrologic behavior at the mine landform-landscape-watershed scale.

Classification framework

The proposed classification framework is based on three primary factors, with decreasing geographic scales of application (Table 1, adapted from Devito et al., 2005). For the first classification factor, AWSC is determined from particle-size distributions of materials in the upper one metre of surficial material. This determination can be applied globally, as it is based on universal principles of soil physics. The next classification factor involves modification of the profile AWSC estimate for topography-based energy regime – these modifications are specific to latitudinal ranges, and thus must be developed specifically at the continental to sub-continental scale. The final classification factor applies regional and local climate information to the potential hygrotope resulting from application of the first two factors to generate an actual hygrotope and identify ecosystems associated with this hygrotope. Thus application of the first classification factor (AWSC) requires only information contained in this paper; application of the second factor (topography/energy) may require modification of information contained in this paper, depending on latitude of application; and application of the third factor (climate) requires information on climate local to the application site and biogeoclimatic or similar classification information.

Table 1 Soil water regime classification framework

Factor	Range of factor		Scale of applicability	Classification outputs
1. PSD of surficial materials	High silt and clay contents, low sand, gravel and cobble contents: higher AWSC	High sand, cobble and gravel contents, low silt and clay contents: lower AWSC	Global	Profile AWSC in surface 1 m
2. Topography and energy	High latitude: slope and aspect significantly affect energy distribution	Tropical and sub-tropical: slope and aspect do not significantly affect energy distribution	Continental to sub-continental	Adjusted AWSC; relative SMR or potential hygrotope
3. Regional and local climate	Dry, arid to sub-humid (P < PET) • storage and ET dominant • runoff and NP may be reduced	Wet, humid (P > PET) • runoff and NP dominant	Regional to local	Actual SMR and hygrotope; identification of associated ecosystems

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 (who often use engineering PSD classification systems) and reclamation specialists (who often use soil-science PSD or texture classification systems). AWSC values were estimated from two databases of material characteristics[1] for all materials with measured PSDs 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 finer (<0.075-mm) particles. The average AWSC for each group was used to populate the ternary subdivision position. If a textural group had little to no available 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 center 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 center-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

---

[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).

classification, low-technology field equipment has also been developed to allow rapid determination of the cobble-and-gravel separate (>4.75 mm) based on a large volume of material, with subsequent determination of the sand and clay-and-silt separates based on laboratory analyses of smaller collected samples.

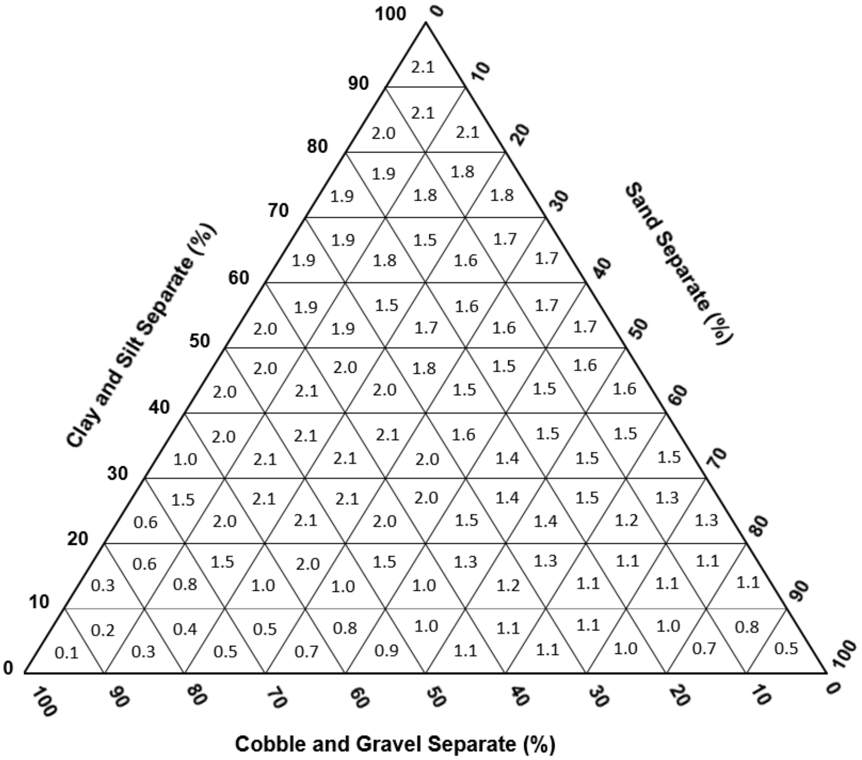

Figure 1 AWSC ternary diagram. AWSC values are in mm available water storage per cm of material depth, and represent the center point of each subdivision of the diagram

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, to estimate AWSC for a 50-cm soil cover placed on mining waste rock or tailings, one AWSC value is calculated for the cover material, another is calculated for the mine-waste material, and an aggregate AWSC is then generated by summing the values. If multiple layers are present within the soil cover (or mine waste), then an AWSC value is 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 is based only on the depth of the soil material, and thus is reduced compared to a 1-m potential rooting zone.

Modification of AWSC values for energy regime

In the British Columbia BEC system, the topographic effect on energy is recognized through "warm" and "cool" site modifiers. These modifiers are applied to slope angles >25% (14°), with warm aspects being southerly or westerly (135°-285°), and cool aspects being northerly to easterly

(285°-135°; Resources Inventory Committee, 1998). This 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 the fact that the shift in energy regime on slopes as aspects change is more accurately a continuous increase or decrease in insolation rather than a categorical shift – the modified classification still uses categories, but incorporates an intermediate neutral category instead of the immediate shift from cool to warm as implied by the BEC system. This modification is supported by evaluation of data on field-measured soil water-content profiles in comparison to estimated AWSC values, which indicates a better fit when southeast and southwest aspects are categorized as neutral than when they are classified as cool (southeast) or warm (southwest).

Modifiers in Table 2 are applicable to northern latitudes of approximately 48-60°. These magnitude of the modifiers could be increased for higher northern latitudes and decreased or eliminated for lower northern latitudes. For southern latitudes, the modifiers as presented or adjusted would be altered to reflect different warm and cool aspect relationships.

Table 2 AWSC energy modifiers

Energy class	Class definition	AWSC modifier
Neutral	Slopes <25% (<14°) Slope >25% (>14°); aspects 085-135° and 235-285°	none
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) are used to determine soil moisture regime, as outlined in Table 3. This table uses the SMR classes of the BEC potential hygrotope, but replaces the relative ranking of various criteria with quantified ranges of adjusted AWSC. AWSC ranges for each SMR class are modified from the oil-sands reclamation land-capability classification system discussed above. 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. Note that these moisture regimes are intended to reflect dominant soil-water conditions over a multi-year period, consistent with the B.C. BEC-system hygrotope.

Table 3 Determination of SMR from adjusted AWSC

SMR	Primary water source	Water-table depth	Available water storage,

---

[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.

		(cm below ground surface)	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: five metallurgical coal operations operated by Teck Resources Limited in southeastern B.C. and 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 molybdenum 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 these coal mines, to provide 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 watershed hydrology.

Actual versus potential hygrotope

PSD data from 65 mine-reclamation and non-mine reference sites were plotted on the AWSC ternary diagram. Resulting AWSC values 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 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 over a profile depth, 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 similar 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).

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-mine research sites where AWC data are available, the AWSC-based SMR classification was evaluated using mean growing-season AWC (Figure 2Figure 2). These data show general support for the proposed classification 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 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 hygrotopic classification using standard subjective keys and the presence of indicator plants. All reference sites studied to date are zonal site series 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.

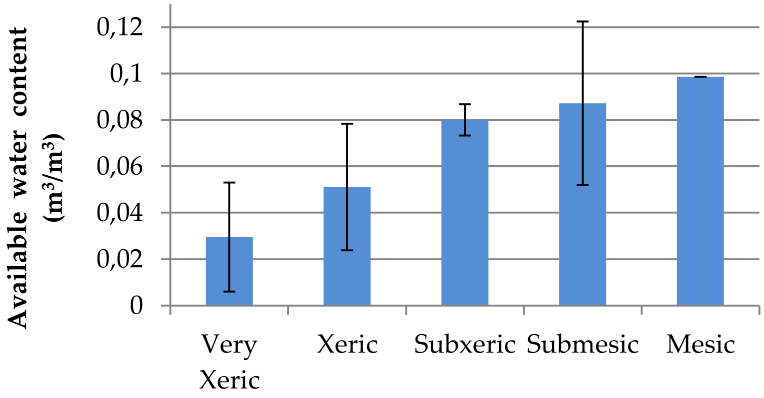

Figure 2 Mean AWC during the 2013 growing season at all sites classified by soil moisture regime – error bars show one standard deviation of the mean

---

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

SUMMARY AND APPLICATIONS

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. 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 – using methods discussed above, soil moisture regime can be estimated for existing or planned landforms and covers, and locally appropriate candidate vegetation species adapted to these hygrotopic positions can be selected for reclamation.
- Assessment of pre- and post-development land capability – using estimated hygrotopic position and the BEC system or similar approaches allows comparison of anticipated post-closure ecosystems to pre-development inventories. These comparisons can then be used to evaluate the effects of mining on dependent values such as wildlife habitat, biodiversity, or land productivity, and can provide the basis for application for custodial transfer of reclaimed lands, or assessment of such applications.
- Quantification of the effects of surficial-materials management on landform surface water balances – when combined with information on local climatic conditions, the proposed classification system can be developed to provide relative estimates of surface-water-balance terms such as evapotranspiration and net percolation. This information can be used by reclamation practitioners to understand the effects of cover placement for reclamation on movement of water through the surface layers of the reclaimed landscape.

This proposed classification system and empirical approach to its evaluation represent a first attempt to populate the AWSC and modifier charts, and will continue to be updated and adapted as additional information is collected and as the classification system is refined.

REFERENCES

Alberta Agriculture and Rural Development (2009) Agricultural Atlas of Alberta: Agricultural Climate Elements. Alberta Ministry of Agriculture and Rural Development: Edmonton.

B.C. Environment (1983) Land capability classification system for agriculture in British Columbia. Province of British Columbia, Victoria.

B.C. Ministry of Energy, Mines and Petroleum Resources (2008) Health, safety and reclamation code for mines in British Columbia. Victoria, B.C.

Barbour L., D. Chanasyk, J. Hendry, L. Leskiw, T. Macyk, C. Mendoza, A. Naeth, C. Nichol, M. O'Kane, B. Purdy, C. Qualizza, S. Quideau, and C. Welham (2010) Soil capping research in the Athabasca Oil Sands Region, volume 1: technology synthesis.

Cumulative Environmental Management Association (2006) Land capability classification system for forest ecosystems in the oil sands, 3rd ed. Alberta Environment, Edmonton.

Devito, K., I. Creed, T. Gan, C. Mendoza, R. Petrone, U. Sillins and B. Smerdon (2005) A framework for broad-scale classification of hydrologic response units on the Boreal Plain: is topography the last thing to consider? *Hydrol. Process.* 19, 1705-1714.

Green, R., P. Courtin, K. Klinka, R. Slaco, and C. Ray (1984) Site diagnosis, tree species selection, and slashburning guidelines for the Vancouver Forest Region. Province of British Columbia, Victoria.

Lloyd, D., K. Angove, G. Hope, and C. Thompson (1990) A guide to site identification and interpretation for the Kamloops Forest Region. Province of British Columbia, Victoria.

Meidinger, D., and J. Pojar (1991) Ecosystems of British Columbia. Province of British Columbia, Victoria.

Pojar, J., K. Klinka, and D. Meidinger (1985) Biogeoclimatic ecosystem classification in British Columbia. Ministry of Forests, Victoria.

Resources Inventory Committee (1998) Standard for Terrestrial Ecosystem Mapping in British Columbia. Province of British Columbia, Victoria.

Soil Survey Staff (1999) Soil taxonomy. 2nd ed. Agriculture Handbook Number 436. United States Department of Agriculture, Washington, DC.

Waring, R., and J. Major (1964) Some vegetation of California coastal redwood regions in relation to gradients of moisture, nutrients, light, and temperature. Ecological Monographs 34: 167-215.

Zettl, J. (2014) Infiltration and drainage through coarse layered soil: a study of natural and reclaimed soil profiles in the Oil Sands Region, Alberta, Canada. M.Sc. thesis, University of Saskatchewan, Saskatoon.