User guide for the quantitative ecohydrological analysis tool for mine reclamation

T. Baker, M. Ryan & J. Straker

Integral Ecology Group

November 12, 2021

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GLOSSARY OF TERMS

A&P - Arya and Paris (1981)

AET - actual evapotranspiration

AET_{max} - theoretical maximum actual evapotranspiration

ASMR - actual (absolute) soil moisture regime

AWSC - plant-available water-storage capacity

BEC - Biogeoclimatic Ecosystem Classification

CF50 - coarse-fragment content in upper 50-cm of soil profile

CWD - climatic water deficit

FC - field capacity

IEG - Integral Ecology Group

IPCC - Intergovernmental Panel on Climate Change

LMH - Land Management Handbook

OM - organic matter

P - precipitation

Pann - annual precipitation

Pgs - growing-season precipitation

PET - potential evapotranspiration

PSD - particle-size distribution

QEA - Quantitative Ecohydrological Analysis

RCP - relative concentration pathways

RSMR - relative soil moisture regime

S&R - Saxton and Rawls (2006)

SMR - soil moisture regime

SMS - soil moisture storage

SNR - soil nutrient regime

SSP - shared socioeconomic pathways

SWD - soil water deficit

T - temperature

T_{fc} - tension at field capacity

TOC - total organic carbon

TN - total nitrogen

UBC - University of British Columbia

WRC - water-retention curve, i.e. soil-water characteristic curve

1. INTRODUCTION

The Quantitative Ecohydrological Analysis (QEA) tool was designed by Integral Ecology Group (IEG) to provide information for mine reclamation practitioners for planning purposes. The key information provided by the tool can be divided into two groups: predictions of site series (i.e., ecosystems) and ecological classification parameters within BC's Biogeoclimatic Ecosystem Classification (BEC) system; and water-balance parameters based on the combination of soil characteristics and location-specific climate data. The ecologically focused outputs will allow users to explore expected ecological outcomes with a given set of soil and site characteristics, with the primary usage likely to be in regards to facilitating the return of pre-mine ecosystems to a landscape through the design of landforms (e.g., slope gradient and aspect) and soils (e.g., texture and depth of cover soils and waste materials). The hydrologically focused outputs are designed to inform long-term water-balance estimates at the landform and mine scales, with particular use likely to be made of estimated evapotranspiration and excess water volumes (Section 3.5).

The tool is based on a model of ecosystem response to water-balance limitations (i.e., seasonal drought or lack thereof) that is of particular relevance to ecosystems in western Canada, across most of which growing-season water deficits are the primary control on ecosystem development. The key to this system is in estimating the amount of plant-available water storage within rooting zones, which is done with peer-reviewed models (Sections 2.3 and 3.1), and is combined with water-balance-based classification rules developed from provincial ecological databases and modelled climate data (Section 3.3) to provide the two types of outputs mentioned above.

The genesis of this approach to predicting the ecological capability and hydrological function of reclaimed sites was in the mid-2010s, as described in Straker et al. (2015a, 2015b). Since then, the model has evolved significantly (Baker et al. 2020). The model's approach of predicting reclaimed ecosystem capability is in keeping with the principles of the forthcoming BC Reclamation Guide from the BC Ministry of Energy, Mines and Petroleum Resources (Straker and McConnachie, in press). The model is currently the focus of ongoing M.Sc. research conducted by Trevor Baker of IEG at the University of British Columbia (UBC) under the supervision Drs. Andy Black, Les Lavkulich, and Tongli Wang. Development of the model is ongoing and future updates are planned in response to feedback from users and the peer-review process. We welcome feedback from all users that make the tool more useful to those in the mine reclamation community.

2. MODEL OVERVIEW

2.1. THE BIOGEOCLIMATIC ECOSYSTEM CLASSIFICATION (BEC) SYSTEM

The QEA model and the associated online tool (https://qea.iegsoil.com), developed by IEG, is based on the rationale and structure of BC's BEC system. Systems with very similar principles are in place in Alberta (Beckingham and Archibald, 1996) and Yukon (Environment Yukon, 2017), as well as other provinces (Bowling and Zelazny, 1992; Keys et al., 2010) and jurisdictions around the world (e.g., Pyatt, 1995). A key principle of these systems is the understanding that vegetation and ecosystem characteristics are largely a result of:

1. climatic conditions relating to water supply (e.g., precipitation) and demand (e.g., evapotranspiration), and
2. soil and topographical characteristics as they relate to water storage and supply.

In the BEC system, biogeoclimatic zones represent broad geographic areas of similar macroclimate and are recognised as influencing the biological characteristics of the resulting ecosystems (Meidinger and Pojar, 1991). In this system, biogeoclimatic zones (e.g., IDF - interior Douglas-fir) are subdivided into subzones (e.g., IDFdk - dry cool interior Douglas-fir), with these subzones representing homogeneous climates at a finer scale and variants (e.g., IDFdk1 - Thompson dry cool interior Douglas-fir) representing localized occurrences of subzones (Lloyd et al., 1990).[1] Typically, at a local scale (e.g., a mine permit area) there are relatively few divisions (e.g., 2-3 different subzones), which are delineated mainly by elevation thresholds that vary slightly by aspect.[2] Within each subzone, there are groups of distinct ecosystems called site series, which are ecosystems with similar physical properties (soils, topography, and climate) that support a particular plant association (i.e., vegetation community) (Pojar et al., 1987). These relationships are illustrated in Figure 2-1. Each site series has an assemblage of plants adapted to its edaphic conditions — a fundamental principle of the BEC system is that sites in a given subzone with similar physical properties have similar vegetation potential (Meidinger and Pojar, 1991).

The relationship between site characteristics – or limitations in climate, topography, and soil (i.e., land capability) – and vegetation communities is conceptualized in the BEC system

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[1] Subzones may have multiple variants, where similar subzones occur in different geographic areas of the province. For simplicity, the term 'subzone' will be used throughout this document rather than 'subzone/variant' with the understanding that some biogeoclimatic units are represented by variants.

[2] Research into current and anticipated climate changes in BC are indicating that biogeoclimatic zones and subzones are already shifting spatially and will continue to shift with time (Mahony et al., 2018; MacKenzie and Mahony, 2021). This is discussed in more detail in Section 3.7.2.

using edatopic grids (Figure 2-2), where site series (numbered, coloured boxes) are associated with particular combinations of soil moisture regime (SMR, vertical axis) and soil nutrient regime (SNR, horizontal axis). The availability of soil water (SMR) is a dominant control on organic-matter production, and, thus, the development and maintenance of a given SNR,[3] and therefore in the BEC system, soil-water availability is believed to have the greatest influence on ecosystem development (Krajina, 1970; Giles, 1983). This is illustrated in Figure 2-2, which exhibits a common pattern of site series progressing diagonally from dry and nutrient-poor to wet and nutrient-rich.

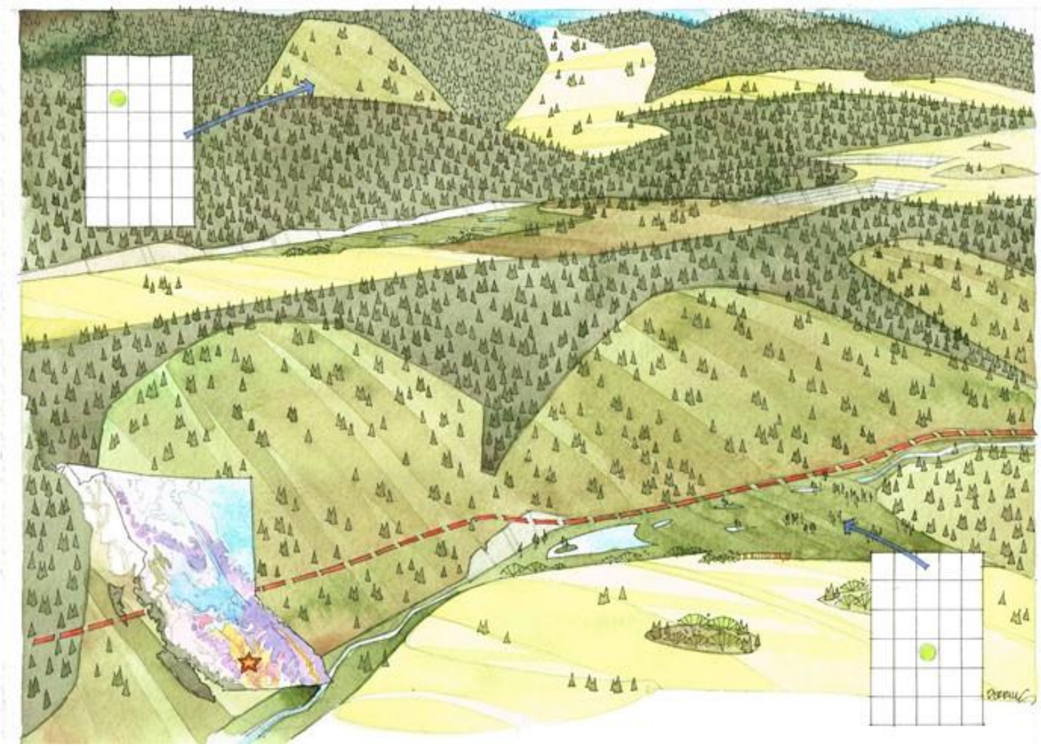

Figure 2-1. Illustration of biogeoclimatic ecosystem classification concepts. The inset map shows occurrence of broad biogeoclimatic zones across the province. The illustration depicts a landscape-scale example at a location marked by the star in the inset map, with the red dashed line indicating a boundary between biogeoclimatic subzones. Different ecosystems shown in the main illustration correspond with different site series, with corresponding positions of these site series depicted on the inset edatopic grids.

[3] For example, a very xeric SMR, defined by prolonged growing-season drought, is very unlikely to sustain a very rich SNR due to low biomass production and consequent low soil organic-matter content.

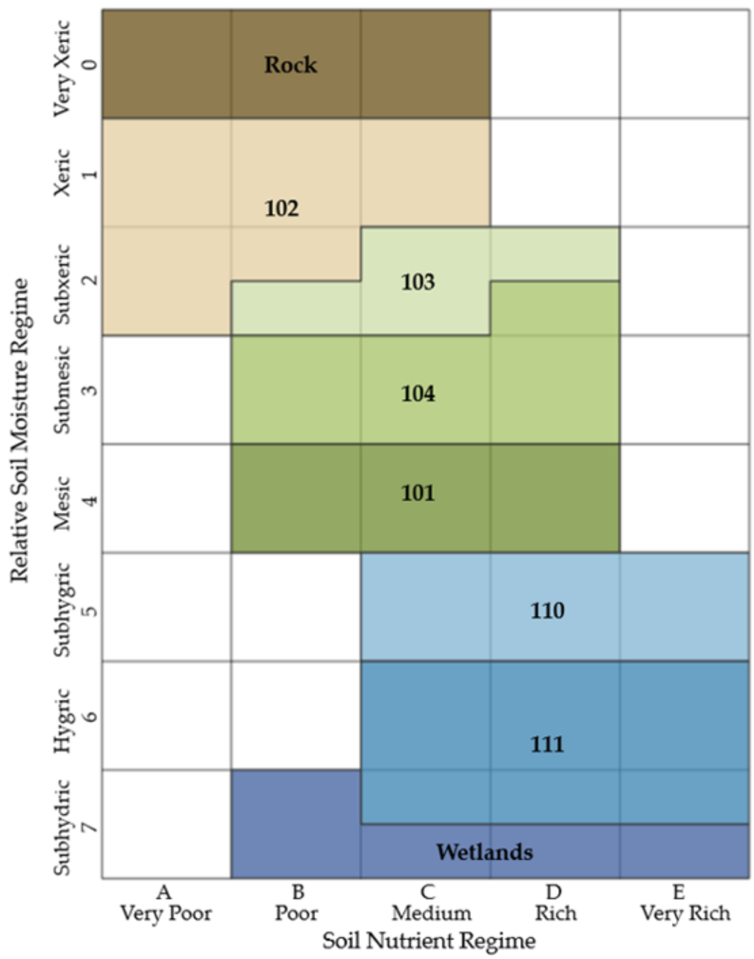

Figure 2-2. Edatopic grid for the ESSFdk1 variant (MacKillop et al., 2018) showing the relationship between site series, soil moisture regime, and soil nutrient regime.

2.2. RELATIVE SOIL MOISTURE REGIME

Relative soil moisture regime (RSMR) is defined as the "capacity of a soil to hold, lose, or receive water ... determined from soils' properties and landscape positions, regardless of climate" (Luttmerding et al., 1990, p. 34). The BEC system incorporates nine RSMR classes ranging from driest (Class 0, or very xeric) to wettest (Class 8, or hydric)[4], and within any given local or regional climate (i.e., subzone), the full range of RSMR classes is expected to occur, from very xeric sites that hold minimal amounts of plant-available water (e.g., rock

[4] The hydric RSMR is not shown on grids produced by the QEA tool because these sites with groundwater levels at or near the soil surface are beyond the scope of the tool, which is focused on the soil-storage-governed upland RSMRs that dominate on reclaimed areas.

outcrops and very thin, rocky soils), to subhydric and hydric sites that have water-table presence near the soil surface throughout the growing season (e.g., wetlands) (Table 2-1).

A key property of RSMR classes is that they are defined without respect to climate (Luttmerding et al., 1990), which makes the concept a universal site diagnostic tool that is transferable across regions. For example, a rock outcrop is classified as very xeric in wet coastal forests and interior desert areas. Likewise, a deep, fine-textured soil on a gentle slope is classified as a mesic RSMR in all areas. However, the same RSMR can support very different plant associations depending on the local climate.

Since SNR expression is largely related to organic matter (OM) inputs, and productivity in most BC ecosystems is governed by growing-season soil water deficits, RSMR is usually the fundamental edaphic factor driving site series expression (Krajina, 1970; Giles, 1983). This is illustrated in Figure 2-2, which exhibits a common pattern of site series progressing diagonally from dry and nutrient-poor to wet and nutrient-rich.

2.2.1. Classification of relative soil moisture regimes

The most important and unique part of the QEA model is in the development of rules to classify RSMR classes quantitatively based on soil-water availability. Currently, there are only two methods for classifying a site's RSMR, neither of which is conducive to use in a predictive context where a site is either unbuilt (i.e., mine projects in the development phase) or not developed enough to exhibit characteristic soil and vegetation features used in field classifications (i.e., nearly all reclaimed mine sites). Furthermore, surface soils on reclaimed landforms are often not analogous to natural soil systems, particularly in the lack of impeding soil horizons or bedrock to force downslope conveyance of water within rooting zones. To our knowledge, no similar attempts at RSMR classification have been made in BC or other jurisdictions. In Nova Scotia, drainage-related topographical properties have been used to classify SMRs, but these parameters performed relatively poorly for prediction of upland ecosystems (i.e., those not influenced by receipt of seepage and run-on water) (Yang et al., 2017).

The first of the standard RSMR classification methods is the use of indicator species and plant community composition, which take decades to centuries to develop. For example, a reclaimed site will likely contain a plant community that is a relic of what has been planted regardless of whether the planting decision is reflective of the site's ultimate potential. In the case of mine projects in development phases, there are no vegetative cues to use and the QEA tool is designed to suggest best-suited site series and inform planting prescriptions. The second method for classifying RSMRs is with dichotomous or score-based keys, which can be used for unbuilt or young reclaimed sites but with unsatisfactory degrees of accuracy. To use one example, a common designation in these keys is whether a soil is shallow (< 50 cm) or deep to underlying root-restricting layers (e.g., bedrock or coarse fragments), which suggests that a soil 49 cm deep has the same RSMR of a soil 5 cm deep and a soil 51 cm deep has the same RSMR as a soil with a depth of 100 cm or more. The same principle applies with designating soils as either 'coarse' or 'fine', or slopes as 'gentle' or 'steep'. These categories are also not well-suited for answering key reclamation questions regarding, for example, the relative benefits of potential soil salvage sources, or the depth of soil cover needed to support a target ecosystem, nor can they be integrated with assessments of soil-water balances on a site and landscape level. Clearly these classifications would be better made on a continuum rather than a dichotomous class system, and, furthermore, a system that explicitly recognizes that all suggested RSMR-classification characteristics pertain directly to availability of soil water.

The QEA model addresses these issues by using peer-reviewed models of soil-water storage and demand (e.g., evapotranspiration effects of slope, aspect and latitude) to calculate quantitative metrics (e.g., plant-available water-storage capacity [AWSC] in mm of water for a soil profile) that can be used to make RSMR classifications. Full details on the development of the QEA model's RSMR classification system based on provincial ecological databases are presented in Section 3.

2.3. AVAILABLE WATER-STORAGE CAPACITY

AWSC is a core concept in the QEA model's estimation of the RSMR of a site, which quantifies the amount of water a material can store over a range of soil-water tensions at which water is accessible for uptake by plant roots.[5] AWSC is a volume of water per unit area and is generally expressed as a depth of water (mm) over a specified soil depth. In the case of the QEA model, soil profile AWSC is quantified in mm of water over the entire soil profile, which extends to 100 cm unless a root-restricting depth is specified by the user.

Soil properties influencing AWSC, and therefore SMR, include:

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[5] AWSC is defined as the volume of water per unit area held between the volumetric water content (VWC) at field capacity (FC) and the wilting point (WP). The FC is the VWC 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 to 33 kPa, depending on soil texture. The WP is the VWC 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.

1. The particle-size distribution (texture) of materials – in general, AWSC increases with pore sizes associated with fine-sand and silt-sized (0.002 - 0.105 mm) particles (Arya and Paris, 1981). Inclusion of larger sands and coarse fragments (gravels, cobbles, etc.) in cover materials will result in growth-medium layers with lower AWSC (although these layers may be used advantageously – see #4 below).
2. The density at which these materials are placed (which determines total pore space and affects diameter distributions) – total pore space and size distributions, and corresponding water storage, decrease approximately linearly with increasing densities (Saxton and Rawls, 2006), and this effect becomes substantially limiting to plant growth as densities approach or exceed 1.8 $Mg \cdot m^{-3}$ (in addition to the negative effects of density on root penetration). Thus, compacted materials will have reduced AWSC. Users can enter soil compaction using a seven-class rating system.
3. The organic-matter content of profile materials – although this effect is influenced by type and state of decomposition of organic matter, AWSC generally increases by approximately 1-2% per 1% increase in organic-matter content in the soil (by weight) over a range of typical organic-matter contents (e.g., 0-8% organic-matter content by weight). These effects are largely due to organic-matter influences on soil aggregation and resulting pore-space and pore-size distributions, which enhance soil-water storage, particularly at lower tensions (Saxton et al., 1986; Saxton and Rawls, 2006). Materials with higher organic-matter contents will have higher AWSC for nearly all soil-texture classes.
4. The layering of different materials in the reconstructed profile – any inclusion of texturally contrasting layers (coarser or finer) in the soil profile enhances the overall water storage of the profile. These changes depend on the magnitude of textural differences between adjacent materials and the depth of the overlying material, but in a general case of a finer reclamation-cover material overlying a coarser waste-rock material, water retention may be enhanced by up to 20% over that of the non-layered overlying cover material.

Table 2-1. Description of relative soil moisture regime classes.

SMR Class	Description	Primary water source
Very xeric	Water removed extremely rapidly in relation to supply; soil is moist for a negligible time after precipitation	Precipitation
Xeric	Water removed very rapidly in relation to supply; soil is moist for brief periods after precipitation	Precipitation
Subxeric	Water removed rapidly in relation to supply; soil is moist short periods after precipitation	Precipitation
Submesic	Water removed readily in relation to supply; soil is moist for moderately short periods after precipitation	Precipitation
Mesic	Water removed somewhat slowly in relation to supply; soil may remain moist for a significant, but sometimes short period of the year. Available soil moisture reflects climatic inputs	Precipitation in moderate- to fine-textured soils and limited seepage in coarse-textured soils
Subhygric	Water removed slowly enough to keep soil wet for a significant part of the growing season; some temporary seepage and possibly mottling below 20 cm	Precipitation and seepage
Hygric	Water removed slowly enough to keep soil wet for most of the growing season; permanent seepage and mottling; gleyed colours common	Seepage
Subhydric	Water removed slowly enough to keep water table at or near surface for most of the year; gleyed mineral or organic soils; permanent seepage < 30 cm below surface	Seepage
Hydric	Water removed so slowly that water table is at or above soil surface all year; gleyed mineral or organic soils	Seepage

2.4. ACTUAL SOIL MOISTURE REGIME

In contrast to the RSMR concept, Actual SMR (ASMR) is a property that emerges from the convergence of site and soil properties (i.e., RSMR) and local climates. ASMR is classified using the ratio between the theoretical maximum actual evapotranspiration (AET_{max}) and potential evapotranspiration (PET[6]), the length of growing-season water deficits, and the occurrence and depth of water tables (Table 2-2). There are eleven ASMR classes ranging from excessively dry to very wet, which is applied consistently across all biogeoclimatic zones (Pojar et al., 1987; DeLong, 2019). For example, an excessively dry ASMR has the same magnitude of water deficit regardless of biogeoclimatic setting and may not occur in all biogeoclimatic zones/subzones.

The ASMR classification rules proposed for BC are presented in Table 2-2 (Pojar et al., 1987; DeLong, 2019). While this table includes both length of growing-season water deficit and the ratio of AET_{max}:PET, the QEA tool uses only the evapotranspiration ratio to classify sites by ASMR due to uncertainty in the definition of water-deficit length and discrepancies between classes derived from the ratio and deficit-length methods. The evapotranspiration ratio is calculated using a simple filling-bucket model based on soil-water storage and modelled climatic water inputs (after Spittlehouse and Black, 1981), which is described in detail in Section 3.

[6] 'PET' is a term that has fallen out of use in current meteorological research, in favour of the more precisely defined reference evaporation (E_{ref} or E_o) concept. Likewise, some literature uses the term 'evaporation' (E) to encompass both surface evaporation and transpiration via plants rather than 'evapotranspiration' (ET). The source for PET data used by the QEA model, ClimateNA (Wang et al., 2020) provides E_{ref} values rather than PET. To remain consistent with BEC literature (e.g., Pojar et al., 1987; DeLong, 2019), which uses the 'AET:PET ratio' terminology, the app uses the terms 'PET' instead of 'E_{ref}' and 'ET' instead of 'E'. However, it may be considered more scientifically current to use terminology such as 'E_{max}:E_{ref}' rather than the chosen 'AET_{max}:PET' terminology. For the purposes of the QEA model, the terms should be considered synonymous.

Table 2-2. Classification rules for Actual Soil Moisture Regimes, following Pojar et al. (1987) and DeLong (2019).

Differentia	Class
Rooting-zone groundwater absent during the growing season *Water deficit occurs (soil-stored reserve water is used up and drought begins if current precipitation is insufficient for plant needs)*	
Deficit > 7 months (Maximum theoretical actual evapotranspiration (AET_{max})/ Potential evapotranspiration (PET) ≤ 30%)	Extremely dry
Deficit > 5 months but ≤ 7 months (AET_{max}/PET ≤ 55% but > 30%)	Excessively dry
Deficit > 4 months but ≤ 5 months (AET_{max}/PET ≤ 65 but > 55%)	Very dry 1
Deficit > 3 months but ≤ 4 months (AET_{max}/PET ≤ 75 but > 65%)	Very dry 2
Deficit > 1.5 months but ≤ 3 months (AET_{max}/PET ≤ 85 but > 75%)	Moderately dry
Deficit > one week but ≤ 1.5 month (AET_{max}/PET ≤ 95 but > 85%)	Slightly dry
No water deficit occurs	
Utilization (and recharge) occurs (current need for water exceeds supply and soil-stored water is used). Deficit ≤ one week (AET_{max}/PET > 95%)	Fresh
No utilization (i.e., need for water does not exceed supply, soil-stored water is not used, temporary groundwater table may present)	Moist
Rooting-zone groundwater present during the growing season (water supply exceeds demand)	
Groundwater table > 30 cm deep	Very moist
Groundwater table > 0 but ≤ 30 cm deep	Wet
Groundwater table at or above the ground surface	Very wet

2.5. CLIMATE DATA

Climate data in the QEA model is taken from the ClimateNA model (version 7.10) by Wang et al. (2021) based on Wang et al. (2016). This model by UBC researchers is peer-reviewed and publicly available for download (http://www.climatena.com). It uses long-term weather station records and global climate models to make downscaled estimates for any point in North America across multiple time periods. For future time periods, data is modelled for numerous climate-change intensities (i.e., relative concentration pathways [RCP] or shared socioeconomic pathways [SSP]), of which the QEA model makes available low (RCP 2.6/SSP 1), moderate (RCP 4.5/SSP 2), high (RCP 7.0/SSP 3), and extreme (RCP 8.5/SSP 5) scenarios.

While the ClimateNA model provides data for any given combination of latitude, longitude, and elevation, the QEA model draws on a dataset generated from the ClimateNA desktop application. This dataset is generated on a grid with spacings of approximately 2 km across the province of BC with appropriate elevations assigned from a digital elevation model, as well as additional points generated in the vicinity of the Alberta oilsands and the southern Yukon. Higher-density climate points exist in the model for selected mines that IEG has worked on recently. The QEA model selects the closest 8 to 15 points (by latitude and longitude) to a given input location and uses an elevation-based regression to estimate climate parameters.

One shortcoming that has been recognized for mines that are in the planning phase is that the elevations generated from a digital elevation model may be significantly different than those planned during mine development (e.g., dump heights above existing elevations). The QEA tool returns information on the closest selected climate points by horizontal distance and elevation difference. If the horizontal distance of the nearest point is further than approximately 3 km or the elevation difference is more than approximately 200 m, IEG should be contacted to add a higher density of points for the study area.

3. METHODS OF THE QUANTITATIVE ECOHYDROLOGICAL ANALYSIS MODEL

A schematic outlining the process of predicting soil moisture regime and site series (or ecosite in Alberta or Yukon) occurrence is given in Figure 3-1 below. This diagram can serve as a guide through this methods section, which gives a full explanation of each calculation step.

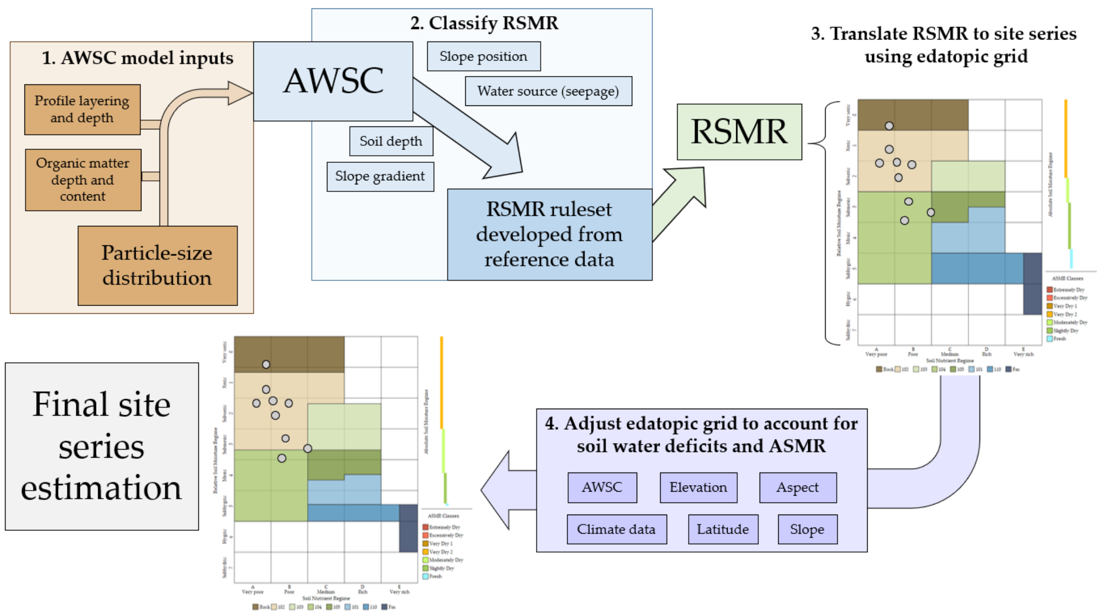

Figure 3-1. The structure of the Quantitative Ecohydrological Analysis (QEA) model used to make estimations of site characteristics. Step 1 describes the data inputs required to calculate plant-available water storage capacity (AWSC). Step 2 shows the use of AWSC and site factors to predict relative soil moisture regime (RSMR). Step 3 illustrates how estimated RSMRs are applied to regional edatopic grids to estimate site series outcomes. Step 4 shows how the published edatopic grid is adjusted to account for water-balance effects related to topography (slope, aspect, latitude), site location within a subzone, and climate change scenarios.

3.1. BASIC AVAILABLE WATER-STORAGE CAPACITY CALCULATIONS

The QEA model is based on a standardized method of estimating plant-available water-storage capacity (AWSC) from soil sample data, using adaptations of peer-reviewed models (following from Straker et al. [2015a, 2015b] with further developments published in Baker et al. [2020]). The primary inputs to the model are soil particle-size distribution (PSD),OM content, soil depth, and topographical data, as well as layering arrangements within the soil profile. Two AWSC models are central to this approach: Arya and Paris (1981; Arya et al., 1999) and Saxton and Rawls (2006; Saxton, 2005).

The Arya and Paris (A&P) approach is a physical model based on the capillary equation and uses only PSD and bulk density as inputs. The PSD-centric approach ignores the benefit of

OM and soil structure on AWSC, and thus appears better suited to poorly developed low-OM soils. To adjust for this omission, the A&P value is adjusted by the percent increase in AWSC attributable to OM according to the Saxton and Rawls (S&R) model.

The S&R approach is an empirical model built on regressions of soil survey data (PSD, OM content, and bulk density) against pressure-plate AWSC results to determine a best-fit prediction of AWSC. Since it is based on agricultural soil samples, it is believed this model is better-suited to higher-OM, better-aggregated soils.

Fine-fraction (< 2 mm) bulk density data were estimated based on texture classes (Saxton, 2005). Whole-soil bulk density was calculated inclusive of coarse fragments (> 2-mm) using an assumed particle density value of 2700 kg/m³ for all mineral materials, with packing voids around coarse fragments estimated as per Zhang et al. (2011). Bulk density (i.e., soil compaction) can be entered into the QEA tool using a seven-class rating system, as outlined in Table 3-1.

Table 3-1. Translation of soil compaction classes into fine-fraction bulk density values. The shown adjustment ratio is applied to the uncompacted bulk density for a given soil texture class as per Saxton (2005).

Compaction class	Bulk-density adjustment ratio	Equivalent bulk density (kg/m³) for a soil texture class with uncompacted bulk density of:	
		1400 kg/m³	1600 kg/m³
Very loose	$\frac{1100}{1400} = 0.786$	1100	1257
Loose	$\frac{1300}{1400} = 0.929$	1300	1486
Normal	$\frac{1400}{1400} = 1.000$	1400	1600
Slight	$\frac{1500}{1400} = 1.071$	1500	1714
Moderate	$\frac{1600}{1400} = 1.143$	1600	1829
Strong	$\frac{1800}{1400} = 1.286$	1800	2057
Extreme	$\frac{2000}{1400} = 1.429$	2000	2286

Both the S&R and A&P models, when combined with bulk density estimates, allow the estimation of water-retention curves (WRC; i.e., soil-water characteristic curves) for each sample, from which the volumetric water content between field capacity and wilting point is taken, and then reduced according to volumetric coarse fragment contents. In the A&P

model, which does not specify the field capacity tension (Tfc) for calculating AWSC from the WRC, Tfc is estimated between 5 and 33 kPa for each sample based on fine-fraction sand content, with coarser samples receiving a lower Tfc. This Tfc value is used in the profile layering corrections described below.

In recognition of the different applicability of the two models (A&P for unstructured vs. S&R for structured, natural soils), the final AWSC value for each layer is calculated as a weighted mean between the A&P and S&R results, with weighting derived from total-soil (as opposed to fine-fraction) OM and clay contents, which are used as proxies for aggregation.

3.2. CALCULATIONS OF SOIL PROFILE AVAILABLE WATER-STORAGE CAPACITY

The material AWSC values for each layer in a soil pit are depth-weighted and summed across the upper metre, or until a root-restricting layer (e.g., bedrock, basal till) occurs, to give a profile AWSC. As layers are compiled, the effects of layering on AWSC are estimated using Clothier et al.'s (1977) model, again based on the capillary equation. This model does not account for AWSC effects of coarse-over-fine layering situations, which is a shortcoming of the current approach. However, the most common layering arrangement in reclamation is the fine-over-coarse type (e.g., topsoil over waste rock), so layering at most sites is accounted for.

The final step to calculating a profile's AWSC is to add the estimated AWSC of any accumulated organic material above the soil surface (i.e., litter layers or organic horizons) (Table 3-2).

Table 3-2. Estimated AWSC values and data sources for organic materials.

Horizon designation	Material description	AWSC value (mm/m)	References
L	Undecomposed litter	35	Sato et al., 2004; Ewell, 2006
F	Partially decomposed fibric (fermented) material	80	Heineman, 1998
H	Substantially decomposed humic material	170	Heineman, 1998
LFH	Litter layers not differentiated in survey	80	Weighted mean assuming 50% of layer depth is L, 25% is F, 25% is H.
LF, LH, FH	Litter layers not differentiated	58, 103, 125	Mean assuming layer depth is equal between horizons.

3.3. CLASSIFYING SITES BY RELATIVE SOIL MOISTURE REGIME

Final profile AWSC, mineral soil depth, coarse-fragment contents in the upper 50-cm (CF50), slope gradient, and presence of seepage are used to estimate relative soil moisture regime (RSMR) corresponding to the BC BEC hygrotope (Pojar et al., 1987) using classification equations and adjustment factors developed with 5789 BC plots from a province-wide database (Baker et al., 2020).[7][8] One linear regression model covers slope positions that are typically do not receive significant volumes of upslope water on reclamation landforms (crest, upper, mid, and lower slopes) (SMR = a*log(AWSC) + b*log(depth) + c*slope + d*CF50 + e), while another covers water-receiving depression and gully slope positions (SMR = a*log(AWSC) + b*slope + c). Toes are classified using the mean of the water-shedding and water-receiving regression results. Regression models were trained over 200 iterations with 80% of points selected at random for model training and 20% used for testing. The mean coefficients over those 200 runs were taken. All terms in the models are significant to the 95% level or better.

Note that these RSMR classifications are intended to reflect dominant soil-water conditions over a multi-year period, consistent with the BEC hygrotope. The AWSC-based method for RSMR determination applies only to upland (very xeric - subhygric) SMRs, as wetter RSMRs 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. Determination of RSMRs wetter than mesic in the QEA model is based on the groundwater-depth-based rules laid out in BC Land Management Handbook 25, *Field Manual for Describing Terrestrial Ecosystems* (BCMOE, 2015). Sample AWSC thresholds are given in Table 3-3 for a selection of slope gradients and slope positions for soil profiles without root-restricting layers.

[7] The regression equations and adjustment factors are described in detail in Baker et al. (2020). This classification system is the subject of ongoing M.Sc. research by Trevor Baker of IEG.

[8] This database was supplied by Will MacKenzie of the BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development. It consists of all upland plots (subhygric RSMR or drier) used for BEC classifications in the ministry's database as of 2018.

Table 3-3. Determination of RSMR from plant-available water storage capacity (AWSC), water-table depth, and primary water source for sites without root-restricting layers in water-shedding (crests to lower slopes) and toe slope positions at selected slope gradients.

RSMR	Primary water source	Water-table depth (cm below ground surface)	Available water storage capacity, surface 1 m (mm)			
			Water-shedding			Toes
			Flat	12° slope	24° slope	12° slope
Very Xeric (0)	Precipitation	>100	< 1	< 1	< 2	n/a
Xeric (1)	Precipitation	>100	1 – 4	1 – 5	2 – 7	< 1
Subxeric (2)	Precipitation	>100	4 – 15	5 – 20	7 – 27	1 – 6
Submesic (3)	Precipitation	>100	15 – 57	20 – 77	27 – 103	6 – 37
Mesic (4)	Precipitation	>100	57 – 213	77 – 289	103 – 394	37 – 213
Subhygric (5)	Precipitation and/or seepage	>100	> 213 (or with seepage contribution)	> 289	> 394	> 213
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			

3.4. CLASSIFYING SITES BY SOIL NUTRIENT REGIME

Since the provincial survey database lacks OM and nutrient data from labs, it was not possible to create SNR classification rules in the same way as for SMR. However, the QEA model for estimating reclamation site series still requires an SNR estimate to be paired with an SMR estimate in order to determine appropriate placement on an edatopic grid, from which site series can be obtained. On reclamation sites, laboratory data for cover soils and mine wastes should be obtained for OM and total nitrogen,[9] but missing values will be filled

[9] OM should be measured by loss-on-ignition except where significant inorganic carbon is present (e.g., in coal waste), in which case it should be measured by the Walkley-Black method. Total nitrogen should be tested as total Kjeldahl nitrogen (TKN). Testing for other forms of nitrogen is not recommended

based on material type (e.g., waste rock, tailings, salvaged soil), as derived from IEG's internal database. An extensive literature survey was performed in order to determine appropriate threshold values for SNR classifications based on lab results for soil total organic carbon (TOC), total nitrogen (TN), and the resulting C:N ratio.[10] Where TN data is unavailable, the rules for TOC alone are used. The mean SNR classification resulting from all applicable rules is given to each site based on surficial material properties in the upper 30 cm (Table 3-4). TOC is converted from OM content using an OM:TOC ratio of 2.0 (Pribyl, 2010).

Table 3-4. Soil nutrient regime classification rules.

Soil property	Unit	Range				
		Very poor	Poor	Medium	Rich	Very rich
Carbon	% wt.	< 0.5	0.5 - 1.25	1.25 - 4	4 - 10	> 10
Nitrogen	% wt.	< 0.025	0.025 - 0.1	0.1 - 0.25	0.25 - 1	> 1
C:N ratio	-	> 100	30 - 100	15 - 30	5 - 15	<5

3.5. WATER BALANCE CALCULATIONS

Climate data for the QEA model is taken from the ClimateNA model (Wang et al., 2020; Section 0). Climate variables provided by ClimateNA (e.g., precipitation, temperature) are given on a monthly basis, whereas the water-balance model used in the QEA model is run on a daily timestep. Precipitation has been broken up into five monthly events with durations of one to four days each based on multi-year weather patterns derived from Environment Canada data from 3 stations: Highland Valley Lornex, BC (2000-2011), Sparwood, BC (2000-2018), and Faro Airport, Yukon (2000-2015). On days with precipitation, PET is estimated as roughly 50% (depending on month length) of the daily mean PET for the month, and days without precipitation are estimated to have PET of roughly 130% of the daily mean PET for the month so that the sum of all estimated daily PET values for the month is equal to ClimateNA's monthly total.

PET is adjusted for the effects of slope and aspect using a model from the United States Geological Survey (R package *EcohydRology*, Fuka et al., 2018) with aspect-based temperature adjustments based on Fu and Rich (2002) and McCune (2007). The percent difference in PET

because the omitted nitrate and nitrite fractions are leached easily and usually minimally present in forest soils.

[10] Literature review sources: Klinka et al., 1984; Courtin et al., 1988; Kabzems and Klinka, 1987; Klinka et al., 1994; Chen et al., 1998; CEMA, 2006; Amacher et al., 2007; Kranabetter et al., 2007

for a given slope and aspect combination relative to the PET for a flat site at the same latitude is applied to the PET given by ClimateNA.

Daily minimum, maximum, and mean temperatures for each month are estimated based on a sinusoidal pattern with an amplitude of 3˚ C.[11] Each temperature (minimum, maximum, and mean) on the first day of a month is the mean of temperatures for the current month and the month previous, and the temperature at the end of a month is the mean of the temperatures for the current month and the month following, in order to define the slope of the sinusoidal pattern across each month.

After daily climate values have been estimated using the steps above, AET_{max} is estimated using a simple filling bucket model run on a daily timestep (after Spittlehouse and Black, 1981) over a water-year from October 1 to September 30 (Figure 3-2). For each day with a mean temperature below 0˚ C, incoming precipitation is added to the snowpack. Sublimation losses from the snowpack are estimated at 16% of the annual accumulation (Reba et al., 2012).[12] As temperatures warm, snowpack is released as meltwater in accordance with Moussav et al. (1989) and is added to any incoming rain for the day.

The maximum storage volume of a soil is defined by the AWSC calculations described above. At the beginning of each day, the available volume of soil-water storage is replenished as possible by any added melt or precipitation. The soil pore volume between field capacity (FC) and saturation is also available for storage of incoming melt or precipitation and extraction by evapotranspiration, but this water is drained at a rate of 50% of the original volume per day and is depleted by the end of the second day. Any melt or precipitation accrued after the soil pore volume is full, plus water drained after temporary storage in the FC-saturation pores, is counted as excess water and lost from the system. Excess water is not specified further as either net percolation or run-off, but field observations indicate that most growing-season excess water will report as net percolation, particularly on waste rock dumps, due to coarseness, and tailings facilities, due to lack of a slope gradient.

Water is removed via evapotranspiration (AET) at a rate that does not exceed PET for the day and is scaled by the proportion of available water in the soil (Spittlehouse and Black, 1981; Giles et al., 1985). The soil moisture storage at the end of the day after addition of meltwater and rain and subtraction of ET water carries over to the following day where the model

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[11] Future iterations of the model will align estimated temperature patterns with those for precipitation and PET.

[12] Sublimation for unsheltered sites is estimated at 16 - 41% of annual accumulation by Reba et al. (2012). The 16% value used in the QEA model is intentionally conservative (i.e., creates higher excess water volumes during snowmelt).

repeats. Over the course of the year, the daily totals are summed into annual estimates which are displayed in the online tool. The cumulative AET for the year represents the theoretical maximum actual evapotranspiration (AET_{max}) that could be supported by the site with a full vegetation cover, which is used in the estimation of ASMR.

The provided AET_{max} value is intended to represent the upper limit of evapotranspiration for a site, and thus produces a best-case (low) estimate of excess water generation. During early stages of reclamation, or on sites that do not reach full vegetation cover,[13] AET will be lower and excess water will be higher.[14]

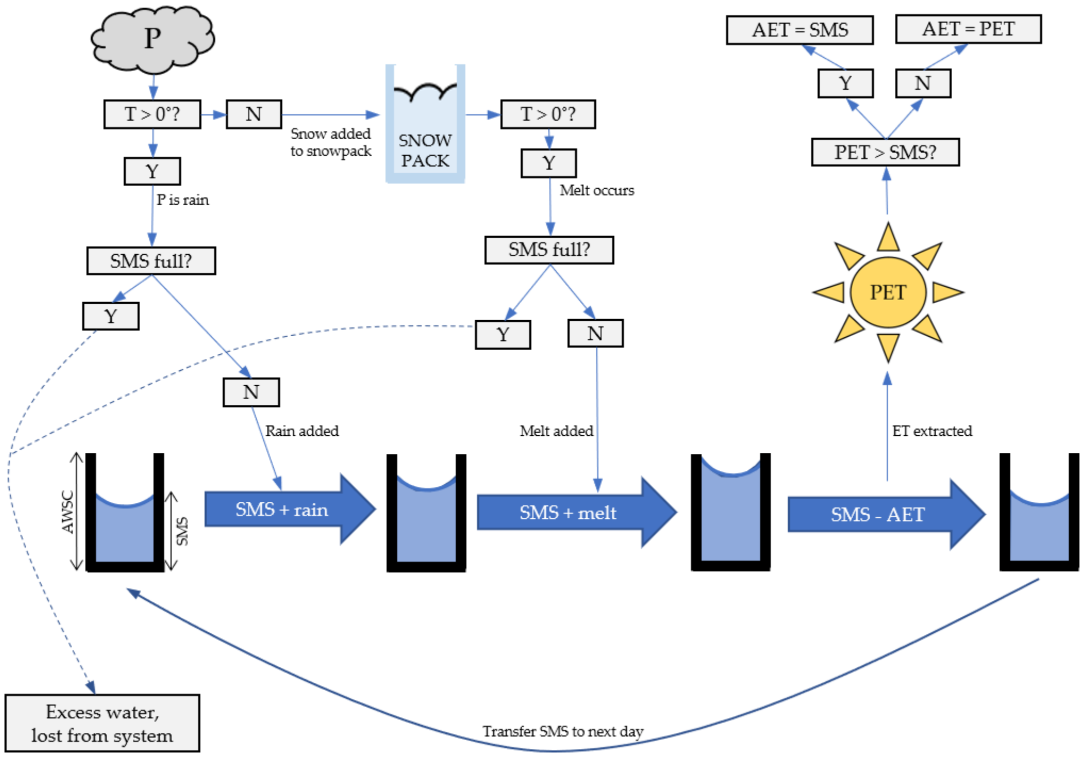

Figure 3-2. Diagram of the filling-bucket model used to estimate site water balances. The diagram depicts one daily timestep, at the end of which the soil moisture storage (SMS) is transferred to the beginning of the next day. The volume of the filling bucket is equal to the available water storage capacity (AWSC), and SMS is always equal to or less than the AWSC with excess input water lost from the system. The type of precipitation and the occurrence of snowmelt are dependent on the mean daily temperature (T). Temporary storage in the field capacity-saturation pores is not shown in the diagram but occurs before excess water is lost from the system.

[13] Full vegetation cover is defined here as he level at which a site is able to maximize ET, which is generally agreed to be above 3.5 to 4 (Lawrence et al., 2007; Wang et al., 2019; IEG unpublished data).

[14] Future versions of the model are planned to incorporate LAI-dependent ET calculations, so water balances can be calculated for sites at all stages of vegetation development.

The app's outputs include two estimates of cumulative water deficits, climatic and soil water deficits. Climatic water deficit (CWD = PET - P, where PET > P; and CWD = 0 where PET ≤ P) is the climatic constraint on ecosystems being able to use as much water as they would if water were not limited. It is a calculation how much of a shortfall of P there is during the growing-season relative to atmospheric demand from PET. The soil water deficit (SWD = CWD - AWSC) describes the severity of water deficits with accounting for mitigation of CWD by soil water supply. A site's SWD may be zero in a climate with a positive CWD if soil water supply is high enough.

3.6. CLASSIFYING SITES BY ACTUAL SOIL MOISTURE REGIME (ASMR)

As described in Section 2.4, in the QEA model ASMR is defined according to the ratio of the AET_{max} to PET. The relationship of ASMR classes to AET_{max}:PET ratios is given in Table 2-2. AET_{max} and PET values used to classify sites by ASMR are taken from the filling-bucket model described in Section 3.5 and Figure 3-2.

3.7. CLASSIFYING SITE SERIES

After each site has been classified with an RSMR and SNR position, its site series is estimated by plotting these coordinates on an edatopic grid. The way this is done in the QEA tool is unique because of the way the hygrotope is conceptualized in our system.

3.7.1. Shifting edatopic grids using actual soil moisture regimes

In the standard conception of the edatopic grid, the position of site series is fixed at the published coordinates, and aspect is accounted for through adjustments of RSMR position. For example, a pair of north- and south-facing sites with identical properties will likely be classified in different RSMRs based on their opposing aspects and, therefore, may have different site series assigned. In the QEA model, aspect does not factor into RSMR classifications for two reasons. Firstly, in the development of regression equations, aspect was found to not be a statistically significant parameter for classifying RSMR. Secondly, on a more conceptual level, this lack of relation between aspect and RSMR makes sense because aspect is a factor that relates to the evapotranspirative demand experienced by a particular site via effects on radiation and temperature — in other words, its climate, which is an ASMR-related feature of a site. Aspect and its effects on evapotranspiration do not fit within the definition of RSMR: the "capacity of a soil to hold, lose, or receive water ... determined from soils' properties and landscape positions, regardless of climate" (Luttmerding et al., 1990, p. 34).[15] Despite not being a significant parameter for predicting RSMR and not fitting into the definition of RSMR, aspect still exerts a strong control on site series occurrence, as repeatedly stated in regional field guides (e.g., Lloyd et al., 1990; MacKillop et al., 2018). Therefore, the QEA model deals with aspect in relation to ASMR (i.e., the balance of water supply and demand) rather than RSMR (i.e., water supply to plants).

The QEA model deals with aspect as an ASMR-related property by shifting the position of site series on edatopic grids according to the changes exhibited in the AET_{max}:PET ratio due to greater or lesser evapotranspirative demand. For example, a particular site series will be associated with a drier range of RSMRs on a north-facing aspect (less water supply and storage is needed to achieve a particular AET_{max}:PET ratio where there is lower PET) and a wetter range of RSMRs on a south-facing aspect (more water supply and storage is needed to achieve a particular AET_{max}:PET ratio where PET is higher). Rather than changing the RSMR classification based on aspect to reflect a different site series, the position of site series on edatopic grids is shifted so that the same RSMR is predicted to support different site series based on aspect (Figure 3-3).

The edatope-shifting approach of the QEA model is based on the proposition that what plants experience is not the RSMR of their soil (i.e., how much water it is capable of supplying) but the ASMR of their soil (i.e., how severe the water deficit caused by imbalances between water supply and demand is). This is supported by the fact that the same plant association is found in different RSMRs depending on regional climate. For example, the *CwHw - Devil's club - Lady's fern* association occurs on mesic RSMRs in the ICHvk, on subhygric RSMRs in the ICHwk, and on hygric RSMRs in the ICHmw (MacKillop et al., 2018).

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[15] Aspect has an effect on a soils ability to receive water (an RSMR-related property) in the form of differences in snowpack retention and melt timing and volumes on warm and cool aspects, particularly in subzones where snowpack represents a significant portion of annual precipitation (e.g., mountainous and/or northern areas). This is under consideration for future versions of the QEA model.

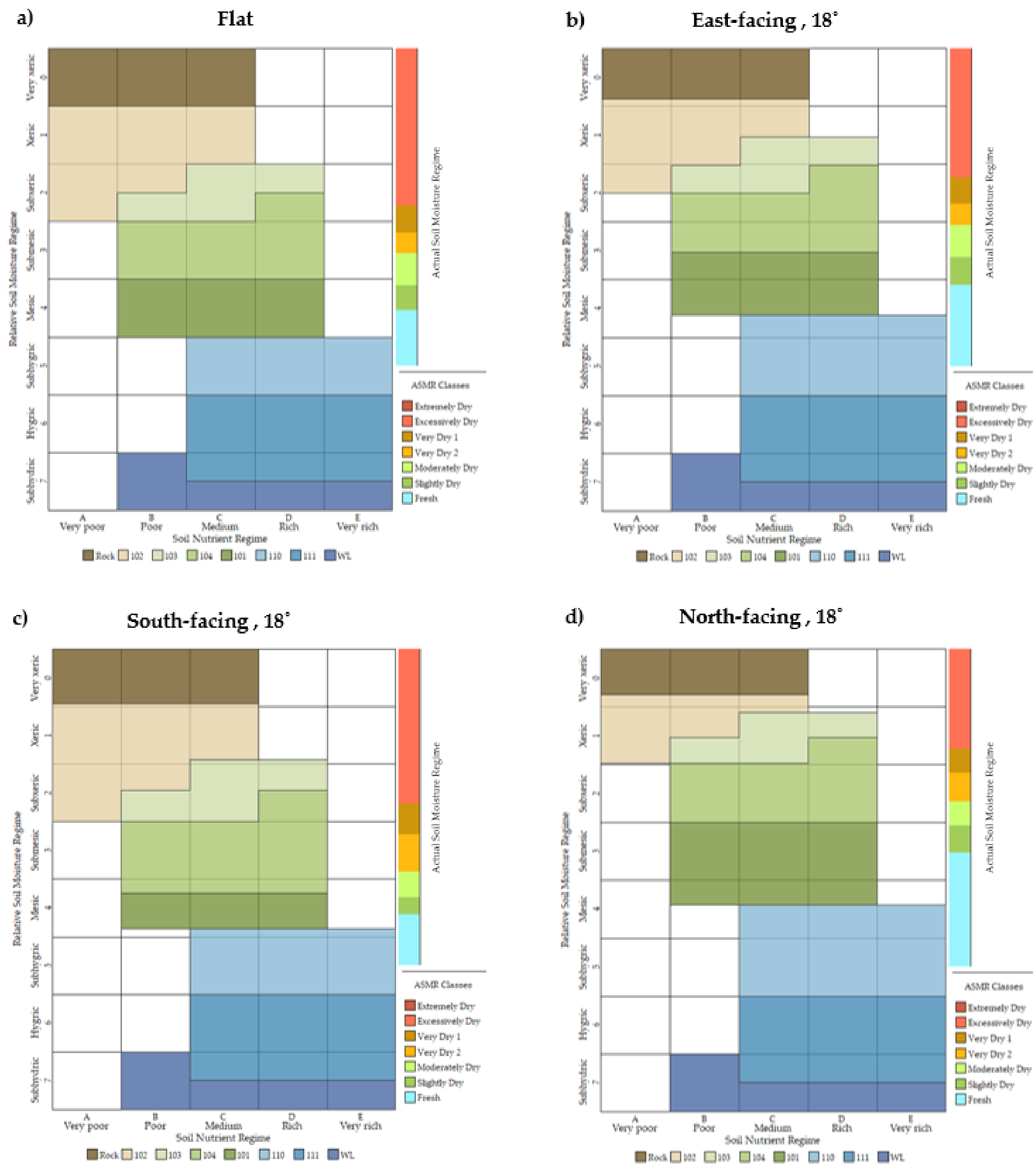

Figure 3-3. The edatopic grid for the ESSFdk1 variant (MacKillop et al., 2018) for a) flat sites (as published), b) east-facing sites on 18˚ slopes, c) south-facing sites on 18˚ slopes, and d) north-facing sites on 18˚ slopes.

The method for shifting edatopic grids is depicted in Figure 3-4 and Figure 3-5. The published edatopic grid is used as a representative of the relationship between RSMR and site series for a flat site. Based on the RSMR classification rules detailed in Sections 2.2 and 3.3, the RSMR axis can be quantified as a continuum of AWSC values using the RSMR class thresholds presented in the 'Water-shedding/Flat' column of Table 3-3.[16] Using the filling-bucket approach outlined above in Section 3.5, each of these AWSC values and its corresponding RSMR position can be then assigned an AET_{max}:PET ratio. In this way, the entire RSMR axis for the published grid has a set of associated AWSC, AET_{max}:PET, and ASMR class values assigned along its length. Of particular note for the grid-shifting process is the AET_{max}:PET ratio associated with transitions between site series — each site series can be defined along the hygrotope axis by a series of AET_{max}:PET ratios that are associated with RSMR positions on a flat site. The relationship between site series transitions and AET_{max}:PET ratios on flat sites is the key to producing grids shifted for the effects of slope and aspect.

The second part of the grid-shifting process quantifies the hygrotope in the same fashion as above, but this time using the PET that a site of interest experiences due to its slope and aspect. In the example of a south-facing site, the PET, as calculated with the steps outlined in Section 0, will be higher than the baseline flat site. Again, using the filling-bucket water-balance model over a simulated water year, all AWSC values along the RSMR axis can be assigned an AET_{max}:PET ratio and an ASMR class. With a higher south-facing PET, the annual AET_{max}:PET ratio associated with each AWSC value will be lower as AET_{max} cannot keep pace with PET because soils progress more quickly to a state of zero available water due to higher PET demands. The inverse is true on a north-facing site, with lower PET values and a higher annual AET_{max}:PET ratio due to having less PET-induced water stress. With the AET_{max}:PET ratios known for each site series on a published grid, as per the paragraph above, the site series can be repositioned with respect to the AET_{max}:PET for the site of interest.

In Figure 3-4 and Figure 3-5, note that the AWSC thresholds for RSMR classes are different between flat sites and the sloped sites, in keeping with Section 3.3 and Table 3-3. However, the AWSC thresholds do not vary by aspect on the grids for east-, south- and north-facing slopes because RSMR classification is not aspect-dependent (Section 3.3). The PET values are different for all four grids in Figure 3-4 and Figure 3-5 due to differences in radiation and temperature (Section 3.5). As depicted in Figure 3-2, the AET_{max} values for each slope-aspect

[16] For the published edatopic grid, as it deals generally with all sites across the entire subzone, the RSMR regression parameter for topsoil coarse-fragment contents (CF50) is determined according to a regression between RSMR and CF50 that uses data from the ecological database of 5789 plots used for creating the classification rules. Slope gradient for the generic published grid is set at zero and soil depth is set at 100 cm.

scenario (and the resultant AET_{max}:PET ratios) are affected by differences in PET (radiation and temperature) and the balance between snow, rain, and snowmelt volumes (temperature), which leads to differing abilities of the soils in each scenario to supply soil moisture throughout the growing season.

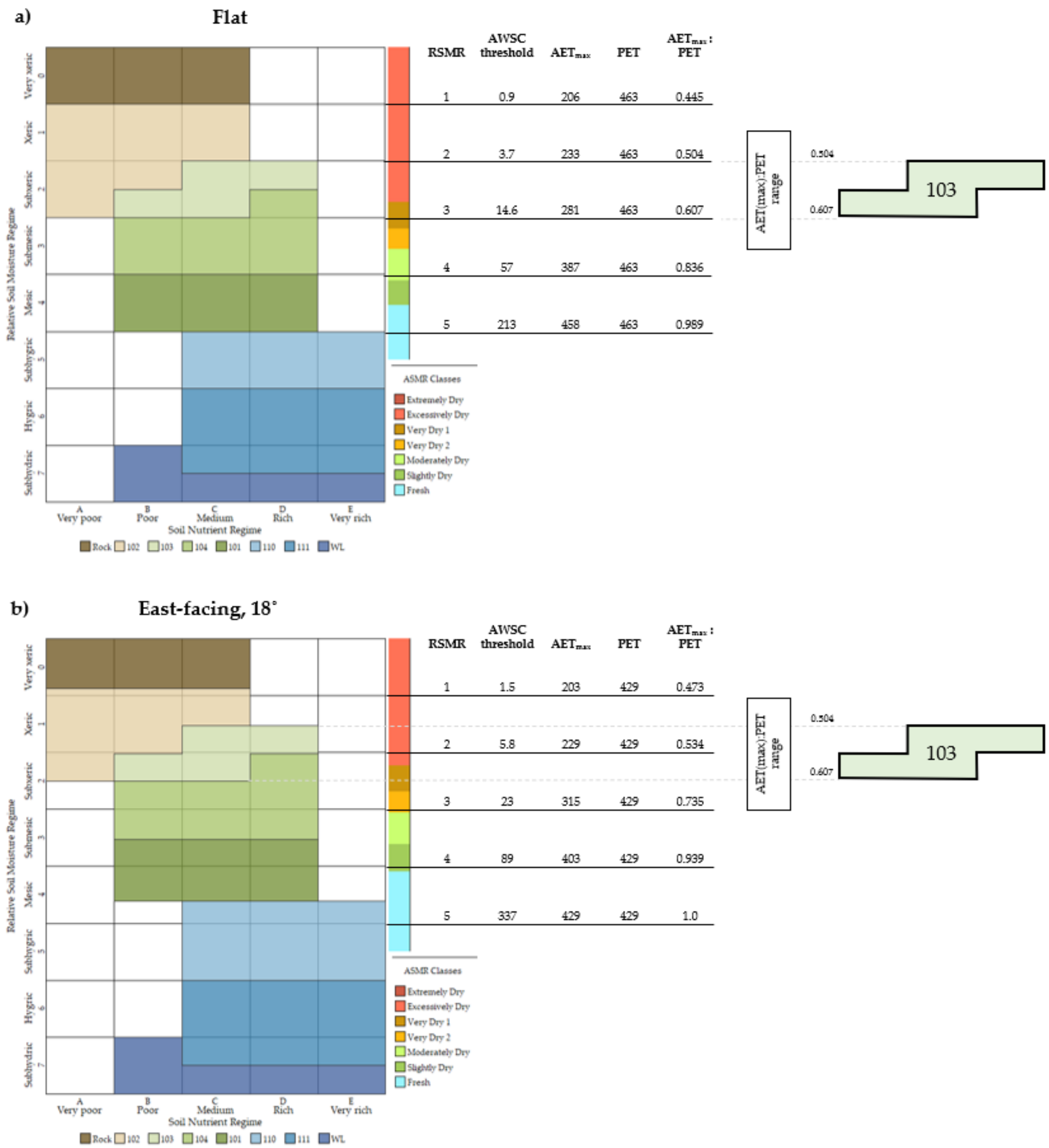

Figure 3-4. Edatopic grids for the ESSFdk1 variant (MacKillop et al., 2018) for flat and east-facing sites annotated with AWSC thresholds, AET_{max} and PET values (in mm), and AET_{max}:PET ratios at each upland RSMR class boundary. The range of AET_{max}:PET ratios for the 103 site series is given at right in order to illustrate that it maintains the same AET_{max}:PET ratio boundaries as the edatopic grid is shifted, which is also true for all other site series.

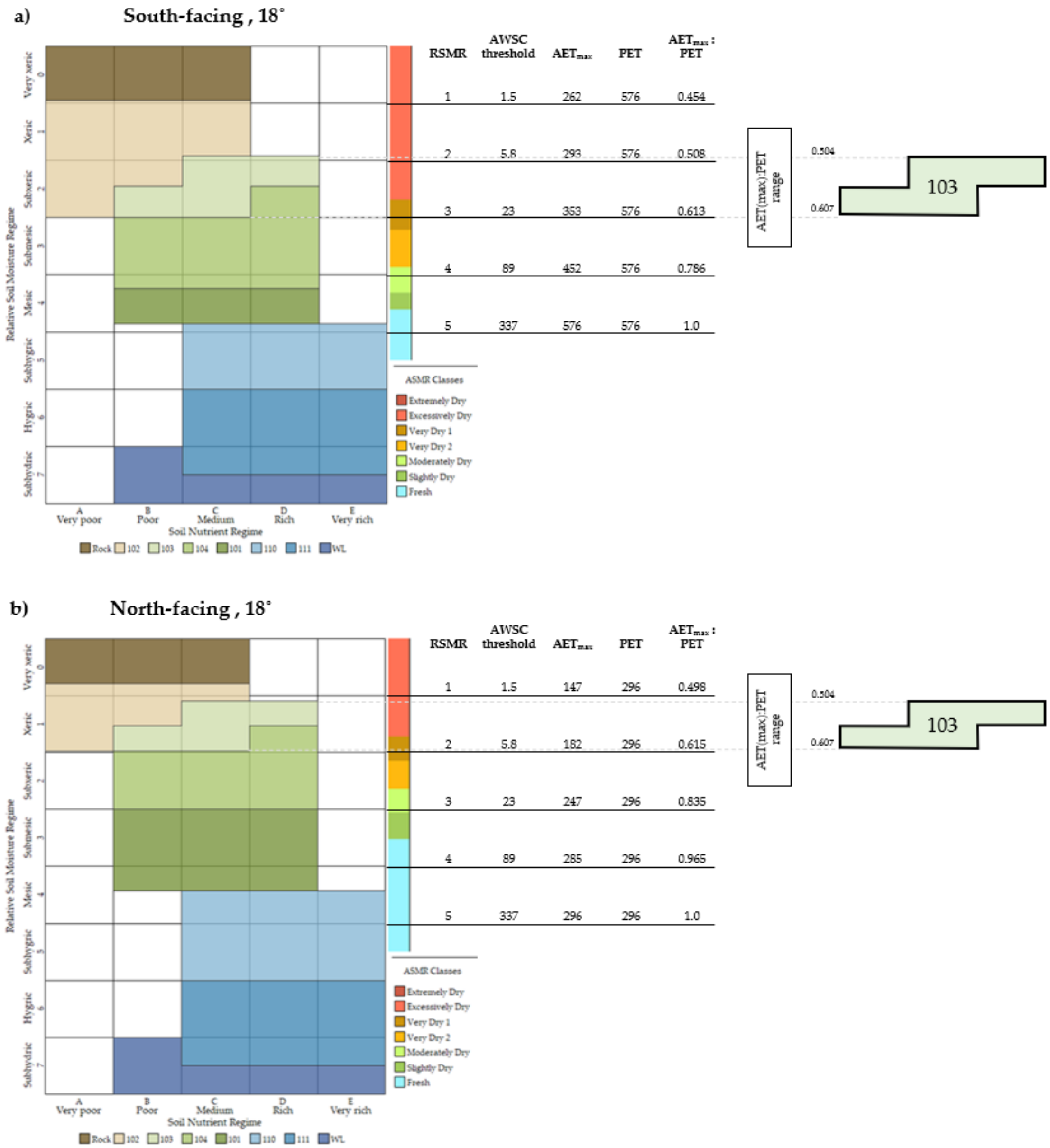

Figure 3-5. Edatopic grids for the ESSFdk1 variant (MacKillop et al., 2018) for south-facing and north-facing sites annotated with AWSC thresholds, AET$_{max}$ and PET values (in mm), and AET$_{max}$:PET ratios at each upland RSMR class boundary. The range of AET$_{max}$:PET ratios for the 103 site series is given at right in order to illustrate that it maintains the same AET$_{max}$:PET ratio boundaries as the edatopic grid is shifted, which is also true for all other site series.

3.7.2. Applications of the shifted edatopic grid concept

In the section above, the concept of shifting edatopic grids was introduced using the example of slope and aspect effects on climate variables and water balances. In addition to slope and aspect, there are two other factors that can have similar effects, the location of a site within a subzone and the effects of climate change.

Location

Assuming that an edatopic grid represents the central tendency of the relationship of site series to soil water balances across an entire subzone, the location of a site can alter these relationships based on being in a relatively wet or dry and/or warm or cool part of the subzone. An easy example of this phenomenon to conceptualize is a site that lies at the upper elevation range for a given subzone. Since the BEC mapping process necessarily involves drawing boundaries through a climatic landscape that is continuously variable, the site in question will have a climate more similar in temperature and/or precipitation to the lower reaches of the neighbouring subzone, and one would expect differences in the relationship of site series and soil water balances. In this case of a site near the upper elevation boundary, the wetter and/or cooler conditions may cause site series to be expressed on drier parts of the hygrotope than they might be expected. The same forces are in effect for a site near the geographic (i.e., latitude and longitude) boundaries of a subzone. Anecdotally, this has been observed by IEG in BEC mapping fieldwork where site series were located on wetter sites than would be expected from the regional grid and indeed the study location was located in an area that was warmer and drier than the mean conditions for the subzone.

In the edatopic grid shifting procedure, this is accounted for by setting the baseline site series-ASMR relationships using the climate point most similar to mean annual PET and precipitation for the subzone as a whole, and then shifting the grid using the AET_{max}:PET ratios calculated for the location of interest in exactly the same way that the flat site forms the baseline for slope- and aspect-based shifting described in the section above. In the online tool, users have the option to override these location-based adjustments in the Climate Settings menu. If the adjustments are overridden, then the effects of latitude, longitude, and elevation will not be accounted for in the shifting of edatopic grids.

Climate change

The adjustment of edatopic grids for the effect of climate change follows the same fundamental logic as described above for slope and aspect, and location. In this case, the baseline grid is defined using climate conditions for a given subzone from the 1961-1990 historical normal as this is the time period during which much of the BEC mapping was done for the province, and, in cases of more recent BEC mapping, the ecosystems being studied will have undergone significant periods in their development in climate conditions similar to these historical normals.

There are several additional factors to be considered when applying future climate scenarios during use of the app. Firstly, the selection of relative concentration pathways (RCPs) must be made. The default setting in the app is the moderate (RCP 4.5) setting, in keeping with ClimateBC projections of future BEC mapping and other work by the BC government (e.g., Mahony et al., 2018). It is beyond the scope of this tool to advise on appropriate RCP selection, but it is advised that all settings be explored to understand the range of potential impacts.[17] Secondly, it is extremely important to recognize that BEC classifications are expected to shift significantly in the future (Mahony et al., 2018; MacKenzie and Mahony, 2021). Users interested in preparing reclamation plans for the coming decades cannot assume that the current subzone will remain in a given area, which has significant impacts on assessing equivalent land capability and deciding on appropriate target site series and revegetation species. Currently, there is no feature in the app to facilitate selection of future subzones for a given area, but other tools are available to facilitate these decisions and should be used.[18]

During testing, it has been noted that the climate-change-based shifts to grids can be quite strong. While in theory, an area projected to have a given BEC classification in the future should have climate data within the app that fits with that classification (i.e., an area projected to be ESSFdk1 in the future should have climate data for that time period similar to the historical conditions for areas currently mapped as ESSFdk1), there are sources of error currently unaccounted for in the tool. For example, future climate projections are made with one climate change scenario (RCP 4.5 [SSP2] in the case of ClimateWNA), while users of the app have the ability to select several RCP scenarios. Also, ClimateWNA provides raster cells of projected BEC classifications that, especially in mountainous areas, can span a wide range

[17] Scenario selection guidance is provided by Mahony et al. (2021) on the 'Guidance' page at https://bcgov-env.shinyapps.io/cmip6-BC. The notation for scenarios on this page is different than used in the QEA tool; RCP 2.6 is listed as 'SSP1-2.6' and is called "pessimistic", RCP 4.5 is listed as 'SSP2-4.5' and called "moderate" and RCP 7.0 is listed as 'SSP3-7.0' and called "pessimistic." RCP 8.5 ('SSP5-8.5') is recommended not to be used as it is considered "extremely unlikely".

[18] ClimateWNA (http://www.climatewna.com/ClimateBC_Map.aspx), an online version of the ClimateNA program, allows for users to download raster files of projected future BEC classifications using the 'Overlays' dropdown menu for BEC zones and the 'Download Overlay raster files' feature. Although there is uncertainty in these projected classifications (MacKenzie and Mahony, 2021), they should be used for input to the QEA tool rather than historic BEC classifications.

of elevations, which means that although a given location may fall within a raster cell, it may not be well-represented by the conditions modelled for the cell as a whole.[19]

As with the other forms of edatopic grid adjustments, users have the option to disable climate-changed-based shifting of edatopic grids in the Climate Settings menu. Exploring results with climate change effects toggled on and off can give an idea of the range of possible outcomes.

3.7.3. Summary of site series classifications

To summarize, site series calls for each site are made in two interacting steps:

- RSMR and SNR classifications are made using site and soil characteristics that are relatively insensitive to climate conditions, at least not on decadal scales, and these are used to position sites on edatopic grids. The procedures for classifying RSMR and SNR are given in Sections 3.3 and 3.4, respectively.

- The position of site series on the RSMR axis of edatopic grids are shifted according to ASMR-related conditions (i.e., AET_{max}:PET) because the species composing a given site series are sensitive to soil-water deficits (i.e., ASMR) rather than simply the ability of a soil to supply water (i.e., RSMR). The RSMR positions associated with a given site series are highly sensitive to slope and aspect effects, as well as climatic conditions, given that the amount of soil-water supply (i.e., RSMR) required to sustain a given ASMR is not a fixed quantity but rather dependent on a site's water- and energy-balance parameters.

4. USER GUIDE

4.1. INPUTS

The QEA tool was developed in R (R Core Team, 2019) using the *shiny* (Chang et al., 2020) and *shinydashboard* (Chang and Borges Ribeiro, 2018) packages and is intended as a user-friendly interface for the QEA model. Data requirements for running the tool are shown in Table 4-1 and Table 4-2 below. Nearly all of these parameters are included in the standard survey methods described in LMH 25 (BCMOE, 2015).

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[19] The future BEC classifications from ClimateWNA should ideally be checked and modified by combining with a digital elevation model to estimate elevation thresholds for future BEC units in the study area. You can contact Integral Ecology Group (tbaker@iegconsulting.com) for assistance with this process.

4.1.1. Site Characteristics

Table 4-1. Explanation of site data inputs.

Field	**Units**	**Data type**	**Notes**	**LMH25 section**
Subzone/ variant	-	drop-down	You must first press the 'Get list' button. The subzone/variant (or equivalent units in Alberta, Yukon, and Ontario) in which the plot is found. Any subzones/variants with a '.nf' suffix indicate non-forested grids. The subzone/variant selected will serve as the basis for the edatopic grid outputs and site series/ecosite estimates. More detailed information about BEC subzones, including links to field guides, can be found at this link: https://www.for.gov.bc.ca/hre/becweb/. If desired subzones are missing, including any non-forested grids, contact IEG (tbaker@iegconsulting.com).	-
Region	-	drop-down	Before a region is selected, a subzone/variant must be selected. Once a subzone/variant is selected, choose the appropriate forest management region, as determined from regional field guides (Land Management Handbooks in BC). This selection determines which edatopic grid will be displayed and used for site series classifications. When working with future time periods, the region selection may not match the site's location as BEC units are projected to move around the province but they are only defined in the field guides for the historical location. In this case, it should not matter which region is selected.	-
Latitude	decimal degrees	numeric	Must be between 48.3 and 65.0. Accuracy to 0.001 degrees is preferable.	-

Field	Units	Data type	Notes	LMH25 section
Longitude	decimal degrees	numeric	Accuracy to 0.001 degrees is preferable.	-
Elevation	m.a.s.l.	numeric	Must be between 0 and 4671, accuracy to the nearest 10 m is sufficient.	-
Slope position	-	drop-down	Select from mesoslope position codes defined in LMH 25.	1.31
Slope unit	-	drop-down	This is the unit of measure for the value in ‘Slope gradient’.	-
Slope gradient	as defined in ‘Slope unit’	numeric	Whether in degrees or percent, this should be given to the nearest whole number.	1.29
Aspect	degrees true	numeric	Must be between 0 and 360. Measured facing downslope, accuracy to the nearest 1 degree is sufficient. The degree symbol is not required.	1.30
Root restriction type	-	drop-down	This only applies to soils where a layer impenetrable to roots exists, such as bedrock, severe compaction, or a low-permeability layer in a reclamation-cover system. It does not apply to soil pits where excavation simply ceased due to survey design or time restraints. It also does not apply to soil pits on younger sites where root systems have not had time to access all depths. It can be difficult to determine if very coarse waste rock will act as a root restricting layer. Layers with greater than ~70% coarse fragments, particularly where dominated by fragments larger than 5 cm in diameter are likely to restrict root growth. To understand the range of possible outcomes, running the site with no root restriction and a lithic (L)	2.11

Field	Units	Data type	Notes	LMH25 section
			restriction at the depth of this layer is advisable.	
Root restriction depth	cm	numeric	This only applies to soils where root restriction occurs. If no root restriction occurs, leave this field blank.	2.11
Water source	-	drop-down	The primary source of water inputs to the plot. For most reclaimed sites, this will be precipitation.	2.12
Seepage depth	cm	numeric	Enter the depth of seepage, in centimetres, observed or predicted during the growing season. Temporary seepage outside of the growing season (e.g., during spring melt) should not be entered. If no seepage occurs at the plot, leave the box empty. The water source entered in the box above does not have to be seepage if seepage only provides a secondary input of water to the site.	2.13

The site data input screen for the QEA model is shown in Figure 4-1

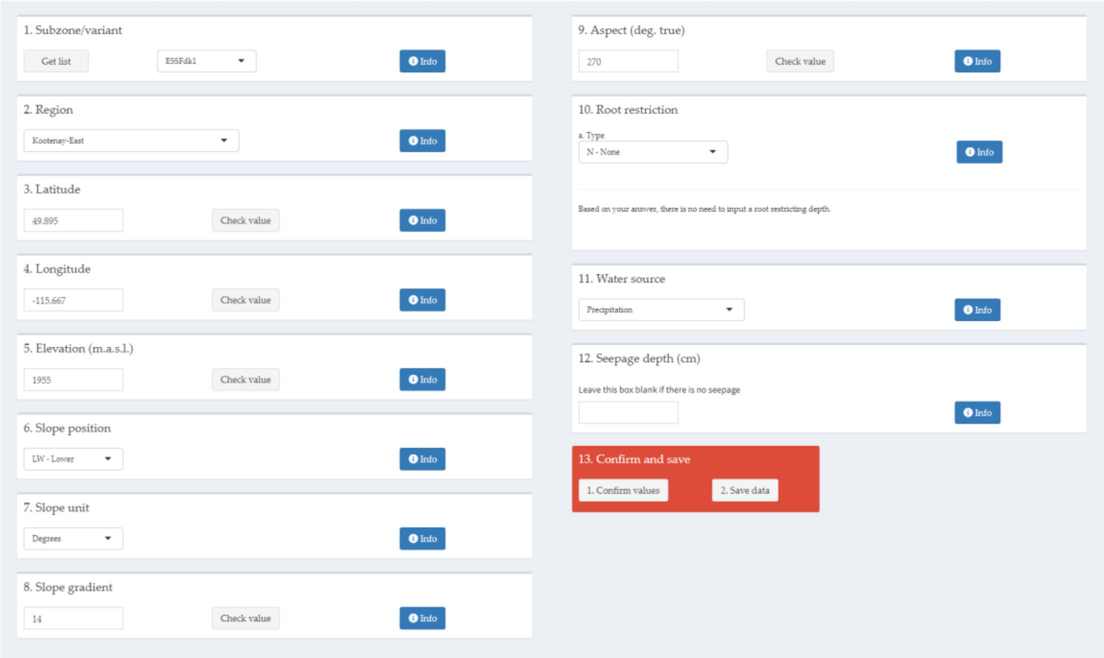


Figure 4-1. The QEA app site data input screen.

4.1.2. Soil Inputs

There are three options for fine-fraction soil texture data, depending on whether data were collected in the field as hand-texture classes or sent for quantitative lab analysis. For quantitative data, there are options to provide basic sand, silt, and clay values, or detailed values with sand subclasses. If sand subclass data are available, they should be used. Lab analyses provide more accurate predictions due to the wide span of AWSC values within some texture classes, particularly sandy loams. For this reason, if only hand-texture classes are collected, their accuracy is very important, particularly notation of relative sand coarseness using the prefixes to indicate dominance of very fine (VF, 0.05-0.1 mm), fine (F, 0.1-0.25 mm), medium (M, 0.25-0.5), and coarse (C, 0.5-2 mm) sands (e.g.,use 'FSL' for a sandy loam with a predominance of particles in the 0.1-0.25 mm size range rather than 'SL' for a generic sandy loam).

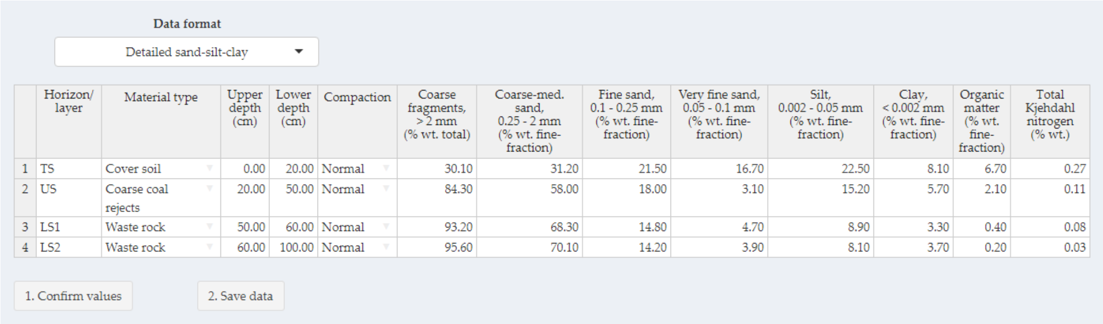
Table 4-2. Explanation of soil data inputs.

Field	Units	Data type	Notes	LMH 25 section
Horizon or Layer	-	character	A unique identifier for each horizon or layer in the profile. Typically, these will be A, B, and C horizons for natural soils and TS (0-20 cm), US (20-50 cm), and LS (50-100 cm) for reclaimed soils, but any values can be entered using letters and numbers only (i.e., no spaces and no symbols).	2.16
Material type	-	drop-down	Options in the drop-down menu include those provided in LMH 25, as well as mine-related materials including tailings, waste rock, coarse coal rejects, overburden, and salvaged cover soil.	Table 2.5; Key 9.13
Upper depth, Lower depth	cm	numeric	The upper and lower depth boundaries of each layer, to the nearest cm is sufficient. Values greater than 100 cm will be overwritten during analysis as this is the limit for soil profiles in the QEA model. Deeper layers beginning beyond 100 cm do not need to be entered. For surface litter layers (LFH), depths must be entered with negative numbers in keeping	2.7 (note: negative numbers must be used for surface organic horizons

Field	Units	Data type	Notes	LMH 25 section
			with the Canadian System of Soil Classification (e.g., L from -5 to -2 cm, H from -2 to 0 cm, A from 0 to 15 cm).	unlike in LMH 25).
Compaction	-	numeric	A subjective description of compaction. These codes function to scale fine-fraction bulk densities. Selecting 'Normal' is sufficient for most layers in reclamation soils. The seven options are detailed in Table 3-1 above.	-
Coarse-fragment content	% whole-soil weight or volume	numeric	The percent of the total soil accounted for by particles greater than 2-mm in diameter. Values are either by volume (for ocular field estimates) or weight (for lab results), for which the appropriate column must be used. Only one coarse-fragment content value is required per row. If both are entered, the weight will be used for that row.	2.28
Texture	-	drop-down	The hand-texture class of the horizon/layer. This is for materials for which no quantitative lab results are known. It is more desirable to provide numeric data to the sand, silt, and clay columns.	2.27
Sand Silt Clay	% fine-fraction (< 2-mm) weight	numeric	This is for materials for which quantitative lab results are known, but sand subclasses are not. The percent of fine-fraction weight represented by the 0.053 - 2 mm (sand), 0.002 - 0.053 mm (silt), and < 0.002 mm (clay) fractions. These three values may contain decimals and must sum to 100. The sand subclass breakdown will be estimated based on the ratio of sand to silt.	-
Very coarse to medium sand	% fine-fraction	numeric	This is for materials for which quantitative lab results including sand subclasses are available. The percent of fine-fraction weight	-

Field	Units	Data type	Notes	LMH 25 section
Fine sand Very fine sand	(< 2-mm) weight		represented by the 0.25 - 2 mm (medium, coarse, and very coarse), 0.1 - 0.25 mm (fine), and < 0.002 mm (very fine) sand sub-fractions. These 3 values may contain decimals, and together with the silt and clay values, must sum to 100.	
OM content	% fine-fraction (< 2-mm) weight	numeric	This is optional to include, and a poor SNR will be assumed if neither OM nor nitrogen are provided. This value can be estimated if not measured. An OM-poor layer, such as most mine wastes, will have less than 1% OM, while an OM-rich layer, such as topsoils, will have approximately 5-10% OM. There is no effect on model calculations past 8% OM. See Section 3.4 of this user guide.	-
Nitrogen	% fine-fraction (< 2-mm) weight	numeric	This is optional and only needs to be included for layers that have analytical lab results. See Section 3.4 of this user guide.	-

The soil input data screen for the QEA tool is shown in Figure 4-2.


Data format

Detailed sand-silt-clay

	Horizon/ layer	Material type	Upper depth (cm)	Lower depth (cm)	Compaction	Coarse fragments, > 2 mm (% wt. total)	Coarse-med. sand, 0.25 - 2 mm (% wt. fine-fraction)	Fine sand, 0.1 - 0.25 mm (% wt. fine-fraction)	Very fine sand, 0.05 - 0.1 mm (% wt. fine-fraction)	Silt, 0.002 - 0.05 mm (% wt. fine-fraction)	Clay, < 0.002 mm (% wt. fine-fraction)	Organic matter (% wt. fine-fraction)	Total Kjehdahl nitrogen (% wt.)
1	TS	Cover soil	0.00	20.00	Normal	30.10	31.20	21.50	16.70	22.50	8.10	6.70	0.27
2	US	Coarse coal rejects	20.00	50.00	Normal	84.30	58.00	18.00	3.10	15.20	5.70	2.10	0.11
3	LS1	Waste rock	50.00	60.00	Normal	93.20	68.30	14.80	4.70	8.90	3.30	0.40	0.08
4	LS2	Waste rock	60.00	100.00	Normal	95.60	70.10	14.20	3.90	8.10	3.70	0.20	0.03

1. Confirm values

2. Save data

Figure 4-2. The QEA app soil data input screen for detailed quantitative lab data with sand size subclasses.

4.1.3. Climate settings

Field	Data type	Notes
Time period	drop-down	The time period to be used for estimating climate parameters. Historical time periods of 1961-1990, 1981-2010, and 1991-2020, as well as future time periods of 2011-2040, 2041-2070, and 2071-2100 can be selected.
Climate change intensity	drop-down	Only required if a future climate scenario is selected. This will have no effect if 1961-1990, 1981-2010, or 1991-2020 time periods are selected. The three intensities are based on representative concentration pathways (RCP) used by the United Nations Intergovernmental Panel on Climate Change (IPCC) to model future greenhouse gas concentrations. See Sections 0 and 3.7.2 of this user guide.
Disable shifting of edatopic grids	drop-down	Recommended to select 'No' as this allows you to see the site series projection on both the adjusted and published edatopic grids in the outputs tab. Selecting 'Yes' will run only the published grid version. As explained in Section 3.7, the QEA system incorporates climatic effects of site location, slope and aspect, and climate change into site series classifications via shifting edatopic grids.
Override grid adjustment for site location?	drop-down	Recommended to select 'No'. If you disabled shifting of edatopic grids in the step above, then this setting will have no effect. This option selects whether the relative position of site series on edatopic grids will be shifted to reflect the difference between climate parameters estimated for a given location and the mean of climate parameters for its entire subzone for the selected time period. This reflects the fact that edatopic grids are designed to represent an entire subzone, while a given location may be, for example, hotter or cooler, or drier or wetter than the mean for its subzone. See Section 3.7 of this user guide for more details. Selecting 'Yes' for this option does not affect the selections in the fields above and below - it will only disable edatopic grid adjustments made based on latitude, longitude, and elevation.

Field	Data type	Notes
Override grid adjustment for slope and aspect?	drop-down	Recommended to select ‘No’. If you disabled shifting of edatopic grids in the step above, then this setting will have no effect. This option selects whether the relative position of site series on edatopic grids will be shifted to reflect the difference between climate parameters estimated for a given slope-aspect position and the climate parameters for a flat site at the same location. This reflects the effect that slope and aspect have on the climatic conditions of a given location; specifically temperature and incoming radiation, which are the primary drivers of potential evapotranspiration, which, in turn, is a key determinant of site water balances and ASMR classifications. See Section 3.7 of this user guide for more details. Selecting 'Yes' for this option does not affect the selections in the fields above - it will only disable edatopic grid adjustments made based on slope and aspect.
Site-specific climate data	drop-down	It is possible to overwrite climate data internal to the QEA model with climate data collected at sites. However, this option is not implemented for online usage. Please contact Trevor Baker at IEG (tbaker@iegconsulting) to discuss.

The climate settings input page for the QEA tool is shown in Figure 4-3.

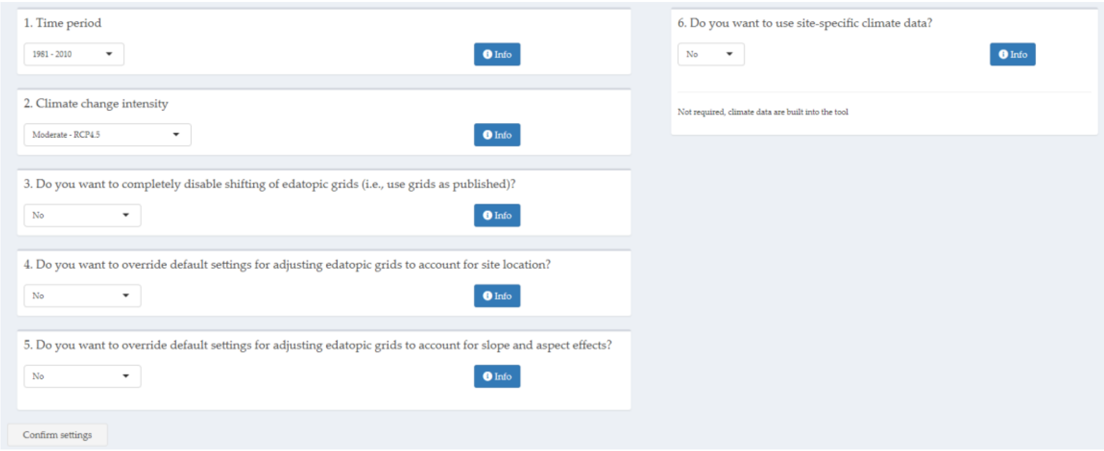


Figure 4-3. The QEA app climate settings input screen.

4.2. OUTPUTS

The QEA tool provides the user with four types of information (Figure 4-4):

1. **Site characteristics –** data are provided for estimated moisture regime and ecosystem (site series) classifications, as well as hydrological performance of the site's surface soil (upper metre).
2. **Soil characteristics –** the tool shows estimated bulk densities for each layer, AWSC values of each material on a per-metre basis, depth-weighted AWSC contributions to profile AWSC by each soil layer, any layering effects that enhance profile water storage, and overall profile AWSC. This soil-profile estimate is used to drive the site characteristics discussed above.
3. **Projected edatopic-grid position** – the model indicates the projected probable position of the site on the edatopic grid for the site's biogeoclimatic subzone/variant, which matches the site series estimates given in the 'Site characteristics' window. The size of the point is a rough estimate of the uncertainty in these predictions or plus or minus one half of an RSMR and SNR class.[20] This site-series projection can be used directly for revegetation planning and estimating capability for biophysical end land uses such as wildlife habitat and commercial forestry.
    - The 'shifted edatopic grid' tab shows the site series as projected using the climate-based grid-shifting routines outlined in Section 3.7.1. This output reflects IEG's best understanding of the relationships between soil, climate, edaphic conditions, and resultant ecosystems.
    - The 'published edatopic grid' tab shows the grid without any grid-shifting applied (i.e., exactly as published). The marked point indicating the site series classification will always be positioned on the same site series as the shifted grid but is usually in a different position on the RSMR axis. This is because the site series classification is determined by water-balance characteristics (i.e., ASMR position as derived from AET_{max}:PET) (Section 3.7.1). This output is mainly for illustrative purposes to understand the predicted site series relative to the original published edatope.
4. **Monthly water-balance graph –** the water-balance parameters provided in the 'Site Characteristics' table on an annual and growing-season basis are summarized on a monthly basis in a graphical format in order to allow the user to better understand the outputs of the water-balance model.

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[20] Work is ongoing to better quantify the uncertainty in these estimates and will be part of future app updates.

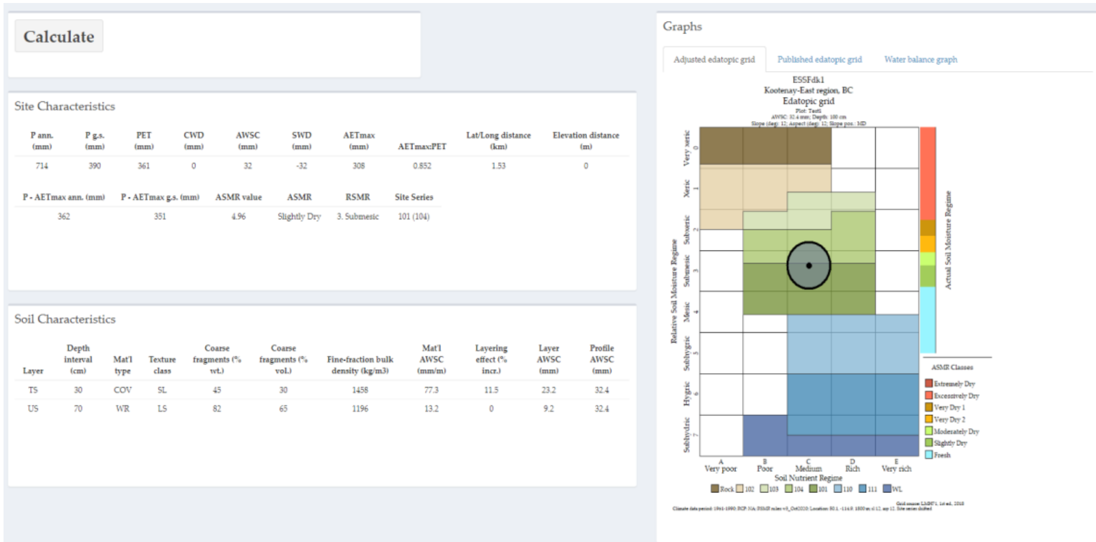

Figure 4-4. The QEA app results screen.

Further detail on the QEA site ecohydrological projections is provided below:

- **P**$_{ann.}$ – annual precipitation.
- **P**$_{g.s.}$ **–** growing-season precipitation. Calculated based on months in which mean air temperature is above 0° C.
- **PET** –annual potential evapotranspiration. The amount of water that would be lost to evapotranspiration if soil water supply were not limiting.
- **CWD** – growing-season climatic water deficit. CWD = PET – P_{gs}. Reflects the amount by which precipitation volumes fall short of meeting atmospheric demand for water. Positive numbers indicate a deficit, negative numbers indicate a surplus.
- **AWSC** – total AWSC for the site as shown in detail in the 'Soil Characteristics' box.
- **SWD –** growing-season soil water deficit. SWD = CWD – AWSC = PET - P_{gs} - AWSC. Reflects the amount by which precipitation volumes plus stored soil water fall short of meeting atmospheric demand for water. Positive numbers indicate a deficit, negative numbers indicate a surplus.
- **AET**$_{max}$ **–** theoretical maximum potential growing-season evapotranspiration given soil and climate conditions. AET_{max} assumes the presence of a fully developed vegetation cover, which is unlikely in the first 20 years of reclamation and may never be achieved on some sites with suboptimal revegetation. This value is useful to establish an upper limit of expected evapotranspiration volumes for use in wider site water-balance modelling.
- **AET**$_{max}$**:PET –** the ratio of the theoretical maximum evapotranspiration and potential evapotranspiration. This is used for ASMR classifications.

- **Lat/Long distance** – the horizontal distance of the study site to the nearest climate point in the database used by the QEA model. If this value is greater than ~ 3 km, then climate data should be added to cover your study area. Contact IEG (tbaker@iegconsulting.com) to discuss this.
- **Elevation distance** – the vertical distance of the study site to the nearest climate point in the database used by the QEA model. If this value is greater than ~ 200 m, then climate data should be added to cover your study area. Contact IEG (tbaker@iegconsulting.com) to discuss this.
- **P_{ann} - AET_{max} –** the difference between annual precipitation and the theoretical maximum annual evapotranspiration (AET_{max}). This is a simple model of excess water in the surface water balance and represents the minimum volume of water expected to annually report as run-off and/or net percolation.
- **P_{gs} - AET_{max} –** the difference between growing-season precipitation and the theoretical maximum annual evapotranspiration (AET_{max}). This is a simple model of excess water in the surface water balance and represents the minimum volume of water expected to report during growing seasons as run-off and/or net percolation.
- **ASMR value** – the decimal position of the site on the actual soil moisture regime scale starting at 0 for Extremely Dry (AET_{max}:PET = 0), 1 for Excessively Dry, and so on (Table 2-2).
- **ASMR** – the projected actual soil moisture regime for the site. ASMR is an estimate of the degree to which an ecosystem is constrained by water limitations (Sections 2.4 and 3.6; Table 2-2).
- **RSMR –** relative soil moisture regime estimate as per the QEA model (Sections 2.2 and 3.3; Table 3-3).
- **Site Series** – the site series (or ecosites) estimated to occur on the site based on RSMR and SNR classifications made by the model. Site series codes given in brackets are secondary classifications that portions of the site might be expected to resemble.

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