Conceptualizing Water Movement in the Boreal Plains

Implications for Watershed Reconstruction

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Table of Contents

Guide for Reader

The aim of this document is to provide guidance on landscape reconstruction based on the results of more than a decade of research in natural forest systems on the Boreal Plains. It is hoped that the synthesis will prove useful to a range of audiences—from general readers interested in the broader concepts and implications of the research to practitioners who require technical details on designing a landscape or directing day-to-day reclamation operations in the field. To help direct readers to sections of highest personal interest, the document is structured and written in a "telescoping" pattern, flowing progressively from broad overviews to more specific and detailed discussion.

The document can be grouped into five main sections (see Figure G.1).

Section A, the Executive Summary, is the **highest-level synthesis** of the conceptual model. It contains the key learnings from the research and their overarching implications for landscape reconstruction.

Section B provides **the research context:** a brief history of the research, focal questions, and locations and descriptions of the study sites.

Section C provides a **synthesis of the core concepts** on which the new conceptual model of water flow in the Boreal Plains has been developed. Section C.1 introduces the structure of the body of the document, which pivots around the hydrologic context, composition, and connectivity, and the water balance as discussed in the Executive Summary. Section C.2 summarizes the basic concepts and key principles and develops the core of the conceptual model. In general, Section C provides the fundamental basis required to develop plans and understand water flow in these landscapes using this new conceptual model.

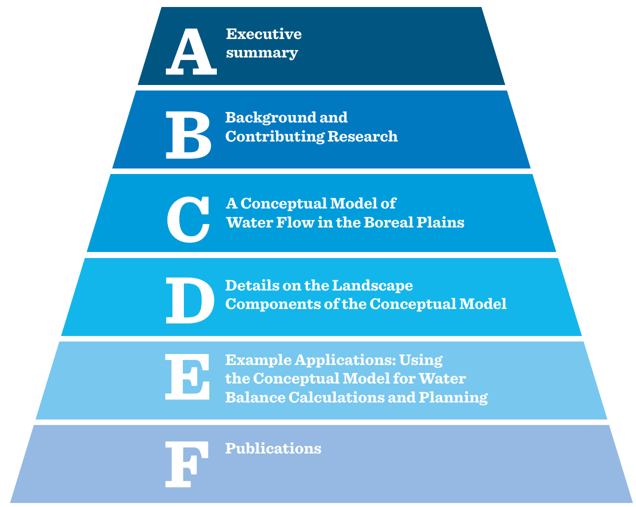
Section D describes the **details of key components of the landscape.** This section fleshes out the underpinnings of the basic concepts and provides details of landscape features.

Section E provides **examples** of how to approach a water balance in these landscapes, some key numbers that can be used to guide the landscape practitioner, a summary of how the information can be used in landscape reconstruction, and some outstanding research needs. This section relies heavily on the details described in Sections C and D.

One core concept arising from the research is that in landscapes there are repeating hydrologic elements and processes that occur at all scales. Therefore, one has to telescope up and down continually to understand the hydrologic behaviour observed at the various scales. Similarly, important concepts and connections run through the document and reappear in numerous sections. Therefore, for the person who reads through the document from beginning to end, repetition of these key ideas in each section will be obvious.

The reader will also note that each section of the document contains a summary of key concepts from the research in natural systems. The implications of these key concepts for landscape reconstruction are reported at the end of each section. This approach is meant to illustrate, as clearly as possible, how the authors arrived at their recommendations for landscape reconstruction based on research predominantly conducted in natural boreal systems. The statements in the body of the document are based on evidence/data collected over a decade of research, most of which may be found in published papers, listed in Section F. The implications for landscape reconstruction are suggestions for consideration, based on the research findings.

FIGURE G.1
Structure of Document.



Executive Summary

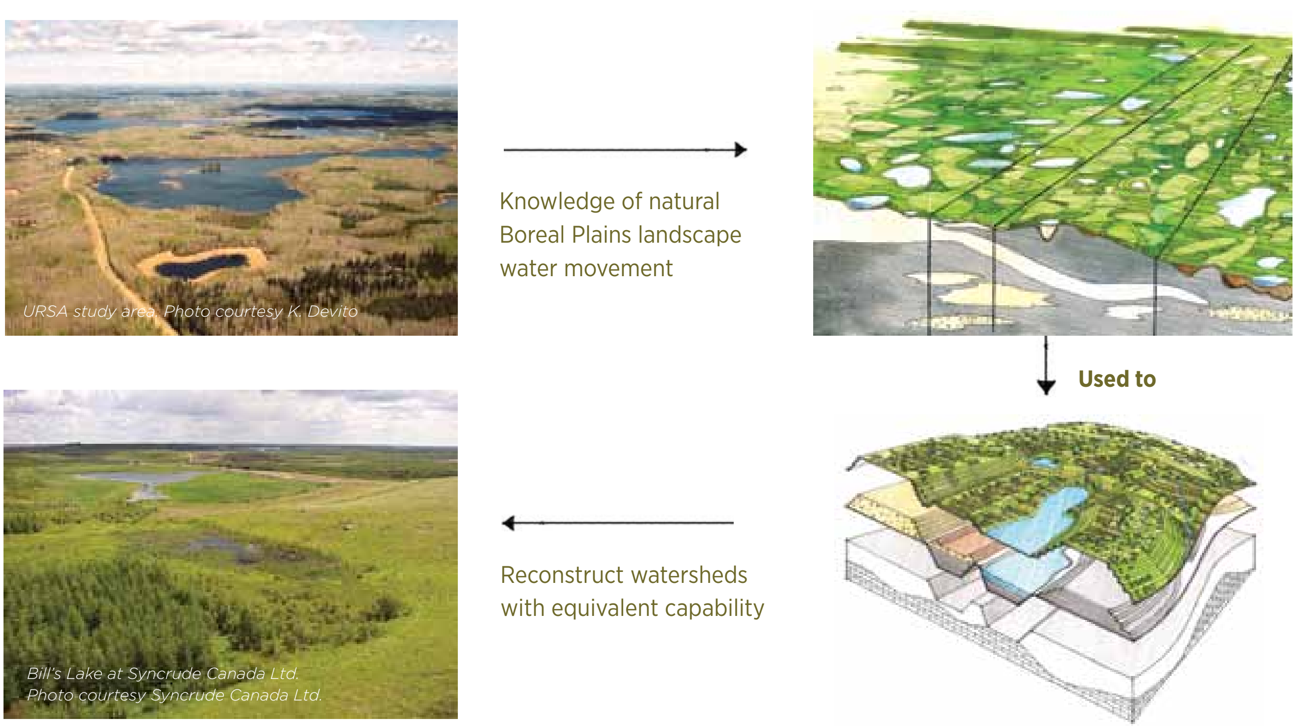
A

Executive Summary

One of the challenges for oil sands companies operating in the Boreal Plains is developing reclamation designs that lead to self-sustaining landscapes consisting of a mosaic of interacting forestlands, wetlands, streams, and lakes. In pursuit of this outcome, operators assume that if they correctly understand the characteristics and processes of natural systems and can mimic them in the design parameters, they can successfully reconstruct a self-sustaining boreal landscape.

A key overarching reclamation research question is thus: What are the appropriate design parameters for reconstructing a boreal landscape that will meet the requirement of equivalent capability? This report synthesizes the results of a series of multi-year studies of the hydrology of natural, self sustaining ecosystems in the Boreal Plains region of the Western Boreal Forest which is similar in its geologic and climate characteristics to those found in the minable oil sands region. The report also describes the implications of those results for landscape reconstruction.

FIGURE A.1
Using the Understanding of Natural Landscapes in the Design of Reconstructed Landscapes



Required Shifts in Landscape Design Concepts

Effectively managing or reconstructing watersheds in the Boreal Plains requires an accurate conceptual model of the hydrologic function of this landscape. Through comprehensive, long-term field studies, the HEAD research program (and associated research) has parameterized ranges of hydrologic variability of Boreal Plains forest and wetland ecosystems, and has identified key hydrologic processes and features of the landscape that have led to ecosystem diversity and integrity across a wide range of landscape scales. From this work, a new conceptual model of this landscape has been developed. The model, in turn has important implications for future work on reconstructed landscapes (Figure A.1).

This model is fundamentally different from previous conceptualizations. Rather than precipitation and runoff, the focus shifts to soil moisture storage, evapotranspiration, and groundwater recharge as the dominant hydrologic processes that need to be considered in all assessment, management, and reconstruction activities. This has direct and important implications for models currently employed for closure planning. For example, many current hydrologic models are able to match runoff volumes using long-term averages. However, they do not adequately or accurately represent key processes that lead to groundwater recharge, runoff, or which produce the threshold hydrologic responses typical of the Boreal Plains. This is largely because they are based on landscape processes typical of other regions of Canada or the U.S. where precipitation and runoff processes dominate hydrologic processes.

The implications of this difference in conceptualization are profound. Although precipitation-runoff models may be useful in projecting average or total volumes of water in aquatic systems, they cannot currently be used to make statements about the life cycles of wetlands or the water quality in groundwater and in receiving water bodies (e.g., lakes or rivers). Salt flushing, for example—that is, the redistribution of salt/nutrient compounds in the Boreal Plains landscape—is a critical performance indicator in reconstructed systems (wetlands or forestlands) in the oil sands region. It is fundamentally linked to surface and groundwater movement. The wetting and drying cycles will profoundly influence the redistribution and timing of release of the compounds, and these cycles are not adequately accounted for.

A more accurate modelling of watersheds in Western Boreal Plains landscapes requires:

- An accurate conceptual model that focuses on evapotranspiration, soil storage, and groundwater, rather than the conventional focus on precipitation and runoff
- Explicit capture of seasonal and between-year climate variability, with calibration and validation targets of less than one year
- Calibration targets based on the hydrologic response in a particular year, and season within a year, to adequately deal with the effects of distribution and timing of precipitation on antecedent moisture conditions
- An appropriate delineation of the hydrologic response areas and hydrologic units (which may be uncorrelated with topographically defined watershed boundaries) in order to correctly identify the sinks and sources of water in the catchment(s) being modelled or gauged. This delineation also fundamentally controls the sinks and sources of compounds of interest (such as salts, nutrients, and organics).

  Implications of this research to watershed modelling are discussed in more detail in Section C.3.

The New Conceptual Model

The underpinnings of the new conceptual model are summarized below.

The existing natural diversity and cycling observed in ecologic communities (terrestrial and aquatic) in the Boreal Plains have evolved within the HYDROLOGIC CONTEXT of:

- A climate with a water deficit (sub-humid) and pronounced annual (seasonal) and decadal (inter-annual) cycles of water availability

  Interacting with

- A deep, heterogeneous geologic landscape, composed of fine-textured, coarse-textured, or veneer type glacial deposits, which can store large volumes of water but varies greatly in storage and transmission properties.

In the Boreal Plains, the interaction between the sub-humid climate and the geology characterized by a large water-storage capacity leads to seasonal (annual) and inter-annual (decadal) soil, landform, and landscape-scale wetting and drying cycles. These cycles control ecological functions and the hydrologic response (timing and intensity) to events such as precipitation and landscape disturbance and management. It is necessary to comprehend the variability in surface materials in order to understand the antecedent moisture conditions (location of the soil, landform, and landscape in seasonal and decadal scale wetting/drying cycles) and to understand and model hydrologic responses (such as runoff) in these landscapes.

Interaction between the sub-humid climate and a heterogeneous geology characterized by a large water-storage capacity yields a HYDROLOGIC COMPOSITION comprising a mosaic of landscape components. These can be functionally divided into hydrologic response areas (HRAs) and Wetland and Forestland hydrologic units (HUs) which appear at a range of scales and have specific characteristics enabling them to perform the dual hydrologic functions of:

i. Storing water and providing or redistributing water to the landscape through the drought cycles and dry periods,

ii. Facilitating the transmission of large amounts of water through the landscape in wet cycles or wet periods.

Forestland HUs and open water bodies act as water sinks in this water-limited landscape, while layered Wetland HUs with no or little standing water are "sources" (runoff-generating areas) of water. The area of "connected" Wetland HUs is the effective surface water catchment area for the landscape most years. Accurately delineating the HRAs and HUs (which may be uncorrelated with topographically defined watershed boundaries) will help to correctly identify the sinks and sources of water in the catchments being modelled or gauged. The accurate delineation of these units will also improve understanding of the movement of other compounds of interest (salt, nutrients, and organics) in the reconstructed landscape.

These landscape components exist on a wide range of scales and are HYDROLOGICALLY CONNECTED at multiple spatial and temporal scales. The multiple scales of appearance and multiple scales of hydrologic connection of the components in the landscape, along with their unique characteristics, underpin the hydrologic functionality and diversity of the Boreal Plains.

How To Use the New Conceptual Model

There are several critical factors to consider in order to understand the source and flow path of water at any point in the landscape or when designing water fluxes at any point in the landscape. This research indicates that these factors must be addressed in a hierarchical order[1].

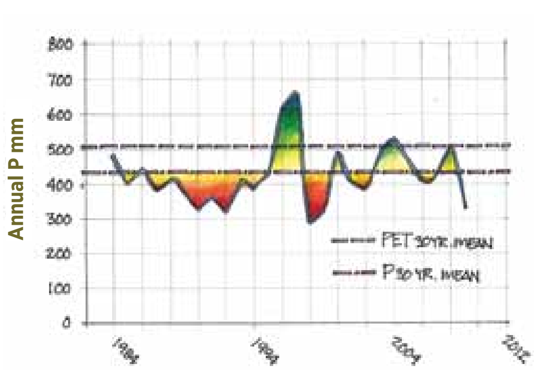
As the hydrology of a system (on any scale, from soil to landform to landscape) can best be understood if each of the factors is considered in sequence, research indicates that these factors must be addressed in a hierarchical order. The implications of this conceptual model are outlined in Figure A.2. and Table A.1.

STEP 1

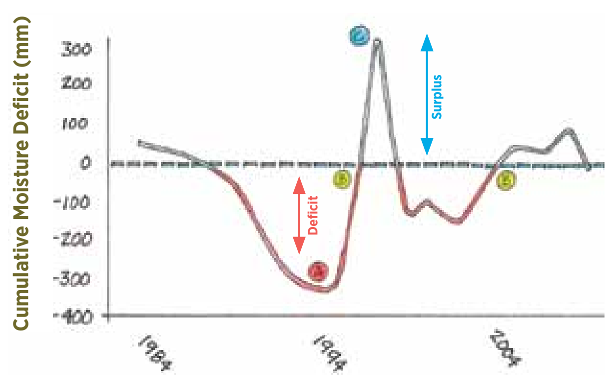
Climate
Explicitly recognize the overriding influence of climate.

STEP 2

Water Demand
Determine how much water is needed and the required residence times in different parts of the landscape through time.

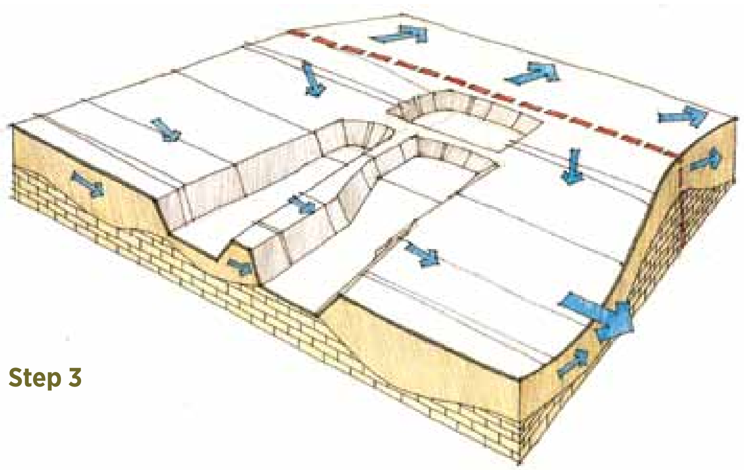


Step 1

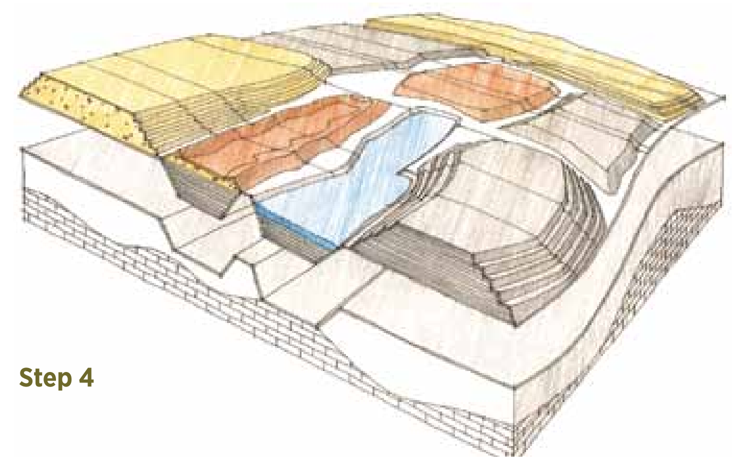


[1]*This hierarchical classification first appeared in Devito et al. (2005) to generalize dominant controls on water cycling and indices to define effective Hydrologic Response Areas. It is applicable in the Boreal Plains, but is also applicable across continents, and is valuable when comparing results from other studies elsewhere in the region or in Canada. The table should be used in the specified order when developing a conceptual framework to determine the dominance of specific components of the hydrologic cycle, and to determine the scale of interaction for a particular scenario.*

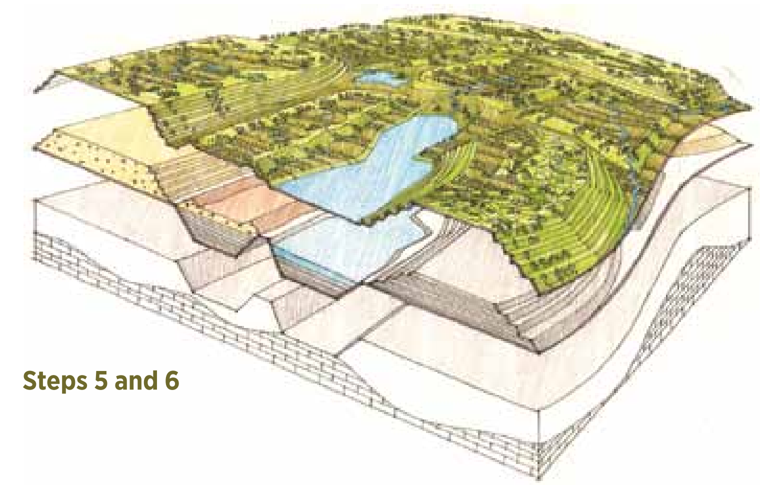
FIGURE A.2
Using the Conceptual Model to Design a Reconstructed Landscape



Step 3



Step 4



Steps 5 and 6

Recheck water balance for each HRA, landscape

Recheck water balance given HU selections

Recheck water balance

STEP 3

Post-mining, Pre-reconstruction Surface
Determine the landscape or regional scale water "outlets" or collection points in the post-disturbance landscape. This will determine the scale of water flow systems feeding the "outlets" or collection points (e.g., streams, lakes) in question.

STEP 4

Macro-scale Drainage and Hydrologic Response Areas (HRAs)a.
Steps 4a and 4b identify thenew macro-scale drainage system and or the first of the hydrologic building blocks (HRAs).

a. Identify the new macro-scale drainage system and/or assemble the "new" surficial geology (the reconstructed landforms) based on material type and hydrologic tendency. Identify the first of the hydrologic building blocks—the HRAs.
b. Determine how much and when water is needed for each HRA. Considering the hydrologic tendencies for each HRA, calculate the water balance through time for the HRA and the landscape. Determine if those balances meet the landscape-scale water volume, water quality, and timing requirements defined in Step 2

STEP 5

Hydrologic Units
Identify the appropriate ratio of HUs (the second type of hydrologic "building block") to overlay on each HRA.

STEP 6

Arrangement and Connectivity of HUs
Build and connect the HUs at a range of scales on each landform.

a. Determine the appropriate arrangement and connectivity of HUs and assemble a network of Wetland and Forestland HUs at the meso- and micro-scale considering water delivery required through time for each HRA and for the landscape.
b. Construct the Wetland and Forestland HUs on each HRA incorporating the required features (e.g., clay lenses, active layers, soil depths and characteristics, proximities of HUs as discussed in Sections D.2 to D.5) as a function of location in the drainage system to enable water storage and transmission as per goals stipulated.

STEP 7

Monitor to track recovery
Anticipate trajectory at reclamation certification. This step is unique to the design process.

TABLE A.1
Using the conceptual model in the design of a reconstructed landscape: How the steps link to the hierarchical factors controlling hydrologic behaviour.

Step	Summary of Step	Factor	Range of Factors		Scale
1	Explicitly recognize overriding influence of climate.	**A** Climate	**Dry, arid to sub-humid** • Runoff (R) poorly correlated with precipitation (P) • Storage or uptake dominates • Tendency for vertical flow	**Wet, humid (P > PET)** • Runoff (R) closely correlated with precipitation (P) • Runoff dominates • Tendency to lateral flow	**Continental to local** 1,000's of km to 10's of m
2	Determine how much water is needed, and the required residence times for water in different parts of the landscape through time.	There is no related factor. This step is unique to a design and reconstruction process			
3	Determine the landscape or regional scale water "outlets" or collection points in the post-disturbance landscape by evaluating post-mining, pre-reconstruction surfaces.	**B** Geologic material not disturbed by mining i.e., post-mining, pre-reconstruction surface	**Permeable bedrock** • Intermediate to regional flow systems • Lack of topographic control on direction of local flow • Vertical flow dominates in surface substrate	**Poorly permeable bedrock** • Characterized by local and predominantly surface flow • Topographic control on direction of local flow • Lateral flow dominates in surface substrate	**Continental to regional** 1,000's of km to 100's of km
4	a. Identify the new macro-scale drainage system and/or assemble the "new" surficial geology (reconstructed landforms) based on material type and hydrologic tendency. b. Determine how much water is needed, and when, for each hydrologic response area (HRA).	**C** Reconstructed Landforms or Hydrologic Response Areas (HRAs)	**Deep substrates** • Intermediate to regional flow systems **Coarse texture** • Vertical flow • Deeper sub-surface flow **Spatially heterogeneous deposits** • Complex groundwater systems • Groundwater flow modelling important	**Shallow substrates** • Local flow most probable **Fine texture** • Lateral flow • Depression storage, surface/shallow sub-surface flow **Spatially homogeneous deposits** • Simple groundwater flow systems • Surface flow modelling important	**Regional to local** 100's of km to 10's of m
5	Identify the appropriate ratio of hydrologic units (HUs) to overlay on each hydrologic response area (HRA)	**D** Soil Type and Depth	**Forestland mineral soil** • Sub-surface flow dominates • Slow flow generation (matrix flow), and macropore flow **Storage** • Deeper with larger water storage potential **Transpiration** • Deep roots access stored water • Actual ET ≥ PET	**Wetland organic soils** • Return flow, surface overland flow pathways dominate • Quick flow generation (return/saturation overland flow) **Storage** • Shallower with small water storage potential • Lower specific yield of organics and compression leads to saturation **Transpiration** • Shallower roots limit access to stored water • Actual ET < PET	**Local to regional** Metres to 1000's of m
6	a. Determine the appropriate arrangement and connectivity of HUs and assemble a network of these at the meso and micro scale. b. Construct the Wetland and Forestland HUs on each HRA incorporating the required features as a function of location in the drainage system	**E** Topography and Drainage Network	**Gentle slope** • Disorganized, inefficient drainage networks • Large groundwater recharge • Small, variable runoff yield	**Steep slopes** • Organized, efficient drainage networks • Small groundwater recharge • Large, uniform runoff yield	**Local to regional** 10's of m to 1,000's of m
7	Monitor to track the recovery trajectory and to anticipate the trajectory at reclamation certification.	There is no related factor. This step is unique to the design and reconstruction process			

Summary of the Implications of the Research

The implications of key findings in the research are presented in each of the subsequent sections of this document. However, they may be summarized as:

The climate of the oil sands region is characterized by a long term moisture deficit. The amounts of precipitation received cannot be controlled, however evapotranspiration and water redistribution can be managed by managing the characteristics, arrangement and connectivity of the geology, soils and vegetation which together act as hydrologic "building blocks" of the landscape. The designer or land manager must consider and capitalize on the intermittent periods, annually and decadally, when excess water is available, to capture these moisture surpluses, conserve that water and redistribute it through the landscape during the extended drought periods.

This can be accomplished by identifying and arranging the hydrologic building blocks at the coarse (HRA) and finer (HU) scales and constructing them with features for water conservation and redistribution. There are trade-offs in volumes and timing of water movement in landscapes as a function of the proportions and connectivity of Wetland and Forestland hydrologic units. Landforms should be developed with abundant meso and micro scale landform heterogeneity in materials and topography to influence amounts of water storage and subsurface flow. Water quantity and quality goals should be defined for the various hydrologic building blocks and the connectivity of those blocks must be considered explicitly early in the design cycle in order to achieve water supply and redistribution goals and equivalent capability targets at the various scales from landform to landscape.

Background and Contributing Research

B

Background and Contributing Research

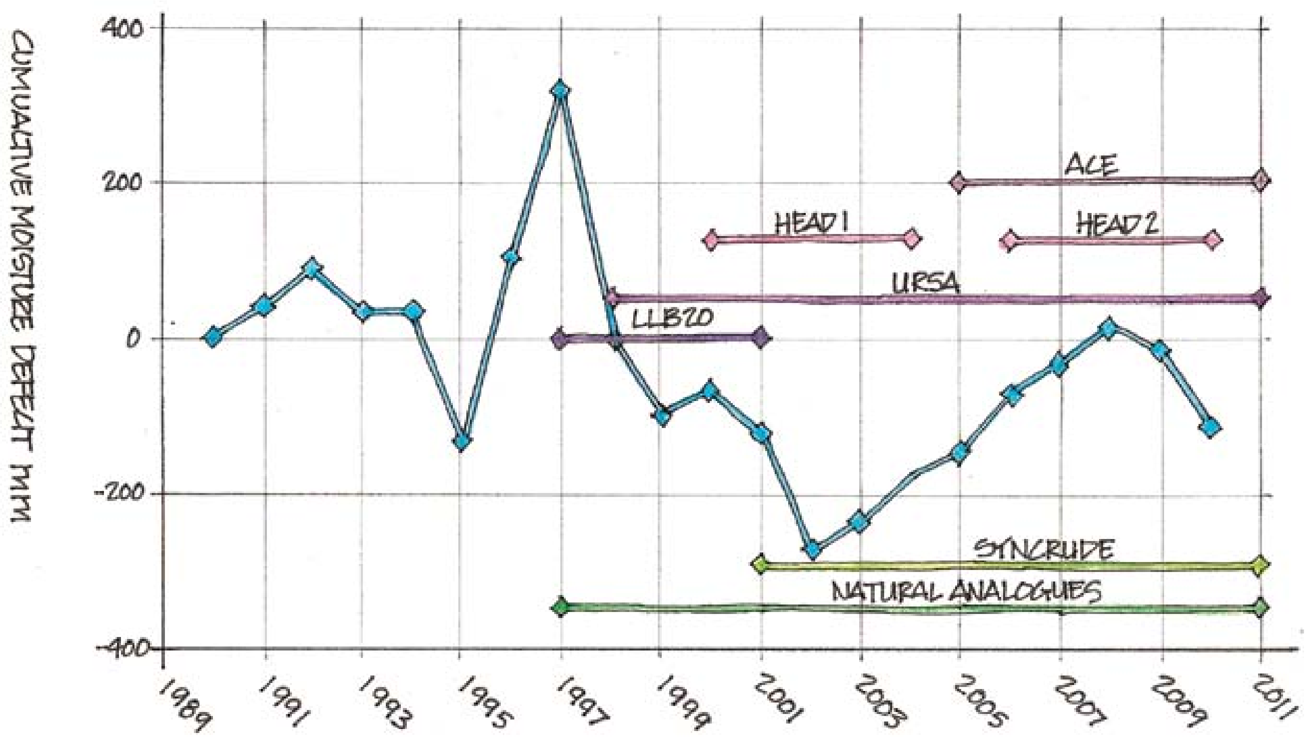
This document summarizes research conducted from 1997 through 2010 on the ecohydrology and hydrogeology of the Boreal Plains region of the Western Boreal Forest, and the potential implications of that work to landscape reconstruction in the oil sands region. A sustainable boreal landscape can only be successfully reconstructed if the characteristics and processes of these natural systems are correctly understood and mimicked in the design parameters. **The primary focus of much of the research and this synthesis is on the hydrologic framework influencing water storage and transfers in these landscapes.**

Through comprehensive, long-term field studies, this suite of research has parameterized ranges of variability associated with the hydrologic functions of boreal forest and wetland ecosystems, and has identified key hydrologic processes and features of the landscape that have led to ecosystem diversity and resilience across a wide range of landscape scales. From this research, critical insights were gained into the influence of the spatial arrangement of landforms, timber harvesting, and road networks on local and regional ecohydrologic and hydrogeologic systems. In addition, the correlation between water balances and vegetation succession and variation in climatic cycles has led to the development of hydrologic recovery models with key functional relationships (with appropriate indices and detail for scales of concern) relevant to the Boreal Plains.

Given that successful closure design and reclamation pivots on water management and reconstruction of hydrologic processes, the results of this fundamental ecohydrology and hydrogeology research can inform the development of closure design parameters, landscape reconstruction and reclamation practices, closure and cumulative effects models, and reclamation certification criteria.

FIGURE B.1
Research Project Timelines in Context of Climate Cycles on the Boreal Plains

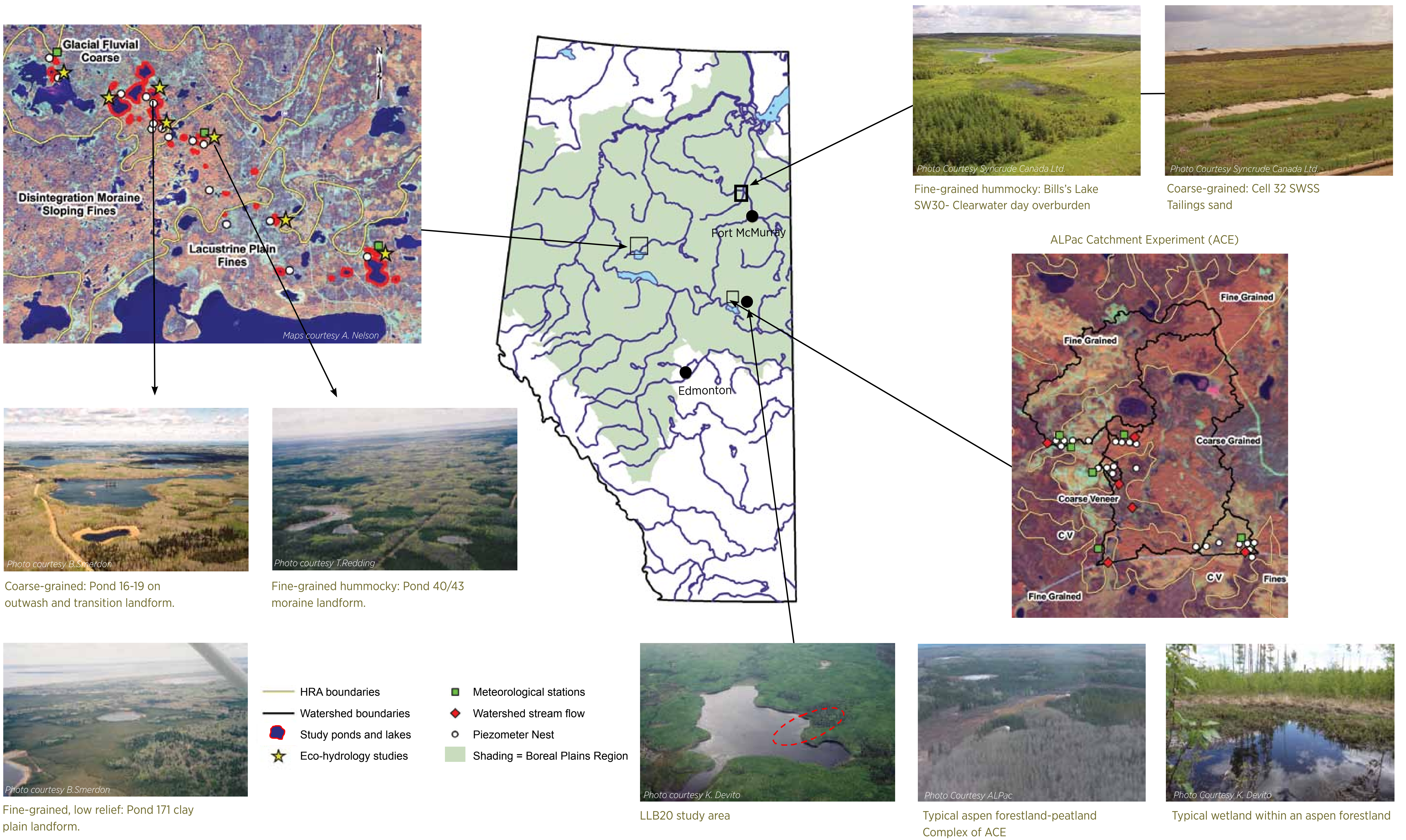
Shown is the cumulative difference between long term average and annual precipitation showing the cycle between extended periods of near average and below average precipitation punctuated by a wet period. The field research projects on which this synthesis is based spanned the range of climate cycles. These cycles result in wide range of local and regional hydrologic connectivity and response. The importance of this will become evident in subsequent sections.



Year

FIGURE B.2
Location of Study Areas in the Boreal Plains of Alberta

Shown is the transect of study pond-wetland-forest sequences across different glacial landforms at URSA, and harvested and non-harvested watersheds at ACE and the small zero order LLB20 watershed relative to the oil sands region.



Research Project Objectives

The overarching research objectives were to develop an understanding of how climate and geology interact with water and energy flow in Boreal Plains landscapes and to understand how land management is affected by this interaction.

The research was undertaken across central and northeastern Alberta, comprising several multi-year projects and funded by a range of partners. These projects, the time lines illustrated in Figure B.1, span the range in climate cycles and hydrologic responses characteristic of the Boreal Plains eco-region.

The projects under which the majority of the research was conducted were:

1. Hydrology Ecology and Disturbance of Western Boreal Forest (often referred to as HEAD 1)
2. Hydrology, Ecology and Disturbance in the Western Boreal Forest, Phase 2 (HEAD 2): Forest Harvest Impacts and Hydrologic Recovery

Early work focused on identifying the natural variation in hydrology, chemistry, and biology of pond-wetland-forestland sequences across a range of glaciated landforms characteristic of the sub-humid boreal forest in Alberta. The understanding of the hydrologic linkages and natural variability of the key processes led to the development of hydrogeological framework for conducting, interpreting, and extrapolating research for watershed management across the Western Boreal Forest.

HEAD 2 built on the knowledge gained from the early work and HEAD 1, and focused both on issues of scale and on the experimental manipulation of studied watersheds to test hypotheses regarding key hydrologic drivers and the effects of management initiatives (including harvesting and road construction) on the key ecohydrologic and hydrogeologic processes. HEAD 2 enabled the refinement of conceptual models developed in HEAD 1, and resulted in the testing and development of numerical models to quantify observed phenomena.

The specific study and project objectives can be found in the NSERC final reports and in the numerous publications. As of the date of publication of this document (Fall 2012), 6 Post-Doctoral Fellows, 13 PhD students, and 24 MSc students completed work on these research topics under the HEAD 1 and HEAD 2 programs alone. In addition, over 40 undergraduate students participated in the research. Over 75 published research papers and reports have been generated and are listed in Section F.

The Study Areas

The summaries contained in this synthesis originate from data collected from study sites across central to northeastern Alberta in the western section of the Boreal Plains ecozone, which is also the location of the Athabasca Oil Sands Region (Figure B.2).

The combination of climatic and geologic characteristics of the Boreal Plains is unique in the Canadian Boreal Forest, when compared to the adjacent Boreal Shield to the east, the Foothills and Cordillera regions to the west, and the subarctic Boreal to the north. This uniqueness was the impetus for this suite of research in northern Alberta.

The climate at each study site and the oil sands region is characterized by average long-term annual precipitation that is equal to or lower than average annual open-water evaporation. Outwash, moraine and lacustrine deposits characterize the geology. The high density of wetlands, ponds, and shallow lakes in the Boreal Plains region reflects complex interactions with shallow-surface and groundwater systems.

Each study area is characterized by wetlands dominated by black spruce (*Picea mariana* (Mill.) B.S.P.) and tamarack (*Larix laricina* (Du Roi) K. Koch), while the forestlands are characterized by trembling aspen (*Populus tremuloides* (Michx.)) or jack pine (*Pinus banksiana*) communities. Most of the detailed water-balance data were collected in aspen-dominated forestland communities and in a range of wetland communities.

Early work was conducted at a small catchment near Lac La Biche, the LLB20 Research Catchment (1997 to 2001). Research focused on hydrology and geochemistry, and the interaction between surface, groundwater, and atmosphere within a 53 ha zero order catchment draining into Moose Lake watershed (Figure B.2).

While this was still underway, the research was expanded to include large catchments where landform-scale hydrologic processes (from a range of landforms) could be studied.

Studies began at the Utikuma Region Study Area (URSA) (56° N, 115° W) near Red Earth Creek from 1998 and continue to the present day (Figures B.1 and B.2). The URSA is located approximately 150 kilometres south of the discontinuous permafrost zone, 300 kilometres northeast of Edmonton, and 250 kilometres southwest of Fort McMurray.

The URSA is a 50-kilometre transect encompassing pond-wetland-forestland sequences across the major glacial deposit-types characteristic of the Western Boreal Plains (coarse sand outwash, fine-grained till moraines, and lacustrine clay Plains). Studies include landscapes that range from isolated headwater systems to large regionally connected systems.

Studies at the Al-Pac Catchment Experiment (ACE) (55° N, 113° W) were initiated in 2005 and continue to the present day near Lac La Biche (Figure B.1 and B.2). ACE is located about 200 kilometres northeast of Edmonton and 200 kilometres south of Fort McMurray. The ecohydrologic and hydrogeological studies included harvested and non-harvested second-order (10 - 20 km^2) and zero-order (less than 1 km^2) watersheds composed of a range of glacial landforms.

In addition, commencing in 2002, these natural analogues were compared to two reconstructed landforms at Syncrude Canada Ltd.'s Mildred Lake operation: Bill's Lake at South Bison Hill (SW30) and the Southwest Sand Storage area (SWSS).

Detailed site descriptions for each of these areas may be found in Ferone and Devito (2004), Devito, et. al. (2005a), Devito, et. al. (2005b), Smerdon, et. al. (2005), Macrae, et. al. (2006), Riddell (2008), and Redding and Devito (2011), as well as in the other publications produced from this research (see Section F). The detailed methodology used to obtain the foundational water and energy balance data is also described in the individual publications and summarized in the Natural Sciences and Engineering Research Council final reports.

Transportability of Conceptual Models

The potential for transporting conceptual models of landscape functioning developed in the natural analogue areas at URSA and ACE for use in the oil sands region is critical. The authors argue that the following key similarities make the learnings highly transportable:

1. The research and the oil sands areas occur in the Boreal Plains of the Western Boreal Forest, a region characterized by a climate with a net precipitation deficit, and geology characterized as heterogeneous and with high water-storage capacity. These characteristics all interact in a mosaic of forestlands and wetlands.
2. Climate data from the two areas demonstrate similar patterns and magnitudes of precipitation (Section C.1.2). The various studies span the natural climate variability and allow for full interpretation of the range in hydrologic responses of reclaimed landscapes. It is well known that precipitation patterns vary widely from place to place, however the similarities in patterns and volumes are greater than the variability. Patterns and volumes of precipitation have been identified as critical to understanding and managing watersheds in these areas.
3. The major hydrologic elements (hydrologic response areas and hydrologic units) in the natural analogue study areas are similar to those currently present in the oil sands region and are the target units for closure planning, from an equivalent capability perspective. For example, clay Plains areas are similar to large, flat, saline-sodic overburden dump tops; coarse-textured hydrologic response areas are similar to tailings sand or coke deposits; and veneer-type hydrologic response areas are similar to sand-capped composite tailings areas.

Linkage studies on reconstructed oil sands watersheds confirm the similarities in processes, and the relative importance of those processes between the natural analogues and the reconstructed watersheds. In both cases, soil storage and groundwater flow play significant roles in the water budget, perched wetlands are common, and runoff is minimal. To a large extent, vertical movement of water dominates these flow systems.

A Conceptual Model of Water Flow in the Boreal Plains

Table of Contents

C.1

A Conceptual Model of Water Flow in the Boreal Plains: Introduction

The hydrologic functionality of the Boreal Plains Mosaic (i.e., its ability to adapt and sustain itself through the extended drought cycles and periodic wet intervals) is a product of its hydrologic context, composition, and connectivity.

The water balance equation is the principal tool for mine and closure planners and land managers to conceptualize and manage or re-establish hydrologic function, such as soil moisture regime and water flow, in any landscape.

In the Boreal Plains, the hydrologic function of ecosystems, and thus the water balance, must be first placed into the hydrologic context of:

a) A climate characterized by a long-term water deficit and pronounced seasonal and decadal wet and dry cycles

b) A deep heterogeneous geologic landscape characterized by large but variable water storage capacity

The interaction of climate and geology leads to annual and decadal soil, landform and landscape scale wetting and drying cycles. These cycles control ecological functions and the hydrologic response (timing and intensity) to events such as precipitation, disturbance and management.

Delineating the landscape into its functional hydrologic elements or appropriate "building blocks" (i.e., defining its hydrologic composition) will facilitate the calculation of the water balance.

Hydrologic connectivity (both intermittent and permanent) is controlled by differences in storage characteristics between and within hydrologic "building blocks", and interaction with climate cycles. This may lead to pronounced time lags in responses, and variable intensities of responses of soils, landforms and landscapes to climate cycles and/or land management as a function of their individual and accumulated antecedent moisture conditions.

The water balance approach within the hydrologic context, composition, and connectivity of the Boreal Plains can be used to understand, adequately describe, anticipate and manage ecosystem response to water inputs, water withdrawals, natural or anthropogenic disturbances, and reconstruction or management activities. This approach forms the basis of this conceptual model for Boreal Plains water movement and is presented in the following section.

C.1.1 The Water Balance Equation: A Focus on Storage

The water balance equation is the essential tool for understanding and managing (to the extent possible) the climate and geology and their interaction at all scales. This section describes the water balance equation and discusses shifts in the importance of its components as compared to conditions in Eastern Boreal Shield landscapes. At the center of the conceptual model for water flow on the Boreal Plains is a focus on storage, which is a new way of looking at the hydrologic budget or water balance.

KEY CONCEPT: BALANCING FOR STORAGE

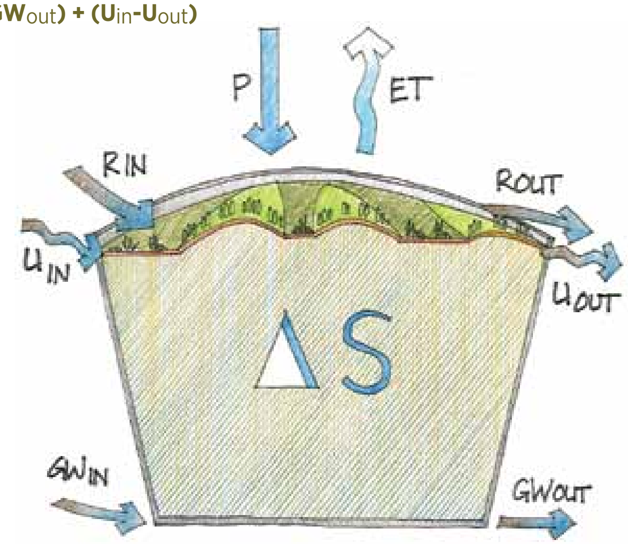
The identification of patterns of water storage and volume in soil and overall system water levels are keys to understanding hydrologic and ecosystem responses and managing reclaimed landscapes When designing a landscape and developing the water balance for a particular area within a given time frame, the land designer or manager should first consider storage with the water balance equation expressed as in Figure C.1.

In comparing water balances across regions, or continents, it is useful to distinguish between components controlled by climate and those influenced more by the geology and physical conditions of the ecosystem.

FIGURE C.1
Basic Water Balance for a Soil, Landform or Landscape.

A system's water balance should be expressed with the focus on storage (S). Change in storage ΔS refers to the change in the amount of water stored on the surface or below the surface in the landform or landscape. We use an operational definition of runoff and groundwater. Runoff refers to a point measurement of lateral flow down to about 0.5 m below ground surface. Thus it includes conventional definitions of overland flow plus interflow. Runoff refers to lateral flow in the active layer in Wetland hydrologic units (see Section C.1.4) and lateral flow in the forest floor (LFH) and surface soil horizons (A/B) in Forestland hydrologic units. Runoff can be measured in typical runoff plots or in shallow weirs at the base of catchments. Groundwater refers to all water flowing laterally and vertically below the active layer in Wetland hydrologic units and below the LFH and A/B horizons in Forestland hydrologic units. Thus, the term groundwater in this text includes conventional definitions of deeper interflow, subsurface storm flow, and groundwater. U or Uplift has been added to the conventional water balance equation, as the research demonstrated the substantial influence aspen root networks have on water re-distribution in Boreal Plains landscapes. Storage of water occurs in 1) depressions at the surface, 2) soil, and 3) groundwater. Therefore, water is stored in places where it can be seen (ponds and depressions) and in places where it is hidden (soil and groundwater). Visible water is subject to different intensities of processes compared to hidden water.

$$\Delta S = P - ET + (R_{in} - R_{out}) + (GW_{in} - GW_{out}) + (U_{in} - U_{out})$$



Legend: ΔS = change in storage; P= precipitation, ET = evapotranspiration, R = Runoff flowing into a system (R_{in}) and flowing out of a system (R_{out}); GW= Groundwater flowing into a system (GW_{in}) and flowing out of a system (GW_{out}); and U = Uplift moving into a system (U_{in}) and out of a system (U_{out}).

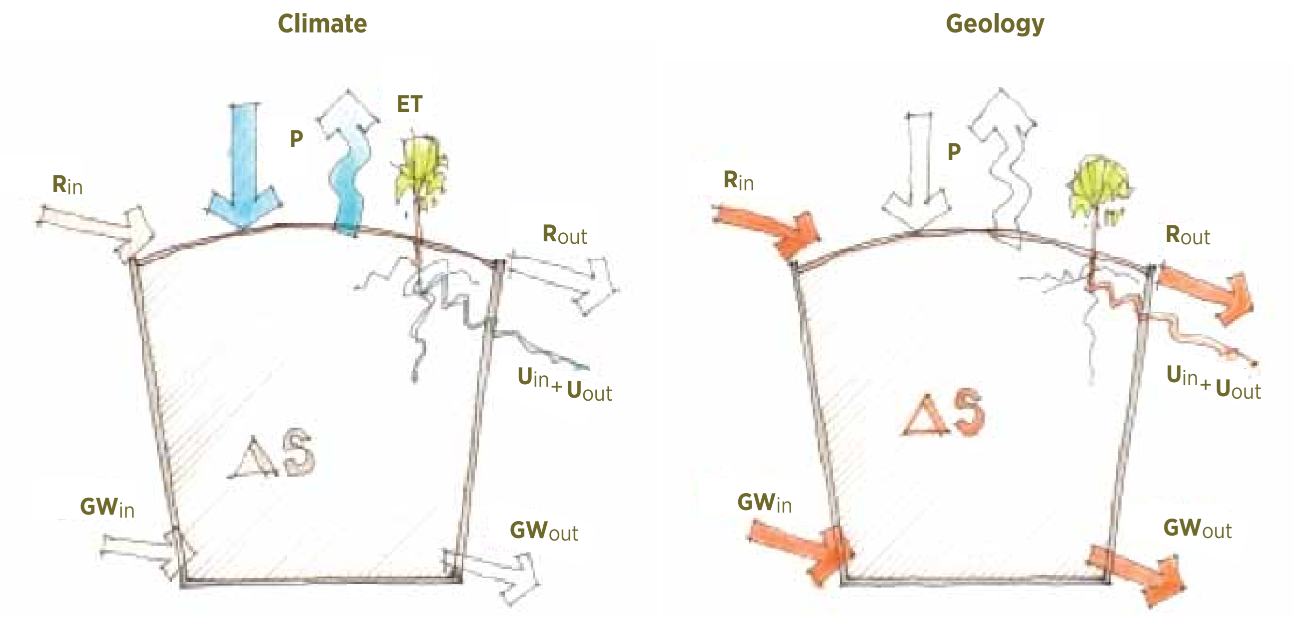
KEY CONCEPT: CLIMATE AND GEOLOGIC COMPONENTS OF THE WATER BALANCE

Climate exerts the primary control on the hydrology of the Boreal Plains as it affects the water balance through precipitation (P) and evapotranspiration (ET) (Figure C.2a). The difference between ET and P is the amount of moisture available for an ecosystem.

While climate plays the key role influencing the overall amount of water available to an ecosystem, geology plays an equally critical part. The size, depth, and composition of geologic deposits within a region (the defined bucket), will affect the amount of water stored, as well as groundwater flow and runoff processes (Figure C.2b).

FIGURE C.2

Water Balance: Climate and Geologic Components



a) In the water balance equation, climate is described by the variables P (precipitation) and ET (evapotranspiration).

b) In the water balance equation geology influences ΔS (change in storage) and GW (groundwater), which then influences R (runoff).

KEY CONCEPT: DIFFERENCES BETWEEN BOREAL SHIELD AND BOREAL PLAINS WATER BALANCES

The water balance variability between Boreal Plains and Boreal Shield landscapes of Canada reflect differences in climate and geology. The approaches used to model the two ecosystems should, therefore, vary, as well.

Conventionally, ΔS and groundwater fluxes are assumed to be small or nil, and the primary manifestation of precipitation (P) inputs are runoff (R) outputs (Figure C.3). These assumptions can be suitable in areas such as the Boreal Shield of eastern Canada, which is characterized by a humid climate (P>ET) with impermeable bedrock and shallow soils. Shallow soils over impermeable layers do, indeed, result in negligible groundwater fluxes and limit soil storage potential. Precipitation greatly exceeds evapotranspiration on the Boreal Shield, the excess water overwhelms storage capacity, and impermeable bedrock geology encourages surface (or near-surface) runoff. Furthermore, the water balance generated by these processes can be calculated over relatively well-defined landscape units (watersheds) given the bounded topography of the region.

In the Western Boreal Forest, and the Boreal Plains in particular, these assumptions do not hold and the values for all (or most) of the water balance components—specifically ΔS, ET, and GW—cannot be assumed. The climate is sub-humid and the volume of excess water is generally minimal (i.e., the P arrow is similar to, or smaller than, the ET arrow on the bucket diagram in Figure C1.3). The small amount of excess water interacts with deep glacial deposits that potentially store large volumes of water. Thus, ΔS must be a major focus in the water balance. Runoff occurs only when the potential storage is exceeded, and this may occur infrequently. In general there is an unbalanced relationship between precipitation inputs and runoff outputs. The deeper deposits promote groundwater recharge and longer connections. Surface topography is less likely to present defined boundaries for watershed units to which the water balance equation can be applied.

FIGURE C.3

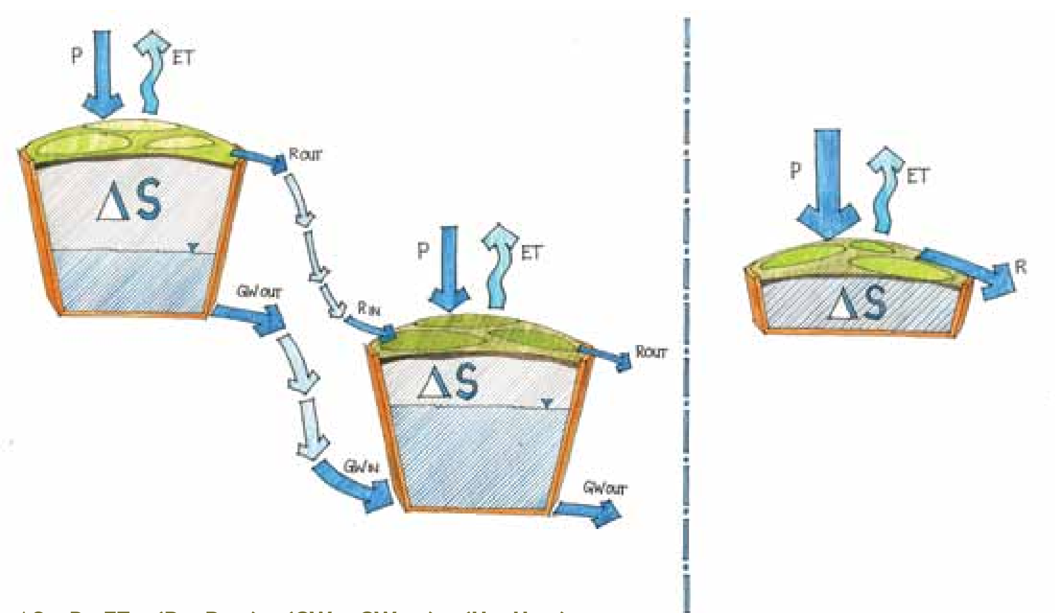
Differences in Approaches to Water Balance Equations of Boreal Plains and of Eastern Boreal Systems

$$\Delta S = P - ET + (R_{in} - R_{out}) + (GW_{in} - GW_{out}) + (U_{in} - U_{out})$$

On the Boreal Plains of Western Canada, S is a large component of the water balance and the equation should be expressed relative to change in storage (ΔS). None of the components of the equation can be assumed to be zero due to deep and variable surface material. In Eastern Boreal regions of Canada, watersheds are confined by impermeable layers underlying relatively shallow soils. Thus ΔS and GW_{out} are often assumed to be small and the water balance in the Eastern Boreal regions is often represented relative to runoff (R_{out}).

Western Boreal Forest Water Balance

Eastern Humid Boreal Forest Water Balance



$$\Delta S = P - ET + (R_{in} - R_{out}) + (GW_{in} - GW_{out}) + (U_{in} - U_{out})$$

$$R = P - ET$$

KEY CONCEPT: VARIATION IN WATER BALANCE WITHIN THE BOREAL PLAINS

The interaction of climate and geology is the overarching control for hydrology and the magnitude of water balance component fluxes characteristic of an ecosystem. The glacial deposits on the Boreal Plains are heterogeneous in depth and material type, and can vary greatly in water storage and transmission properties. In an area where the climate components may remain relatively consistent across the landscape geologic variations can result in large differences in the magnitude of water balance components such as ΔS, R and GW. By focusing on ΔS as the dominant control in the redistribution of climate fluxes, regions of similar geology and physical characteristics provide effective boundaries or "buckets" for the application of water balance equations on the Boreal Plains (detailed in Section C.1.4).

Soil moisture and surface water level changes result from the interaction of climate and geology. Although soil development, vegetation and ecosystem types reflect and integrate the soil moisture conditions, one cannot necessarily use vegetation or ecosystem type as an indicator of the geologic component of the water balance without understanding the climate interactions. The implication is that a firm understanding of the interaction of both climate and geology is required to effectively design and manage reconstructed landscapes. This is detailed in the following sections.

C.1.2 Climate on the Boreal Plains: Hydrologic Context - A Water Deficit Modulated by Seasonal and Decadal Cycles

Climate is, in fact, the chief controlling factor of eco-hydrologic function. In the water balance equation, the climate is described by the variables P (precipitation) and ET (evapotranspiration). The evapotranspiration to precipitation ratio, "dryness index", is a useful indicator of the dryness of a soil, landform, or landscape. It can also shed light on eco-hydrologic behavior (Figure C.4).

The Western Boreal Forest, and particularly the Boreal Plains, is characterized by a water deficit over the long term (PET ≥ P). Understanding how natural wetlands and forestlands exist, and how to reconstruct similar ecosystems that can be sustained in this dry landscape was one of the central questions in the research. This question singularly brings into focus the importance of climate in the conceptual model.

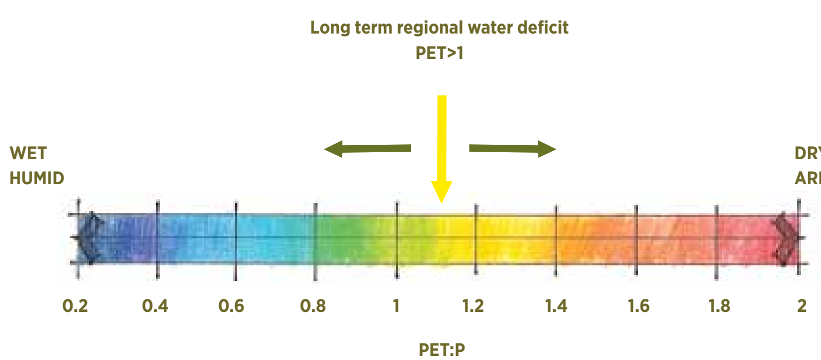
Although the ecosystems on the Boreal Plains exist in a long term regional water deficit (PET:P > 1), the difference between ET and P is small. Thus, *deviations from the average condition* of either may magnify other processes in the water balance, particularly storage. Water deficit or surplus varies intra-annually with seasonal changes in ET and P and inter-annually with decadal and multi decadal precipitation cycles. Spatially, differences in long term ET rates due to variations in landscape position of soils and vegetation features result in long term net moisture surplus for many wetlands, and net deficits for forest and aquatic systems. These deviations from average conditions are critical to the hydrologic functionality and movement of water within and among landforms and to maintenance of forest and wetland ecosystems. Accounting for them in design of reconstructed landscapes is critical.

FIGURE C.4
The Dryness Index

Evaluating the relative differences between ET and P by using the ratio of the two (ET:P) helps in understanding the amount of moisture available for an ecosystem and, hence, the potential dryness of a soil, landform or landscape.

In hydrology ET is expressed as PET (potential evapotranspiration) or AET (actual evapotranspiration). PET is defined as the rate of water removal that could occur given no restriction on the availability of free water, while AET is the amount of water actually removed, and may be much less than PET if water availability is restricted (e.g., water held under an "active layer" or mulch like in Wetland hydrologic units- this is discussed in subsequent sections). Here the dryness index is expressed as PET:P.

The ecosystems on the Boreal Plains exist in a long-term regional water deficit (PET:P > 1), however, that dryness varies seasonally and inter-decadally (left and right arrows). Natural Boreal Plains systems have features to capitalize on the variability, enabling water to be retained and transmitted as necessary to maintain ecosystem function despite the long-term average water deficit. This is the focus of the rest of the document.



C.1.2.1 Long term Trends: Moisture Deficit

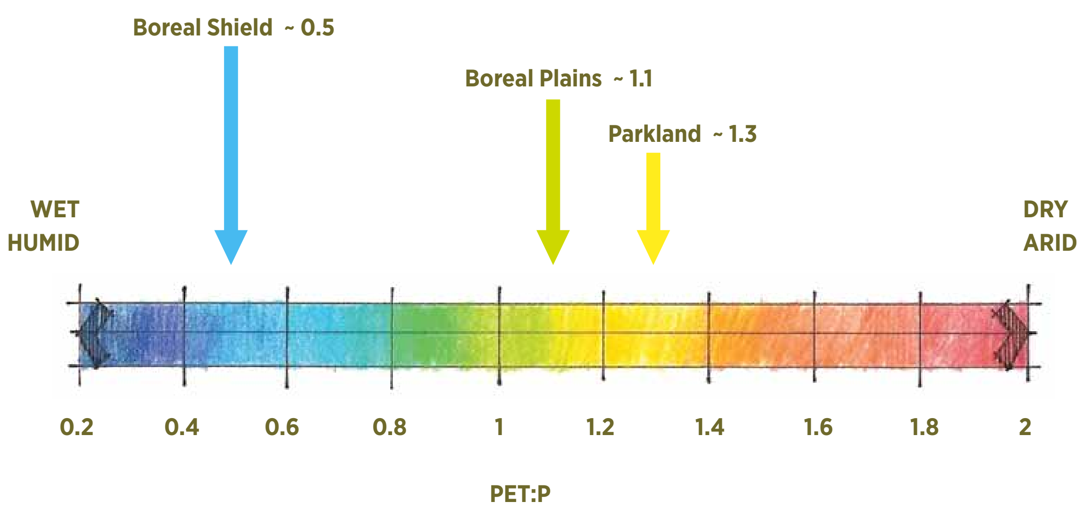
The identification of long-term climate norms is useful in setting the climate context for the water balance and eco-hydrology of a region.

KEY CONCEPT: THE BOREAL PLAINS EXISTS IN A LONG-TERM ANNUAL WATER DEFICIT

The landscapes in the Boreal Plains are, over a 30 year average, in a water deficit. Typical values for PET:P are about 520mm:480mm, respectively with a dryness index about 1.1 (Figure C.5). Comparisons across Canada show that the Boreal Plains index is lower than that for the Parkland eco-region (PET:P ~ 1.3), but is much higher than that of the eastern Boreal Shield eco-region (PET:P ratio ~ 0.5). These are dry conditions for forest and particularly peatland development.

FIGURE C.5
The Annual Dryness Index (PET:P ratio): Regional Variability

The annual dryness index (PET:P ratio) of a typical Boreal Plains region in comparison eastern to Boreal Shield and Parkland regions.



KEY CONCEPT: LONG-TERM SEASONAL VARIATION IN ET AND P ARE KEY TO UNDERSTANDING IF AND WHEN SURPLUS WATER IS AVAILABLE FOR REDISTRIBUTION IN THE LANDSCAPE

Marked seasonal trends in long term monthly P and ET occur in the Boreal Plains with synchronous timing of the highest precipitation with the highest plant water use (Figure C.6). Even though the region is in a net water deficit, the annual “effective dryness” index varies seasonally, with potential net surplus in the non-growing season, countered by net deficit during the growing season (Figure C.7). These seasonal variations are key to understanding water movement during extended dry periods.

The synchronicity of the rainy season with the timing of highest plant use potentially enhances the dryness and water deficit of Boreal Plains. Here, the majority of the annual precipitation (65-75%) arrives during the growing season (May-September) and potentially can be “lost” back to the atmosphere through evapotranspiration. The amount of precipitation received during the growing season is important, as aspen forestlands are water limited (i.e., they can use more water than they receive in most years in this region) and although summer rainfall amounts are relatively large and represent the largest portion of annual precipitation, they are still typically lower than PET during this period. Thus, the dryness of the Boreal Plains may be accentuated relative to other areas of the province or country with similar total annual average PET:P ratios. If such areas receive a larger proportion of precipitation during the non-growing season, when precipitation is less affected by plant use, their actual ET will be smaller than on the Boreal Plains, rendering them effectively less dry.

In contrast to the growing season, a much greater proportion of the precipitation accumulated during the non-growing season (October through April) is available for redistribution in the landscape on the Boreal Plains because plants are dormant and thus there is low ET. Although the amount of precipitation that comes during the non-growing season represents less than 30% of the total annual precipitation, this accumulated non-growing season precipitation (fall rains, accumulation of snow, and spring rains) results in a net surplus of about 100 millimetres of water, on average, at the end of the non-growing season.

It is this relatively small volume of *surplus* of water that is consistently available for moving around the landscape, and depending on antecedent moisture conditions (see Section C1.6.1) it may:

- Initially move into the ground as storage (S in the water balance equation) later to be used by plants, or for salt flushing and nutrient redistribution in soils and landforms; then eventually
- Thereafter percolate for groundwater (GW) recharge,
- Or move over the ground as runoff (R) to feed ponds, lakes and streams

FIGURE C.6

Long-term Monthly Climate Norms for the Boreal Plains

These graphs show the long-term monthly precipitation (P) and potential evaporation (PET) norms for Fort McMurray and the Utikuma Region Study Area (URSA). Studies of natural sites at URSA show the same patterns as Fort McMurray. They are climate analogues. It is worth noting that the oil sands region is, on average, somewhat drier than URSA. Thus any eco-hydrologic effects may be slightly accentuated in the oil sands area compared to the natural analogue study areas. It is also important to note that P and PET are synchronous.

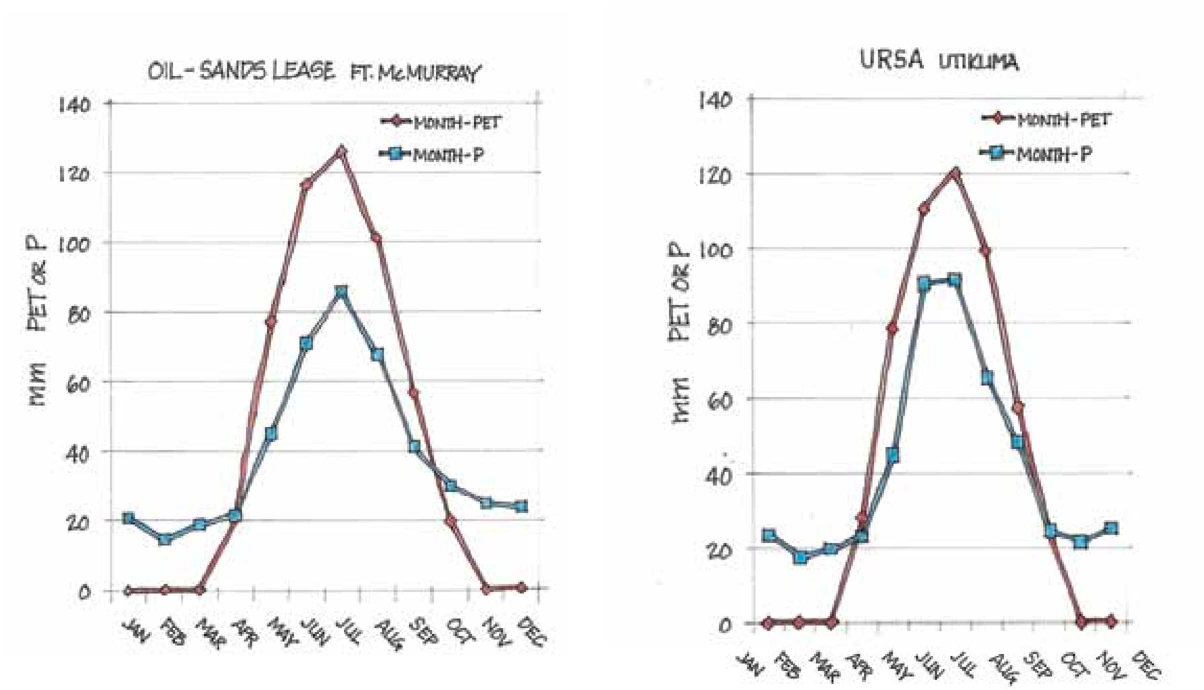
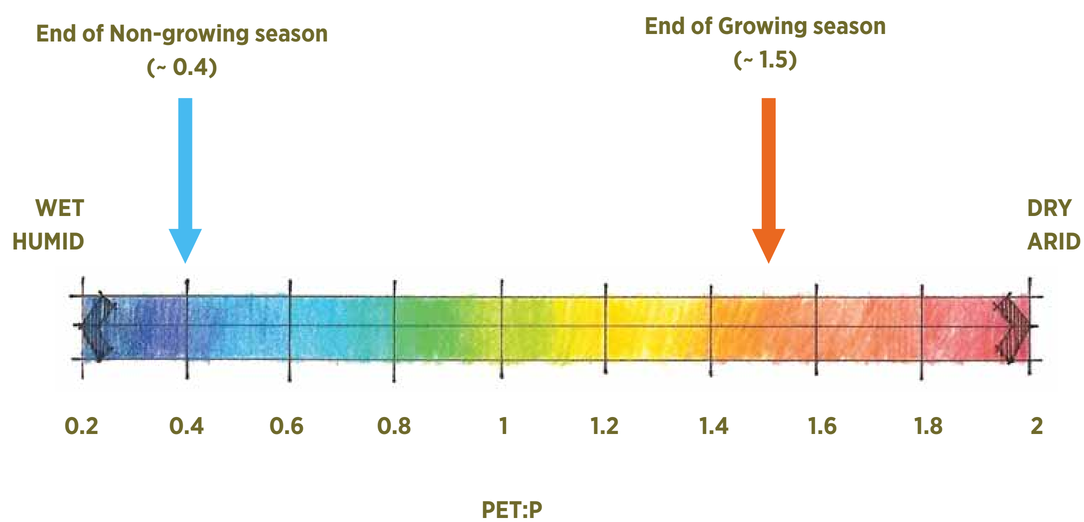


FIGURE C.7

Seasonal (Intra-annual) Variability in Dryness Index, Boreal Plains

Comparison of typical growing season (May-September) and non-growing season (October-April) dryness indices (PET:P) based on long-term climate norms for URSA.



C.1.2.2 Deviations from Long-term Means

Although on average the Boreal Plains region is in a water deficit, the relative differences between P and ET are small. As a result changes in either can have a significant impact on water balance processes-storage in particular. The periodic *variations or deviations* from the long-term annual and seasonal average values for P and ET can represent critical periods for storage or redistribution of water in the landscape.

Examining inter-annual (decadal and multi-decadal) cycles and the occurrence and distribution of shorter-term weather events is important for accurate conceptualization of overall hydrologic behaviour and optimization of design to ensure capture and storage of water during the periodic water surpluses followed by water release during the extended dry periods.

KEY CONCEPT: LONG-TERM *INTER-ANNUAL* VARIATION IN PRECIPITATION

The interaction of major global circulation phenomena[2] results in considerable inter-annual variability around long-term average annual precipitation of the Boreal Plains (Figure C.8). Inter-annual variations in annual precipitation range from just over 300 millimetres to 700 millimetres or greater. In contrast PET is much more consistent, rarely varying more than 30 millimetres from the average of about 520 millimetres a year. The decadal and multi-decadal precipitation cycles modulate the overall water deficit and result in inter-annual PET:P ratios ranging from net surplus (~0.75) to large deficits (~1.8) (Figure C.9).

Typical long-term precipitation patterns for the Boreal Plains are characterized by:

1) Extended periods where PET exceeds precipitation, with relatively predicable cycles of three to five years per decade of annual amounts consistently below the long-term average precipitation (dry years characterized by large moisture deficits with PET:P ratios of 1.2 to 1.8). These alternate with three- to five-year periods per decade of precipitation amounts that fluctuate more closely around the long-term average (mesic years), post lower PET:P ratios (0.9 to 1.1), but are still "effectively dry".

This common scenario is then punctuated with

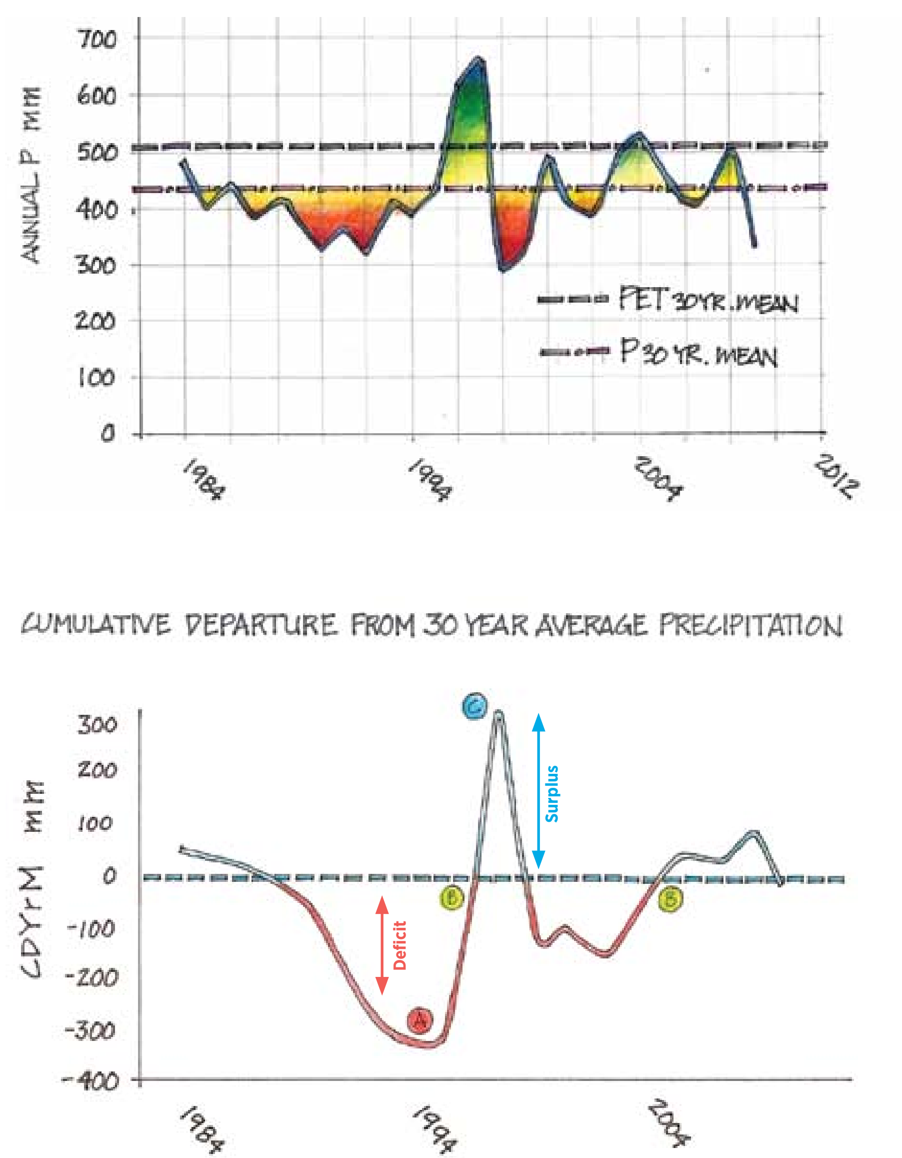
2) Short episodes of significantly wet years, with a frequency of approximately 2 to 3 decades, in which precipitation is well above the long-term average (wet years). In these few years the PET:P ratio approaches 0.75 and the landscape is "effectively wet".

[2]These phenomena are El Niño, the Southern Oscillation, and the Pacific Decadal Oscillation. Each of these highly influential phenomenon has its own pattern of appearance. These phenomena occasionally coincide with or counteract each other, which is when extreme "wet" or extreme "dry" periods occur. See Mwale et.al. (2009) and Carrera-Hernandez et.al. (2012) for more detail including discussion of longer-term patterns and an illustration of the effects of these cycles on soil moisture and groundwater recharge through time.

FIGURE C.8
Typical Inter-annual Variation in Precipitation and Accumulated Moisture Deficit in the Boreal Plains

A) Typical decadal and multi-decadal cycle in annual precipitation for the Boreal Plains, shown relative to long-term mean PET and P.
B) Cumulative departure of annual P from the long-term yearly mean P (CDYrM)* for a representative region of the Boreal Plains. Accumulation above zero indicates potential surplus moisture (blue arrows), while negative values indicate deficit and large available soil storage (red arrows). On this graph: A) represents cumulative moisture deficit and “dry” or low antecedent moisture condition; B) represents “mesic” (mean) antecedent moisture over a period where slight moisture deficits are countered by slight moisture surpluses and net moisture deficit is near zero; C) represents “wet” or high antecedent moisture conditions with one or two years well above the mean P resulting in accumulation of a large moisture surplus (vertical blue arrow). The wet periods occur less frequently than the cycles of dry and mesic antecedent moisture conditions.

- To determine CDYrM, the difference between the mean P and the current-year P is calculated. The differences are summed over the period of interest. For example, successive periods of below-average P will accumulate moisture deficit (negative differences) as in the years 1987 to 1994.



KEY CONCEPT: UNDERSTANDING THE CYCLES OF *CUMULATIVE* MOISTURE DEFICIT OR SURPLUS CAN HELP IN UNDERSTANDING HYDROLOGIC RESPONSE

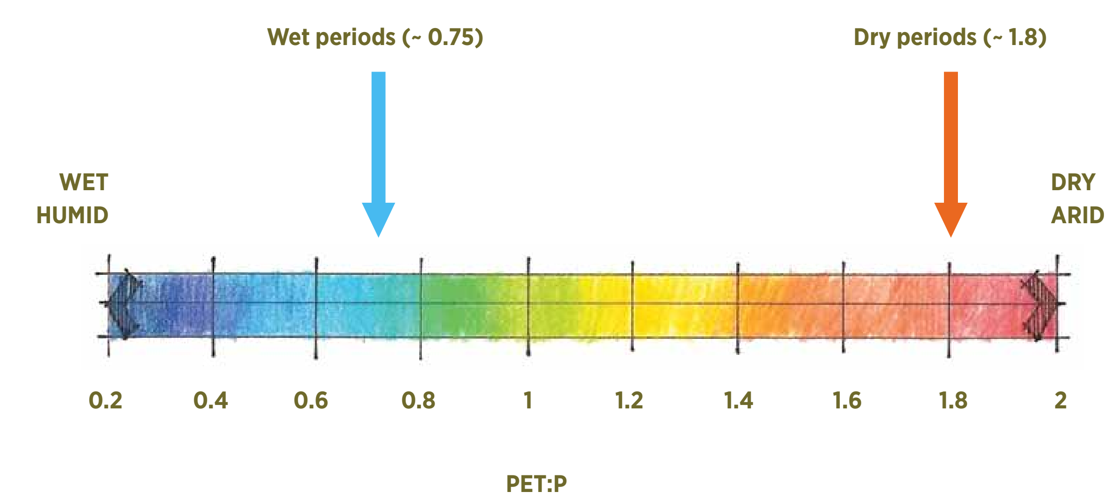
The ecosystems of the Boreal Plains have evolved within the context of a long-term moisture deficit characterized by long periods of precipitation fluctuating close to the long-term mean punctuated by short periods of moisture surplus. A way to understand the cumulative effect on the landscape of these cycles is to track (or accumulate) the number of years during which precipitation deviates above or below the long term mean (Figure C.8b). This can provide a visual representation of the cumulative moisture deficit or surplus over time and be used to infer potential antecedent moisture conditions (see also Section C.1.6.1).

Boreal Plains landforms cycle between periods of precipitation near the long-term mean where accumulated soil moisture is near zero (mean or mesic condition) and periods of precipitation consistently below the annual mean where the soil moisture deficit can accumulate to as much as 300 millimetres (dry condition). Following the accumulated dry period, successive years must collectively make up this deficit with years of above-average precipitation. These decadal cycles of mesic to dry antecedent moisture conditions are punctuated every two to three decades by one or two years of large accumulated moisture (up to 300 millimetres) resulting in accumulation of surplus moisture (wet period). The influence of accumulated moisture deficits and surpluses on hydrologic response and landscape hydrologic connectivity are detailed in Section C.1.6.1.

Thus to understand current observations it is useful to consider data in the context of the long term moisture cycle. For example, in Figure C.8a, the annual rainfall in 1994 is similar to that of 2006 (just below the mean P). However the response of the landscape to each year’s precipitation may be very different. The rainfall in 1994 came after many years of below-average precipitation and was interacting with potentially very-dry soils, with an accumulated moisture deficit of over 300 millimetres. In contrast, rainfall in 2006 followed a mesic period in which soil moisture levels may be much higher, and a different hydrologic response to precipitation inputs would be expected.

FIGURE C.9
Inter-annual Comparison of Dryness Index in the Boreal Plains

PET:P ratios vary substantially over the long term on the Boreal Plains with extended dry cycles punctuated by wet periods.



KEY CONCEPT: SEASONAL AND SHORTER-TERM VARIATIONS IN EVAPOTRANSPIRATION AND PRECIPITATION MODULATE THE LONG-TERM WATER DEFICIT

Similar to the decadal and multi-decadal cycles, deviations from the seasonal (intra-annual) distributions and the intensity of precipitation events can modulate the long-term water deficit and influence the relative thresholds of water availability for redistribution in the landscape. There are two critical seasonal water input periods: the non-growing season and the growing season.

Non-growing season precipitation: Small variations in the long-term average non-growing season precipitation may have a large impact on between-year (inter-annual) variations in moisture redistribution in the landscape. A comparison of precipitation patterns in 2006 and 2009 (Figure C.1) illustrates this. The accumulated non-growing season (November-April) precipitation for 2006 and 2009, was 75 millimetres and 180 millimetres, respectively, compared to an evapotranspiration loss of about 50 millimetres for each period. Thus, the potential surplus at the end of the non-growing season was only 25 millimetres in 2006 compared to 130 millimetres in 2009, even though total annual precipitation was greater in 2006. That is a 100 millimetre difference. In this dry landscape and during this season, the 100 millimetre difference represents a considerable amount of water. Depending on when this occurs in the multi-decadal cycle, and where in the landscape it occurs, the gap could trigger a threshold response that causes substantial water re-distribution in the landscape.

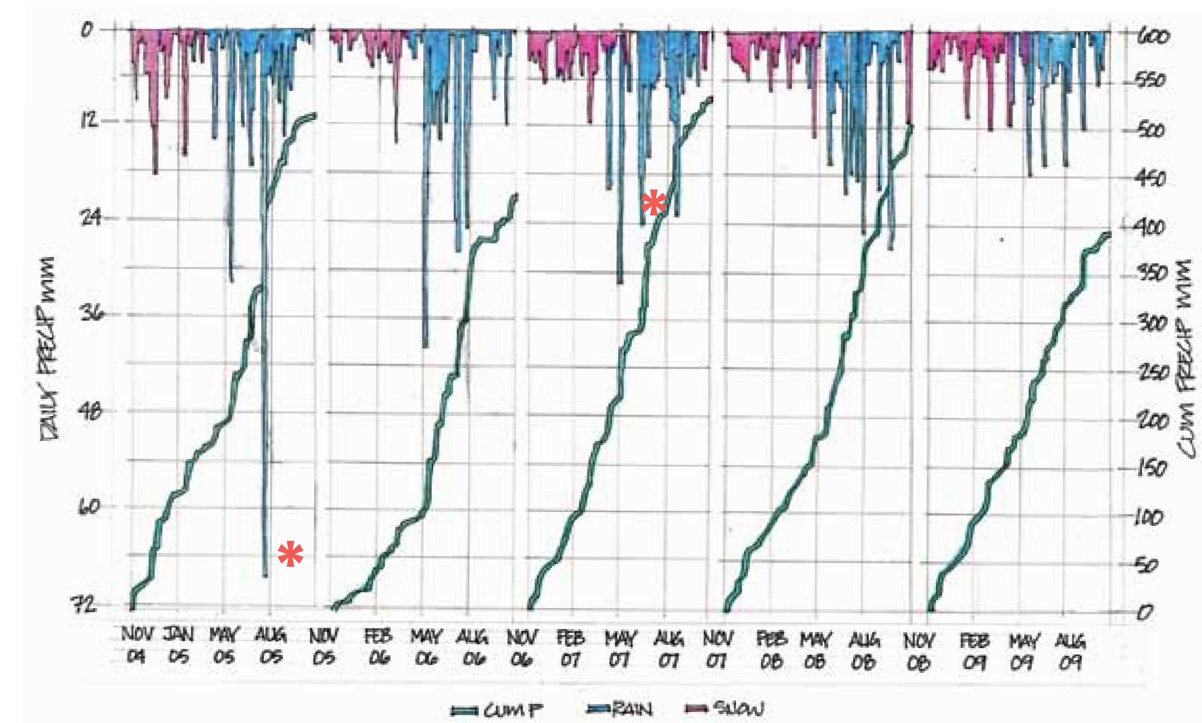
Growing Season P: Due to high PET during the growing season, surplus moisture can be accumulated only: 1) in areas such as wetlands where actual evapotranspiration is reduced (next section), and 2) over the short term during intense summer storm events which can overwhelm short term evapotranspiration rates and effectively "get past the trees."

The example in Figure C.10 shows that on the Boreal Plains, most of the summer rains occur as events of less than 20 millimetres per day and are relatively isolated in time. The research has shown that summer rain events in excess of 20 millimetres are needed to fill both forest interception and forest floor storage, as well as bypass plant roots to wet the underlying mineral soil. In over ten years of study at URSA, only a few large intense summer storms occurred that significantly exceeded summer rain event thresholds. Whether such large rain events trigger a runoff response will depend primarily on the decadal cycle of soil moisture status. The precipitation from the large storm in 2005 (see * on Figure C.10) was absorbed into the soils, as this event followed several dry years. The repeated moderate sized storms in July 2007 came after accumulated soil moisture increased and triggered a moderate runoff response at URSA.

Peak runoffs where not observed during the 12 years of study at URSA. Peak runoff events that contribute to high runoff years generally are restricted to the growing season where intense and large rain events occur (Figure C.10). Experiencing a series of large storms concurrent with high antecedent soil moisture is rare, and occurs only on multi-decadal time scales. Estimating the probabilities of relatively rare summer precipitation exceeding critical summer rain event thresholds is consequently also important in determining soil, landform or landscape "dryness" or the amount of water available for redistribution.

FIGURE C.10
Seasonal Distribution and Variability of Snow and Rain at URSA

This figure illustrates the inter-annual differences in fall rains, snowmelt plus spring rain (non-growing season), and summer storm intensity which can influence soil, landform and landscape "dryness". The seasonal distribution of daily snow is indicated by the pink bars, rain depth by the blue bars, and the annual accumulation of precipitation by the solid green lines. Note the different axes for cumulative precipitation.



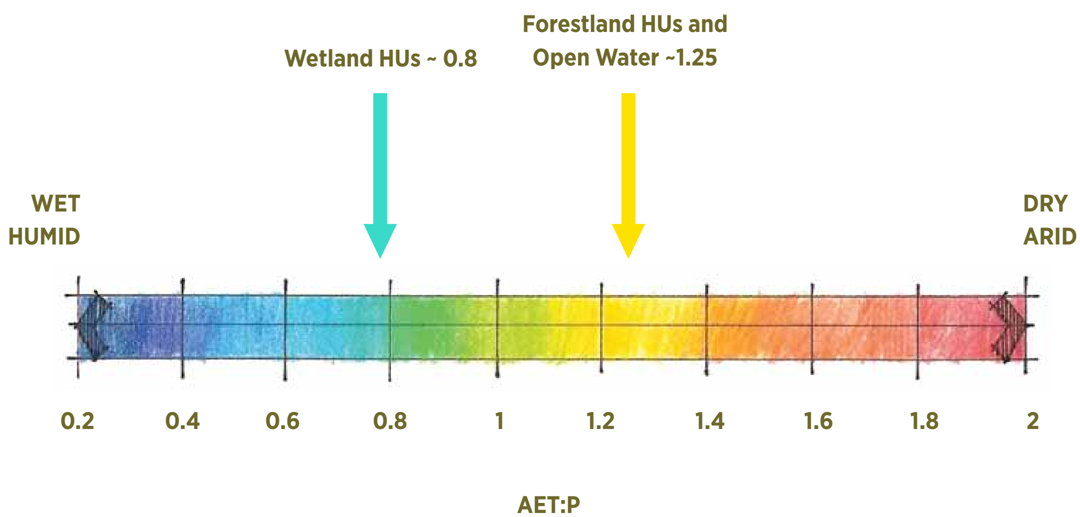
KEY CONCEPT: SPATIAL VARIATION IN SOILS AND VEGETATION AND HOW THEY INFLUENCE THE *EFFECTIVE* DRYNESS

In this research, *actual* evapotranspiration, and thus *effective* dryness (ET:P ratio) was shown to vary over short distances in a landscape as a function of changes in soil and vegetation type and structure. Non-standing water wetland ecosystems, particularly peatlands, were shown to have a lower actual evapotranspiration rate than their open water counterparts, and adjacent aspen forestland communities (Figure C.11). As a result, typical wetlands with non-standing water have a moisture surplus (ET:P approximately 0.8). In contrast, adjacent forestlands or open water areas, have a considerable moisture deficit (ET:P approximately 1.25).

This difference in effective dryness is central to the conceptual model of water flow in the Boreal Plains and is pivotal for understanding landscape level hydrology and connectivity. Thus, it is necessary to delineate the landscape into functional units composed of "building blocks" representing various geologic components and their varied responses to large climate fluxes (see Section C1.4).

FIGURE C.11
The Effective Dryness index for Wetlands, Open Water and Forestlands

The effective dryness index uses actual ET:P ratios and illustrates the difference in actual ET of different soil-vegetation coverage characteristic of the Boreal Plains. Non-open water wetlands, Open water and forestland "hydrologic building blocks" or hydrologic units (HUs) are defined in Section 2.3 and discussed in detail in Section D.



C.1.3 Climate on the Boreal Plains: Implications for Landscape Reconstruction

A number of key findings arise from an examination of the sub-humid climate on the Boreal Plains. In particular, while there is a long-term water deficit, the inter-annual precipitation variations from mean values can be appreciable. Significant seasonal variations in evapotranspiration and precipitation also lead to cycles of cumulative soil-moisture surplus and deficit.

DESIGN CONSIDERATION: LONG-TERM CLIMATE TRENDS ON THE BOREAL PLAINS

The Boreal Plains, in particular the aspen forestland, is one of the driest forests in the world, and the modelling of reconstructed watersheds must carefully consider all of the components that produce this condition if local and regional hydrologic functionality (and, hence, equivalent capability) in the oil sands region of northeastern Alberta are to be sustained. Creating the dual functionality required requires consideration of the long-term climate trends. The reconstructed landscape must have features to sustain itself through the predominant drought conditions, but also store and transmit appropriate proportions of excess water during the periodic water surpluses.

Because most of a typical year's precipitation occurs during the growing season, and given the synchronicity between precipitation and PET, management efforts must also account for the impact of vegetation type, coverage, and succession on regional dryness, soil moisture, and runoff.

Too, both in design of landforms and in numerical modeling, it is important to account for the surplus moisture annually available in the spring, as this relatively small amount of water is the only moisture that is consistently available for redistribution in the landscape.

DESIGN CONSIDERATION: IMPORTANCE OF DEVIATIONS FROM LONG-TERM TRENDS

The forestlands, wetlands and aquatic systems of the Boreal Plains have evolved in the context of short and long term climate cycles and heterogeneous geology. Although precipitation cannot be managed, understanding its periodicity is important in understanding, and hence more effectively re- establishing, the core hydrologic functionality of reconstructed landscapes.

Designs for reconstructed watersheds should focus on two potentially competing aspects of landscape capability:

1) Design for rapid removal of water that may accumulate during periodic large-surplus periods to maintain the integrity of reconstructed structures

However, designs must also consider drought conditions that will eventually follow, and

2) provide for the effective capture, storage and transmission of water during periodic wet cycles as well as the transmission or redistribution of stored water to sustain the landscape during the more typical and extended drought or dry periods

There is minimal hydrologic or biologic value in using average annual precipitation data in landscape design, performance modelling, or projections. Rather, probabilities of historical and projected climate patterns (seasonal and decadal) must be considered when assessing trajectories of watersheds toward achievement of equivalent capability. The approach will also inform decisions as to when selected indicators might or can be measured to assess reclamation success with respect to:

- Salt-flushing of soils, landforms, and landscapes
- Water quality and water volumes in wetland and lake systems over time
- Vegetation recruitment in both forestlands and wetlands and subsequent wildlife habitat development

DESIGN CONSIDERATION: MANAGING EVAPOTRANSPIRATION TO MANAGE "EFFECTIVE DRYNESS"

Evapotranspiration can be managed, to some extent, through manipulation of the type and distribution of hydrologic building blocks such as landforms and wetlands and forestlands. By doing so, the designer can influence how "effectively dry" a landscape or portion thereof is to some extent. Understanding the relationship between evapotranspiration and precipitation, both temporally and spatially, will enable the land designer or manager to:

- Understand where and why water is distributed in the landscape through time
- Anticipate the recovery trajectory
- Understand where and why a reconstructed or managed landscape is on a particular trajectory

Areas possessing similar hydrologic properties, or "hydrologic building blocks," that have characteristic moisture surplus or deficits to facilitate application of water balance across a landscape should be identified and delineated in numerical models used to design and model closure landscapes. These may be uncorrelated with topographically defined watershed boundaries. The characteristics and arrangement of the hydrologic building blocks to facilitate achievement of hydrologic functionality are discussed in subsequent sections.

C.1.4 Geology on the Boreal Plains: Hydrologic Composition - Hydrologic Response Areas and Hydrologic Units

Different parts of the Boreal Plains landscape respond differently to the climate cycles discussed previously due to variations in geology. Both the natural and reconstructed (oil sands) landscapes in the Boreal Plains are composed of heterogeneous geologic deposits with large, but variable water storage and transmission capacities. The geologic deposits in natural systems and the reconstructed landforms, or portions thereof, in post-mining landscapes can be delineated into hydrologic "building blocks" - hydrologic units (HUs) overlaying hydrologic response areas (HRAs).

C.1.4.1 Delineating Hydrologic Building Blocks on the Boreal Plains Landscape

The Boreal Plains is a mosaic of wetlands and forestlands overlaying and interacting with the heterogeneous landscape composed of fine textured, coarse textured, and veneer type glacial deposits. Each of these, the wetlands and forestlands as well as the geologic deposits or landforms on which they reside, have unique eco-hydrologic properties. As a result they can be considered hydrologic "building blocks" to conceptualize processes and facilitate water balance calculation (see Figure C.12).

FIGURE C.12
The Hydrologic Components of the Boreal Plains Landscape: Visualization

The Boreal Plains is a mosaic of Wetland and Forestland **hydrologic units** (HUs), on a wide range of scales, superimposed on heterogeneous glacial deposits that behave as discrete **hydrologic response areas** (HRAs). The designer or manager must explicitly consider both the surface and subsurface.

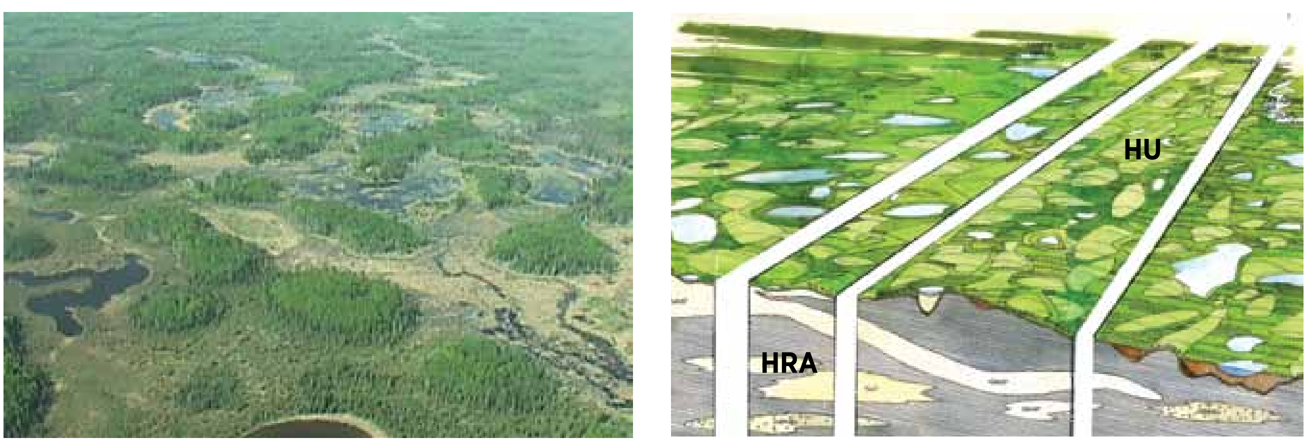
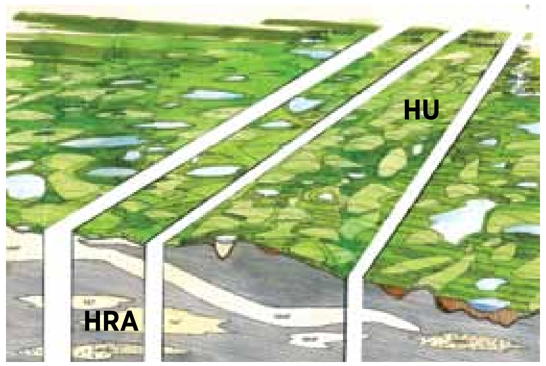


FIGURE C.12 CONTINUED

The Hydrologic Components of the Boreal Plains Landscape: Visualization

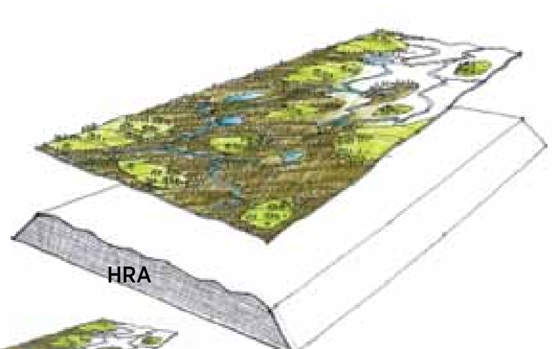
The Boreal Plains is a mosaic of Wetland and Forestland **hydrologic units** (HUs), on a wide range of scales, superimposed on a heterogeneous glacial deposits that behave as discrete **hydrologic response areas** (HRAs). The designer or manager must explicitly consider both the surface and subsurface.



Each **hydrologic unit (HU)** has characteristic soil properties which result in discrete soil-vegetation-atmosphere interactions (dryness indices). The HUs enhance differences in hydrologic responses of the HRAs, over which they lay, to climate cycles.
There are two types of HU: **Wetland and Forestland.**
· Wetland HUs are water "sources"
· Forestland HUs tend to be water "sinks"

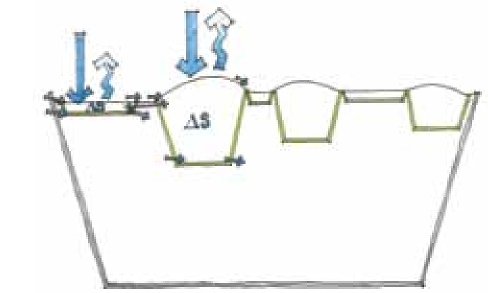
A **hydrologic response area** (HRA) is an area (on any scale) in the landscape with similar grain size and permeability (similar water storage and transmission properties).

There are three main types of HRA in the Boreal Plains:
· Coarse, Fine, and Veneer-type.



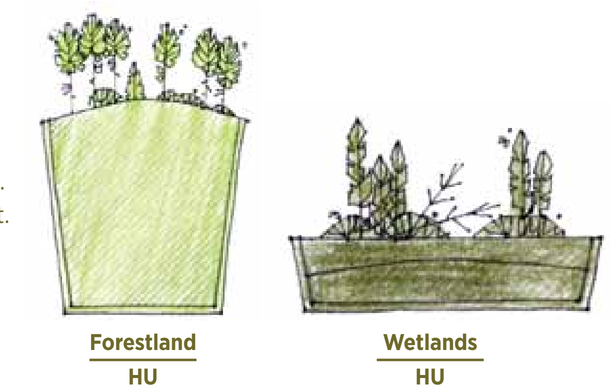
The presence and connectivity of the hydrologic elements (HUs and HRAs) at a range of scales is essential for the hydrologic functionality of a Boreal Plains landscape

One can visualize HUs or HRAs, as "buckets" or storage spaces for water. The landscape can be thought of as a collection of these buckets. One can use various scales and combinations of buckets to understand and estimate the water balance and water flow in the landscape.

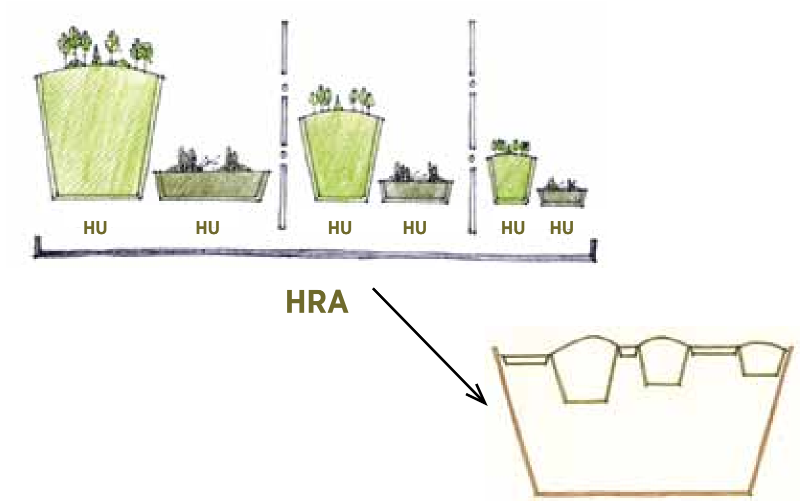


Each HU has a different water storage capacity and ET:P ratio. The storage capacity of an HU (the size of the bucket) is a function of the size of HU, the soil depth, and soil characteristics .

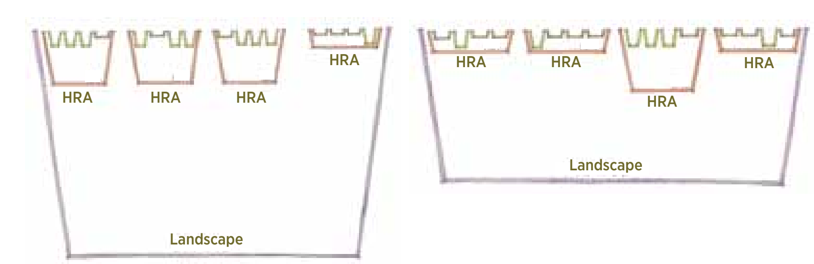
· Forestland HUs: large storage capacity = deep bucket.
· Wetland HUs: small storage capacity = shallow bucket.



Each **HRA** has a characteristic bucket. The HRA bucket is an integration of the HRA's geologic characteristics and the size and proportion of HUs within it.



A landscape is made up of a collection of HRAs. The proportion of and how the elements are connected, will affect the overall water balance of the landscape "bucket".



KEY CONCEPT: DELINEATING HYDROLOGIC BUILDING BLOCKS: TWO TYPES OF HYDROLOGIC UNITS (HUS).

This research suggests that there are two types of hydrologic units (HUs) in the Boreal Plains each with unique soil and vegetation properties that result in discrete soil-vegetation-atmosphere interactions that enhance differences in response to climate cycles (see section D for details).

1) Wetland HUs. In general, wetlands are areas with long-term average surplus moisture and are potential sources of water for the landscape. Wetland HUs are represented with a shallower bucket (Figure C.12). They are characterized by dynamic water tables near the surface, and soils or sediments have layering (organic or mineral) that promotes saturation, limited storage, and near surface flow. The proportion of open water in a Wetland HU influences its hydrologic behaviour. In Wetland HUs with no standing-water, vegetation and soil processes result in low evapotranspiration and a net moisture surplus. However, in areas with open water evapotranspiration is elevated and a net moisture deficit can occur. Open water areas represent net moisture deficit and net removal of moisture as long as standing water persists.
2) Forestland HUs are areas of deeper, drained soils, where ET can be significant because of root access to considerable depth. Consequently, as water is removed from the landscape, Forestland HUs become potentially large water storage areas and are areas of long-term moisture deficit or moisture sinks in the landscape. Forestland HUs are represented with a deeper bucket (Figure C.12).

KEY CONCEPT: DELINEATING HYDROLOGIC BUILDING BLOCKS: HYDROLOGIC RESPONSE AREAS (HRAS).

The interaction between Wetland and Forestland HUs is largely influenced by the landform they are associated with. An HRA is an area (on any scale) in the landscape with similar grain size and permeability that results in characteristic water storage, as well as scale of and type of flow processes. HRA's have a characteristic response to climate cycles (see section D for details).

There are three general categories of hydrologic response areas in the Boreal Plains (Figure C.1):

1) Fine textured HRAs have considerable silts and clays that greatly reduce water transmission. This may occur on sloping, or hilly terrain such as till rich moraines, or on flat and low relief areas such as those influenced by glacial lacustrine processes.
2) Coarse textured HRAs have considerable sands and larger materials with greatly increased water transmission. This occurs in areas influenced by glacial fluvial or eolian processes.
3) Veneer-type HRAs have distinct layering of coarse over fine material, or fine over coarse materials with complex water transmission processes. These areas occur frequently in the Boreal Plains landscape, often near transitions of fine and coarse textured landscapes

C.1.5 Geology on the Boreal Plains: Implications for Landscape Reconstruction

DESIGN CONSIDERATION: DELINEATION AND ARRANGEMENT OF HYDROLOGIC BUILDING BLOCKS IN THE RECONSTRUCTED LANDSCAPE

The arrangement, distribution, and connectivity of the hydrologic building blocks (geology) influence the relative wetness or dryness of a landscape, its response to climate cycles, the type and amount of hydrologic connectivity, and, hence, its fundamental eco-hydrologic character and functionality. By accurately delineating the HUs and HRAs in reconstructed landscapes, soil, landform, and landscape scale water redistribution can be understood and managed to the extent possible.

The dominance of water storage in these landscapes, and large variation in subsurface (groundwater) connectivity with landform texture, limits the use of topography to define water balance units and groundwater connectivity.

Reflecting the natural Boreal Plains landscape, the reconstructed landscape will generally be comprised of all three HRAs: coarse-textured (e.g., tailings sand, coke), fine-textured (e.g., Clearwater overburden, fine tailings), and veneer-type (e.g., sand-capped fine tailings) geologic materials placed in deposits. Wetland (open and non-open water varieties) and forestland HUs will be both designed and appear opportunistically on the HRAs

Planning of landscape scale water redistribution involves consideration of the arrangement, distribution and connectivity of the hydrologic building blocks (HUs and HRAs) within the landscape. Correct delineation of these hydrologic components is necessary for conceptual understanding, design and modelling of potential water storage, memory and movement at the soil, landform and landscape scales through time

C.1.6 Complexities of Climate and Geology Interactions: The Importance of Antecedent Moisture and Hydrologic Connectivity

On Alberta's Boreal Plains the interaction of the geology, characterized by a large water-storage capacity, with the climate, characterized by an overall water deficit modulated by seasonal and decadal precipitation cycles, produces unique and variable seasonal and decadal scale wetting and drying cycles across all scales of the landscape. These cycles control eco-hydrologic function.

This interaction also controls the timing, type, and intensity of hydrologic responses within the landscapes to events ranging from rain storms and precipitation cycles, natural disturbances and anthropogenic activities, such as vegetation management or reconstruction and reclamation. The pronounced observed **thresholds** and **time lags** in responses, and the variable intensities and timing of the responses of the hydrologic "building blocks" to climate cycles and/or management, as a function of their individual and accumulated antecedent moisture conditions, forms the basis of this conceptual model of Boreal Plains hydrology.

The hydrologic building blocks of Boreal Plains landscapes exist and are hydrologically connected at multiple scales in the landscape through time. This variably connected network of hydrologic building blocks maintains the entire mosaic through the wetting and drying cycles, and thus imparts the required hydrologic functionality.

In order to understand, and subsequently design for, the distribution of optimal water quantities, to assure adequate water quality, and to anticipate water flow at any location, whether in the natural or reconstructed Boreal Plains landscape, knowledge of how and why the building blocks connect hydrologically, and when and where that connectivity manifests (i.e., as groundwater or surface water) is necessary.

C.1.6.1 Thresholds, Time Lags and Antecedent Moisture

Among the key characteristic of Boreal Plains landscapes are the observed thresholds and time lags in responses to "events." On the Boreal Plains, similar types of responses may be hydrologic or biologic. Events can be anything from precipitation or climate cycles discussed here to natural disturbances or anthropogenic events, such as vegetation management, disturbances, or reconstruction. As an example, this section discusses the commonly modelled response of runoff to a rain event or climate cycles. However, another important hydrologic response is groundwater recharge, which is linked to flushing of salt and other compounds of interest. The general concepts remain the same.

KEY CONCEPT: ANTECEDENT MOISTURE AND CLIMATE CYCLES

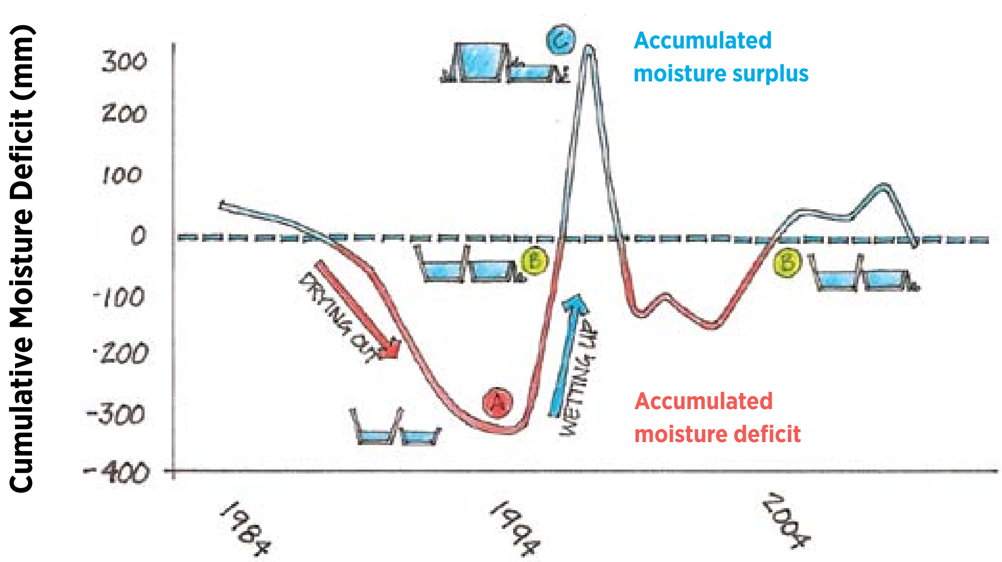
Time lags and thresholds in soil, landform and landscape scale runoff responses to precipitation events are a function of the antecedent moisture conditions of the hydrologic building blocks (HUs and HRAs). Antecedent moisture refers to the amount of water stored in a soil, landform, or landscape prior to an event, which determines the runoff response to an event and is intimately tied to climate cycles of water surplus and deficit.

The antecedent moisture and the pattern of drying out or wetting up in Boreal Plains landscapes can be anticipated to some extent by looking at climate data in terms of cumulative departure of current precipitation from the long term mean, or the cumulative moisture deficit (Figure C.13, first presented in Figure C.8b). After long, dry periods of accumulated soil moisture deficit, very low antecedent moisture conditions can occur, as conceptualized by a low water level in the water balance bucket (Figure C.13). With the large soil storage potential, precipitation inputs at this time will go primarily into storage, with little or no groundwater or runoff response. During wet periods that produce large accumulated moisture surplus, the antecedent moisture condition will be very high. With a water table near the surface and little of no available storage, precipitation inputs contribute directly to runoff and /or groundwater flows.

FIGURE C.13

Relating CDYrM to Soil Moisture Deficit/Surplus and Landscape Level Antecedent Moisture Condition over Climate Cycles

The red and blue vertical arrows indicate the cumulative moisture deficit and surplus, respectively, over climate cycles: A) dry periods, B) mesic periods, and C) wet periods. The buckets represent soil storage (water level) in the water balance equation, showing low antecedent moisture conditions in dry periods (A), variable antecedent moisture conditions during mesic periods (B), and high antecedent moisture during wet periods (C).



KEY CONCEPT: VARIABLE WATER MEMORY OF CLIMATE CYCLES AND RUNOFF THRESHOLD IN THE BOREAL PLAINS

Understanding the varying lengths of time between or **time lags** in runoff responses, as well as the intensity of and threshold-type responses to, events at the soil, landform and landscape scale in the Boreal Plains requires, in turn, knowledge of spatial and temporal variability in antecedent soil moisture. A fundamental difference between the relatively more simple Boreal Shield hydrology and Boreal Plains systems, is that in the Boreal Plains the storage component in the water balance does not reset to a similar value at the end of each annual cycle, and ΔS is generally not near zero. Thus, the landscape and its hydrologic components have a **"memory"** of the length and intensity of climate cycles, particularly drought. The memory must be accounted for as it influences the timing and intensity of how that landscape responds to events. To further complicate the relationship, the water memory and antecedent moisture condition varies with storage capacity. Thus, water memory will differ substantially between Wetland and Forestland HUs, HRAs, and various landscapes depending on the composition and arrangement of the these "building blocks."

Wetland and Forestland HUs occur in all landscapes, represent a wide range in storage processes (bucket sizes), and have a large influence on landscape hydrology. They are illustrated in the example for **water memory** (Figure C.14). Recalling the "bucket" image, the depth of storage or of the bucket determines how many years it takes to fill or empty it.

Forestland HUs have much longer water memory than Wetland HUs due to their deep available water-storage capacity, or larger bucket (Figure C.14). As a result, Forestland HUs are influenced continuously by the long-term moisture deficit of the region, and thus, have a longer memory of drought conditions. In general, forestland evapotranspiration maintains or accumulates the long-term moisture deficit, with roots accessing water deep in the soil profile. Consequently, these HUs do not respond to short term climate deviations in the same way Wetland HUs do. Their response to short term events is buffered during most years. Following drought they require large moisture surpluses, accumulated over several to many years, to fill available storage and subsequently spill over. One important hydrologic example of this buffering is that the return period for runoff from Forestland HUs can be 20 to 30 years.

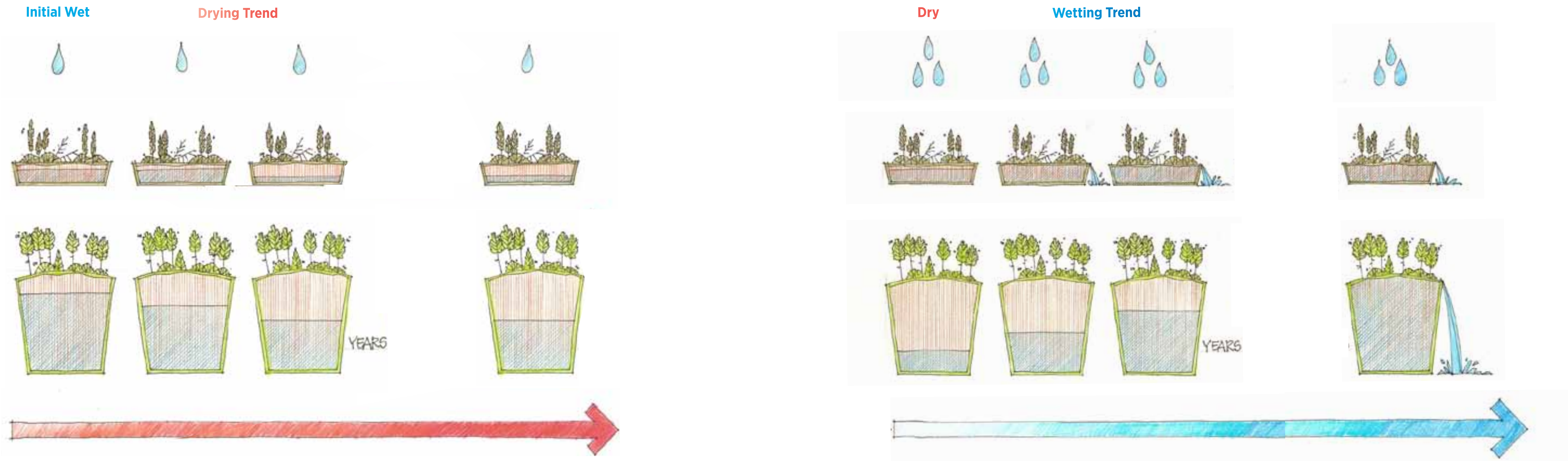
By contrast, **Wetland HUs**, particularly layered types or peatland systems typically have short-term water memory, on the order of one to two years (Figure C.14). Available storage is limited by shallow root depths, lower ET, and compaction and layering of sediments, which also promotes lateral surface flow (see Section D.3.3). Consequently, during drought periods Wetland HUs reach maximum thresholds in storage more quickly, and "remember" only the first years of a drought. Wetland HU storage is filled rapidly in response to short term deviations in moisture surplus relative to most Forestland HUs. The hydrologic manifestation of this short memory is that the observed return period for runoff from wetland (layered) HUs is approximately two years. Wetland HUs represent a consistent and often primary source of surface water in the landscape.

Open water portions of Wetland HUs are the exception. When open water occurs, for example in the case of large surface depression ponds (deep basins), water memory may be greatly increased in proportion to the depth or storage of the depression. Typically, long term evapotranspiration exceeds precipitation for open water, and a long-term accumulation of moisture deficit can occur depending on the depth of the surface storage. Water conservation feedback mechanisms of Wetland HUs are discussed in more detail in Section D.3.3.

FIGURE C.14

Differences in Water Memory of Hydrologic Units (HUs)

This series of images aims to assist in conceptualizing the interaction of climate and storage capacity and its effects on water memory, antecedent moisture conditions and runoff response. In this example, shallow and deep buckets can represent Wetland HU's and Forestland HU's, respectively (see Section D.2). Bucket size indicates potential available storage, the water levels in the bucket indicate antecedent moisture condition and the "fill and spill" thresholds are represented by water flow over the bucket.



When full (high antecedent moisture), both a shallow (small storage capacity) and a deep (large storage capacity) bucket have little room to store further incoming moisture, i.e., there is a small deficit in storage to fill the bucket.

During an extended drought both buckets dry out (moisture deficit accumulates/antecedent moisture reduces) but to different extents. The maximum storage deficit, or amount of water required to re-fill the bucket, is limited by the depth of the bucket, or the storage capacity.

In a shallower bucket, reductions in antecedent moisture occur only over the first year(s) of a moisture deficit (drought). After that, extension of the drought does not result in further reduction of antecedent moisture levels or storage deficit. Shallow buckets have a short "memory" because of the relatively low storage capacity and can only "remember" the first year(s) of the accumulated drought moisture deficit.

In contrast, deeper buckets have a long memory of the drought or accumulated moisture deficit due to their large storage capacity and the potential to create a large storage deficits. As a drought progresses, the antecedent moisture levels continue to reduce and the moisture deficit accumulates. Over time, the storage deficit of the deeper bucket becomes much larger than the shallow bucket. The reduction of antecedent moisture and increase in storage deficit (space to fill) in a deep bucket can match the entire accumulated deficit of a drought. Thus, the water deficit of entire drought periods can be "remembered".

When a wetting cycle occurs the difference in bucket size and relative "fullness" (storage or "water memory" capacity and antecedent moisture conditions) determines how readily the bucket can re-fill , and potentially "spill" or runoff.

At the start of a wetting cycle even small accumulations of moisture surplus can rapidly fill the shallow bucket typical of Wetland HUs. Within the first year(s) of a wetting cycle, surplus moisture may spill out (i.e., runoff) of a shallow bucket. In a deeper bucket (typical forestland HUs) the response to the initial year(s) of accumulated surplus water is simply an increase in water storage levels, but the antecedent moisture remains low. It may take several years to refill the large buckets typical of many Forestland HUs. Total accumulated surplus water supplied in the wet cycle must equal the drought deficit (space in the bucket) in order to re-fill the buckets (replenish the water storage deficits) before runoff (fill and spill) can occur.

The return period for runoff (when the shallow buckets "fill and spill") from Wetland (layered) HUs is approximately two years . In typical Forestland HUs there is an extended time interval (decades) between threshold runoff responses. The deeper bucket "remembers" the length and intensity of the drought more than the shallow bucket. In other words, there are variable time lags to fill buckets, and there are thresholds to runoff (fill and spill). The time lags and thresholds are controlled by the depth and the composition (soil layering and geology) of the hydrologic building blocks or "buckets" and where they are in a climate cycle (antecedent moisture condition).

C.1.6.2 Landscape Hydrologic Connectivity – Climate and Geology

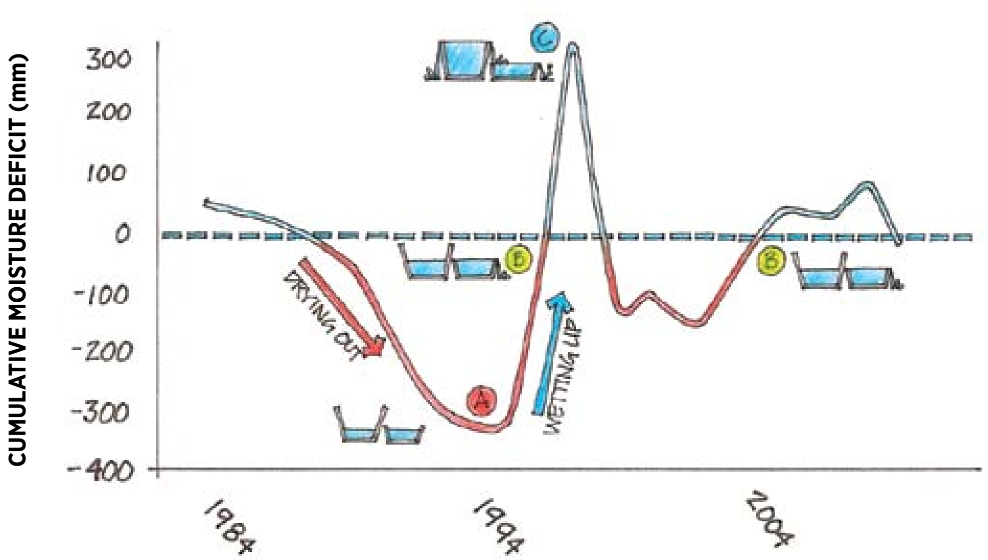
The variation in water memory, threshold responses and hydrologic connectivity through time and space of the mosaic of Wetland and Forestland HUs assembled on HRAs of various types is critical to understanding the hydrologic function of landscapes in the Boreal Plains.

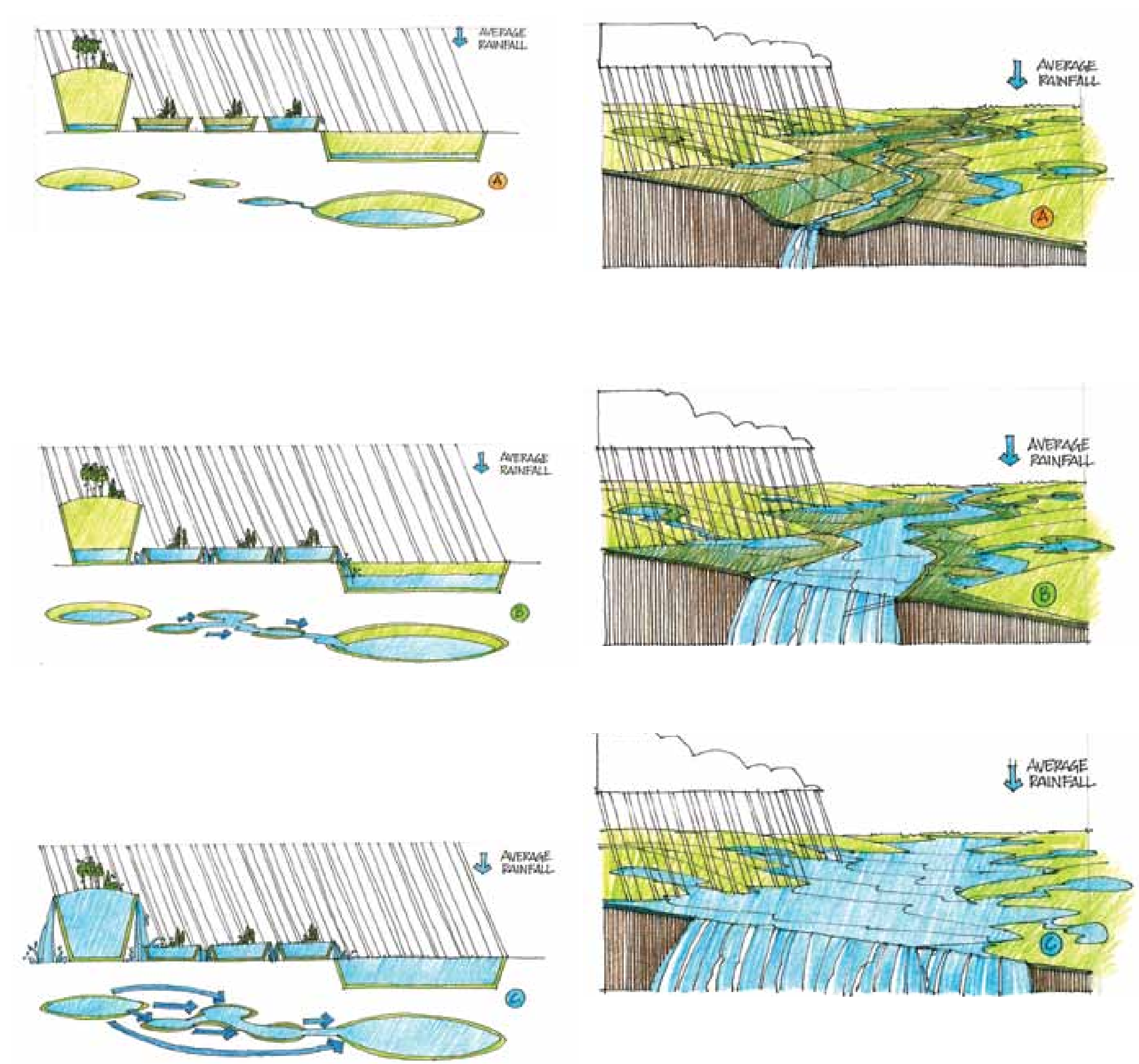
An improved appreciation of controls on landscape scale responses to events facilitate understanding the controls on water quality and ecosystem functioning, such as lake-level oscillation, and plant community regeneration after a disturbance.

FIGURE C.15
Influence of Variability in Water Memory and Antecedent Soil Moisture in Hydrologic Response and Landscape Scale Connectivity

Shown is the large variability in hydrologic connectivity and the resulting variable runoff response to a given precipitation event (in this case average rainfall), based on the variable antecedent moisture conditions of the hydrologic building blocks of a landscape during observed climate cycles typical of the Boreal Plains. Cumulative departure of annual precipitation from the long term mean (CDYrM) is used to represent the potential accumulated soil moisture deficit of the component building blocks of a landscape through a series of decadal and multi-decadal wetting and drying cycles.

Storage and runoff from HUs are represented by water balance “buckets”. Large buckets represent Forestland HUs, or portions of landscape dominated by Forestlands. Small buckets represent Wetland HUs, or portions of a landscape dominated by wetlands. Contributions of smaller component “building blocks” to the landscape runoff and connectivity to an open water wetland (lake) system are indicated by the arrows. This emphasizes the imperative that water storage must be considered on all scales and over time to adequately understand the hydrology of a soil, landform, or landscape in the Boreal Plains.





KEY CONCEPT: VARIATION IN LANDSCAPE RESPONSE TO RAIN EVENTS

The role of water memory or the profound effect of variation in soil storage and antecedent moisture on the response of building blocks of a landscapes to an event is illustrated by the observation of runoff response to given precipitation events over typical climate cycles.

Figure C.15 shows that precipitation events of similar size (be they individual rain storms or total annual precipitation) can result in little or no response, some response, or a very large response in surface runoff depending when the event occurs in the climate cycle and the differential antecedent moisture of HUs comprising the landscape. During extended dry periods with a cumulative moisture deficit both Forestland (large bucket) and Wetland (small bucket) HUs, have low antecedent moisture. There is little surface connectivity between HUs or within Wetland HUs. Both HUs store the precipitation resulting in no or little runoff response. As cumulative moisture deficits decline with mesic conditions, the spatial variation in storage and water memory between HUs becomes more evident. Forestland HUs with long water memory maintain low antecedent moisture conditions and these areas of the landscape continue to store precipitation inputs. Wetland HUs, with less storage potential and short memory, begin to fill and then spill available surplus moisture to adjacent wetlands. During infrequent wet periods with large cumulative moisture surpluses, the large storage space in Forestland HUs is filled and the antecedent moisture content of all HUs are high. This can result in a large runoff response to average precipitation events as both Forestland and Wetland HUs contribute to landscape runoff.

KEY CONCEPT: TYPE AND EXTENT OF HYDROLOGIC CONNECTIVITY THROUGH CLIMATE CYCLES

The hydrologic building blocks (HRAs and HUs) in a landscape are hydrologically connected by roots, surface and near surface water and groundwater (U, R and GW, respectively, in the water balance equation. The proportions, spatial configuration, and connectivity of the hydrologic building blocks influence water delivery or flow paths at all scales, both spatially and temporally.

During drought periods of the decadal cycle, Wetland HUs may go through phases of "disconnection" where they are poorly linked, and much of the open water is gone (Figure C.15). Typically larger water bodies also become disconnected and experience water level reductions. However, even with large regional cumulative deficits, Wetland HUs can respond to short-term deviations in climate and transport some water. Layered wetlands directly adjacent to other larger depression or open water systems (e.g., lakes and streams) may represent small, but important sources of water during drought periods. Similarly, Wetland HUs may represent significant sources of water to adjacent Forestlands to maintain forest growth. The dominant connection between HUs during this climatic regime is via root systems from wetland to forestlands (see Sections D.4 and D.5).

During mesic periods of the climatic cycle, Wetland HUs of various types and sizes wet up and connect. The spatial arrangement of the HUs is important during this period, as connectivity varies greatly in magnitude and direction between Wetland Hus and Forestland HUs. During precipitation events Wetland HUs generate runoff the volume of which is related to their surface area and connectivity. Connected wetlands provide surface water for adjacent depression or lakes, and add to regional runoff. Larger open water depression wetlands and streams well connected to other Wetland HUs begin to fill. Large open water depression wetlands predominantly linked to Forestland HUs may not receive significant inputs, and may lose water to the adjacent Forestland HUs during this period. Wetland HU to Forestland HU connectivity is the dominant hydrologic interaction during both dry and mesic cycles and can be important in forest productivity in a landscape. Whether this movement of water is upward or downward will be determined by the landscape arrangement of Wetland HUs and Forestland HUs in the low relief landscape, as many forestlands lie below adjacent wetlands in the Boreal Plains. This intermittently linked network of Forestland and Wetland HUs and HRAs represents the most common scenario over long periods and provides important context for the assessment of much of the hydrologic functionality characteristic of the Boreal Plains.

When the dry to mesic cycles are punctuated by wet periods of large accumulated moisture surplus, both Wetland and Forestland HUs fill and link up, connecting at multiple scales. During this period the landscape is fully "recharged" and hydrologic connectivity from forestlands, wetlands and larger open water systems is high. These periods can be important as runoff from Forestland HUs may supply significant water inputs to larger open water depressions or lakes that may not be well connected to Wetland HUs for the rest of the decade.

These soil, landform and landscape scale wetting and drying cycles, or cycles of progressively more hydrologic connectivity affect other hydrologic, biogeochemical and ecologic processes. Fish populations, for example, depend on periodic wet periods and large-scale landscape hydrologic connectivity. Some fish species move "up" in the landscape to spawn when the intermittently linked network of Wetland HUs "connect". These cycles also exert important controls on nutrient sinks and sources, which also influence ecosystem process in ponds and lakes that are undergoing decadal wetting/drying cycles. For example, in very high flow periods (wet cycles) dilution of algae in ponds was observed (Sass, et al. 2008). Bayely and Prather (2003) demonstrated variability in submerged aquatic vegetation dominance as a function of "connectedness" of wetlands.

KEY CONCEPT: SCALING WATER MEMORY AND HYDROLOGIC RESPONSES ACROSS LANDSCAPES

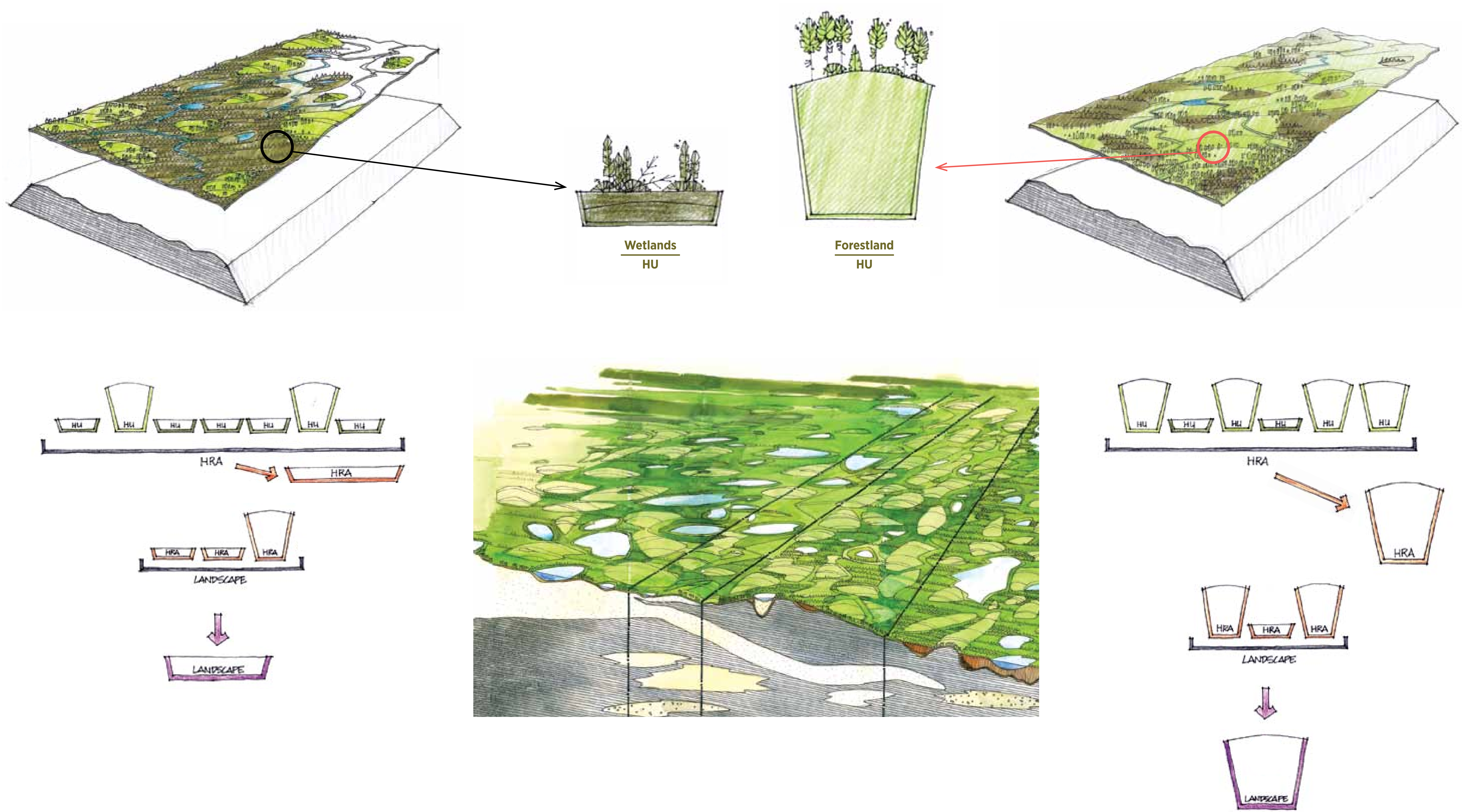
Comparison of wetland and aspen forestland dominated landforms (HRAs) illustrates how the storage, groundwater and runoff characteristics of Wetland and Forestland HUs telescope to a variety of scales (Figure C.15). Research has shown that small isolated Wetland HUs demonstrate similar storage properties, saturation frequencies and runoff return periods to large networked series of Wetland HUs. Interestingly, even when surrounded by Wetland HUs with high water tables, small aspen stand islands (of about 100 metres in diameter) can maintain water table depths in excess of three metres below ground, and have the large storage properties and water memory seen in larger aspen forestlands (Figure C.16). Thus, regardless of the landscape position of the HU(upland or lowland), the strong contrast in hydrologic characteristics are observed for individual HUs of a variety of sizes throughout a landform or landscape.

The surface area, distribution and connectivity of the HUs will then influence the cumulative landform and landscape storage and thus groundwater and runoff responses. Using the bucket representation, an HRA can be represented by HUs of different sizes (Figure C.16). Landforms (HRAs) dominated by Wetland HUs (i.e., Figure C.16, left) will tend to have hydrologic behaviour similar to a shallow bucket. Similarly, HRAs dominated by Forestland HUs typically have greater storage and longer memory, like that of a "large bucket". Runoff and base flow studies of streams across the Boreal Plains indicate that landscapes dominated by one HU tend to have similar overall hydrologic behaviour as the dominant HU or HRA. How to integrate and telescope up from the soil to landform to landscape scale is a key research question.

FIGURE C.16

Cumulating Hydrologic Properties of HUs to Coarser Scale HRA's and Landscapes in the Boreal Plains

These images compare a landform or landscape on the Boreal Plains dominated by a relatively greater or lesser proportion of Wetland HUs or Forestland HUs to illustrate how hydrologic characteristics may scale in the Boreal Plains. The Wetland and Forestland HUs are represented by the size and number of water balance buckets, corresponding to each HU. The dominant hydrologic behaviour of a hydrologic response area (HRA=landform) will correspond to the dominant HU. Similarly, hydrologic behaviour of a landscape in the Boreal Plains will correspond to the characteristics of the dominant HRA.



C.1.7 Interactions of Climate and Geology: Implications for Landscape Reconstruction

Anticipating and understanding the large spatial variability in reconstructed geology (HUs and HRAs) and controls on antecedent moisture in conjunction with the climate cycles, can inform the land designer or land manager about thresholds and time lags in expected responses as manifestations of "water memory" in the landscape.

Practitioners will then be able to anticipate and plan for water quality, water quantity, and timing of water flows on all scales in the reconstructed landscape, and hence controls the ecosystem functioning (e.g., plant community regeneration after a disturbance, lake-level oscillations).

DESIGN CONSIDERATION: ANTICIPATING WATER MEMORY AND SPATIAL AND TEMPORAL VARIATIONS IN ANTECEDENT MOISTURE – I.E., TIMELINES FOR RECLAMATION CERTIFICATION

Land designers and managers should expect and plan for large spatial and temporal variations in antecedent moisture of forest soils and in water levels in wetland sediments and ponds of reconstructed oil sands landscapes. This is due to the inherent large variability in storage capacity of HUs and HRAs in constructed landscapes that interact with short- and long- term climate cycles.

The interpretation of biological, hydrologic and geochemical response measurement (e.g., stressed tree stands, low pond orlake water levels, or low stream flow at runoff gauging stations), require that land managers consider historic climate data and patterns, the individual and cumulative soil properties, and hence the relative water-storage capacities of the building block (HRA or HU) being assessed. To assess the potential antecedent moisture of the soil, landform, or landscape within a climate cycle the land designer and manager needs to interpret the data both within the year of observation and within the context of longer-term patterns (previous three to five and 20 to 30 years). The landscape feature may be exhibiting the cumulative effects of a wetting cycle or a drying cycle that may not be immediately evident from the precipitation data of the current year.

Land managers should anticipate variability in the time it takes to reach reclamation targets since the initiation and completion of reclamation activities will occur at different points in climate cycles. In addition, trajectories of recovery could vary between HUs and among HRAs within a reconstructed landscape relative to the storage capacity of the materials used in the reconstruction. Assessment and timelines for reclamation certification of landscapes must consider hydrologic history since landscapes are reconstructed and reclaimed with varying mixes of materials and at different periods in the climate cycle.

An important difference between the natural analogues and the reconstructed oil sands landscapes is the antecedent moisture conditions of the reconstructed landforms (HRAs). Landforms placed dry by the truck and shovel method, may take several years or decades to "wet up". Landforms placed hydraulically, like some tailings, may take multiple years to drain or "dry out." In the interim, these antecedent moisture conditions must be considered in the context of the climate cycles and the wetting up or drying out pattern each landform or building block will manifest given this "time zero" antecedent moisture condition.

If antecedent moisture conditions of the hydrologic building blocks are not factored into landscape reconstruction activities, the resulting ecosystem's responses to various natural or anthropogenic stimuli may be largely unpredictable.

DESIGN CONSIDERATION: LANDFORM HYDROLOGIC CONNECTIVITY

A proper accounting of the variability in the "water memory," threshold responses, and hydrologic connectivity through time and space of the mosaic of wetland and forestland HUs assembled on HRAs of various types will be critical to the optimal functioning of reconstructed landscapes. And challenges will often be compounded by competing objectives: ensuring removal of excess water during high runoff periods to maintain the integrity of engineered structures, for example, while also holding or providing water to sustain a variety of ecosystem functions on reclaimed landscapes over extremes in wet to dry climate cycles.

While the designer and manager have no control over climate cycles, some control can be exerted over the landscape water balance and landscape connectivity. The designer can begin to plan and anticipate landform and landscape trajectories of response to events by manipulating the arrangement, distribution, and connectivity of the HU and HRA characteristics (geology, soils and vegetation) in the reconstructed landscape to mimic the functional mosaic of natural landscapes. Water removal structures and networks will need to incorporate local and landscape scale storage and generation of water surplus mechanisms. By assembling a network of Forestland HUs and a network of connected and isolated Wetland HUs within and around Forestland HUs of various scales on HRAs, local to landscape scale ecosystem processes should be sustained through the range of anticipated climate events typical of the Boreal Plains.

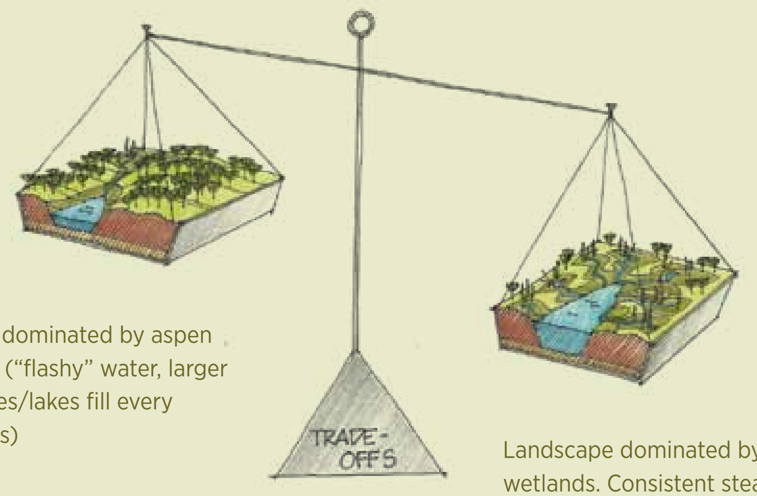
DESIGN CONSIDERATION: LINKING LOCAL TO LANDSCAPE SCALE HYDROLOGIC RESPONSE – TRADE OFFS

At the landscape scale, consideration of the compatibility of multiple ecosystem functions constructed with respect to water supply will be required. Landscape scale water redistribution involves understanding the probabilities of wet and dry periods (seasonal and decadal) and the cumulative influence or the arrangement, distribution and connectivity of the hydrologic building blocks (HUs and HRAs) required for given functions. With variable storage and transmission properties of the HUs and HRAs there are trade-offs at the landscape scale (Figure C.17) between having a consistent supply of fresh water for runoff to feed surface water bodies and having forest dominated systems providing a more "flashy" water supply.

For example, large expanses of forest production have large water demands and may not provide consistent water quantities required to maintain large end-of-pit lakes. EPLs may require that less land be put into production of forests and a greater proportion of the landscape be designed as networks of connected wetland HUs to provide more consistent water supply through the year and over climate cycles.

FIGURE C.17
Trade-offs for Water Distribution on the Boreal Plains

The water storage vs. production in a landscape will be influenced by the proportion and arrangement of HUs and HRAs. There is a trade off between large water demand and storage for extensive forestland production, and generation of consistent water supply from extensive and connected wetlands.



Landscape dominated by aspen forestlands ("flashy" water, larger water bodies/lakes fill every 2-3 decades)

Landscape dominated by connected wetlands. Consistent steady supply of water to water bodies

C.2

Summary of the Conceptual Model: Hydrologic Context, Composition and Connectivity and the Water Balance Equation

The hydrologic functionality of the Boreal Plains mosaic (i.e., its ability to evolve and sustain itself through the extended drought cycles and periodic wet intervals) is a consequence of the region's hydrologic

- Context –climate, geology and their interactions
- Composition – landscape building blocks of the Boreal Plains, and
- Connectivity – intermittent and permanent water fluxes between and within hydrologic "building blocks."

The water balance equation is the tool for characterizing and designing for this functionality.

This research has quantified each of the components of the water balance at the soil, landform and landscape scale through multiple time frames for the unique conditions found on the Boreal Plains and identified fundamental changes in how the equation should be approached when trying to understand, manage or design watersheds in this area.

FIGURE C.18
Hydrologic Functionality and the Water Balance Equation

HYDROLOGIC FUNCTIONALITY → = (Is a result of)

Hydrologic functionality—observed in natural systems and that needs to be recreated in reconstructed systems—is the ability of landscape to provide water through the extended drought cycles (dry periods), and store or facilitate transmission of large amounts of water during the periodic wet cycles (wet periods). This leads to the ability to meet needs of ducks, fish, and forests for example.

Natural

Reconstructed

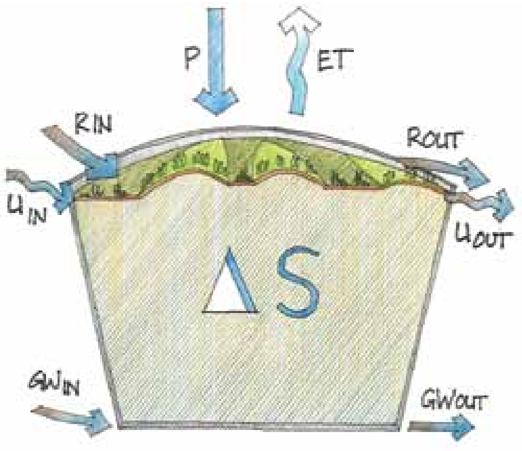
The tool for understanding, designing, projecting, and managing hydrologic functionality in a landscape is the water balance equation. The water balance equation quantifies amounts of water going in to a soil, landform or landscape, and how much is "spilling"(runoff) or "leaking" out (groundwater recharge, vegetation community use) at any point in time

In the Boreal Plains the water balance is dominated by storage and should be expressed as :

$$\Delta S = P - ET + (R_{in} - R_{out}) + (GW_{in} - GW_{out}) + (U_{in} - U_{out})$$

ΔS The change in storage (amount of water stored on the surface or below the surface in the landform or landscape).
P Precipitation
ET Evapotranspiration
R Runoff
GW Groundwater
U Uplift*

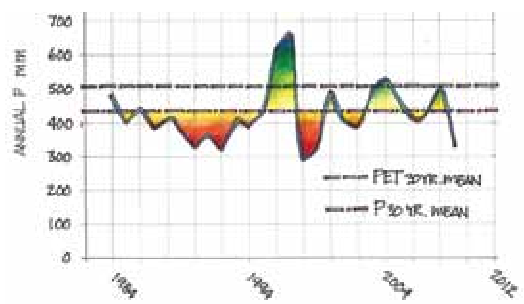
** U or"uplift" has been added to the conventional water balance equation, as this research demonstrated the substantial influence aspen root networks have on water redistribution in Boreal Plains landscapes.*



CONTEXT ✚ COMPOSITION ✚ CONNECTIVITY

CONTEXT

A primarily **"dry" climate** punctuated by occasional wet periods

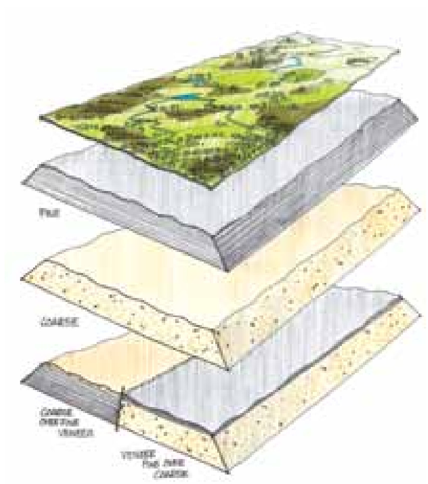


Interacting with
Heterogenous geology composed of interacting layers (HUs over HRAs).

COMPOSITION

The critical functional elements of which are : the "hydrologic building blocks" with characteristic texture, soil-vegetation-atmosphere interactions

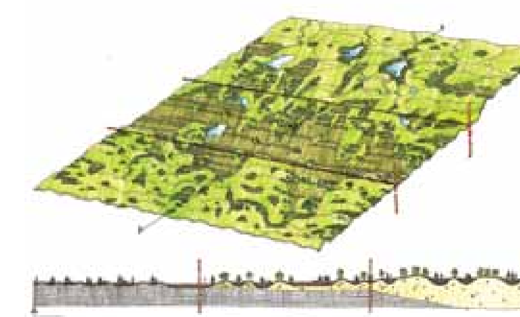
There are two types of hydrologic units (HUs): Forestland and Wetland HUs. These sit in various combinations "on top" of 3 general types of hydrologic response areas (HRAs) coarse, fine and veneer.

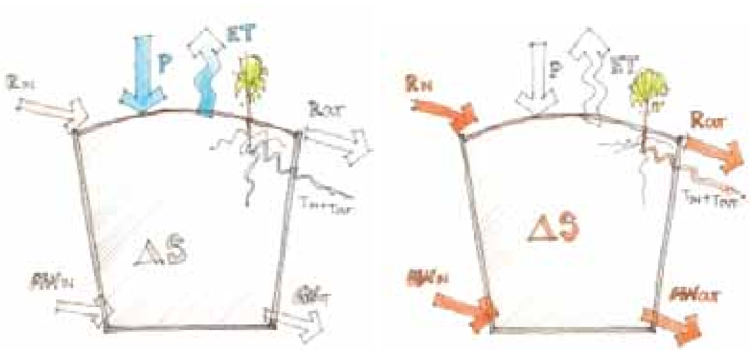


CONNECTIVITY

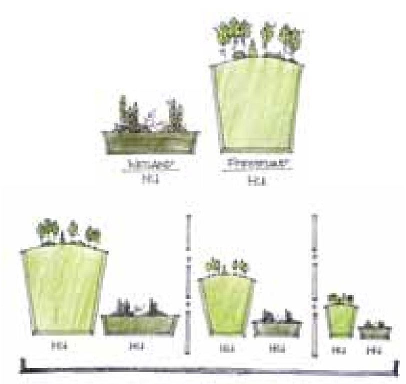
The HUs and HRAs (composition) are present (natural systems) or constructed and **connected** at a range of scales .

Subsurface, surface connectivity at local and regional scales.





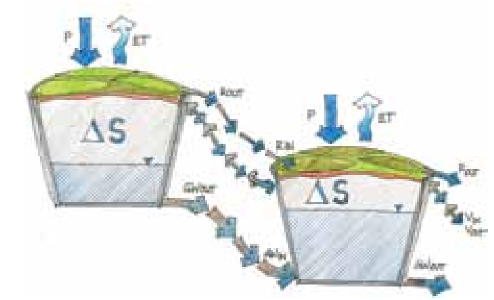
Conceptualize a soil, landform or landscape being like a "bucket" or reservoir of water. To understand and quantify the water balance of the landscape one must examine how the climate varies over time and how it interacts with the spatially variable geology.



Appropriate delineation of the HU buckets with their characteristic storage and hydrologic properties facilitates application and quantification of the water balance.

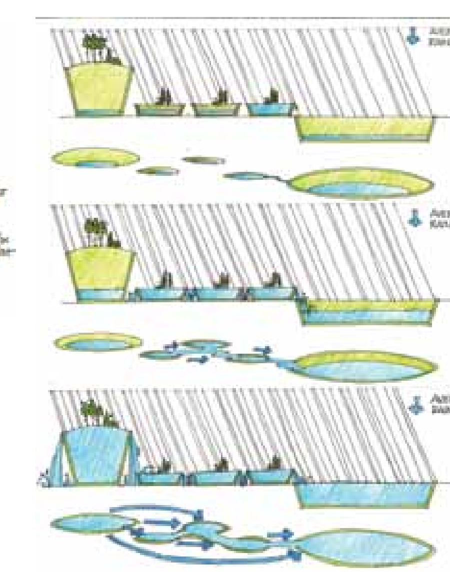
The HRA bucket is an integration of the HRA's geologic characteristics and the size and proportion of HU buckets within it.

Designing for and managing this "composition" influences the ET and ΔS (and hence R, GW and U) terms for the various buckets.



One example of small scale connectivity between HUs

Dry antecedent conditions



Wet antecedent conditions

Example of large scale connectivity in the landscape

C.2.1 The Water Balance Equation

The water balance equation, concurrent with accurate delineation of effective hydrologic units, is the numerical tool for quantifying the conceptual model of water flow. It is essential for understanding and then managing (to the extent possible) the climate, the geology and the interaction of the two at all scales. The water balance equation focuses on storage and the relative contribution of climate and geology in balancing water inputs to and water outputs from a soil or landform and within a particular time frame. The relative magnitude of the terms in the equation combined with the patterns of their change in magnitude through time is the hydrologic "fingerprint" of a particular landscape.

Considering the large spatial variability in geology, and thus storage, the landscape must be effectively delineated into functional hydrologic building blocks (HUs, HRAs or collections of HRAs) to apply the water balance equation. Figure C.18 illustrates how the water balance equation helps in understanding the relative contributions of the key hydrologic processes to the functionality of the Boreal Plains landscape.

C.2.2 Hydrologic Context

The mosaic of wetlands and forestlands characteristic of the Boreal Plains exists in the context of:

- A climate characterized by a water deficit modulated by annual (seasonal) and decadal precipitation patterns.
- A deep, heterogeneous geologic landscape composed of fine-textured, coarse-textured, or veneer-type glacial deposits, which have the potential to store large volumes of water but vary greatly in storage and transmission properties.

The interaction of a generally dry climate with a geology characterized by a large water-storage capacity, leads to annual and decadal soil, landform, and landscape-scale wetting and drying cycles. These cycles control the eco-hydrologic function and response (timing and intensity) to events such as precipitation, disturbance, and management.

C.2.3 Hydrologic Composition

The hydrologic functionality of the Boreal Plains can be best characterized as a mosaic of Wetland and Forestland hydrologic units, on a wide range of scales, superimposed on a heterogeneous landscape composed of fine-textured, coarse-textured, or veneer-type glacial deposits that behave as discrete hydrologic response areas. Application of water balance approaches requires effective delineation of these hydrologic "building blocks".

- A hydrologic unit (HU) is a unit within an HRA with characteristic soil properties that result in discrete soil-vegetation-atmosphere interactions that further enhance differences in response to climate cycles.
- A hydrologic response area (HRA) is an area (of any scale) in the landscape with similar grain size and permeability that results in characteristic water storage and flow processes and characteristic response to climate cycles.

The presence of hydrologic units on a range of scales in the mosaic is essential for the hydrologic functionality of the landscape.

C.2.4 Hydrologic Connectivity

Water quantity and quality, and the timing of water flow in the Boreal Plains landscape are regulated by the intermittently linked network of Wetland and Forestland HUs. The Wetland HUs and Forestland HUs, and the HRAs on which they are found, are linked via water flow through groundwater, roots, and surface and near surface runoff.

The type of connection between Forestland HUs and Wetland HUs is controlled by 1) the nature of the HRA, 2) the relative position of the HUs in the HRA, and 3) the vegetation composition of the HU. The strength and direction of the connection is determined by the composition of the HRA and the climate cycles (i.e., there is a strong interaction between climate and geology).

The hydrologic connectivity between HUs and water tables within the glacial deposits, or reconstructed landforms, (HRAs) are usually not based on the topography of those deposits (i.e., watershed boundaries are not reliably identified by topography), but rather on the composition of the HRA.

Hydrologic connectivity occurs on a wide range of scales through the landscape and through time. The characteristic of multiple scales of hydrologic units and multiple scales or levels of connectivity underpins the hydrologic functionality and character of the Boreal Plains landscape

C.2.5 Implications

DESIGN CONSIDERATION: WATER BALANCE

The water balance equation is the principal tool for quantifying the spatial and temporal variability in water storage and connectivity of a reclaimed landscape during a myriad of scenarios. Appropriate delineation of hydrologic units (or buckets) together with climate provide designers and land managers with essential information to understand the hydrologic context in which they are operating, and to re-establish hydrologic functionality (composition and connectivity) at a range of scales in reconstructed or managed systems over time.

Key components of the water balance such evapotranspiration and ΔS can be manipulated and managed, within the characteristic variability in precipitation, to influence local to regional connectivity and water redistribution. Design and planning teams can "telescope" up and down the scales of the "building blocks" or "buckets" to assess the effects of changes to the individual and cumulative water balances through the design process.

DESIGN CONSIDERATION: HYDROLOGIC CONTEXT

All design and modelling of reconstructed landscape must focus on the climatic context: a water deficit that is modulated by annual and decadal precipitation patterns.

The design must account for a potential long-term water deficit, but, and perhaps more importantly, it must recognize and reflect the influence of annual to decadal cycles of drying and wetting (Section C1.3) on hydrologic and ecologic function of a landscape.

Both natural and reconstructed landscapes are composed of heterogeneous geologic deposits that do not respond in the same way to the climate cycles. These deposits can be delineated into "hydrologic "building blocks".

Typically, design focuses on managing the periodic large precipitation events that may cause reconstructed landform failures. It is necessary to design for these events, but a complete design must intentionally build responsiveness to both wet and dry climate cycles into landforms. Incorporating water storage and generation features in landform units and into the broader regional landscape is a critical design element to sustain the reconstructed ecosystems through the frequent and persistent dry periods.

The natural landscape has features that perform both these functions. The connected network of Wetland HUs, punctuated by Forestland HUs (the wetland/forestland mosaic) overlaying geologic deposits with a range of water storage characteristics, accommodates the large wet events and the extended dry periods.

DESIGN CONSIDERATION: HYDROLOGIC COMPOSITION

Similar to natural systems, measurable properties or features of reconstruction material can be used as guides for identifying and classifying hydrologic building blocks (HUs and HRAs) that act as critical functional elements in the reclamation landscape and permit landscape water budgets to be managed.

A key functional characteristic to incorporate in designs is heterogeneity at all scales. Often conventional landform reconstruction practices often smooth and remove heterogeneity in the one meter to ten meter scale.

A more beneficial approach would be to mimic the variability found in the natural analogues where variations in topography, repeated across the landscape, at all scales (micro to meso) are required to create the functionality of the boreal mosaic. Small units are required to create or sustain the medium-sized units, which, in turn, are required to create or sustain the large units. What is done at a micro-scale affects the larger-scale units, and connectivity between the units must be explicitly considered.

DESIGN CONSIDERATION: HYDROLOGIC CONNECTIVITY

In reclamation efforts, it is possible to mimic natural systems and arrange HRAs in the landscape and position and connect HUs on the HRAs to determine and promote:

- The emergence and sustainability of the range of ecological communities (terrestrial and aquatic) that characterize the Boreal Plains, which has implications for equivalent capability.
- The quantity, quality, and timing of water flow in the reconstructed landscapes at all scales, from small ponds and wetlands on individual dumps to end-pit lakes.

By designing for multiple scales of interconnections between wetland and forestland units, it should be possible to accommodate the large wet events and the extended dry periods (dual hydrologic functionality), and therefore to:

- Increase confidence in geotechnical performance (i.e., manage large wet periods or events) by storing moderate amounts of water in discrete landscape features and by enhancing evaporative losses.
- Sustain forest and wetland diversity and productivity through dry cycles.

However, the cumulative influence of local scale designs on the water balance of the larger landscape must be considered. There are trade-offs between constructing landforms or landscapes dominated by Wetland HUs that potentially provide consistent and often large amounts of fresh water for runoff to open-water systems (rivers, ponds, or lakes) versus landscapes dominated by open water and/or Forestland HUs that behave as freshwater sinks and provide “flashy” runoff over time (see Section C.1.4, Figure C.16).

C.3

Modelling Watersheds in the Athabasca Oil Sands Region: Implications of the Conceptual Model

C.3.1 What is Needed

The following are essential components for the accurate modelling of landscapes in the Boreal Plains:

1. An accurate conceptual model that focuses on evapotranspiration, soil storage, and groundwater rather than the conventional focus on precipitation and runoff
2. Explicit capture of seasonal and between-year climate variability with a calibration target of less than one year
   - To adequately deal with the strong effect of antecedent moisture conditions on hydrologic response calibration and validation targets need to be based on a particular year, and season within in a year, not annual or multi-year averages.
3. An appropriate delineation and characterization of the hydrologic response areas and hydrologic units, which may be uncorrelated with topographically defined watershed boundaries, in order to correctly identify the sinks and sources of water in the catchments being modelled or gauged
   - This also fundamentally controls sinks and sources of compounds of interest such as salts, nutrients, and organics.

C.3.2 Current Approach

Currently, precipitation-runoff models with "lumped" physical representations of the watershed are often used to simulate watershed hydrology. Such "lumped models" (the Hydrologic Simulation Program Fortran is an example) are able to match runoff volumes, on average for larger watersheds. However, they do not adequately or accurately represent key processes in play, such as large soil water storage, in the landscape that lead to groundwater recharge or to runoff.

The implications of this are profound. Although such models may be useful in projecting average or total volumes of water to aquatic systems, they cannot currently be used to make statements about the life cycles of wetlands, or the water quality in groundwater and receiving water bodies (e.g., lakes and rivers).

Salt flushing—the redistribution of salt, nutrients, and other compounds of interest in the landscape—is a critical performance indicator in reconstructed systems (wetlands or forestlands) in the oil sands region, and is fundamentally linked to water movement in these landscapes. The wetting and drying cycles of the landscape profoundly influence the redistribution of elements of interest and hence need to be considered in any modelling effort.

Current modelling approaches for reconstructed landscapes differ from the recommended approach in a number of ways:

1. The current conceptualization and application of lumped models do not adequately deal with antecedent moisture and thresholds for hydrologic events, such as runoff.
   - Lumped models are calibrated using precipitation and runoff, and thus do not build strong enough connections between evapotranspiration, soil storage, and groundwater, and their attendant contributions to or effects on runoff volumes. Although soil storage is represented in current lumped models, the depth and distribution of storage and groundwater interaction are inadequately represented, and thus, soil storage is underestimated.
2. The calibration targets in current modeling efforts are often multi-year averages, which neglect consideration of decadal and multi-decadal climate cycles.
3. The water balance equations are applied to topographically defined surface-water watershed areas, which will fail to capture the large spatial variability in hydrologic units (HUs and HRAs) in most locations.
4. Because of the above, intra and inter-annual variations in stream flow or runoff data are not adequately interpreted in many modelling efforts.

C.3.2.1 Examples to Illustrate Issues with the Current Approach

1. A model that averages inputs and fails to adequately represent and weight soil storage, evapotranspiration, and groundwater recharge, mutes the effects of the wetting and drying cycles in the landscape, resulting in misleading interpretations or projections.

1.1 An example of this would be using an average annual runoff of 70 millimetres over 30 years when, in reality, the cycle was more like two years of more than 300 millimetres, 14 years of 10 millimetres, and 14 years of 100 millimetres (in four to five-year cycles). Large fluctuations around the runoff average are a manifestation of the effects of climate cycles leading to large variations in the amount of water stored in the landscape. This variability plays a key role in new landscape evolution by influencing the timing and volume of water moving into soil storage and, in the process, potentially flushing salts from the system rather than simply running off.

1.2 Failure to account for antecedent moisture and its effects on the landscape often result in misalignment with actual data. To compensate for the variability, water balance components such as PET are modified to improve the "fit" of the model. In addition to failing to accurately identify the actual causes of the variability (e.g., multiple and large soil moisture storage "buckets"), this modification of PET numbers further confounds outputs, as actual evapotranspiration (AET) values vary substantially between and within hydrologic units, and have distinct upper limits depending on the classification of the hydrologic unit (Section C.1.4).

2. Current approaches use streamflow runoff as the primary and obvious manifestation of climate influences on watersheds. This may work for landscapes characterized by geology with minimal water storage, but water storage and evapotranspiration dominate the water balance in most watersheds in the Boreal Plains, and in reconstructed systems. Thus, calibrations need to measure changes in water storage within the soil as well as accounting for runoff.

2.1 Runoff in the Boreal Plains is generally of very low and highly variable volume, poorly correlated with mean annual precipitation, and characterized by high flow return periods of two to three decades due to the interaction between climate patterns and heterogeneous geologic units with a high storage capacity. As a result, runoff is not, on its own, an appropriate index for hydrologic sustainability. It must also be coupled with soil water storage and groundwater indices.

2.2 When potential water storage is insufficiently emphasized (i.e., the soil water storage bucket is very shallow) in current approaches, the modelled landscape "generates" a lot of excess water. This excess then has to be allocated into the landscape to obtain a water balance. Often the modeller "pushes" this excess water into groundwater or into additional evapotranspiration (pushing the limits on parameter estimates). These are arbitrary allocations to surface and sub-surface water flow paths, made to compensate for an less appropriate conceptual model. The allocation ratios need to be physically quantified independently.

3. Streamflow runoff data are not adequately interpreted in many modelling efforts due to the inaccurate delineation of surface-water catchment areas. This can lead to inadequate gauging or estimates of runoff.

3.1 Due to the dominance of water storage over runoff in Boreal Plains landscapes, it is important to classify the landscape into the correct hydrologic response areas and hydrologic units. These hydrologic "building blocks" may be uncorrelated with topographically defined watershed boundaries. The classification effort is required to better understand and predict the response of catchments to climate or management events, and to adequately interpret streamflow runoff data.

3.2 Currently, outflows in many model simulations are measured against stream gauges at the bottom of a series of variably connected or unconnected hydrologic response areas. As a result, streamflow runoff data interpretations are confounded by the lack of appropriate delineation and poor understanding of catchment boundaries and contributing areas. Furthermore, if similar conceptual models for surface water catchment areas are employed to make projections regarding salt flushing or redistribution of "compounds of interest" in reconstructed landscapes, the designer will probably miss critical source areas and pathways and inaccurately predict loading rates to aquatic systems.

3.2.1 For example, in a topographically defined catchment with a single streamflow gauging station, runoff may be measured as 90 millimetres for the entire catchment area. This research has demonstrated that the effective surface- water catchment areas are the total surface area of the connected wetland hydrologic units, and often runoff from such units is in the order of 300 millimetres. In a catchment with 30% wetlands, the 90-millimeter measurement is correct, but does not adequately reflect the source of that water within the catchment. Lack of understanding of water sinks and sources within the catchments severely limits the ability to extrapolate to other catchments such as reconstructed landscapes.

3.3 Proper calibration of these models demands a firm understanding of the location and extent of runoff-generating source areas that export water to aquatic ecosystems. The models also need to reflect measures of lithology, water table dynamics, soil water content, and runoff within the catchment, as well as an independent characterization of the individual parameters.

C.3.3 Recommendations

In order for a model to provide more instructive outputs, it needs to be a simplified distributed model that:

1. Centres on evapotranspiration, soil storage, and groundwater rather than the classic or conventional focus of precipitation and runoff relationships
2. Explicitly captures seasonal and between-year climate variability with a calibration target of less than one year (i.e., calibration targets need to be based on a particular year, and season within in a year, in order to adequately take into account the strong effects of antecedent moisture conditions on hydrologic response)
3. Appropriately delineates the hydrologic response areas and hydrologic units that influence water movement, rather than topographically defined watershed boundaries that may incorporate functionally different hydrologic units. This is required to correctly identify the sinks and sources of water in the catchments being modelled or gauged in a low relief and heterogeneous landscape.

However, modelling efforts (and the models themselves, to some extent) could be modified and simulation improved to better represent the water storage thresholds by first delineating the fraction of deep and shallow water storage areas typical of HUs in the landscape. This could be achieved by using broader calibration windows for storage parameters in such a way to accurately reflect the known physical characteristics of the Boreal Plains.

C.3.4 Innovative Modeling for Landscape Reconstruction

C.3.4.1 Modelling Lake-groundwater Interactions

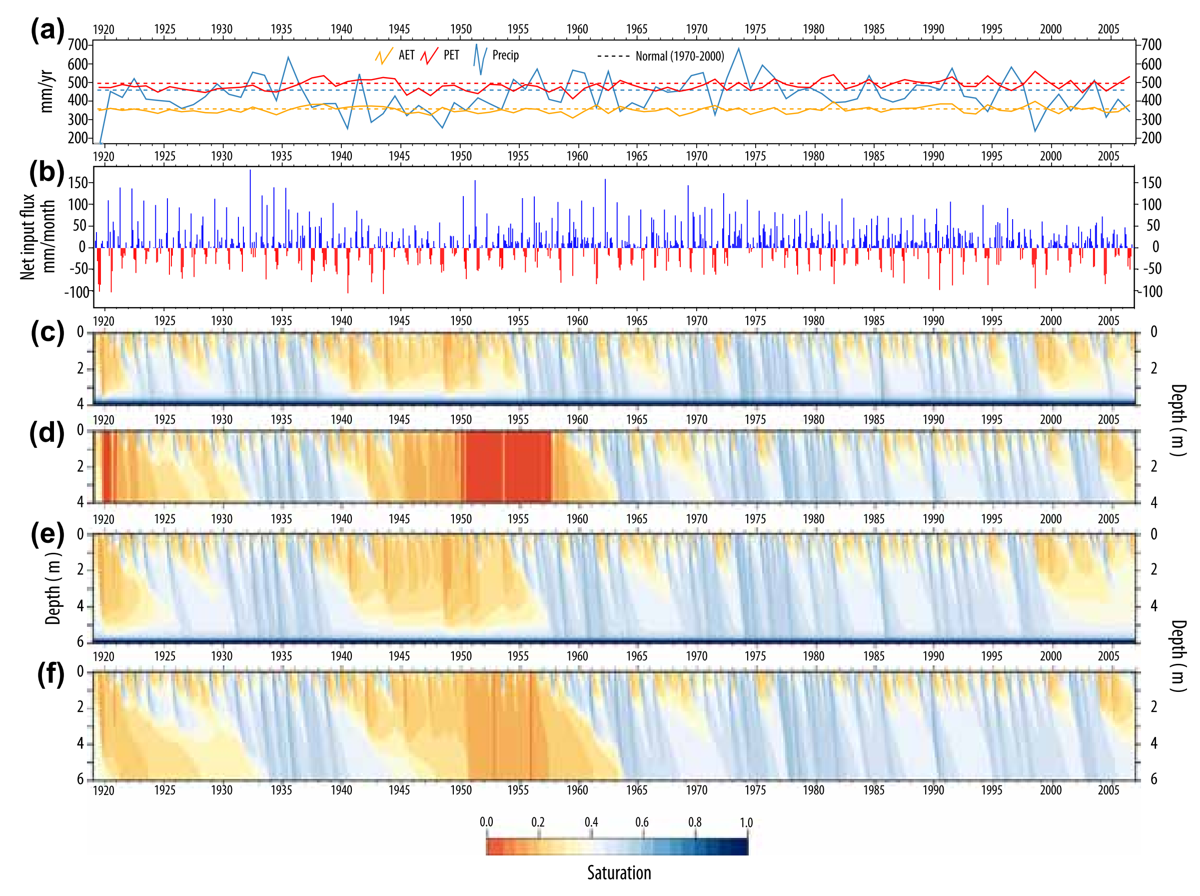
The Integrated Hydrology Model (InHM) can be applied to lake-dominated hydrologic systems, and can also be used to investigate landscape and atmospheric controls on hydrologic processes (Smerdon et al. 2007). The modelling framework would be appropriate for larger areas, specific hydrologic landscapes, and for longer-term applications (i.e., landscape management and reclamation) because it is not hampered by excessive numerical intervention (i.e., minimizing a priori assumptions). The physical boundaries of the model domain need not be surface catchments or watersheds (Devito et al., 2005a). However, successfully applying the model depends greatly on the ability to define spatially variable, sub-surface hydraulic properties. This type of robust model will provide insights when investigating the responses of hydrologic systems in areas where anthropogenic changes (imposed by landscape disturbance or variation in climate) might be masked or subdued by natural variations in water cycles.

C.3.4.2. Recharge as a Function of Climate: Effects of Variation of Soil Covers, HRA Material Type, and Climate Cycles on Groundwater Recharge

In the paper by Carrera-Hernandez et al. (2012) this work, historic climate data, available data on forest water use, and data on the grain size of various theoretical HRAs were used to illustrate the effects of climate cycles on landform moisture status and groundwater recharge, as a function of the properties of the HRA and the climate. In this study, the effects measured were the time lags between precipitation events and their observed influence on the landscape. This work demonstrates how managing HRA material type (fine, coarse) and soil-capping thickness can influence groundwater recharge, and how the depth to the water table influences the periodicity or cycling of recharge, for example, when Forestland HU moisture is completely full and has the potential for runoff (Figure C.19).

FIGURE C.19
Modelled Soil Moisture Distribution over the 80-year Climate Cycles Relative to Depth and Texture of Overburden for Reconstructed Landscapes

This series of figures from Carrera-Hernandez et al. (2012) illustrates soil moisture dynamics in a sandy loam HRA, with different depths to water table (available storage).



Details on the Landscape Components of the Conceptual Model

D

Table of Contents

D

Details on the Landscape Components of the Conceptual Model

This section expands on the spatial variability of the geologic components of a landscape and its influence on landscape connectivity as discussed in the conceptual model of water flow in Section C.

The spatial and temporal variability in the water balance of the Boreal Plains mosaic is a function of hydrologic context, composition, and connectivity. Studies of natural analogues illustrate that hydrologic functionality in the region is a consequence of the interaction of climate—characterized by a long-term moisture deficit modulated by intermittent wetting cycles—with geologic components or hydrologic "building blocks"—characterized by a large but variable storage capacity.

Hydrologic connectivity and water flows in the natural and reconstructed landscapes may be anticipated or better understood and managed by a diligent consideration of this climate-geology interaction and the antecedent moisture conditions of the landscape and its components. The importance of climate and climate cycles was discussed in detail in Section C. The spatial variability in the geologic composition of the Boreal Plains, and its influence on the type and magnitude of connectivity and water flow, is detailed here.

While climate cycles cannot be "managed," the water balance and the effects of the interaction of climate and geology can, in some measure, be anticipated and influenced by managing the composition and connectivity of "hydrologic building blocks." This hydrologic control can be exercised by:

- Accurately identifying "building blocks" (hydrologic response areas, or HRAs, and hydrologic units, or HUs) in the watersheds
- Designing and building those "blocks" with a range of water storage and transmission properties and then connecting them effectively such that they can contribute water to the target ecosystems (e.g., wetlands, lakes, forestlands) during drought or drying cycles, and store and transmit water effectively during wet cycles
- Planning the arrangement of water sinks (e.g., Forestland HUs and open-water bodies) and sources (e.g., Wetland HUs) in the landscape, thereby spatially influencing evapotranspiration, the primary mechanism of water loss from these landscapes
- Recognizing and managing the influence of vegetation community development trajectories, which will affect all components of the water balance

The remainder of this document expands on these four management processes and—to facilitate improved understanding of the variability in landscape linkages, connectivity, and hydrologic response—provides further detail on the HRA and HU landscape components.

D.1

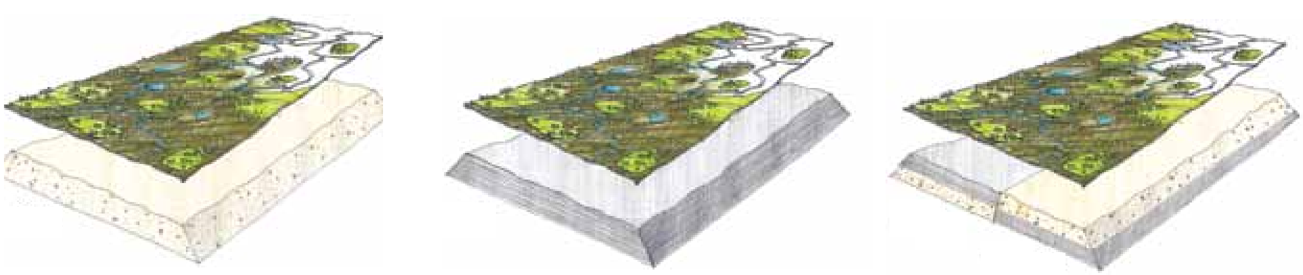
Hydrologic Response Areas: Delineating Landscape Heterogeneity

In addition to improving the water balance calculation in the Boreal Plains, a more precise delineation of HRAs will produce a more accurate definition of watershed divides. Due to the deep heterogeneous glacial deposits characteristic of this region, topographically defined watershed boundaries are not always representative. Watershed boundaries are a function of both the material type (confining layers and surface geology) and the topography.

In reconstructed landscapes, HRAs are defined in the same way as in natural landscapes. As in the natural analogues, bulk hydrologic properties govern hydrologic behaviour, and reconstructed landforms on oil sands leases can be grouped into HRAs based on their material type (coarse-textured, fine-textured, or veneer-type).

FIGURE D.1
Three Main Types of Hydrologic Response Area

The first layer to be considered or delineated in the natural or reconstructed landscape is the HRA. This level or layer is delineated as an area with unique hydrologic properties (storage and transmissivity) due to its texture. It is important to note that this layer has no scale. *The layer floating above these HRAs will be the hydrologic unit mosaic layer as defined in Section D.2.



Coarse-textured HRA **Fine-textured HRA** **Veneer-type HRA**

D.1.1 Defining Hydrologic Response Areas

An HRA is an area (of any scale) in the landscape with similar material type or grain size and permeability that result in characteristic water storage and water transmission properties, and characteristic responses to climate cycles as defined by the material type coarse-textured, fine-textured, or veneer-type (Figure D.1).

Fine-textured HRAs have considerable silt and clay content which greatly reduces water transmission. In natural systems these HRAs may occur on sloping or hilly terrain such as till-rich moraines or on flat and low-relief areas such as those influenced by glacial lacustrine processes. In reconstructed systems a fine-textured HRA may be a saline sodic overburden landform or a densified tailings deposit.

Coarse-textured HRAs have considerable sand and coarser-textured material content with a higher capacity to transmit water. In natural systems these occur in areas influenced by glacial fluvial or eolian processes. In reconstructed systems a coarse-textured HRA may be a tailings deposit or a coke pile or coke deposit.

Veneer-type HRAs have distinct layering of coarse over fine, or fine over coarse material with complex water transmission processes. This is the only HRA type with a defined vertical scale. This type of HRA is defined as the area where the interface of the textural discontinuity is within two metres of the ground surface. These areas occur frequently in the Boreal Plains landscape, often near transitions of fine- and coarse-textured landscapes. In reconstructed landscapes a veneer-type HRA might be a sand-capped composite or consolidated tailings deposit or other type of sand-capped fine tailings.

KEY CONCEPT: HRAS DEFINE CHARACTERISTIC HYDROLOGIC PROPERTIES AND CONNECTIONS

The material type (coarse-textured, fine-textured, or veneer-type) along with topographic position in the landscape determines the nature and extent of hydraulic connections between HRAs and the hydrologic units on top of them. In all cases in the Boreal Plains where a long-term moisture deficit predominates, trees place a high demand for water on the system. The material type of the HRA affects how easily water moves vertically or laterally in response to water supply (by the climate) and water demand (by the trees).

In **fine-textured** HRAs (Figure D.2 top):

- Groundwater connectivity is limited to local scale because the lower hydraulic conductivity limits lateral movement of water.
- Water table configurations typically reverse under the Forestland HU adjacent to the Wetland HU, with hydraulic depressions below Forestland HUs on fine-textured HRAs.
- Wetland HUs will be largely hydraulically isolated or perched and act as recharge areas for adjacent Forestland HUs. Discussion of the effects of the HRAs on the distribution of wetland and forestlands on each type of HRA can be found in Section D.5.

In **coarse-textured** HRAs (Figure D.2 middle):

- Groundwater connectivity ranges from local to regional scale because coarse-textured deposits enhance infiltration and lateral subsurface flow.
- In a sub-humid climate (such as that of the Boreal Plains), the water table responds to deeper geology rather than the topography, resulting in water tables that link beyond local topographic divides.
- Wetland HUs predominantly occur as "perched" on fine-grain lenses or in discharge areas in larger-scale features.

In **veneer-type** HRAs (Figure D.2 bottom):

- Occurrence is in the transition zone between coarse-textured and fine-textured HRAs.
- Coarse material enhances percolation of surface water to the lower confining layer where the veneer-type is coarse over fine. The water table mirrors the underlying confining layer rather than the topography.
- The fine-textured materials where the veneer type is fine over coarse (no figure presented) perch water and evapotranspiration has a substantial influence on the water table, resulting in configurations similar to those described for the fine-textured HRA.

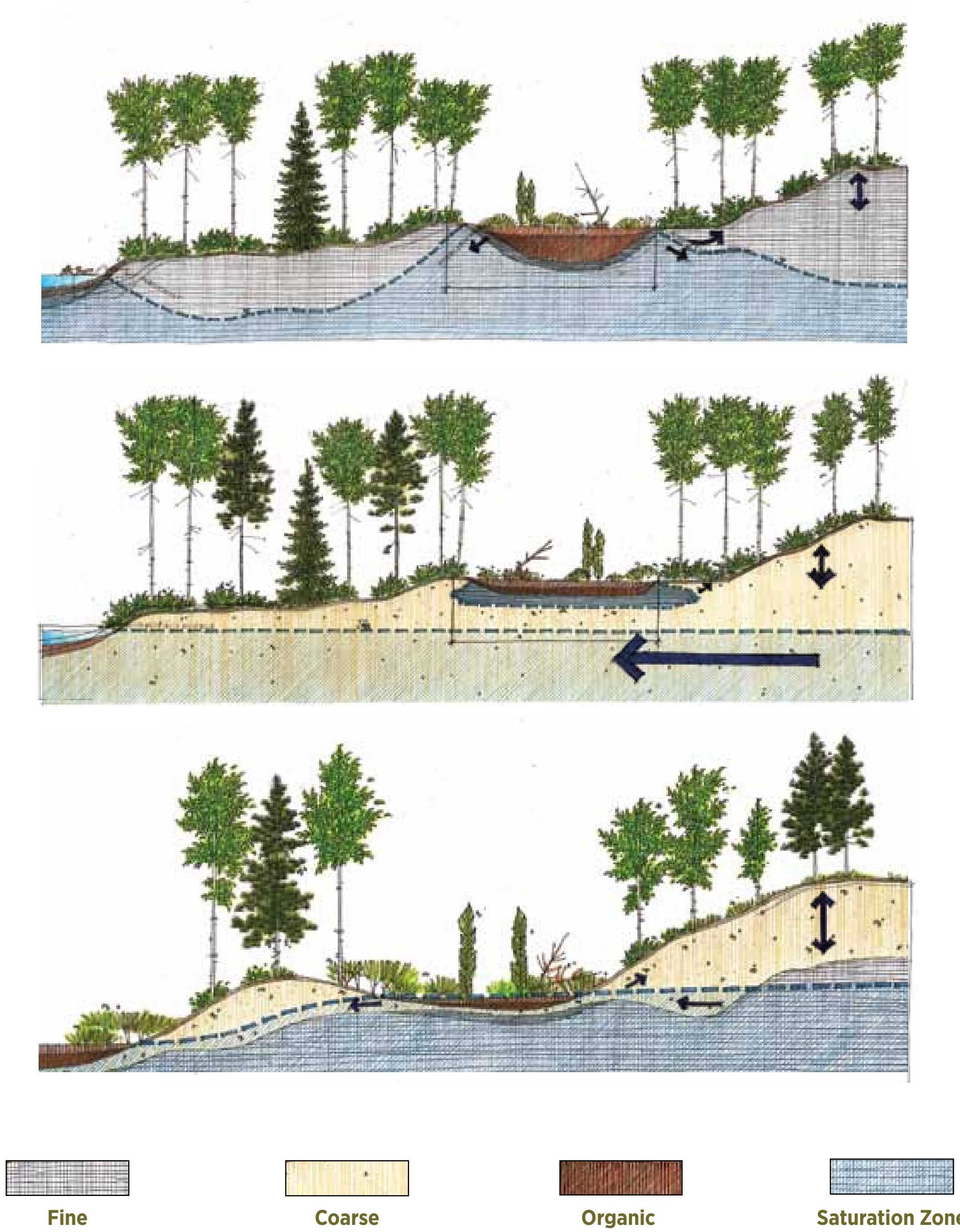
KEY CONCEPT: HRAS OCCUR AT A RANGE OF SCALES

An HRA can range from metres to kilometres in width and from one metre to 100 metres in depth. The veneer-type HRA is the only HRA with an implied vertical scale of two metres in depth.

FIGURE D.2
HRA Types: Typical Water Table Configurations

Typical cross-section showing distribution of vegetation type, mineral and organic material, and long-term saturation or water table configuration in a) a fine-textured HRA, b) a coarse-textured HRA, and c) a veneer-type (coarse over fine) HRA. Horizontal and vertical scales are similar.

Trees place a high demand for water on the system. The arrows represent orders of magnitude of water movement (vertically or laterally). In coarse-textured material, water is more easily transmitted in the lateral direction as compared to movement through fine-textured material. In coarse-textured HRAs the lateral movement can be three orders of magnitude higher than the vertical movement (the reverse of fine-textured materials).



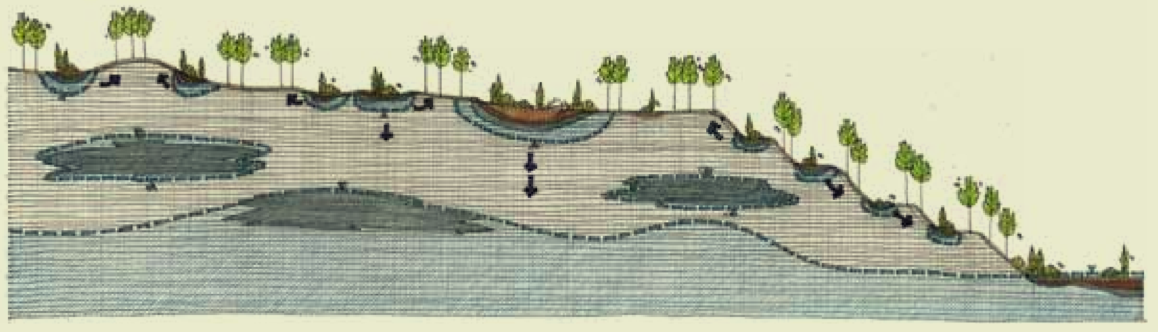
D.1.2 Hydrologic Response Areas: Implications for Landscape Reconstruction

When conducting closure planning and estimating water fluxes and water quality in reconstructed landscapes, it is important to delineate the landscape into appropriate hydrologic response areas. By doing so, the type and scale of water flow and connectivity can be correctly identified, which also enables correct identification of the sinks and sources of the compounds of interest in the watersheds being modelled or gauged. It must be remembered that the HRAs delineated may be uncorrelated with topographically defined watershed boundaries.

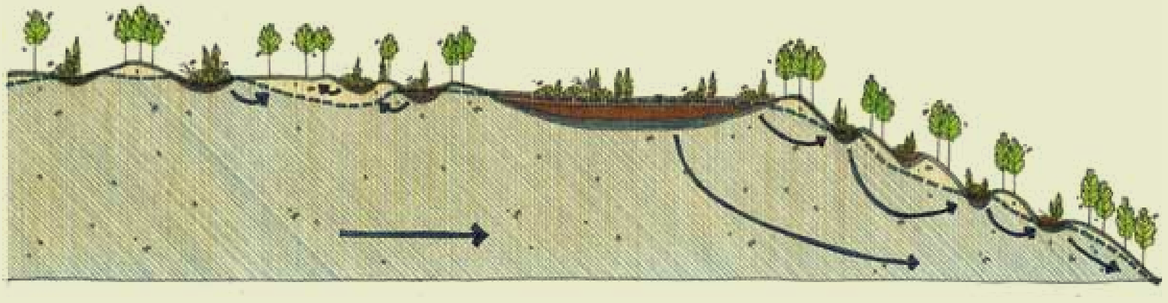
FIGURE D.3
Reconstructed HRAs: Examples

As in the natural system diagrams, the arrows represent potential water movement (vertically or laterally). Shown are (a) a possible clay shale overburden dump and (b) a possible tailings sand dump. In fine-textured reconstructed HRAs like shale overburden dumps which are placed dry, Wetland HUs are expected to be dominantly perched and isolated. The example depicted in (b) for a reconstructed coarse-textured HRA shows a probable water table configuration once the hydraulically placed materials have drained. In such cases, Wetland HUs are expected to be dominantly perched and isolated but with wetlands forming in the discharge areas at the toe.

a)



b)



DESIGN CONSIDERATION: DELINEATION OF HRAS WILL IMPROVE THE ABILITY TO ANTICIPATE WATER REDISTRIBUTION IN THE LANDSCAPE

Each HRA type will have a predominant tendency for certain kinds of flow (surface flow or groundwater recharge) regardless of the topography constructed. Ideally, the hydrologic tendencies of each type of HRA will be discerned early in the design phases so that the HRAs (landforms or subsections of them) can be arranged in the landscape to generally meet the stated spatial and temporal water-use and eco-hydrologic goals. Precise HRA definition will also enable more effective planning of the distribution of wetland and forestland hydrologic units (Section D.5) and identification of the required features (e.g., soil layering) for enhancing the viability of those units (Section D.3.3).

A **fine-textured HRA** on constructed landscapes (Figure D.3a) may be composed of fine-textured overburden (e.g., Clearwater formation derived) or may be a densified tailings deposit.

A **coarse-textured HRA** on constructed landscapes might be a tailings sand structure (Figure D.3b) or a coke pile or coke deposit.

A **veneer-type HRA** could be sand-capped composite or consolidated tailings (CT) in which the interface of the textural discontinuity is two metres or less from the ground surface.

DESIGN CONSIDERATION: VARY THE SIZE OR SCALE OF HRAS TO ADD COMPLEXITY AND BREADTH OF HYDROLOGIC FUNCTIONALITY

HRAs in reconstructed landscapes may be an entire landform or a subsection of a landform (i.e., an HRA may occur at a variety of scales). Incorporating a range of scales of these building blocks into landscape designs will provide a range of important water storage and transmission capabilities both temporally and spatially.

DESIGN CONSIDERATION: ANTECEDENT MOISTURE CONDITIONS DURING MATERIAL PLACEMENT INFLUENCE THE TRAJECTORY OF HYDROLOGIC CONNECTIVITY

The structures diagrammed in Figure D.3 represent possible end members for water table configurations in reconstructed HRAs. There is a crucial difference in the behaviour of reconstructed HRAs when the added geologic material has been placed hydraulically (“wet”) versus when it has been placed “dry” by trucks.

When placing fine-textured or coarse-textured material by trucks (i.e., dry), the resulting HRA is expected to develop or exhibit similar groundwater regimes to the natural analogues that have largely drained over thousands of years (see Figure D.3a).

In contrast, when the geologic material has been placed hydraulically, a period for drainage is expected before groundwater regimes similar to those found in natural analogues become established. For example, tailings sand or coke poured hydraulically will drain for decades (as a function of grain size or artificial drainage) before developing the characteristic “flat” water tables that mimic the underlying confining layer as observed in the natural analogues (Figure D.3b).

D.2

Hydrologic Units: Defining Wetland and Forestland HUs

Although there is a diverse array of vegetation or forest types in the Boreal Plains, from a hydrological point of view they can be clustered into "wetland" and "forestland" community types, and designated as hydrologic units (Figure D.4).

A hydrologic unit (HU) is a unit within a hydrologic response area (HRA) with characteristic soil properties that result in discrete soil-vegetation-atmosphere interactions that further enhance differences in response to climate cycles already inherent due to the hydrologic tendencies of the HRA.

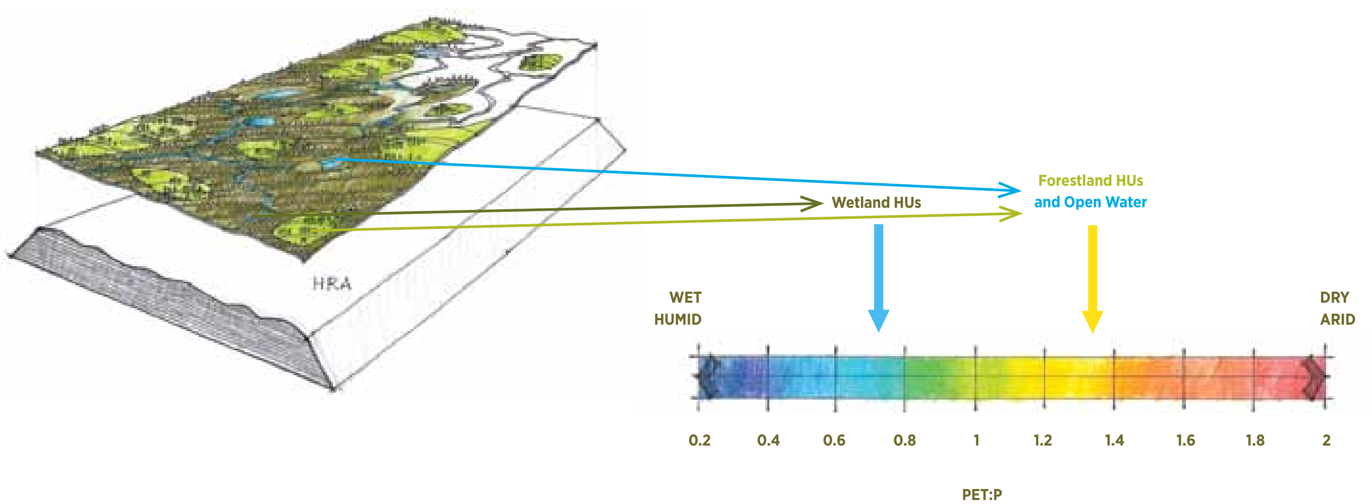
In the Boreal Plains, Wetland HUs (which include layered terrestrial-type wetlands as well as open-water systems) and Forestland HUs:

- Can behave independently (hydrologically)
- Have distinct water storage and transmission characteristics (soil properties)
- Have unique vegetation controls on their water balances (Figure D.4)

The Wetland and Forestland HUs reside on HRAs of all types. The implications of HU and HRA interactions on gradients of water flow and connectivity will be discussed in Section D.5. Specific details of Wetland and Forestland HU physical features and water balance characteristics are detailed in the following sections.

FIGURE D.4
Wetland and Forestland Hydrologic Units in the Boreal Plains

The second layer to be considered or delineated in the natural or reconstructed landscape is the HU mosaic. The forestland and Wetland HUs comprising the mosaic have distinct water storage and transmission properties and unique vegetation controls on their water balances, resulting in Wetland HUs tending to the wet side of the dryness index while open-water areas and Forestland HUs register on the dry side.



KEY CONCEPT: HYDROLOGICALLY, WETLAND AND FORESTLAND HUS CAN BEHAVE INDEPENDENTLY

The ranges of water table configuration and hydrologic connectivity between wetland and Forestland HUs on a variety of HRAs were discussed in Section D.1 and represented in Figures D.2 and D.3 and are also discussed in more detail in Section D.5. Typical water table configurations observed in Wetland and Forestland HUs often reflect water demands placed on the system by vegetation and indicate hydrologic connectivity between individual HUs (Figure D.5). Among differences between the units:

- A Wetland HU *does not* require a Forestland HU in order to maintain itself hydrologically. The presence of the wetland is not driven by the classic concept of runoff or groundwater flowing from an upland or forestland unit "down" to a wetland, but by climate and evapotranspiration to precipitation ratio dynamics (Figure D.5).
- Because of the moisture deficit in forests and the potential of the Wetland HU to function as a source of water, a Forestland HU may require an adjacent Wetland HU for long-term vigour through natural disturbance or climate cycles.

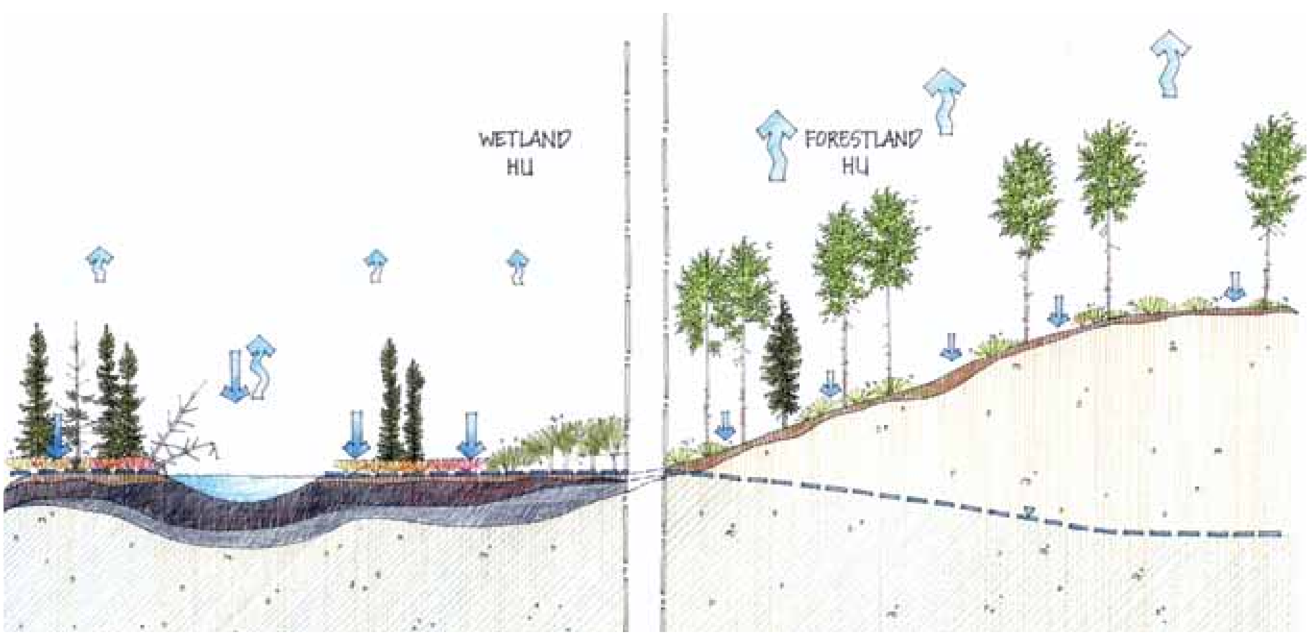
It is important to note that the terms "upland" and "lowland" are not used as descriptors for hydrologic units since topographic position rarely defines whether a portion of the landscape will be wet or dry. It is common to find "upland" wetlands and "lowland" forests.

In summary, the two HUs can initially be conceptualized as independent units. Details of their individual characteristic water balances and the features of each HU will be presented in the following two sections. The potential interaction and connectivity between and within Wetland and Forestland HUs and implications for moisture distribution throughout the landscape are discussed in later sections.

FIGURE D.5

Wetland and Forestland HUs may or may not be Hydrologically Connected

Comparison of typical vegetation structure, soil layering, water levels, and atmospheric exchange in Wetland and Forestland HUs that occur across all types of HRAs. Wetland HUs may not be connected hydrologically to the adjacent Forestland HU and thus the two can be conceptualized as independent units.



D.3

Wetland Hydrologic Units

Wetland hydrologic units occur in areas that have a long-term average moisture surplus and function hydrologically to pond water and promote surface saturation in a region of long-term average moisture deficit (recall Figure D.4). A Wetland HU can be one or a combination of types (e.g., fens, bogs, thicket swamps, ephemeral draws, marshes, shallow open waters) found in the Boreal Plains. Wetland HUs can appear as isolated entities or poorly- to well-connected networks that function as the effective catchment areas for water in Boreal Plains landscapes.

The structures for maintaining saturation in Wetland HUs are varied. They range from units that provide depression or detention storage and which create evaporative losses of water (where evapotranspiration is greater than precipitation) due to a dominance of open water, to locations with soil layering that contributes to a net moisture surplus (where evapotranspiration is less than precipitation), promotes surface saturation, and generates lateral water flow for both the HU and the landscape mosaic (Figure D.6).

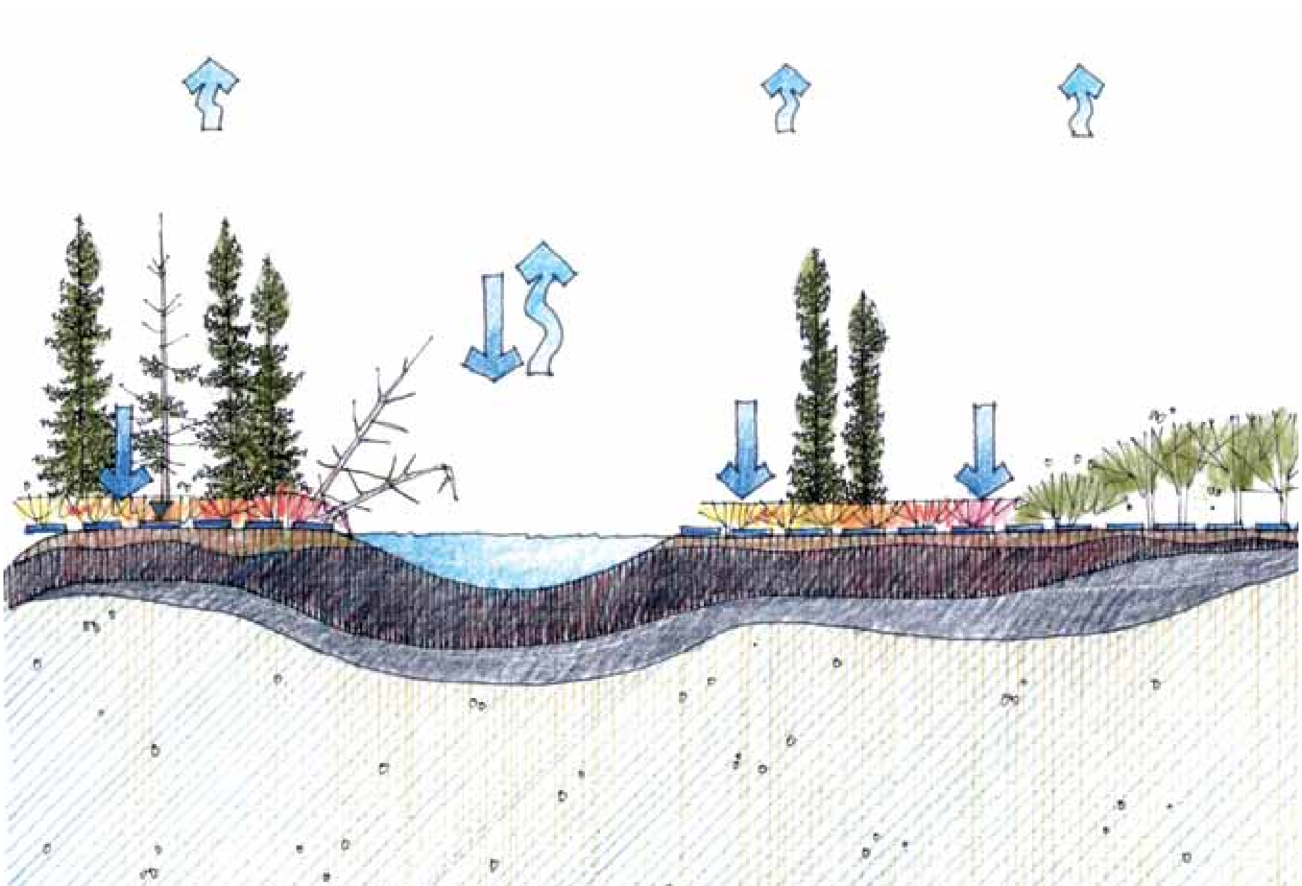
The former instance requires constant regeneration of water supply and a landscape configuration suitable for receiving surface runoff or groundwater discharge ("external" water) to maintain the wetland. In contrast, the latter case is characterized by a long-term water surplus generated by a precipitation rate exceeding evapotranspiration ("internally" generated water), enabling this type of Wetland HU to take advantage of shorter-term deviations from the long-term water deficit to ensure persistent saturation and runoff. This water surplus can then be redistributed to other Wetland and Forestland HUs and to larger lakes and streams as a function of the distribution and connectivity of the Wetland HUs across the landscape.

An effective Wetland HU design must consider the properties (e.g., geology, landscape position, and surface connectivity) that determine whether a Wetland HU, in whole or part, is a net water source or a net water sink. The physical structure and position of a Wetland HU constructed on an HRA will dictate surface water balances and the landform design features required to maintain the unit's function supplying moisture to surrounding HUs.

FIGURE D.6

Wetland Hydrologic Units: Range of Types of Wetland from Open-Water to Terrestrial Types

Typical open water (pond), deep and shallower soil-layered wetland systems in the Boreal Plains. Shown is the general water level and range of atmospheric fluxes of precipitation (down arrow) and evapotranspiration (up arrow) across different wetland types.



D.3.1 Definition: Areas of Long-Term Surplus Moisture

A Wetland HU in the Boreal Plains landscape is defined neither by the type of wetland present (vegetation) nor by topographic position, but by how the unit functions hydrologically to receive and store water and/or promote surface saturation and become an area of long-term average surplus moisture.

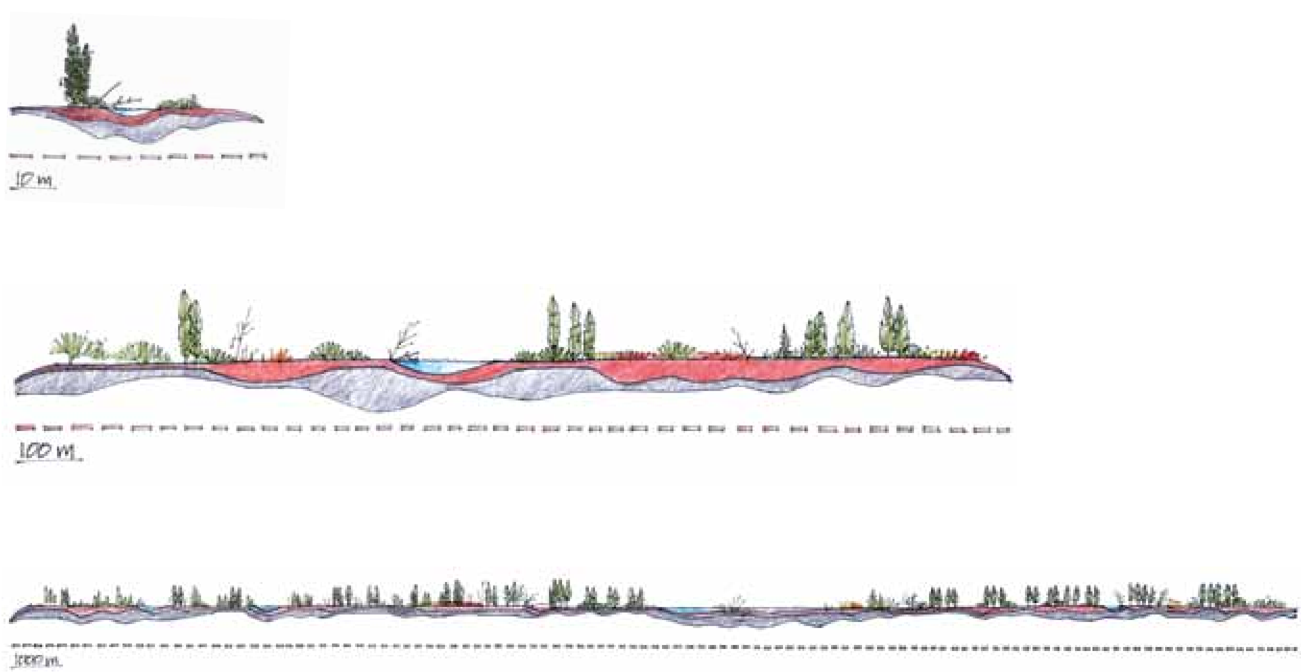
KEY CONCEPT: WETLAND HUS HAVE NO PREDEFINED SCALE BUT A BROAD RANGE OF FUNCTION

Wetland HUs can be one or a combination of the conventionally defined wetland types found in the Boreal Plains (e.g., fens, bogs, thicket swamps, ephemeral draws, marshes, and shallow open waters.) A Wetland HU is often a complex or a combination of these wetland types and has a range of structures and processes and, thus, hydrologic function.

Wetland HUs, or complexes thereof, can range in size from ten- to more than a thousand-metres (Figure D.7) across. Complexes of Wetland HUs can also be associated with larger lake (standing water) or river (flowing water) systems in the landscape (Figure D.8).

FIGURE D.7
Ranges in Type and Scale of Wetland HUs

Wetland HUs may be individual wetlands or complexes of wetland types ranging from open-water systems to deep- and shallow-layered "terrestrial" wetlands. Shown is a series of cross-sections through wetlands and wetland complexes, each representing a Wetland HU, ranging in size from ten metres to kilometres across. Wetland soil layers: 1) organic in red-brown, 2) confining layer in grey, 3) open water in blue.



KEY CONCEPT: AQUATIC SYSTEMS (OPEN WATER) MAY OR MAY NOT BE PRESENT IN WETLAND HUS

Open waters are present at some time, and in some proportion, in most wetland types and are classified as Wetland HUs. Open waters at all scales expand or contract within Wetland HUs seasonally, decadally, and multi-decadally as a function of the climate. As a result of this very dynamic character, and the low relief of the Boreal Plains landscape, distinguishing open water and marsh systems from other more terrestrial wetland types is quite arbitrary as illustrated in Figure D.9.

All open-water areas, including larger (meso-scale) lakes, marshes, and streams are classified as Wetland HUs or components of Wetland HUs because:

- When present, small- to meso-scale lakes and rivers are typically associated with, and often surrounded by, other wetland types (i.e., they are typically a component of a complex of wetland types forming a Wetland HU) (Figure D.8).
- There are water conservation feedback mechanisms for open-water systems that are similar to or include other Wetland HUs of different form.
- Over multi-decadal climate cycles, most open-water lakes and streams will go through a more terrestrial wetland phase during dry periods, and terrestrial wetlands will flood for extended periods during wetter cycles (Figure D.9).

FIGURE D.8

Association of Lakes and Streams with Wetland HUs Typical of the Boreal Plains

Aerial view of open-water and terrestrial-type wetlands within (a) pond or lake and (b) stream or river systems in the Boreal Plains. Open-water wetlands and other wetland types are closely associated. Forestland HUs typically border with, and many large surface-flow systems are dominated by, terrestrial-type layered wetlands.

a)

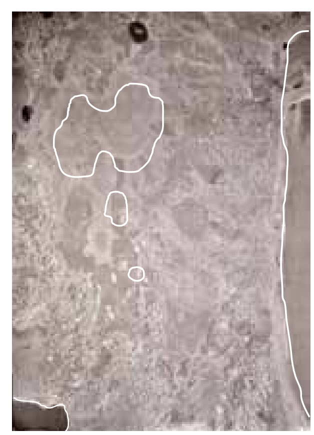
b)

FIGURE D.9

Dynamic Fluctuations in Presence of Open Water in Wetland HUs

Air photos showing the distribution of an open-water wetland phase during a wet period in 1974 (left photo) and during a terrestrial wetland phase during a historical dry period in 1949 (right photo) at the Utikuma Region Study Area. The dry terrestrial phase was observed again in 2002.

1974



1949

D.3.2 Definition: Wetland HU Water Balances: Losses or Gains from the Atmosphere

Although Wetland HUs are areas with long-term average surplus moisture, differences in the presence of standing free water and vegetation and soil structure within or between Wetland HUs influence the relative dryness (evapotranspiration to precipitation ratio) of the HU and the potential to provide water for the Boreal Plains landscape (Figure D.10). Wetland HUs can be composed of terrestrial wetlands or open water or myriad combinations or relative proportions of the two as discussed in the previous sections.

KEY CONCEPT: EXTENT OF OPEN WATER DICTATES WATER SOURCE VERSUS WATER SINK BEHAVIOUR

In locations in the Wetland HU **where the water table is just below the soil surface** of the wetland (terrestrial wetlands), evaporation is near zero and water loss to the atmosphere is primarily through plant transpiration. Actual evapotranspiration is limited, and non-standing water portions of Wetland HUs have evapotranspiration to precipitation ratios of 0.7 to 1.0 (Figure D.10). This is because saturated, cold, anoxic conditions created by the unique soil properties and layering (detailed in section D.3.4) prevent plant roots from extending into deeper soil layers and also delay vegetation-community use of water late into the growing season.

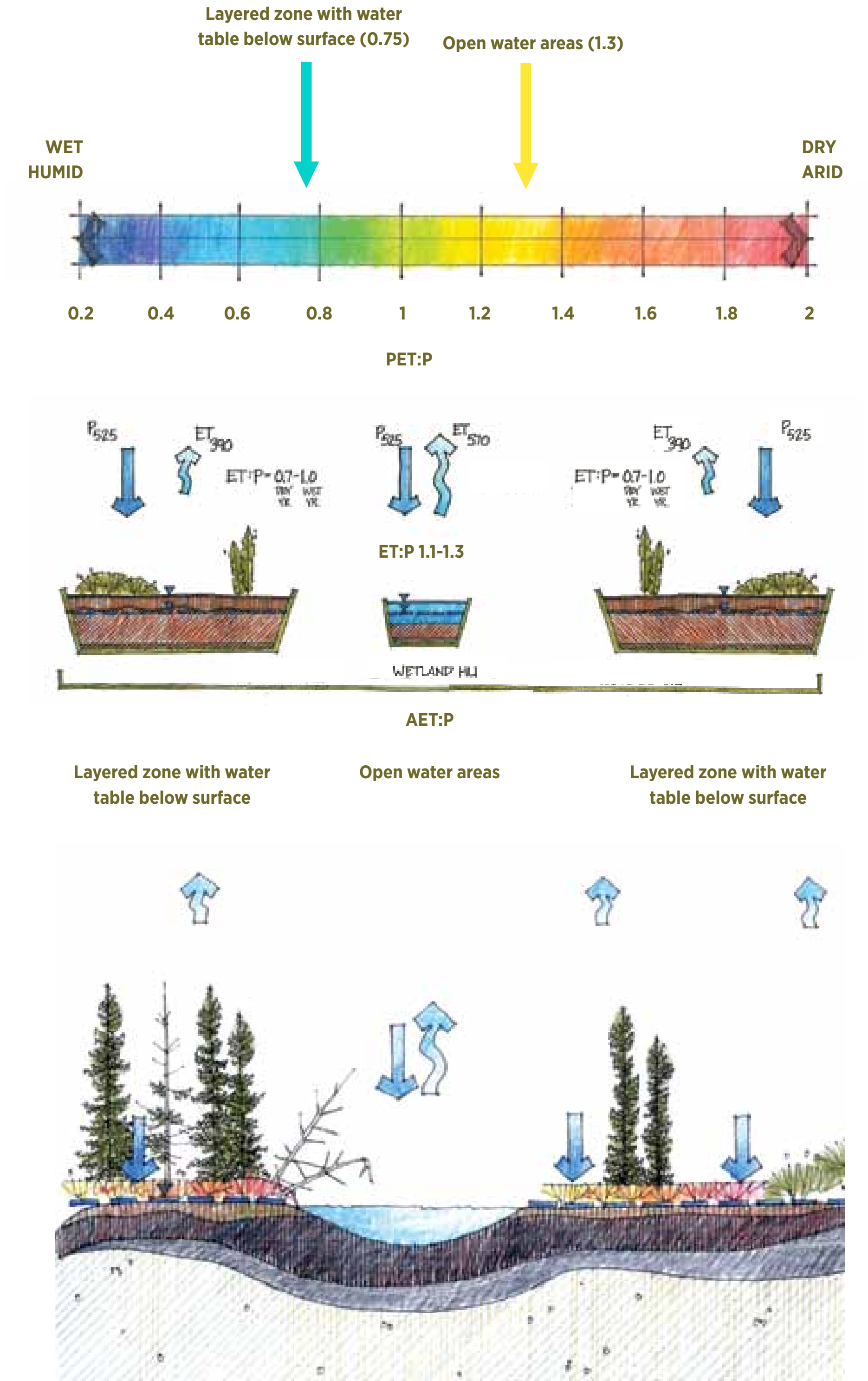
As a result, losses by transpiration (the "T" in ET) are much lower in Wetland HUs than in adjacent Forestland HUs. In addition, the surface "active layer" behaves as a mulch and results in losses to evaporation (the "E" in ET) being much lower than in adjacent open-water areas. Although subtle, this change in the water balance results in a long-term net surplus of moisture and **these areas of the Wetland HU behave as a source for water** within the Wetland HU and, potentially, for the landscape.

In sharp contrast, when open water is present the long-term rate of evaporation is higher than for terrestrial wetlands due to direct exposure and the lack of an active layer or mulch. This typically contributes to an evapotranspiration to precipitation ratio of more than 1.1. There is a net loss to the atmosphere and **open-water areas behave as water sinks** within the Wetland HU and in the landscape.

FIGURE D.10

Wetland HU Water Balances: Effective Dryness as a Function of Proportion of Open Water

Wetland HUs typically have dynamic proportions of open water vs. areas with the water table below the surface (terrestrial type wetlands). These two conditions have different effective dryness (AET:P) ratios, and whether a Wetland HU behaves as a source of water or a sink for water in the landscape is a function of the proportion of open-water area. Thus, although counter-intuitive, the more open water present, the more effective the Wetland HU in removing water from the system because of higher rates of evaporation.



D.3.3 Where Wetlands Form: Key Features

Understanding where and why wetlands form can provide valuable insights into the hydrologic function of, and how to construct, wetland systems. For Wetland HUs in the Boreal Plains to maintain surface saturated conditions or excess water, the long-term regional climatic water deficit must be overcome (Section C.1).

KEY CONCEPT: WETLANDS OCCUR IN CLIMATE-GEOLOGIC SETTINGS THAT HOLD AND GENERATE SURPLUS WATER

Wetland HUs occur in areas of excess water and which then effectively hold and conserve that excess water. These are areas where soil layering, geology, landform shape, and landscape position interact with the climate to enable a long-term moisture surplus.

In general, among the range of wetland types in the Boreal Plains, there are two key processes that may develop discretely or in combination to enable the HU to maintain surface-saturated or ponded conditions:

a) Surface depression storage (landform shape), typical of marshes and shallow open ponds

b) Soil layering that impedes flow and promotes surface saturation, typical of peatlands and ephemeral draws

The structure or mechanism for holding water or impeding water movement will determine the dominant hydrologic function over climate cycles (Figure D.11) and mechanisms or processes required for maintaining the excess water. Natural Wetland HUs can receive or generate excess water from:

1) Outside the Wetland HU (externally) through contributions from surface water runoff or groundwater discharge

2) Within the Wetland HU (internally) by a reduction in actual evapotranspiration below precipitation over the long term (see Section D.3.2)

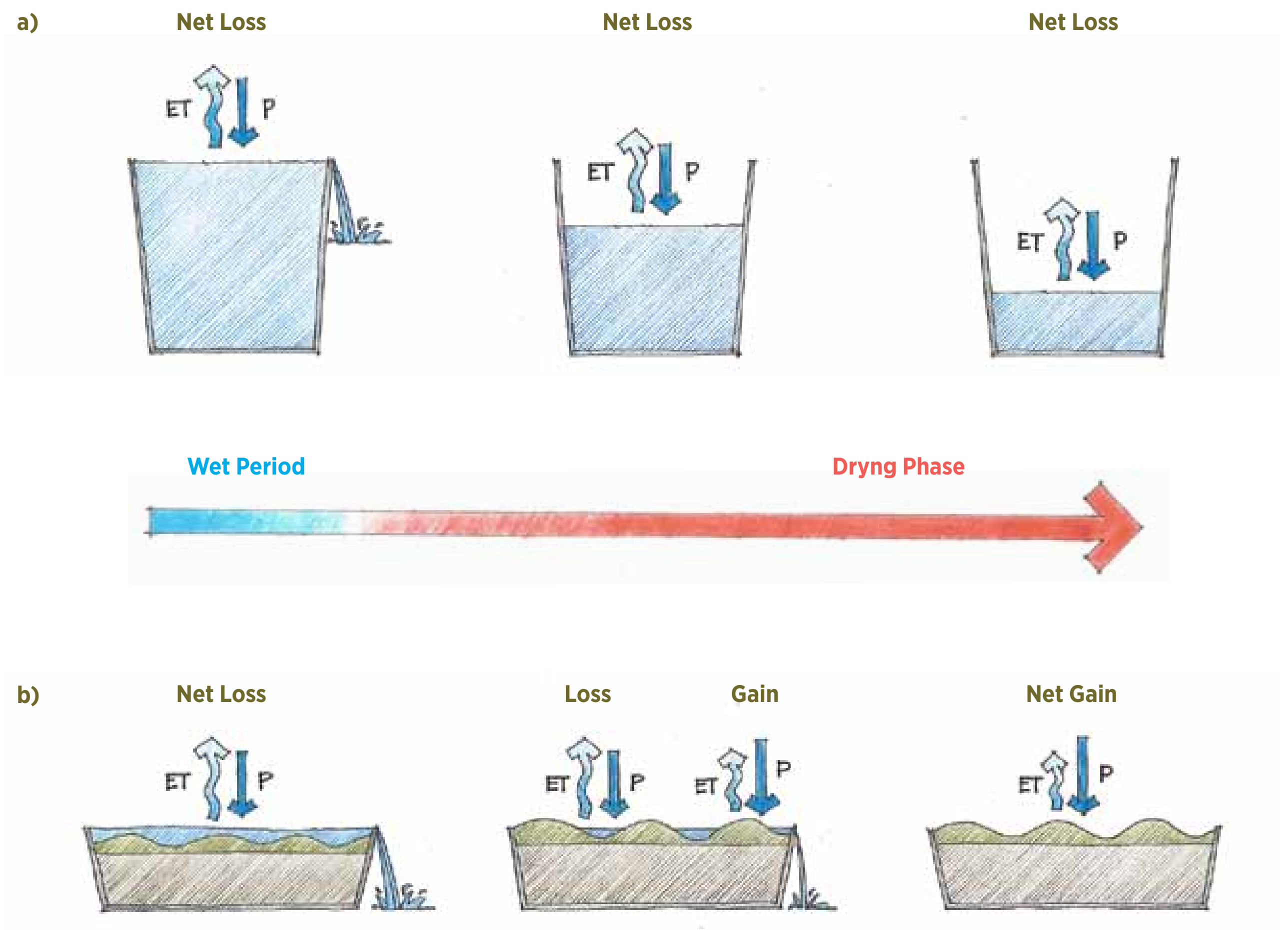
Wetland HUs will often have a combination of these structures and mechanisms for creating and maintaining excess water. Table D.1 under the Implications section (D.3.6) describes possible ways to obtain surplus water in various landscape positions and on different HRA types in light of the mechanisms observed in the natural analogue areas.

FIGURE D.11
Water Storage and "Water Memory": Open Water Non-layered Wetlands Versus Layered Wetlands

Comparison of ET:P and water storage and memory from high (wet) and to low (dry) water tables in **a) open water** depressions and **b) soil-layered** wetlands over a climate cycle.

a) Open-water, depression-type wetlands act like deep buckets and collect large amounts of water during the wet phase of a climate cycle. However, they have a long-term net loss of water to the atmosphere (AET > P) through time, and over extended dry periods they create a large storage space that must be filled.

b) Layered wetlands have net loss (AET > P) of moisture only when the water table is high, the wetland is flooded, and open-water areas appear during the wet periods (annual or multi-decadal) of the climate cycle. When the water table falls below the soil surface, the water conservation mechanisms inherent in the wetland layers operate, reducing AET to less than P. Following extended dry periods, the majority of the layered wetland still stays wet.



D.3.3.1 Soil-Layered Wetlands: Small Storage, Net Gain of Moisture

Terrestrial-type or soil-layered Wetland HUs can form on relatively flat landscapes (paludification) or in shallow basins. In natural areas, the layers form when the units fill in with fine-textured mineral material (e.g., clay) and with varying depths of decomposed or compressed organics (e.g., peat).

KEY CONCEPT: SOIL LAYERING CAN PROMOTE MOISTURE SURPLUS AND SOIL SATURATION

Soil layering can generate a moisture surplus internally over the long term by promoting water saturation and consistent reduction of actual evapotranspiration below precipitation. The influence of soil layering on water conservation is illustrated generally in Figure D.11, while the hydrologic functionality and properties of the layers themselves are described in Figure D.12. The lower layers not only impede losses to vertical drainage, but also promote surface saturation even without the presence of a depression. Due to their compacted nature, the deeper layers have low water storage capacity. Additions of very small amounts of water (e.g., through precipitation) result in rapid wetting up or saturation of the deeper layer. The surface layer is very porous, reduces evaporation, limits the water table to just below the surface, and promotes lateral flow and surface drainage. The combination of a low water table and a net moisture surplus (where AET:P < 1 as discussed in Section D.3.2) along with low storage capacity and short-term memory of climate cycles, results in layered wetlands responding to short-term precipitation events (Figure D.11).

Many Wetland HUs in the Boreal Plains are perched or isolated systems confined above regional groundwater flow in both fine- and coarse-textured HRAs (see Figures D.2 and D.3). They obviously do not receive excess water from external sources such as runoff or groundwater. The common occurrence of wetlands in these landscape positions confirms that soil layering can create the conditions of moisture surplus required for development and perpetuation of Wetland HUs .

KEY CONCEPT: WETLAND HUS HAVE A RANGE OF SEDIMENT OR SOIL DEPTHS, TYPES, AND LAYERS

Soil layering provides mechanisms to maintain frequent saturation for all types of wetlands from deep organic peatlands to shallow organic or mineral ephemeral draw and riparian areas. This layering also provides for the water conservation feedback mechanism during dry periods as illustrated in Figure D.11. Peatlands have the thickest organic layers, while ephemeral draws and marshes typically have the thinnest (Figure D.12).

Peat Formations and the other Functions of Wetland HU layers note to layout:

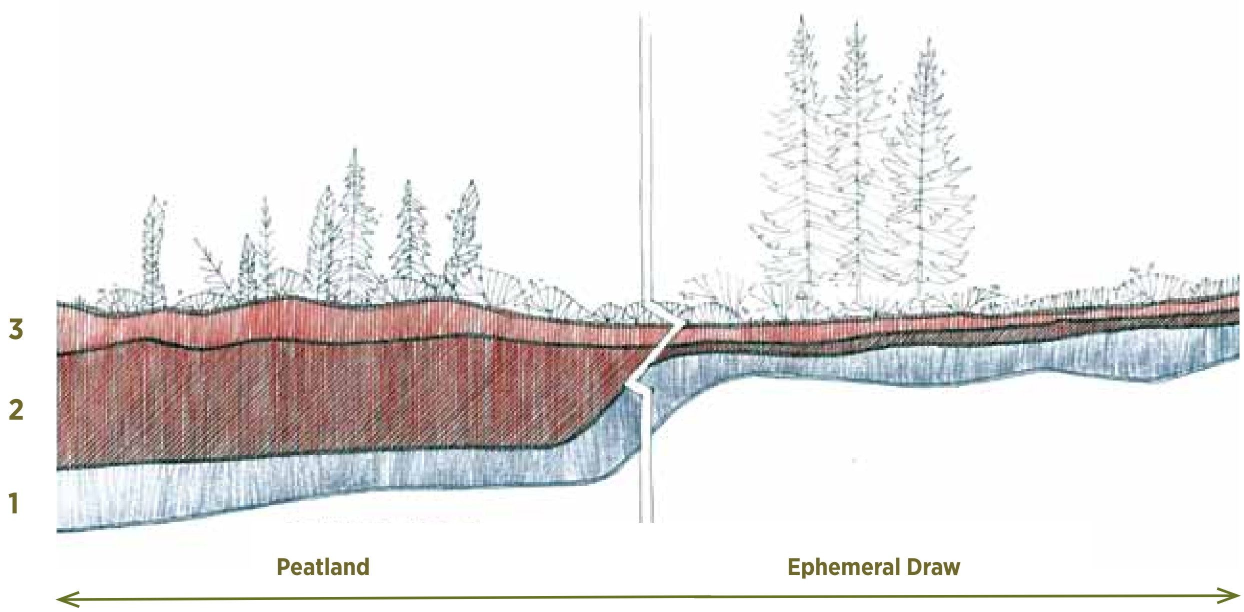
Peat tends to form in water-saturated areas over the very long term. Since partially decomposed or compacted peat often has hydraulic properties that impede flow, peat accumulation can dam water, creating additional wet areas in which more peat can form. This positive feedback mechanism influences hydrology and can create a new landscape. For example, the formation of a domed bog can influence local and regional topography such that the groundwater systems associated with the bog can be independent of the underlying mineral terrain.

The organic layers in a Wetland HU provide many more "services" to the HU than just water storage and transmission. The soft gyttja at the bottom of the study ponds is an important structural component of invertebrate habitat in boreal ponds. They are also important sources of nutrients to wetlands and any associated open-water bodies. These nutrient contributions influence vegetation diversity and affect the quality of wildlife habitat.

FIGURE D.12

Hydrologic Functionality and Properties of Wetland HU Layers

Range in type, depth, and properties of soil layering in Wetland HUs typical of the Boreal Plains. Wetland HUs typically have 1) an underlying fine-textured (clay) or confining layer, overlain by variable depths of 2) compacted or partially decomposed organics and 3) surface organic materials, referred to as the active layer. These layers play a large role in the hydrologic function of Wetland HUs. Peatlands and ephemeral draws represent the spectrum of Wetland HUs. Peatlands have the thickest organic layers and ephemeral draws have the thinnest organic layers.



Peatland

3 Active layer
- 20–50 cm thick
- Porous, low bulk density
- High lateral flow
- High specific yield

2 Organic layer
- Low effective porosity
- High bulk density
- Hard to dry out
- Low vertical and lateral flow
- Low specific yield

1 Mineral layer
- Within 0.5 m of bottom of organic layer*
- Fine textured
- Unfractured with low vertical and lateral flow
- Low specific yield which promotes saturation above it

Ephemeral Draw

3 Active layer
- 20–50 cm thick
- Porous, low bulk density
- High lateral flow
- High specific yield

2 Organic layer
- Thin or absent

1 Mineral layer
- Within 0.5 m of bottom of organic layer, present under all ephemeral draws
- Fine textured
- Unfractured with low vertical and lateral flow
- Low specific yield which promotes saturation above it

** the only time this fine-textured mineral layer is not observed or required is when a wetland occurs at the bottom of a large regional flow system, such that the Wetland HU is constantly receiving groundwater as a source of external water (i.e., it is not solely reliant on precipitation)*

KEY CONCEPT: EPHEMERAL DRAWS AND RIPARIAN AREAS ARE CLASSIFIED AS WETLAND HUS AND ARE IMPORTANT SOURCES AND CONDUITS OF WATER IN BOREAL PLAINS LANDSCAPES

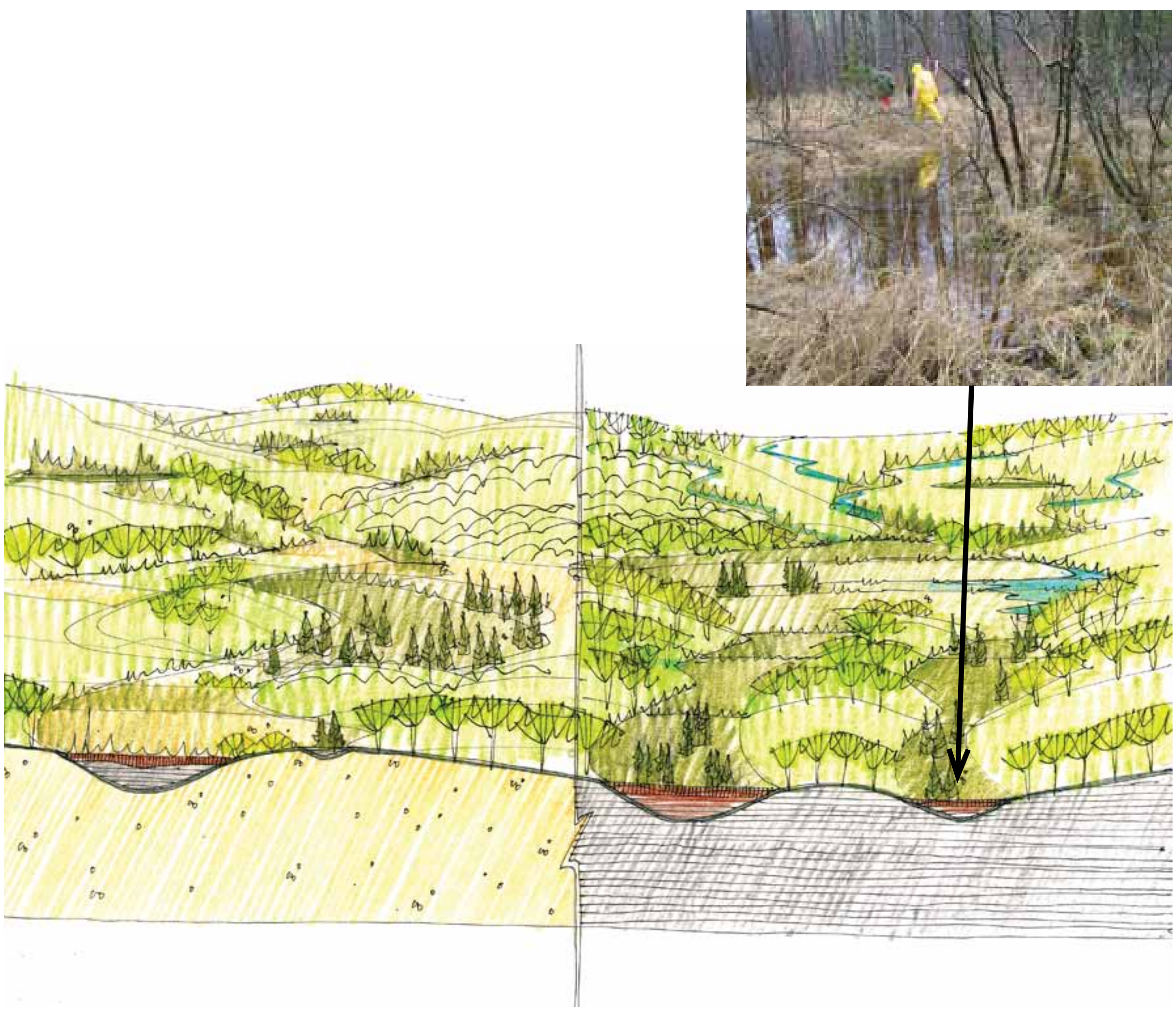
While they may not initially look like conventional wetlands, ephemeral draws and riparian areas have the required soil structure, layering, and storage dynamics to promote surface saturation within the landscape thus distinguishing them from Forestland HUs. As Wetland HUs, they are often immediately adjacent to Forestland HUs and hence are key connectors of the two unit types in the overall landscape. They are important, but often overlooked, sources and conduits of water in Boreal Plains landscapes (Figure D.13). Among the features of ephemeral draws:

- They are often the "fingers" of Wetland HUs that extend into Forestland HUs.
- Persistent water saturation and development of concrete ice in winter and spring contribute to making these areas a source of water (see Section D.3.3.3 on ice).

FIGURE D.13

Ephemeral Draws: An Important Type of Wetland HU

Distribution and surface network (i.e., fingers) of ephemeral draw wetlands extending between other Wetland HUs and into Forestland HUs on coarse-textured (left side of diagram) and fine-textured (right side of diagram) HRAs. These end-members of Wetland HUs are important conduits for surface runoff in the Boreal Plains. They are difficult to identify from air photos, but have characteristic vegetation and can be identified by the "squishy boot" experience of hydric soils when walking in the field (photo).



D.3.3.2 Open-Water Wetlands: Large-Depression Storage, Net Loss of Moisture

Open water can occur in any Wetland HU. Some types of Wetland HUs, however, are dominated by open water: marshes and shallow open ponds are examples. These types of wetland are often basins (surface depression wetlands) with a confining fine-textured (impermeable) layer that can trap or dam water and impede drainage creating the required water surplus.

KEY CONCEPT: OPEN-WATER DEPRESSION WETLANDS ENCOURAGE EVAPORATION AND REQUIRE EXTERNAL WATER SOURCES TO BE MAINTAINED

The surface-water storage capacity of these types of wetlands is often large (i.e., they can be large buckets). However, they have little or no mulch layers and thus have long-term average rates of actual evapotranspiration greater than precipitation (Figure D.11). To compensate for the moisture deficit they require externally generated sources of water and are located in landscape positions and geology types that provide runoff or groundwater flow from adjacent Forestland HUs or adjacent and connected Wetland HUs.

In fine-textured HRAs, the source of near-surface water for this type of Wetland HU is usually local runoff from adjacent uplands. This water input, however, is generally infrequent, occurring only during the periodic wet cycles when threshold responses of the HU to the climate cycles can occur (see Section C). As a result of these infrequent inputs of water, larger depression storage (a deeper bucket) is required to maintain surface water through the extended dry periods. Due to their typically large storage capacity, these types of Wetland HU also tend to have a long water memory of climate cycles (Figure D.11). Such systems are limited to wetland types that can adapt to larger and long-term water level fluctuations with climate cycles typical of many marsh and shallow pond or lake systems. See Section D.3.5 and Table D.1 for suggestions on construction of such wetlands.

In coarse-textured HRAs, Wetland HUs located in topographic lows that receive groundwater discharge do not require large storage basins but instead rely on intersecting the groundwater discharge to supply the excess water required to offset the water deficit inherent in the climate. Groundwater-surface water interactions in Wetland HUs in all the HRAs are discussed in Section D.1

KEY CONCEPT: DYNAMIC FEEDBACK OCCURS BETWEEN THE OPEN WATER AND THE TERRESTRIAL EDGE (RIPARIAN AND EPHEMERAL DRAWS) OF WETLAND HUS

Due to differences in storage and water balances (Figure D.11) there are dynamic interactions between open waters and the adjacent wetland types within complexes of Wetland HUs. Open-water areas expand or contract at multiple scales and interact with the adjacent wetland types within complexes of Wetland HUs seasonally, decadally, and multi-decadally in response to climate cycles. In marshes, or even lakes, a feedback cycle occurs during these open-water area expansion and contraction cycles. When open water occurs, the increase in evapotranspiration acts to limit and reduce the current expansion of standing water. Likewise, evapotranspiration decreases in riparian edges when standing-water areas shrink or dry down to the soil surface, thereby slowing further water evaporation and maintaining saturation in the Wetland HU and on the riparian edge. Thus, during drawdown of open water in depression wetlands or lakes the expanding riparian areas can represent water sources to the adjacent open water[3].

Similarly, there are dynamic distributions of standing water that may occur on top of or in close proximity to layered wetlands. Cycles of flooding and drying out (expansion and contraction) of the open-water areas occur frequently at the surface of these Wetland HUs, but saturation is consistently maintained in the layered soils below or adjacent (Figure D.11, bottom) to the open-water area. Thus, the layered wetland below or the connected layered wetland components of a wetland complex (such as ephemeral draws) become sources for water and the location where water flow is consistently generated.

[3]Beaver activity such as damming and ditching can flood or drain large areas of Wetland HUs and influence the net water sink or net water source function of the wetland HU by rapidly changing the volume of open water.

D.3.3.3 Importance of Freezing and Ice Formation

Ice is a critical contributor to the conservation of water and the creation of conditions suitable for Wetland HU maintenance in the Boreal Plains. Thick and persistent concrete ice lenses can form in the soil layers of all Wetland HUs that experience consistently high antecedent moisture (from peatlands to riparian areas to ephemeral draws). As well, open-water dominated Wetland HUs typically freeze thick (to one-metre depth)—and often to the bottom of shallow ponds—in the Boreal Plains climate. This distribution and persistence of ice can greatly influence water storage and transmission dynamics in the HU and in the landscape.

The terms "thick" and "persistent" are defined as:

- Thick: up to approximately one metre
- Persistent: not permafrost, but ice that endures beyond typical ice-out dates for Forestland HUs and ponds (open water)

KEY CONCEPT: SOIL ICE FORMATION PERFORMS A CRITICAL WATER CONSERVATION OR STORAGE FUNCTION AND FACILITATES WATER TRANSMISSION IN WETLAND HUS

Conservation and Storage of Water by Ice

Considerable volumes of water are "locked" in ice in open depressions (ponds) or in soil layers through the winter and into the growing season in all Wetland HUs. Persistent ice lenses typically form in the deeper saturated layers of layered Wetland HUs (Layer 2 in Figure D.12). Ice thickness and persistence increases with organic layer thickness, particularly when insulated by dryer surface-active layers of organics or mulch. Ice lenses are generally thicker and more persistent in peatlands than in ephemeral draws.

When ice is thick and covered with the insulating active layer, it "locks" in the water – the water is not available for plants during the high demand period of the early and mid-growing season, and it can't drain away deep in the soil profile or down to the water table. Thus, the ice lenses "store" water and release it upon melting later in the year than might otherwise be expected. The delayed release process provides water to maintain the saturated conditions later in the growing season.

In dry cycles, the ice lenses persist even later into the summer because, as the surface active layer of a layered Wetland HU dries out, it effectively becomes a deeper mulch or insulation layer, and thus becomes more effective at insulating the ice below and preventing it from melting. This enhances the water conservation feedback mechanism imparted by the layers (discussed previously) by extending water storage as ice and reducing evapotranspiration rates due to cold temperatures well into the growing season. Ice-out in layered Wetland HUs typically extends to late June, but can extend to as late as July or August in some peatlands during some years. In ephemeral draws with shallower organics, ice-out generally extends to late May or early June, about three weeks later than in the surrounding Forestland HUs that they traverse.

The storage of the previous year's moisture in ice can also reduce the potential water storage capacity of the Wetland HU soil layers in the current year, resulting in enhanced water transmission during the months of spring. Available water from melting snow and ice, and from spring rains, can be perched and stored over top of the remaining ice from the winter. The ice lenses promote surface saturation by preventing both 1) deeper recharge (vertical losses) and 2) significant evapotranspiration loss as the ice maintains cold soil temperatures that reduces vegetation growth.

Transmission of Water by Ice Lenses

Concrete ice formation in the Wetland HU soil layers facilitates a rapid runoff response to melting ice and snow and to spring and early summer rains. Lateral water flow along the top of the ice lenses through the surface active layer in layered Wetland HUs due to the reduction in soil-water storage capacity and increased antecedent moisture conditions is an important water transmission mechanism. This mode of water movement is non-erosive as surface water is usually transmitted through the fibrous and porous surface organic layers, often called the hydrologic active layer. When Wetland HUs, ranging from ephemeral draws to peatlands, are connected in the landscape, substantial amounts of water can be transmitted in a non-erosive way during spring and early summer periods through the active layers.

Ice lenses that persist late into the summer can maintain these higher antecedent moisture conditions and enhance runoff responses in Wetland HUs even during summer rains—the period of largest annual rainfall. This contrasts sharply with the adjacent Forestland HUs, where antecedent moisture and runoff potential is greatly reduced.

There is an important distinction between Forestland HUs and ephemeral draw or riparian Wetland HUs with respect to ice formation. Forestland HUs frequently have low antecedent moisture conditions during the fall and, thus, their soils freeze in a permeable state (honeycomb frost). These frozen permeable conditions result in infiltration and storage of spring moisture. Conversely, the ephemeral draws, although often difficult to distinguish in a Forestland HU (Section D.3.3.1), are Wetland HUs, have higher moisture content in the fall, can thus freeze as concrete ice, and thereby promote surface-water transmission the following spring or early summer.

D.3.4 How Wetland HUs Supply Water to the Landscape

KEY CONCEPT: WETLAND HUS REPRESENT THE EFFECTIVE WATERSHED AREAS FOR SURFACE FLOW IN THE LANDSCAPE

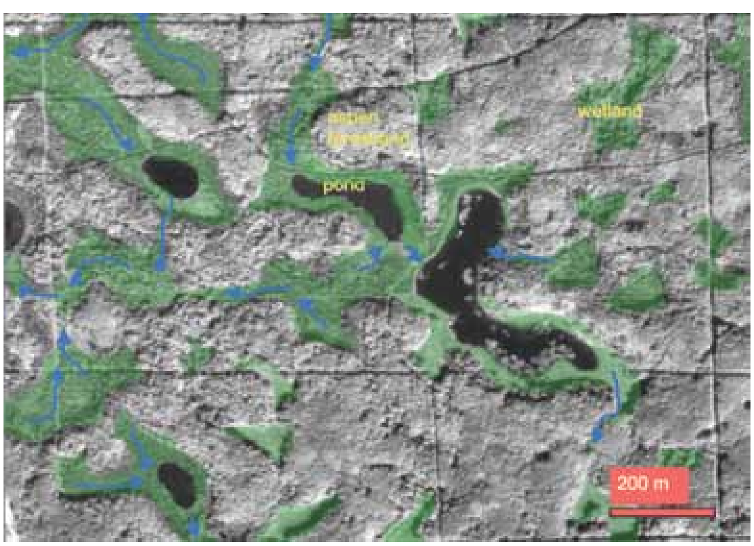
Previous sections have demonstrated that Wetland HUs occur in settings where persistent near-surface saturation and ice lens formation generate consistent lateral surface and near-surface runoff for the unit as well as for the entire Boreal Plains landscape mosaic. In most years minimal runoff comes from Forestland HUs (often called uplands) in Boreal Plains landscapes. Groundwater recharge in coarse-textured and veneer-type HRAs can provide substantial base flow in these landforms; however, high runoff from Forestland HUs has a return period of greater than two decades (recall Section C.1.6 on water memory)

Wetland HUs reach storage thresholds more quickly and respond more rapidly to short-term deviations in climate cycles than most Forestland HUs. The effectively shallow buckets of layered Wetland HUs can “fill and spill” more readily than deeper Forestland HU buckets. The hydrologic manifestation of high antecedent moisture conditions is twofold: a high runoff-return period for Wetland (layered) HUs of approximately two years; and the highest frequency contribution to regional runoff.

The distribution and connectivity of Wetland HUs (individual wetlands and complexes) is a key factor in the redistribution of moisture surplus to adjacent Forestland HUs and to other Wetland HUs including marshes, shallow ponds, and larger lakes and streams. In the low relief Boreal Plains landscape, stream drainage networks and channels can be poorly developed. Due to the width of the flow area and the porous active layer that modulates surface flow, water is transmitted non-erosively as near-surface runoff within the network of connected “active layers” characteristic of the fens, bogs, thicket swamps, and ephemeral draws that make up the larger interconnected Wetland HU. These runoff characteristics scale from single, small Wetland HUs to large, networked series of Wetland HUs. Current landscape models equate wetland flow networks with stream channel networks (Figure D.14). Even in the absence of streams, the effective surface-water catchment area for a Wetland HU (and in most years, for the entire landscape) is the total area of connected Wetland HUs.

FIGURE D.14
Surface Networks of Wetland HUs as Effective Catchment Areas

Surface connectivity of peatland, riparian, and ephemeral draw-type wetlands forming the effective catchment area on a fine-textured hummocky area at the Utikuma Region Study Area. The grey areas are the Forestland HUs and the connected network of Wetland HUs that make up the effective catchment area are highlighted in green. Blue arrows indicate near-surface water movement.



D.3.5 Wetland Hydrologic Units: Implications for Landscape Reconstruction

3.5.1 Establishing Wetlands in Reconstructed Landscapes

Wetland HUs perform critical water storage and transmission functions in Boreal Plains landscapes. Accordingly, their reconstruction post-disturbance will be essential for re-establishing eco-hydrologic functionality (equivalent capability). The importance of surplus water stored and transmitted extends beyond the Wetland HUs, themselves, into the adjacent Forestland HUs and downstream ecosystems in this region characterized by long-term water deficits.

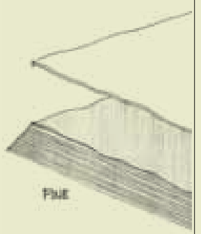
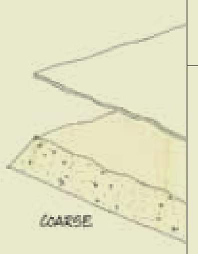
DESIGN CONSIDERATION: CREATING A WATER SURPLUS IN A REGION OF LONG-TERM AVERAGE WATER DEFICIT

To create a Wetland HU the landscape must be constructed to capture and hold water to generate a water surplus. While the options for achieving this outcome are limited only by the creativity of the designer and the relative costs of each approach, water management goals must be considered since Wetland HUs, depending on their composition and predisposition to open-water phases, will influence overall landform and landscape water balances.

Careful consideration of seasonal and longer-term climate cycles and targeted hydrology is required because some components of Wetland HU functionality are more easily and reliably designed than others. The wetland type (for isolated HUs), or predominance of wetland types (for a composite or networked HU), and their predisposition to open water will determine whether the HU is a net moisture source or sink and will dictate the complexity, cost, and secondary effects (e.g., increased salinity) of the landscape design needed to maintain the selected wetland type.

The research synthesized in this report indicates that Wetland HUs dominated by open water (e.g., surface depression marshes, shallow ponds, lakes) experience high evaporative losses and, thus, can be net water sinks. On the other hand, Wetland HUs dominated by terrestrial or soil-layered type wetlands minimize these losses and are net water sources. Given the long-term average moisture deficits typical of the Boreal Plains, effective design should consider water management goals and create the conditions to provide the necessary range of hydrologic functions required for sustaining the reconstructed landscape in its entirety. Ultimately, a water surplus must be generated and water held to maintain Wetland HUs of any type. Table D.1 describes some possible approaches for achieving this goal.

TABLE D1.
How to Obtain Surplus Water in Wetland HUs in a Region with a Long-term Average Water Deficit

HRA Type	Issues	Strategy	Solution
	Runoff from adjacent upland Forestland HUs only received every 2-3 decades	⇧R_{in}	1 Enhance depression storage (deeper buckets) to hold infrequent, but large water inputs. Accept or create systems that can adapt to large and long term water level fluctuations (e.g., marshes and some shallow lake systems). 2a Link wetland to ephemeral draws "fingering" into adjacent Forestland HUs or, 2b Link to other layered wetlands (shallow buckets) higher in the landscape which "fill and spill" every 2 years and may provide more consistent runoff water to the wetland of concern (creating a composite Wetland HU composed of several types of wetlands).
	1 Minimal groundwater discharge to wetlands in topographic lows, except at the base of large regional groundwater flow systems 2 Possible salinization	⇧GW_{in}	1 Counteract salinity using ephemeral draws to provide consistent fresh runoff water (as above), 2 Rely on R_{in}.
	Limited flow, high water use by Forestlands	**Render AET < P**	Landform shape, liner and layering (see Figure D.15), at landscape scale change relative proportions of Wetland:Forestland HUs
	Runoff from adjacent upland Forestland HUs only received every 2-3 decades	⇧R_{in}	Prepare wetland "basin" with the correct shape and an impermeable lining (as per A and B in Figure D.15), then link to ephemeral draws "fingering" into adjacent Forestland HUs or to other layered wetlands higher in the landscape (as above).
	1 Large storage basins not required, but only if wetland intersects base of regional groundwater system 2 Salinization	⇧GW_{in}	Counteract salinity using ephemeral draws to provide consistent fresh runoff water (as above).
	High water use by Forestlands	**Create conditions where AET < P**	Landform shape, liner and layering (see Figure D.15), at landscape scale change relative proportions of Wetland:Forestland HUs

DESIGN CONSIDERATION: OPEN-WATER DOMINATED AND SOIL-LAYERED WETLAND HUS

A range of Wetland HUs will need to be constructed in the post-mining landscape, however, conceptualizing and constructing soil-layered wetlands (shallow buckets) with low storage capacity, short water memory, and rapid responses to precipitation events, may be the more viable alternative to building non-layered, open-water wetlands (deeper buckets) with deep surface storage, a potentially long-term “memory” of climate cycles (high evaporative losses and prolonged dry down and refilling), and their associated need for water provided from external sources, like runoff or groundwater from other HUs or HRAs.

Creation of soil layers is potentially easier than management of groundwater-surface water interactions. While the design for and management of these interactions are disciplines in their infancy, with outcomes as yet largely untested, soil and peat salvage and placement are standard procedures. Consequently, landform shaping and construction of layered-soil systems are the more conservative options for encouraging development of Wetland HUs. In fact, these approaches will be essential for creating fresh-water wetlands on coarse-textured HRAs that are not fed by groundwater. Establishing peat layers as parts of the reconstructed Wetland HUs should create the hydrology necessary to maintain a moisture surplus. Additional research is required to determine if the water-conserving function of natural layers can be achieved with mineral soil layers (e.g., sand over clay) or with replaced organics.

Construction of Wetland HUs with large depression storage that promotes open water, may initially be easier, but comes at a cost of high evaporative losses. These are useful if net reduction in water in the landscape is a goal. When open water wetlands like surface-depression marshes or shallow ponds are planned, there will be a need to design for an external water source, such as the construction of surface catchments for runoff or landforms for groundwater discharge. In these cases, the designer must consider the effects of time lags in groundwater flow, water memory, and threshold responses (Section C.1.6) for surface water. Basin design for capturing water for long-term storage will also be needed.

Neither will the construction of coarse-textured HRAs that rely chiefly on groundwater for overall hydrologic function come without extra demands on the designer’s ingenuity—specifically, dealing with higher salinity and variable water chemistry. For example, Price (2005) reported that flushing seepage wetlands at the toe of a reconstructed coarse-textured HRA would take upwards of 200 years, while perched systems and those higher in the groundwater-flow regime would require 20 to 50 years.

Developing persistent surface-water runoff as an external water source for a constructed wetland also presents challenges given the long-term regional moisture deficit and interaction with climate cycles (see Table D.1). To generate persistent surplus moisture to sustain ecosystem function, development of layered-soil wetlands distributed throughout the constructed landscapes should be considered. The result of constructing such systems effectively is a subtle, but sufficient, shift in the water balance, resulting in excess near-surface water that can be redistributed in the landscape (i.e., water can be directed to runoff instead of storage or evapotranspiration).

Perched wetlands are common on all HRA types in the natural analogue areas. Applying the knowledge of how perched wetlands are maintained in the natural analogue systems will help in design and construction of soil-layered Wetland HUs to generate surplus water. Various landform shapes and material layering for constructing perched Wetland HUs are illustrated in Figure D.15.

To design surplus moisture for receiving systems (e.g., wetlands and end-pit-lakes), ephemeral draws (one end of the Wetland HU spectrum) may be created in reconstructed landscapes in areas where compaction by access roads of all scales exist (all-terrain vehicle to truck scale). In fine-textured HRAs, the compaction inherent in the pre-existing road is likely sufficient to initiate an ephemeral draw. In coarse-textured HRAs, a lens of finer-textured material would likely be required.

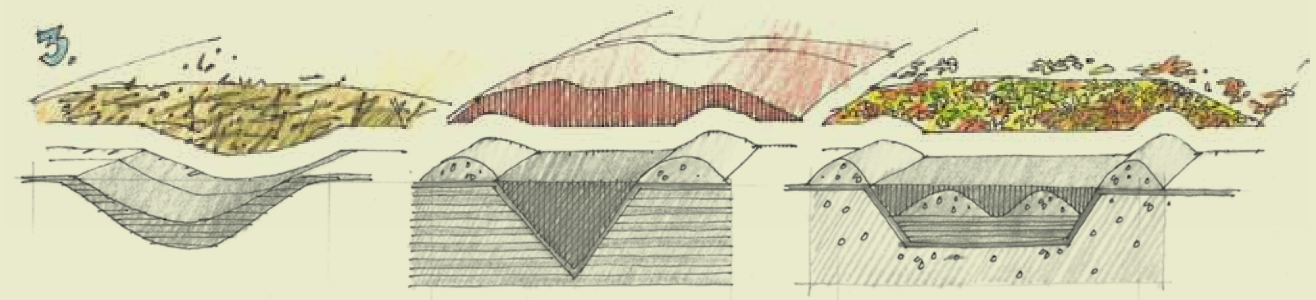
FIGURE D.15

Constructing Wetland HUs Where External Water Inputs are Limited

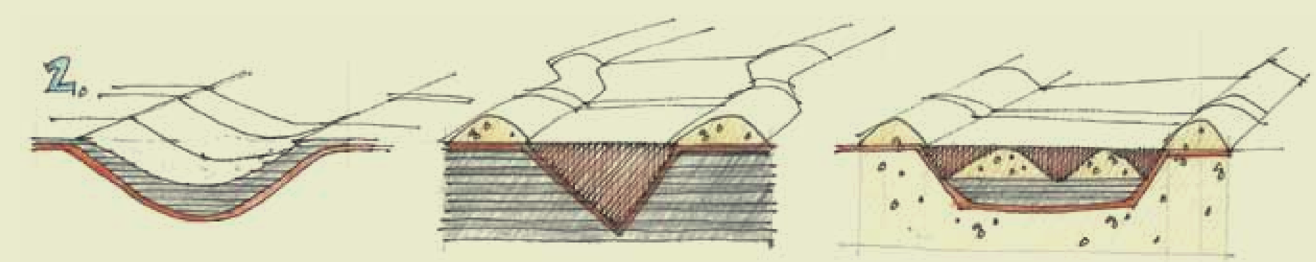
Wetland HUs can form where the conditions exist such that:

A) Small water additions result in water saturation and accumulation within the area
B) It is difficult to lose that water back to the atmosphere
C) Excess water can be delivered to other Wetland units/forests/lakes

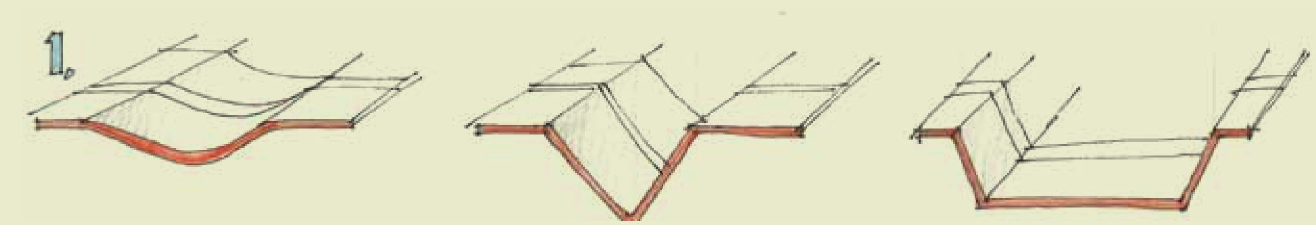
The elements required to create these conditions are illustrated here.



Element 3: The Active Layer on the surface that acts as a mulch (reducing evaporation), an insulator, and a non-eroding lateral water-flow conduit (B and C). This surface layer could be composed of living or dead moss, decomposed leaf litter, grass thatch, etc.



Element 2: A layer or combination of layers of materials forming a confining layer that effectively minimizes water from leaking away or being pulled out, and that saturates and stays saturated with minimal water inputs (A and B). In almost all cases the basic confining layer is unfractured clay. Once the confining layer is created, other materials or layers can be employed to manage water table fluctuations, thereby controlling the type of wetland to be created. Where soil saturation is maintained, the opportunity for organic matter accumulation is enhanced. If dense organic catotelm layers could be placed, such as those found in natural peatland systems, similar water retaining capacity might be reestablished. In constructing ephemeral draws (the opposite end of the Wetland HU spectrum from peatlands) the fine-textured mineral layer might be the only confining layer required.



Element 1: Landform shape to allow for accumulation of water. The landform shape can be worked with or overcome by designing the overlaying layers (elements 2 and 3 above). Shallow “basins” or “saucers” are common but other configurations are possible.

DESIGN CONSIDERATION: SOIL FROST AND ICE LENSES TO PROMOTE DELIVERY OF FRESHWATER

Developing surface connectivity of layered Wetland HUs that promote ice formation and persistence and, thus, non-erosive lateral flow is key to generating excess moisture and redistributing it within the reconstructed landscape.

However, ice behaviour (formation and melting) may be one of the key differences between natural systems and disturbed and reconstructed systems in the Boreal Plains region of Alberta. In the natural analogue areas, where disturbance had occurred, the melt rate within a peatland was observed to increase and evapotranspiration was subsequently enhanced. Reconstruction of soil layers as it affects ice formation requires further research.

Where some reconstructed landscapes retain heat from their deposition (tailings deposits) or generate heat (some coke deposits), the thermal regime of the landform may be different than the natural system's for variable periods of time. The experience of the authors, however, is that near-surface thermal regimes on saline-sodic overburden and tailings sand are similar to the natural systems studied, with surface soils and ponds freezing in a similar fashion as compared to those observed in the natural analogue study sites.

D.3.5.2 Wetland HUs and Design for Landscape and Ecosystem Sustainability

During the landscape design phase, reestablishment of a large range of wetland types and functions, scales, distribution, and connectivity within and between Wetland HUs should be considered. Given the long-term average moisture deficits typical of the Boreal Plains, this variety will encourage the desired flow regime and anticipated surface-water storage required to meet various landscape goals. The surplus water available in Wetland HUs is important not only for the unit itself, but also for adjacent forests (Section D.4) and down-stream ecosystems.

The design of constructed watersheds in the Boreal Plains region should draw on landform requirements for wetland creation different than those typified by traditional approaches that use upland to wetland ratios to determine the sustainability of wetland features. Landscape-scale design must be informed by Wetland HU targets. Incorporating a Wetland HU structure that promotes open water instead of a unit that internally generates water saturation imposes a different set of demands on the landscape design. A key consideration in the design is that runoff from forested uplands cannot be relied upon to provide *consistent flows* in the landscape.

Constructed wetlands relying on these areas for runoff will need structures to capture and hold sufficient water through the extended drought cycles characteristic of the region and should be expected to experience substantial water level fluctuations.

When designing watersheds where abundant, consistently supplied surface water is required (e.g., ponds, end pit lakes), it is important to create larger and sufficiently connected layered Wetland HUs to provide a network for water generation and transport.

As well, the landscape-scale design needs to consider the water supply requirements for sustaining the Forestland HUs through the long term. Forestland HU to Wetland HU ratios are likely an important indicator of supply of water to, and hence viability of, forestlands in constructed landscapes. Construction of isolated or minimally networked, layered Wetland HUs within Forestland HUs can provide water and enable its transfer into the adjacent forestlands.

D.4

Forestland Hydrologic Units

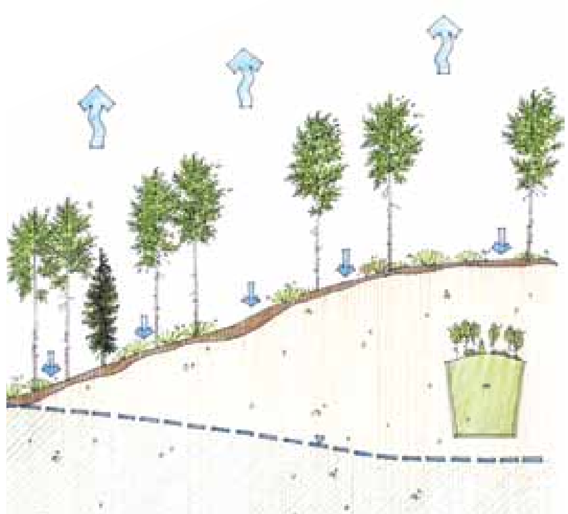
Forestland hydrologic units are defined as areas of long-term moisture deficit where the ground slope exceeds the ability of the materials (soil texture) of a specific HRA to hold the water level and the saturated zone (capillary fringe) near the ground surface resulting in surface soils draining freely. Forestland HUs can be any one or a combination of forest stand types found on the Boreal Plains.

Forestland HUs are responsible for a large portion of the water losses in the Boreal Plains as established vegetation imparts a large demand on soil moisture by transpiration. Transpiration in these units is usually greater than the annual precipitation received. Forestland HUs typically lose as much or more water to the atmosphere as they receive from precipitation (ET:P > 1), and may be sustained in part by adjacent Wetland HUs. As a result, these areas are often characterized by low antecedent moisture conditions, "deep bucket" water levels (metres below the surface), and subsurface water storage (via soil storage) for the Boreal Plains (Figure D.16).

An improved understanding of the large storage and water demand functions of Forestland HUs will help to better design for and manage the demand, source, and redistribution of water in the context of the soil moisture deficit of the Boreal Plains.

FIGURE D.16
Forestland Hydrologic Units: Deep Buckets

Typical vegetation structure, soil depth, and water table configuration of an aspen Forestland HU. Shown is the general water level and range of atmospheric fluxes of precipitation (down arrow) and evapotranspiration (up arrow) across a Forestland HU.



D.4.1 Where Forestlands Occur

KEY CONCEPT: FORESTLAND HUS OCCUR IN UNSATURATED SOILS AS CONTROLLED BY GROUND SLOPE AND HRA MATERIAL TYPE

The water saturation and drainage characteristics of a soil are a function of the grain size (or HRA type) and the ground slope. In general, gentler slopes hold water levels nearer the ground surface. Finer-textured materials have poor subsurface drainage and hold the water level closer to the ground surface longer than coarser material. In addition, the height of soil saturation above the water table (capillary fringe) increases with finer-textured materials. Forestland HUs occur where the interaction of the soil grain size (HRA type) and the relief is sufficient to overcome the water level and the wicking effect of the capillary fringe and the soils can drain freely.

On fine-textured HRAs, Forestland HUs occur on land surfaces that slope away from a Wetland HU (Figure D.17).

On coarse-textured HRAs, very low relief is required and Forestland HUs occur both on slopes and on mounds where there is at least a one- to two-metre distance above an existing fine-textured lens or deposit or regional water table (Figure D.18). In low-lying positions of coarse-textured HRAs, trees on Forestland HUs in these locations may access regional water since roots extend to one metre and further.

It is rare to see uninterrupted Forestland HU slopes that exceed five metres in height that are not punctuated with a Wetland HU. In fine-textured HRAs, these can be level regions (terraces) or depressions where surface saturation is promoted and wetlands form. In coarse-textured HRAs, there may be major breaks in slope that encourage groundwater discharge to the surface or patches of fine material that result in the formation of perched wetlands. Where there is a greater separation of forestland and Wetland HUs, poorer tree vigour is observed due to excessive drainage on extended slopes (Figure D.19).

Aspen Forestland HUs may require connections to Wetland HUs for long-term vigour and to be sustained through natural disturbances and climate cycles. Conifer forestlands may or may not require connections to Wetland HUs.

FIGURE D.17
Forestland HUs on a Fine-textured HRA

Distribution of Forestland HUs and water level location (blue) relative to Wetland HUs on a fine-textured HRA.

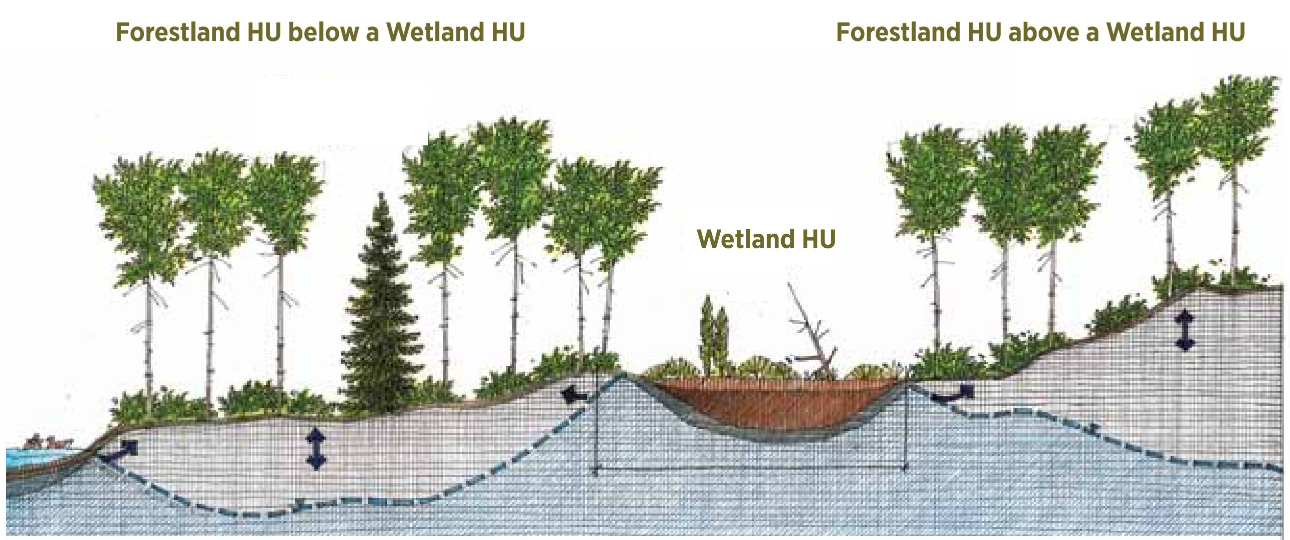


FIGURE D.18
Forestland HU on a Coarse- or Veneer-type HRA

Distribution of Forestland HUs and water level location (blue) relative to Wetland HUs on a coarse-textured (left) and coarse over fine texture veneer-type (right) HRA.

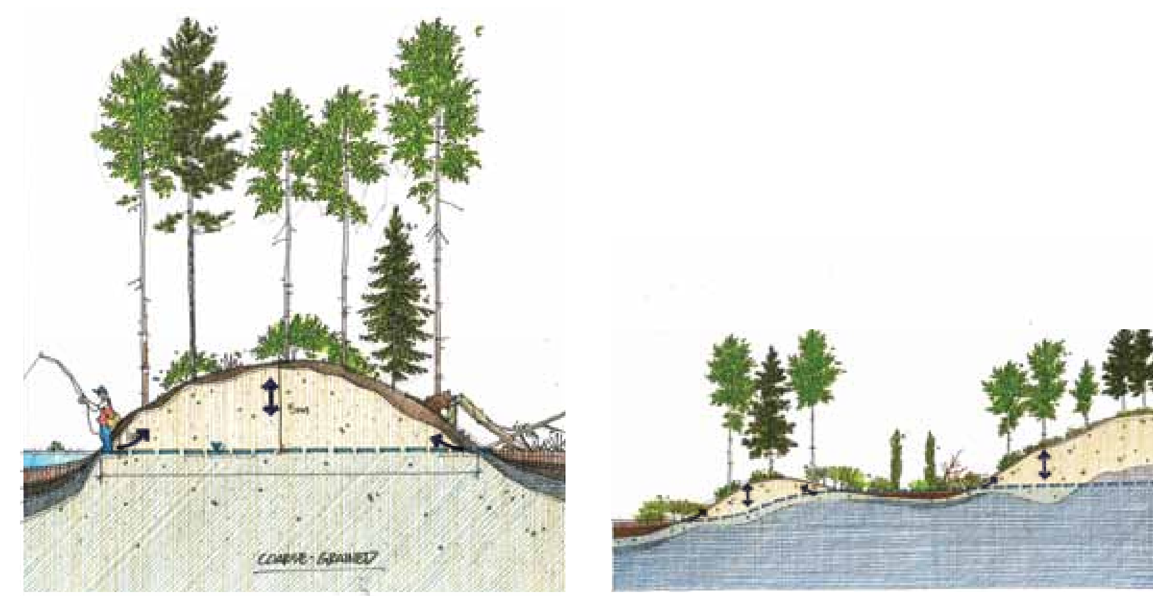
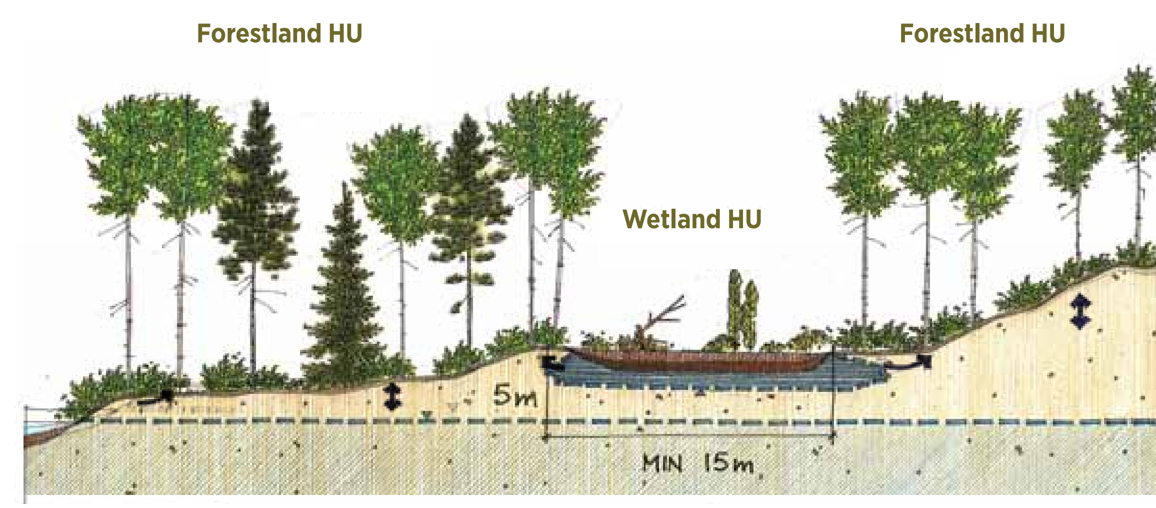


FIGURE D.19
The "Five-metre Rule"

It has been commonly observed that slopes in Forestland HUs frequently have interspersed Wetland HUs which act as potential sources of water. Poor tree vigor is observed when slopes exceeding five metres in height are not punctuated with a Wetland HU.



D.4.2 Forestland HU Water Balances: Storage and Loss to the Atmosphere

KEY CONCEPT: FORESTLAND HUS ARE RESPONSIBLE FOR THE MAJORITY OF WATER LOSSES IN BOREAL PLAINS LANDSCAPES

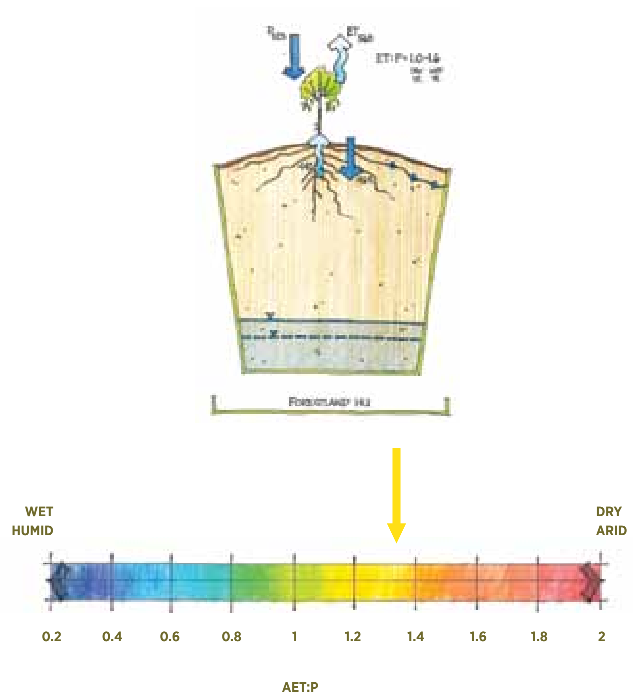
The long-term water demand by Forestland HU vegetation is greater than the long-term precipitation because of vegetation structure and root depths that can access stored water within and adjacent to the HU. Consequently, Forestland HUs typically lose more water to the atmosphere than they receive as precipitation and are net water users or sinks in the landscape. The evapotranspiration to precipitation ratio is variable and related to the amount of available water. Plants will use more water (i.e., post higher evapotranspiration rates), up to a limit, if water is available. The evapotranspiration to precipitation ratio inForestland HUs often varies from near 1.0 in dry years (less moisture available) to 1.6 in wet years (Figure D.20).

KEY CONCEPT: FORESTLAND HUS ARE RESPONSIBLE FOR LARGE MOISTURE STORAGE IN BOREAL PLAINS LANDSCAPES

The drawings of Forestland HUs across different HRAs in Figures D.17 through D.19 and the bucket analogy depicted in Figure D.20 show the low water levels and low antecedent moisture conditions characteristic of Forestland HUs due to the large water demand relative to precipitation inputs in most years. Deep rooting distribution, allowing trees access to water at depth, further reduces antecedent moisture levels during dry periods, thereby enhancing potential storage for upcoming wet periods (see Section C.1.6 on water memory). Due to the large available soil storage, excess water available from short-term increases in the soil moisture surplus (as discussed in Section C.1.2.2, from snow melt or summer storms, for example) will move into soil storage rather than runoff in most years.

FIGURE D.20
Forestland HU Water Balance and Dryness Index

Bucket illustration of the water balance components and the AET:P ratio (effective dryness index) for a typical aspen Forestland HU. These HUs are conceptualized as "deep" buckets where the water balance is dominated by precipitation (P), evapotranspiration (ET), and change in storage (ΔS). The potential distribution of tree roots is indicated, and lateral up-flux of water by roots from a potentially adjacent Wetland HU is shown. Groundwater loss occurs depending on the forestland position and the type of HRA. Runoff occurs infrequently but can be a significant flux during wet periods.



D.4.3 Some Key Features of Water Movement in Forestland HUs

KEY CONCEPT: VEGETATION AND FOREST FLOOR INTERCEPTION STORAGE PLAY A LARGE ROLE

The low antecedent moisture conditions of Forestland HUs are enhanced by vegetation and forest floor interception. The forest floor (LFH) of a Forestland HU intercepts and holds substantial amounts of water in a location where it is readily accessible for tree uptake, thereby enhancing soil-vegetation-atmosphere water cycling.

The research synthesized in this report has shown that the storage capacity, or interception capacity, of the forest floor is likely to be about 1.5 millimetres for every centimetre of aspen forest floor depth. Given an average aspen forest floor depth of 10 centimetres, 15 millimetres of a precipitation event will be held in the very shallow subsurface, where it will be readily accessible for uptake by trees.

During the growing season, when most large rain events occur, the tree canopy intercepts approximately three to five millimetres of any rain event, and the forest floor of an aspen Forestland HU will store and retain about 15 millimetres. Thus, climate events will need to generate more than about 15 to 20 millimetres of precipitation to produce movement of water into mineral soil (thus generating the potential for recharge of regional groundwater systems) or, possibly, promote lateral flow (runoff) in aspen Forestland HUs. The probability of such events is quite small given the precipitation patterns in the Boreal Plains. As much as 50% of summer rainfall in the region can be attenuated in the leaves and forest floor during a typical summer rain.

KEY CONCEPT: VERTICAL DRAINAGE IS THE DOMINANT TENDENCY FOR WATER MOVEMENT IN FORESTLAND HUS ON ALL HRAS

Hydrometric, geochemical, and isotopic data of snow melt and soil water storage show that during both growing and non-growing seasons soil storage and vertical recharge are dominant processes in both harvested and non-harvested Forestland HUs across HRAs. In fact, this dominance of infiltration and vertical recharge buffer the effects of aspen harvesting on streamflow (see Section D.4.5).

Due to the dominance of vertical flow and low antecedent moisture conditions, lateral flow (R in the water balance equation) will not occur until the large potential moisture storage available in the entire soil column is satisfied. The fate of precipitation and the potential for lateral flow and runoff generation on the Boreal Plains is illustrated in Figure D.21. Due to the demand by vegetation for water and the high water-storage properties of an aspen forest floor and its underlying soil layers, the probability of exceeding Forestland HU soil water-storage capacity and generating significant runoff (lateral flow) is low, occurring only once every 20 to 30 years or more.

FIGURE D.21

Conceptual Flow Chart for Determining the Fate of Incoming Precipitation and the Probability of Generating Lateral Flow from a Forestland HU in the Boreal Plains

This flow chart shows the fate of precipitation and the storage and flow process that must be satisfied to determine if a precipitation event in a Forestland HU on a fine-textured HRA will move vertically into soil storage and potentially recharge groundwater or move laterally and run off. It illustrates the need to consider antecedent moisture (soil storage at field capacity) conditions as well as climate characteristics when assessing the hydrologic effects of a precipitation event (recall Section C.1.6 on climate memory and antecedent moisture). This flow chart is from Redding and Devito, 2010.

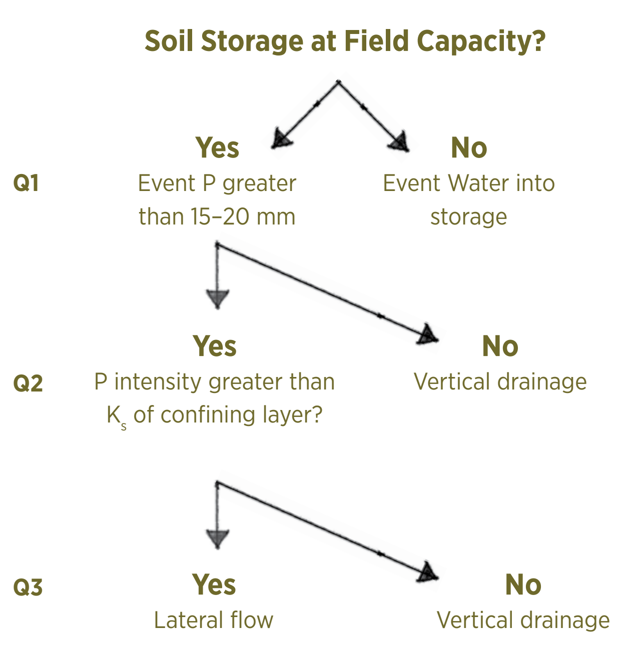
Field capacity is for the top 150 centimetres of soil storage on a Forestland HU.

Q1 When a precipitation event occurs, Q1 evaluates the antecedent moisture condition and determines whether the soil storage (forest floor, 150-centimetre mineral soil) is filled. If not, then precipitation will go directly into storage. This is, in fact, the usual outcome as Forestland HU antecedent moisture is low (the bucket is not full).

Q2 During wet climate cycles when the Forestland HU antecedent soil moisture is low and the soil storage is at field capacity (the bucket is full), Q2 evaluates the size of the event. Even with low antecedent moisture conditions, events of less than 15 – 20 millimetres will vertically drain into the surface soils regardless of the intensity.

Q3 When the soil capacity is filled and a large precipitation event occurs, Q3 evaluates the intensity of the event. If a large event occurs during low antecedent moisture conditions, and the rain- or snow-melt intensity is greater than the vertical hydraulic conductivity (K_s – lower soil infiltration capacity) of the low confining soil layer, then significant lateral flow will occur. Most storm intensities do not exceed the lower Ks of lower soils and, thus, the added moisture drains vertically.

Significant runoff potential from Forestland HUs requires that a large, and very intense, storm occur during a period when the soil storage has been previously filled. The probability of having all these conditions occur simultaneously is very low, with these events only occurring every two to three decades.



KEY CONCEPT: THE MAJORITY OF GROUNDWATER RECHARGE OCCURS IN FORESTLAND HUS ON COARSE-TEXTURED HRAS

Vertical flow dominates over lateral flow in Forestland HUs on all HRAs and represents potential recharge for local and regional groundwater. Groundwater recharge for regional systems and streams primarily occurs in Forestland HUs on coarse-textured materials (silt and coarser) due to higher infiltration and percolation rates. On fined-textured HRAs, recharge is limited to shallow soil layers. Most vertical drainage is impeded by lower rates of vertical percolation and water is used by forest vegetation.

KEY CONCEPT: FORESTLAND HUS ARE CHARACTERIZED BY LONG-TERM LAGS AND THRESHOLDS IN GROUNDWATER RECHARGE AND RUNOFF

In a landform (HRA) dominated by Forestland HUs the landform typically has a long water memory due to the generally large water-storage capacity of the soils (forest floor and mineral) and the underlying geologic materials. Time lags in groundwater recharge and runoff-return periods in response to precipitation events on landforms dominated by Forestland HUs are on the order of decades, the actual timing being a function of material type, depth to the water table, and climate patterns.

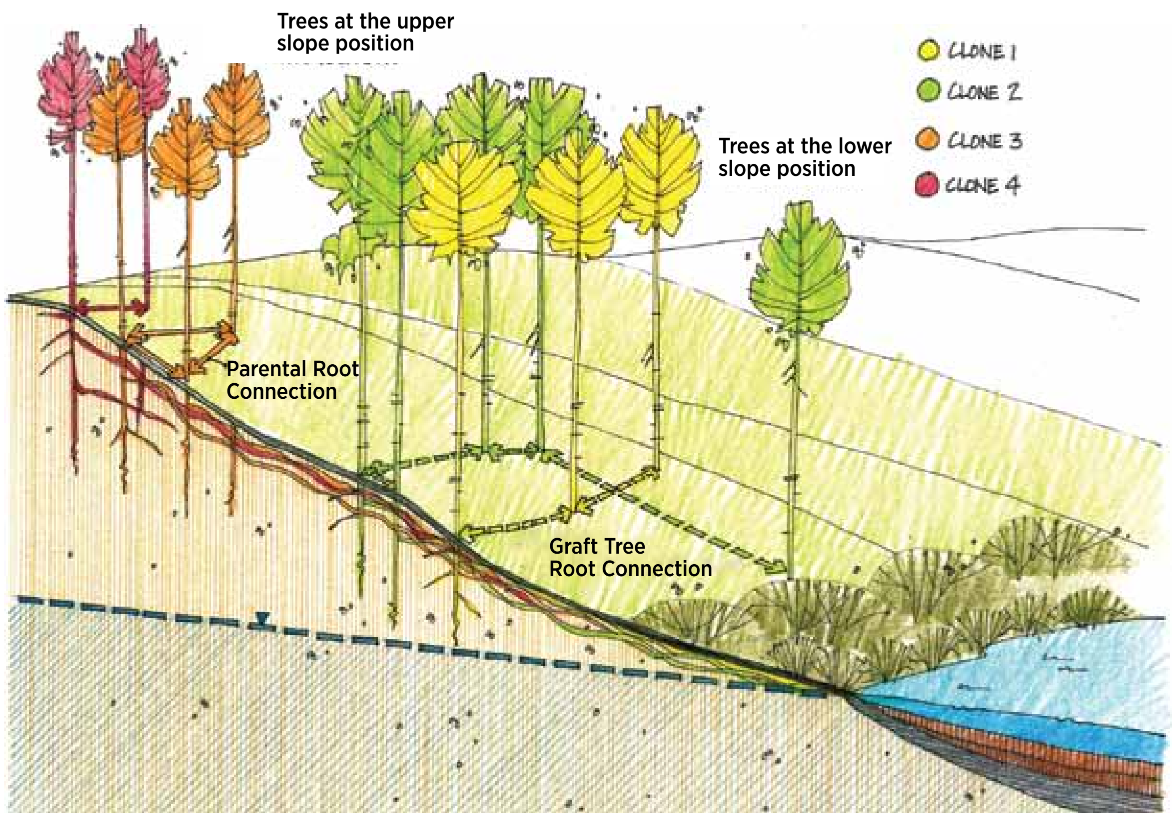
D.4.4 Aspen Water Use

The hydrology of the Boreal Plains is strongly controlled by the vegetation communities present. Vegetation exerts a critical control on soil landform and landscape water balances through its effects on evapotranspiration and net precipitation. In the Boreal Plains landscape the subtle differences in the magnitudes of these processes create a situation where the region is able to sustain wetlands despite long-term average moisture deficits. Understanding vegetation community trajectories and their influence on the water balance improve the ability to anticipate trends and manage water in these landscapes

Because the region is so dry and because the aspen species occupy such a large area, aspen water use is vital to the hydrology of Forestland HUs and the landscape mosaic and, thus, was a central focus of the research.

FIGURE D.22
Aspen Clone Root Connection in a Forestland HU

The distribution of aspen clones and root network of a Forestland HU adjacent to a Wetland HU on a coarse-textured HRA at the Utikuma Region Study Area (URSA).



KEY CONCEPT: ASPEN FORM ROOT CONNECTIONS AMONG AND BETWEEN CLONES TO ACCESS WATER DOWN-SLOPE AND TO REDISTRIBUTE WATER FROM WETLAND HUS INTO FORESTLAND HUS

Aspen stands throughout Forestland HUs pull water up or redistribute water from Wetland HUs into Forestland HUs via root connections formed between aspen clones (Figures D.22 and D.23). Long (16 metres), down-slope lateral roots appear integral in linking trees in higher slope positions in Forestland HUs to those in lower slope positions closer to the Wetland HUs (water sources).

Detailed mapping of aspen rooting demonstrates that roots parallel to the hill slope move twice as much water as similar sized roots oriented across the slope. Furthermore, trees located at the bottom of the slope transpire two times more per unit leaf area than trees at the top of the slope. In addition, taproot length is correlated to slope position: trees higher up the slopes tend to have deeper taproots. Just above one of the Wetland HUs in a research area, taproots range from 50- to 175-centimetres deep, and five metres upslope into the Forestland HU they range between 100- and 300-centimetres deep (measurements made in a Forestland HU on sand). Root surface area is greatest in the top ten centimetres of the soil profile, but substantial water movement was measured through coarse roots in the deeper soil layers.

The above measurements—in combination with the general observations that it is rare to find uninterrupted forestland slopes that exceed five metres in height that are not punctuated with a Wetland HU, and that where there is a greater separation of forestland and Wetland HUs poorer tree vigour is observed—lead to the "five-metre rule" discussed previously.

That is:

"Aspen Forestland HUs require a connection to Wetland HUs for long-term vigour and to be sustained through natural disturbances and climate cycles."

It is not clear if conifer Forestland HUs require this connection and further research is merited.

The good correlation between water movement (transpiration and root water uptake) and soil water potential suggests that soil water potential may be a good analogue for longer-term and broader-scale monitoring of plant-soil water relationships and health.

FIGURE D.23
Extensive Root Networks of Aspen Stands

Root connections (left) and extensive root networks (right) extending from Forestland HUs to Wetland HUs.

Photo courtesy Jessica Sneddon

Photo courtesy Uldis Silins

KEY CONCEPT: PROPOSED ADDITION OF A NEW WATER BALANCE COMPONENT FOR MOVEMENT OF WATER UP FROM WETLAND HUS INTO FORESTLAND HUS

The observations and measurements presented above, along with analyses of the water balance numbers from the detailed hydrologic monitoring in the field study areas, have led to the addition of the terms U_{in} and U_{out} (uplift in and uplift out) to the water balance equation in order to emphasize the importance of root translocation on water balances (Figure D.24).

U represents water moving into or out of a hydrologic unit via the aspen root "pipeline."

While actual values of U were not measured in this research, the extensive evidence discussed above indicates that aspen roots "pump" water out of Wetland HUs. This is a physical manifestation of hydrologic connectivity as discussed in Section D.5.

The U value is considered to be additional to the measured evapotranspiration (ET) since it is speculated that, without Wetland HU water input to the Forestland HUs, the plants would have been more stressed and Forestland HU ET would have dropped. In addition, without this output from the Wetland HUs, dry-down would not occur because of the water-conserving properties of these units.

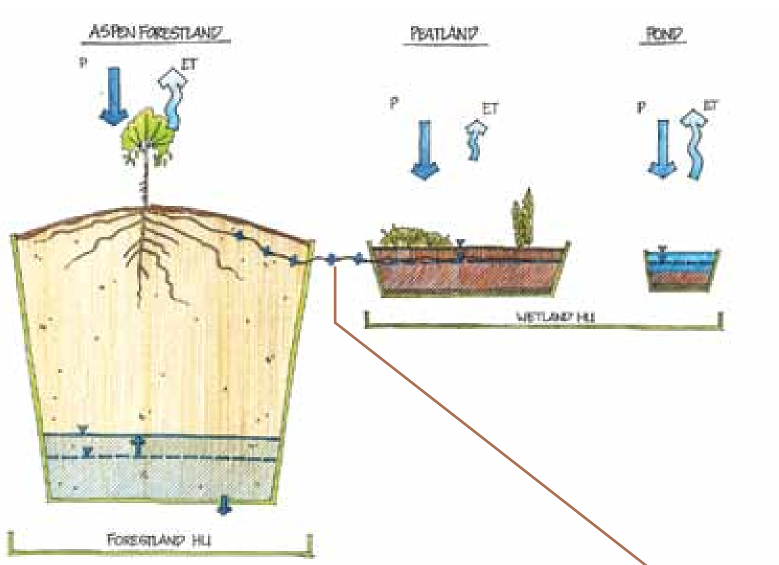
In Forestland HUs, U_{out} is always zero and in Wetland HUs, U_{in} is always zero.

The ratio of Forestland U_{in} to Wetland U_{out} is a function of the perimeter-to-surface area relationship of the Wetland HU, or the ratio of the amount of Forestland HU to Wetland HU in an HRA. If a Wetland HU is too small relative to the surrounding aspen Forestland HU, the former will dry out because the aspen in the Forestland HU can access or use all of the water that may periodically be available from the small Wetland HU. See Section E for examples of how U is used in the water balance equation.

FIGURE D.24

The "U-factor" in the Water Balance: Uplift of Water from Wetland HUs into Forestland HUs Via the Aspen Root Pipeline

Shown are the water balance buckets representing the Forestland HU and Wetland HU and the root pipeline between the two that is commonly observed in aspen Forestland HUs. It is suggested that this water conduit should be represented in the water balance equation by an additional term, U, for root uplift of water.



Legend:

ΔS = Change in storage

P = Precipitation

ET = Evapotranspiration

R = Runoff

GW = Groundwater

U = Uplift

Subscripts in and out represent movement of water into or out of a system.

$$\Delta S = P - ET + (R_{in} - R_{out}) + (GW_{in} - GW_{out}) + (U_{in} - U_{out})$$

D.4.5 Effect of Forest Removal and Vegetation Community Recovery on Water Use

The HEAD2 project focused on water balances for a set of paired watersheds associated with two ponds (Ponds 40 and 43). As part of the study, one watershed of the pair was harvested and the recovery trajectory of the water balance mapped on both for four years (2007 through 2010). Removing the aspen temporarily shifted the water balance.

KEY CONCEPT: EVAPOTRANSPIRATION TO PRECIPITATION RATIOS RECOVER VERY QUICKLY (WITHIN THREE YEARS) FOLLOWING VEGETATION REMOVAL IF SUCKER REGENERATION IS VIGOROUS FOLLOWING A DISTURBANCE

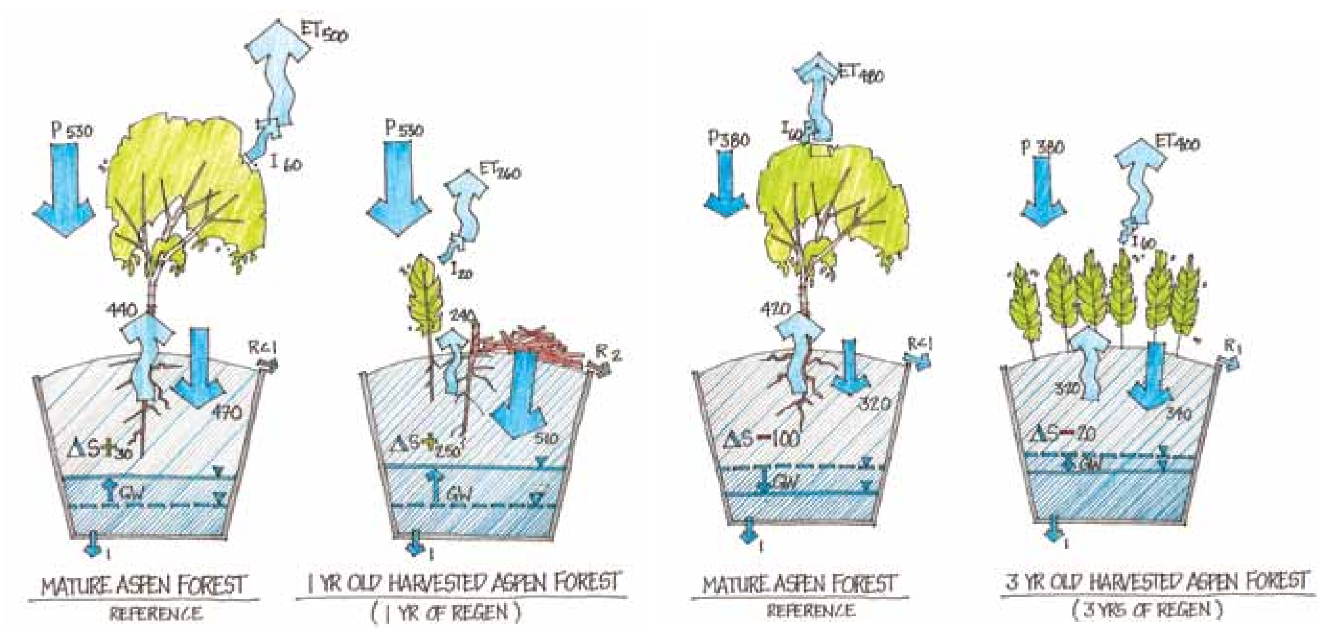
In 45-year-old aspen stands (pre-harvest), evapotranspiration approximates precipitation. Immediately following aspen removal, the evapotranspiration to precipitation ratio drops by 50%. Evapotranspiration does not drop to zero because suckering starts in the first growing season (year zero), there is still evaporation from the soil surface, and slash piles and woody debris act as significant sources of moisture for evaporation (Figure D.25).

By the third year after harvest, the ratio recovers significantly, approaching 75% of a mature stand. This is due both to the removal of canopy shading and to the former understory

FIGURE D.25

Water Balance Comparison in Regenerating Aspen Forests

Comparison of the changing water balance in an aspen stand on a fine-textured HRA at the Utikuma Region Study Area in the years following removal of the trees. The comparison on the left is between a mature stand and a newly harvested stand (first growing season). The comparison on the right is between the mature stand and a three-year regenerating stand.



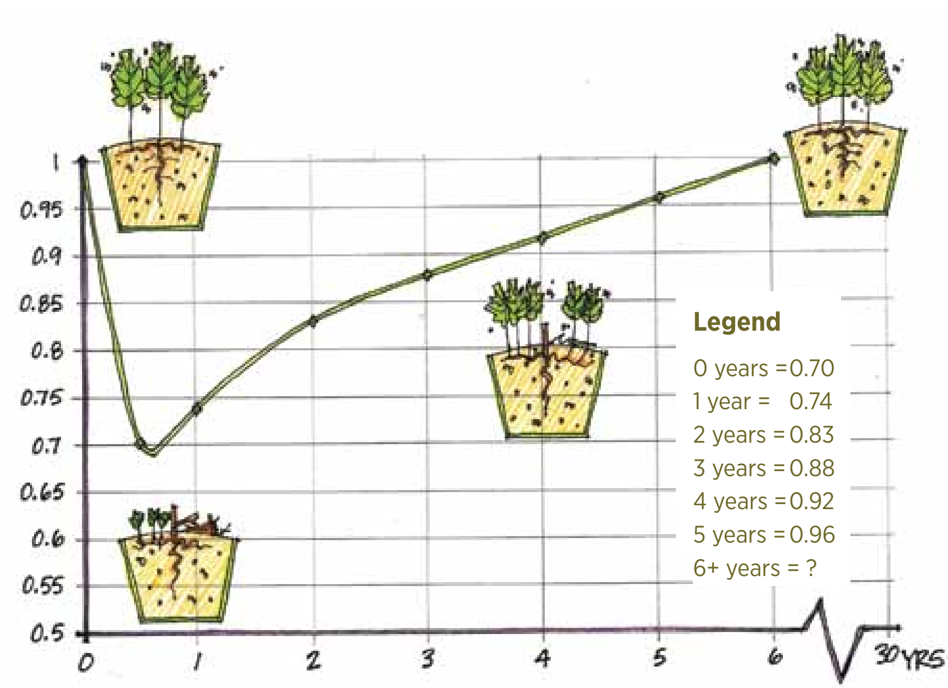
vegetation and shrubs receiving more incoming radiation and, hence, becoming more connected to atmospheric water demand (i.e., they receive more sun and use more water than when shaded by trees). Figure D.26 illustrates the evapotranspiration recovery trajectory.

An important aspect of the evapotranspiration component of the water balance is forest canopy interception. The type of canopy, in combination with the characteristic summer rainfall of the Boreal Plains region (small, low-intensity rainfall events), results in a substantial amount of the precipitation never reaching the root zone. It is easily caught in aspen tree canopies and “lost” back to the atmosphere due to evaporation from the leaves.

Mature aspen forest canopy interception is 25% to 30% (about 60 millimetres) of typical summer rainfall (200 millimetres to 250 millimetres) in this region due to the small size and low intensity of most rainfall. Tree removal increased the amount of water reaching the forest floor by 40 millimetres. Rapid regeneration of the aspen through suckering resulted in the interception term of the water balance recovering back to original values (60 millimetres of total precipitation intercepted by the canopy) within three years.

FIGURE D.26
Evapotranspiration Recovery Trajectory for Aspen-dominated Forestland HUs

Evapotranspiration as a function of time for an aspen Forestland HU. Evapotranspiration is expressed as a percentage of the mature stand ET rate.



KEY CONCEPT: ASPEN HARVEST (TREE REMOVAL) INFLUENCES SOIL MOISTURE STORAGE, NOT RUNOFF, AND FOLLOWING TREE REMOVAL, RAPID REGENERATION OF ASPEN RESULTS IN RAPID RECOVERY OF SOIL MOISTURE STATUS AND GROUNDWATER LEVELS

Although conventional theory would suggest that harvesting should increase runoff, virtually no change in catchment outflow was observed in aspen stands the year immediately after harvesting, nor over the subsequent four years of vegetation community recovery: most of the precipitation received was taken up by soil storage, shrub interception, and groundwater recharge (see next key concept). It is important to note that the study area was logged in a wet year and, thus, had the most potential to generate excess water for runoff, yet no runoff was observed.

Tree harvesting removes a large amount of evapotranspiration capacity from the system. This increases the probability that precipitation events will have the potential to exceed Forestland HU soil storage capacity and, subsequently, induce the soil-, landform-, and landscape-scale "fill and spill" phenomenon discussed in Section C where GW_{out} and R_{out} expand appreciably. The **probability** of connecting the landscape hydrologically in this way is dependent on the antecedent moisture conditions and the climate history leading up to the harvest.

Research indicates that tree removal caused the soils to wet up, but most moisture movement was vertical (i.e., to soil storage and groundwater) as opposed to lateral (runoff). Soil-moisture increases were short-lived, however, and increased groundwater recharge due to harvesting was limited to one year following the harvest. Within three to five years the evapotranspiration rates recover almost completely (Figures D.25 and D.26) with leaf area indices (LAI), interception (I), and actual evapotranspiration values close to those of a mature aspen forest due to the vigorous shrub layer and the presence of intact aspen roots that still access soil moisture and cause rapid suckering. Soil moisture trends and volumes also recovered within three years following tree removal due to the rapid regeneration of aspen.

As a result, it appears any enhancement in HU- or HRA-scale hydrologic connectivity induced by aspen tree removal is short-lived, leading to the conclusion that the window for Forestland HU "wetting up" or the period of higher probability "fill and spill" is relatively short in aspen forests.

KEY CONCEPT: CLIMATE (PRECIPITATION CYCLES AND PATTERNS) ARE THE MOST IMPORTANT CONSIDERATION IN LANDSCAPE WATER BUDGETS, AND CAN OVERWHELM THE INFLUENCE OF VEGETATION MANAGEMENT

The aspen harvest primarily influences the evapotranspiration component of the water balance equation and, given average precipitation volumes and distribution, will have a strong influence on the amount of water available for redistribution in the HU or overall landscape. However, as discussed in Section C, the periodic high precipitation years, and particularly the periodic inter-annual variation in snow pack levels, can have a even stronger influence on soil-, landform-, and landscape-scale water balances. During the harvest experiments, large water table rises were observed in both the uncut and the cut (harvested) aspen Forestland HUs. The experiments were conducted in high precipitation years, a cycle that overwhelmed the vegetation management treatment effect (reduced evapotranspiration) on the water balance. This observation reinforces the view of climate as the most important consideration in landscape water budgets.

KEY CONCEPT: ASPEN HARVEST HAS LITTLE INFLUENCE ON SNOW REDISTRIBUTION

Snow accumulation and melt, although a small portion of total annual precipitation, exerts a critical control on water balances in landscapes in the Boreal Plains. Vegetation influences how much snow is lost to sublimation and influences snow redistribution in the landscape.

Because snow can readily be held on the branches of conifers, snow sublimation is much greater in conifer forests and conifer-dominated wetlands than in deciduous forests and deciduous plant-dominated wetlands. Sublimation losses in the Boreal Plains can exceed 30 millimetres to 40 millimetres annually.

Snowmelt is important for plants and for replenishing soil, landform, and landscape moisture, but not as important for ponds in the Boreal Plains as for prairie ponds where snow redistribution (i.e., drifting, followed by melt) contributes substantially to pond water levels. This is due to the structure of the forest vegetation which radically reduces snow redistribution. In aspen-dominated Forestland HUs, the shrub layer and rapid regeneration by suckering results in little change in snow redistribution, even following tree removal.

KEY CONCEPT: DISTURBANCE OF FOREST-FLOOR INFLUENCES VEGETATION COMMUNITY RECOVERY IN ASPEN FORESTLAND HUS

The forest floor material (LFH) of a Forestland HU intercepts and holds substantial amounts of water in a location where it is readily accessible for plant uptake, thereby enhancing soil-vegetation-atmosphere water cycling in Forestland HUs (discussed in Section D.4.3). Forest floor water interception along with canopy water recovery also influences vegetation-community recovery trajectories in aspen Forestland HUs.

In research experiments where the LFH had been left intact, early succession pathways suggest a recovery trajectory towards the original plant community. Areas where the LFH had been removed were dominated by invasive species and tended towards a different succession pattern compared to those areas where the organic layer had not been removed.

Canopy recovery also influences the trajectory. If canopy recovery is low, grasses may out-compete the understory. Grass invasion or persistence may determine the trajectory and stability of intermediate communities. This merits further research.

KEY CONCEPT: TREE REMOVAL FROM ASPEN FORESTLAND HUS HAS LITTLE IMPACT ON ADJACENT RIPARIAN AND PEATLAND WETLAND HUS

Conventional theory regarding peatland formation suggests that, following harvesting, increased surface runoff from the upland deforested areas should be observed. This should manifest as a “wetting up” of the riparian zone around the peatland and the subsequent expansion of the peat into the riparian area. Research at the Utikuma Region Study Area suggests that this process does not regularly occur in the Boreal Plains region.

The hydrologic status and, hence, vegetation community status of peatlands and riparian areas around ponds are controlled more by the characteristics of the Wetland HU to which they belong than by the adjacent “hill slope” or Forestland HU. Wetland HUs and Forestland HUs may or may not be hydrologically connected.

Harvesting had no effect on Wetland HU vegetation-community composition since most water generated by changing the Forestland HU vegetation community went into soil storage in the Forestland HU and did not run off to the Wetland HUs (Figure D.27).

In Wetland HUs, changes in vegetation communities (peatland and riparian) were more strongly correlated to the inter-annual wetting and drying cycles than they were to harvesting. With rapid recovery of aspen, water balances were quickly re-established and no long-term changes to the moisture regime were observed. Thus, the hydrologic status and, therefore, the vegetation community status of the riparian and peatland communities in the Wetland HU were unaffected.

Overall, there was little difference in low- and high-flow measurements, water chemistry, or the vegetation dynamics of Wetland HUs adjacent to Forestland HUs in the harvested or intact aspen forest catchments. The exception was where road construction cut more deeply and was also aligned perpendicular to slopes resulting in channelled flow into adjacent wetlands and streams.

FIGURE D.27

Forestland-Wetland (Riparian) HU Interface

Forestland HU-Wetland HU interface on a fine-textured HRA at the Utikuma Region Study Area. No changes in the Wetland HU vegetation community were observed in response to harvesting of the aspen Forestland HU.

D.4.6 Forestland Hydrologic Units: Implications for Landscape Reconstruction

Forestland HUs are critical components of the Boreal Plains mosaic and must be reassembled in the landscape to achieve equivalent capability. The relative proportion of Forestland HUs in a reconstructed landscape influences the water balance of that landscape by affecting the relative amount of water lost to evapotranspiration. These HUs should be viewed as water "sinks" and landscape designs need to incorporate features to ensure additional moisture for long-term viability of the Forestland HUs, themselves, as well as the Wetland HUs and water bodies surrounding them. Soil water storage and water demand by vegetation in Forestland HUs should be placed into the context of HRA type (geology), the sub-humid climate, and climate cycles of the Boreal Plains in order to adequately reflect the implications of Forestland HU composition and arrangement on the reconstructed landscape hydrology.

DESIGN CONSIDERATION: HETEROGENEITY OF MATERIALS AND TOPOGRAPHY

When trying to establish Forestland HUs, consideration of the heterogeneity of reclamation materials and topography is important. Extensive and steep slopes can essentially increase water storage and decrease water levels thereby enhancing long-term moisture deficit situations as growing forests mature. The creation of features to maintain fresh-water sources that are accessible to tree roots in Forestland HUs can offset the moisture deficits and ensure the long-term vigour of Forestland HUs through the dry cycles characteristic of Boreal Plains climates. The "five-metre rule," discussed previously, is related to this need to provide fresh-water retention features (e.g., soils, Wetland HUs) that will offset the average long-term moisture deficit.

Incorporating heterogeneity of materials (confining layers) and rolling relief into landscape designs can facilitate development of Wetland HUs (an "internal" water source), limit the height of slopes, and, therefore, also limit the distance from fresh-water sources. The appropriate degree of heterogeneity will vary with the ability of HRA material to drain or hold the water level near the surface and within reach of tree roots.

In reconstructed landscapes, Forestland HUs should not be relied upon to consistently generate significant water inputs for Wetland HUs or the landscape in general. Forestland HUs represent areas of large storage and low antecedent moisture (deep buckets) and the memory of climate cycles and substantial time lags in "filling and spilling" of these HUs should be considered when designing for runoff volumes or for groundwater flushing.

DESIGN CONSIDERATION: ASPEN IN REVEGETATION PLANS

In reconstructed landscapes and large Forestland HUs, designers should consider the significance of aspen roots in the redistribution of water and connections to Wetland HUs that will help sustain the long-term vigour of the forest through natural disturbances and climate cycles.

Soil cover depths and configurations should be designed to enable sufficient lateral and taproot system development. This is particularly important in coarse-textured landscapes (HRAs) and in upper-slope positions where water deficits may occur frequently. Where trees are situated near Wetland HUs it may be possible to place shallower soil covers if effective lateral root development and root connections can be formed to access water available in either the Wetland HU or stored in the soil profile, but further research is required on this possibility.

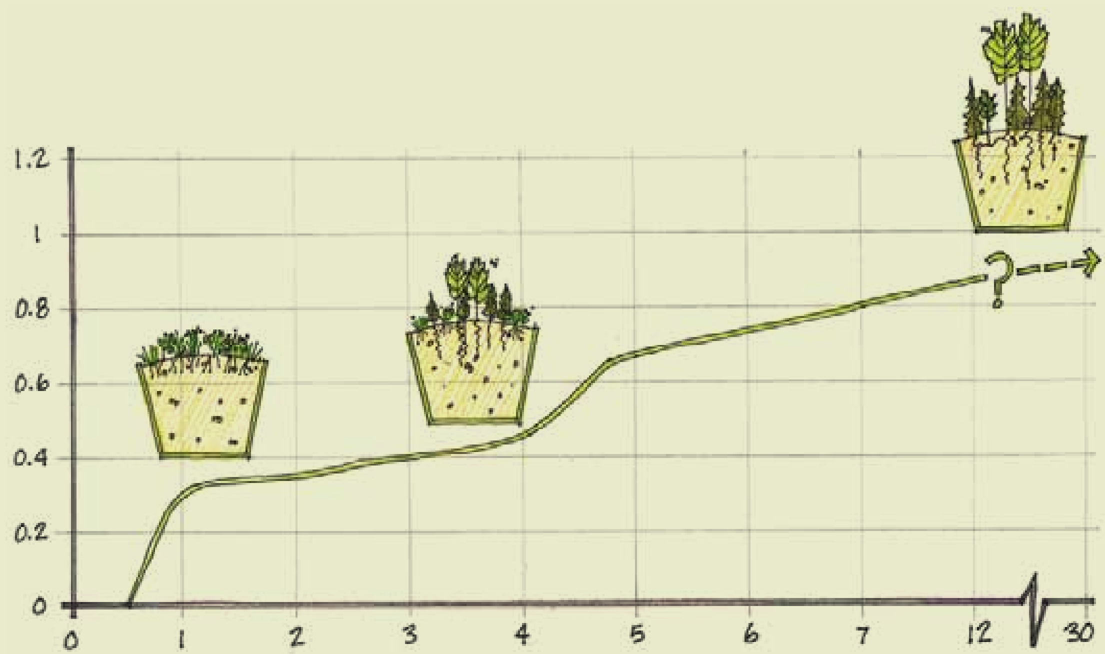
Given the clonal nature of aspen and the important role root connections play in the redistribution of moisture, post-planting stand management practices that encourage the formation of root connections, including the trimming or burning of young planted aspen stands to encourage suckering, should be considered. It is speculated that clonal root systems take 100 to 200 years (i.e., a period encompassing two or more disturbance events that remove above-ground portions of the aspen forests) to develop, but verification research is, again, required.

Effective design of Wetland and Forestland HUs requires that attention be paid to the perimeter-to-surface area relationship of the Wetland HU (i.e., the relative amount of the Wetland HU edge abutting an aspen Forestland HU) along with the relative proportions of Forestland HU to Wetland HU and their distribution on an HRA. Forestland HU vigour and Wetland HU survival will be affected because aspen roots redistribute water away from Wetland HUs into Forestland HUs. This is reflected by the addition of the U element in the water balance equation; examples of its use in can be found in Section E.

FIGURE D.28

A Possible Evapotranspiration Recovery Trajectory for a Reclaimed Aspen Forestland HU

Illustration of potential evapotranspiration recovery trajectory in a reclaimed landscape given that aspen is planted, rather than regenerating from suckers. Defining actual patterns of evapotranspiration recovery is the focus of research currently being conducted by Drs. Rich Petrone (Wilfrid Laurier University) and Sean Carey (McMaster University).



DESIGN CONSIDERATION: ASPEN FORESTLAND HU SUCCESSION TRAJECTORIES AND IMPACTS ON WATER BALANCES

Because the HU and HRA water balances are controlled, in large part, by vegetation, vegetation succession trajectories will be accompanied by changes in the magnitudes of water balance variables. The water balance itself will also display a "trajectory" (i.e., it changes as a vegetation community changes). Studies of aspen regeneration after tree removal in natural Forestland HUs provide insight as to the water balance recovery trajectory that might be anticipated in reclaimed areas. In natural aspen-dominated forests, in which aspen regenerates by suckering, evapotranspiration rates recover to mature stand rates within three to five years. However, in reclamation areas, aspen seedlings are planted at lower densities than regenerating aspen stands in harvested areas. In addition, aspen seedlings grow more slowly than aspen suckers. The reconstructed system is likely on a primary succession-type pathway from a vegetation water-use perspective. Figure D.28 shows a concept of what the evapotranspiration trajectory might look like.

A reconstructed landscape has a different evapotranspiration recovery "trajectory" than a natural landscape. Following soil placement and planting, it takes a few years for the shrub layer to become established. Over time, as forests develop on reconstructed landscapes, it is expected that evapotranspiration will increase, resulting in a general decrease in soil antecedent moisture levels. It is also expected that with maturation of forests on reclaimed landscapes, the long-term average moisture deficit conditions typical of natural Forestland HUs will prevail. Over time, because of the development of the forest vegetation, reconstructed Forestland HUs will show an increase in time lags and threshold responses to precipitation inputs like those observed in natural Forestland HUs. Consideration of reconstructed Forestland HU antecedent moisture conditions will help the land manager anticipate hydrologic response to climate cycles at different successional stages.

As discussed in Section C, snow, although a small portion of the total water balance in Boreal Plains landscapes, exerts a strong influence on soil, landform, and landscape water redistribution. Forestland HU vegetation strongly affects snow redistribution in these landscapes. Limited drifting and redistribution of snow on reconstructed landscapes within the first years following harvesting indicates that snow-drifting is not a viable option for the accumulation of excess moisture. Caution should be taken when making analogies between boreal and prairie pond systems, as prairie ponds gain a substantial portion of moisture from blowing snow redistribution where vegetation is removed due to agricultural harvesting. In reclaimed and forest-harvested landscapes, vegetation structure develops enough within one to two years to appreciably reduce snow redistribution and its effects on pond filling.

Finally, research involving tree removal followed by tracking of forestland and Wetland HU response showed that the presence of post-disturbance forest floor material (LFH) places the Forestland HU system on a recovery trajectory towards more native forest communities which is in alignment with results from previous research in reclaimed systems (Mackenzie et al. 2010). The work also suggests that when designing peatland plant communities, the hydrologic status of the Wetland HU to which they belong is a more important consideration than that of the Forestland HU adjacent.

D.5

Hydrologic Connectivity: Soil-, Landform-, and Landscape-Scale Connections

The hydrologic "building blocks"—the hydrologic response areas (HRAs) and hydrologic units (HUs)—of the Boreal Plains exist on a wide range of scales and are hydrologically connected at multiple scales in the landscape through time (recall Figure C.14). The intermittently connected network of hydrologic building blocks maintains the entire mosaic through the wetting and drying cycles and, thus, imparts the required hydrologic functionality.

In order to understand, and subsequently design for, water distribution (water quantity, quality, and the timing of water flow at any location through time) in a Boreal Plains landscape, the connectivity of this variably linked network of hydrologic elements (HRAs and HUs) must also be understood.

In reconstruction efforts the proportion of HUs, how they are positioned and connected on HRAs, and the arrangement of HRAs in the landscape will influence:

- The emergence and sustainability of the range of ecological communities (terrestrial and aquatic) that characterizes the Boreal Plains; this has implications for the achievement of equivalent capability goals
- The quantity, quality, and timing of water flow in the reconstructed landscapes on all scales—from small ponds and wetlands on individual dumps to end-pit lakes

D.5.1 Flow Interactions Between and Within HUs and HRAs

KEY CONCEPT: HYDROLOGIC CONNECTIONS AT ALL SCALES CAN INVOLVE ROOT (UPFLUX), GROUNDWATER, AND RUNOFF PROCESSES

Conceptualizing the water balances of, and hydrologic connectivity between, Wetland HUs, Forestland HUs, and the HRAs on which they are found requires consideration of water redistribution by roots as well as groundwater and surface and near-surface runoff processes (Figure D.29). The spatial arrangement of the HUs, and the HRAs they are on, in concert with the effect of the contrast in their respective water balances, influences the hydrologic connectivity and, hence, water flows and water quality in the landscape (Figure D.30).

Water redistribution is represented in the diagrams by arrows. Evidence from root flow and soil hydraulic lift measurements show that root uptake can occur in either direction regardless of slope (two-way arrows, Figure D.29). For the most part, groundwater and runoff waters flow from HUs or HRAs situated in high topographic positions to those located in lower positions. However, due to the low relief typical of the Boreal Plains, surface and/or groundwater levels in HUs in lower topographic positions frequently rise and breach adjacent HUs that may be positioned at a higher surface elevation, resulting in flow reversals.

In natural landscapes on the Boreal Plains, the relative position of and direction of flow from one type of HU or HRA to another is not consistent through the landscape because of the low relief characteristic of the Boreal Plains. Wetland HUs, or HRAs dominated by Wetland HUs (i.e., shallow buckets), frequently occur above or upslope of Forestland HUs or forest-dominated HRAs. This may seem counterintuitive, as the opposite arrangement—with Forestland HUs "above" Wetland HUs—is more often pictured. However, both arrangements do occur in Boreal Plains landscapes.

FIGURE D.29
Hydrologic Connectivity Via Groundwater, Runoff, and Roots

There are three types of hydrologic connections within and between HUs and HRAs: Surface and/or near-surface runoff (R), groundwater (GW), and roots (U).

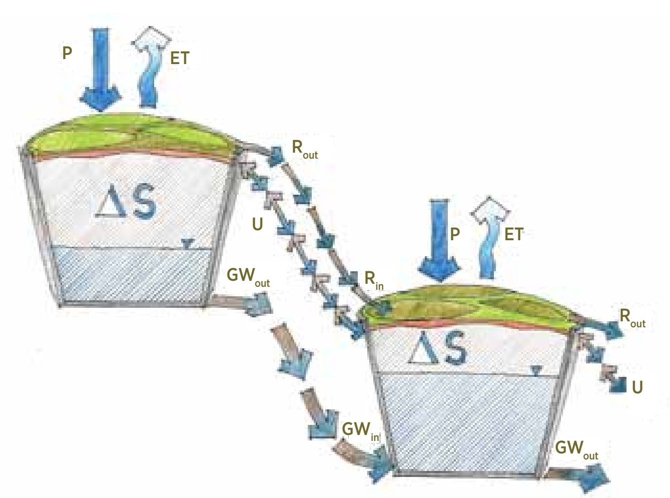
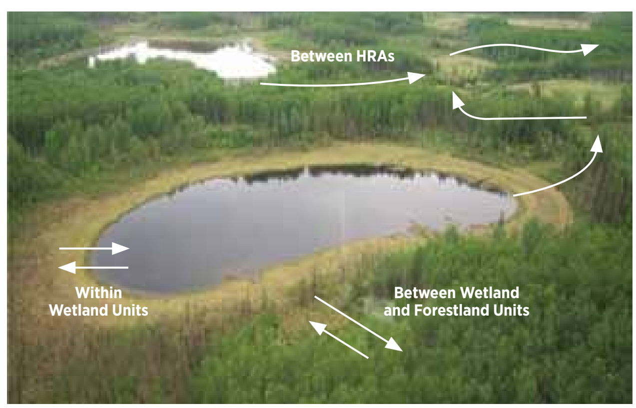


FIGURE D.30
Hydrologic Connectivity a) Within Wetland HUs, b) Between Wetland and Forestland HUs, and c) Between HRAs

Typical Wetland HU-Forestland HU mosaic but with the scale of interactions within Wetland HUs, forestland and Wetland HUs, and larger-scale flow from the HRA illustrated. The arrows indicate direction and the length indicates magnitude of flow. Where two arrows in reverse directions are depicted, flow reversals occur usually due to changes in water balance during climate cycles (see text).



The long-term tendency for water movement (hydrologic connectivity) between hydrologic building blocks (HRAs and HUs) in the low relief environment of the Boreal Plains is driven by the spatial variability of vegetation, soil layering, and storage characteristics of different HUs.

KEY CONCEPT: CONTRASTS IN WATER SURPLUSES AND DEFICITS WITHIN THE HUS DRIVES HYDROLOGIC CONNECTIVITY AND LONG-TERM FLOW DIRECTION WITHIN AND BETWEEN HUS

In the long term, in the absence of large topographic slope differences, the contrasts in water balances between HUs result in a low water table, below the influence of the vegetation water demand in the Forestland HU, and water tables near the surface in the Wetland HU (Figure D.31). The long-term (most frequent) movement of water will be from the soil-layered portion of the Wetland HU (net water source) to the adjacent Forestland HU (net water sink) and to the open-water portion (net water sink) of the Wetland HU. The flow processes can change and direction periodically reverse within the context of climate cycles (See Sections C and D3.4).

Hydrologic connectivity between the layered portion of the Wetland HU and the Forestland HU occurs via:

- Roots and hydraulic lift, primarily from Wetland HUs to aspen Forestland HUs
- Groundwater, primarily from the Wetland HU edge recharging into a Forestland HU
- Runoff as surface and subsurface storm flow from Forestland HUs to Wetland HUs as a function of climate cycles

Hydrologic connectivity between the layered portion and the open-water portion of the Wetland HU occurs via:

- Groundwater, primarily from the layered to the open-water parts of the HU through the deeper peat
- Runoff as surface and subsurface flow in the active layer from layered to open-water portions of the HU

FIGURE D.31
Contrasts in Water Balance Components and Effective Dryness that Drive Hydrologic Connectivity Between and Within HUs

Top:

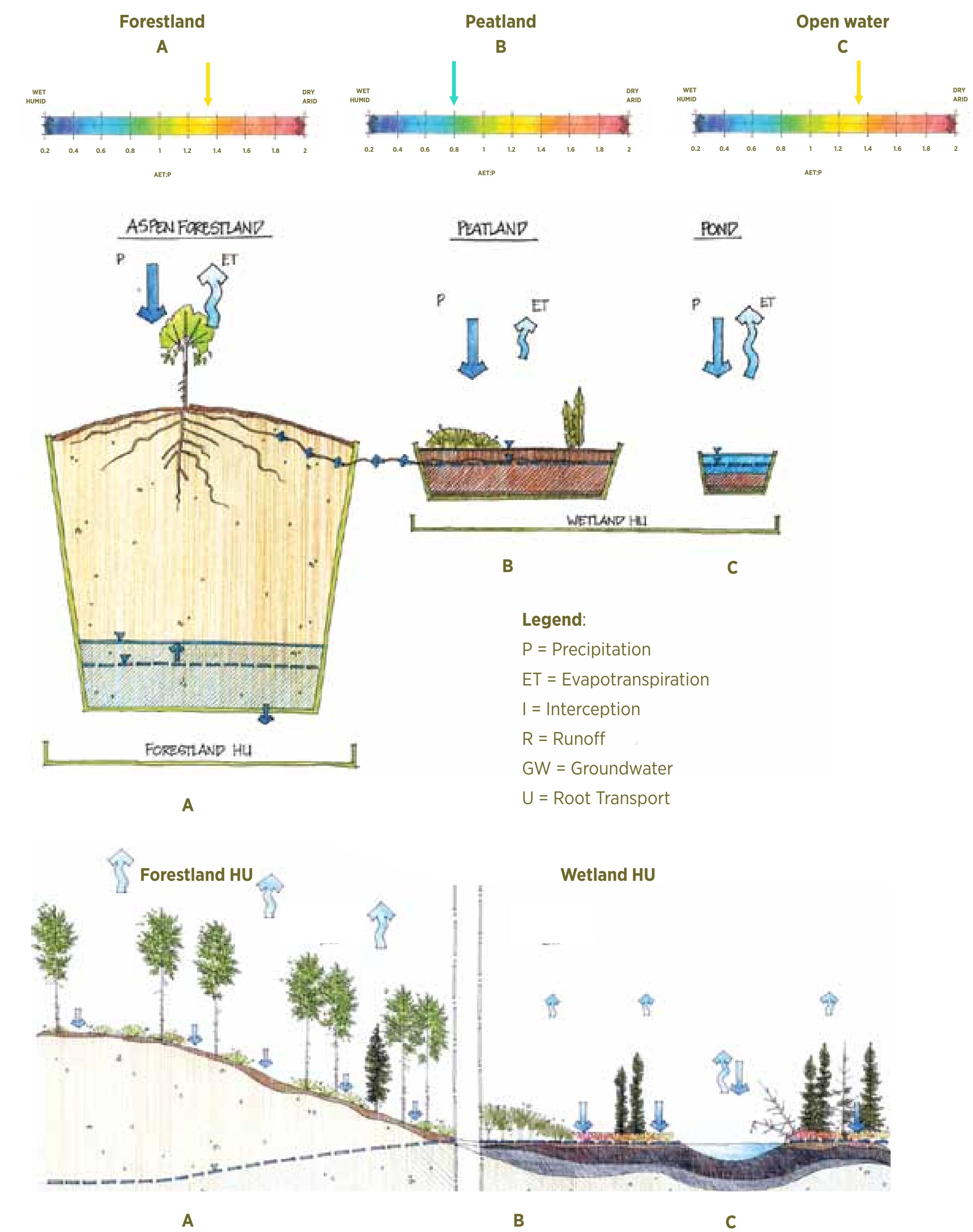
Effective dryness indices for Forestland HU, peatland, and open water portions of Wetland HUs, respectively.

Middle:

Magnitude of water fluxes for a representative year for an aspen stand Forestland HU and shallow pond surrounded by a poor fen peatland Wetland HU on a fine-textured (moraine landform) HRA at the Utikuma Region Study Area. The size of the arrows represents the relative magnitude of fluxes.

Bottom:

Water table configuration, vegetation type, and soil layering within a conceptual wetland and Forestland HU cross section. Each HU can function independently from the other (i.e., can be hydrologically connected or unconnected) depending on the climate as suggested by the blank space shown at the interface between the two.
Due to the relative differences in water balance components between and within these building blocks, water tends to move from the layered Wetland HUs to the Forestland HUs or from layered Wetland HUs towards the open water areas.



KEY CONCEPT: THE PROPORTION OF HUS INFLUENCES THE WATER BALANCE AND CONNECTIVITY ON A WIDE RANGE OF SCALES THROUGH THE LANDSCAPE AND OVER TIME

The proportion of Wetland to Forestland HUs influences the water balance of a landscape by controlling the relative amount of water lost to evapotranspiration in the context of the long-term moisture deficit in the Boreal Plains. The proportion and connectivity also influence the dominant movement of water between Wetland HUs and Forestland HUs and potential runoff from landscapes (Figure D.32).

FIGURE D.32
Relative Proportion of Forestland to Wetland HUs Influences Landscape Water Balance and Connectivity

Range of combinations of wetland and Forestland HUs on a landscape. The light green represents Forestland HUs and the dark green and blue represent layered and open-water portions of Wetland HUs.

No scale or slope is implied. This range of spatial arrangement of HUs could occur on no relief or sloping away from or towards the larger open-water system. It could occur over a 100 X 100 m^2 or 10 X 10 km^2 area.

Top:

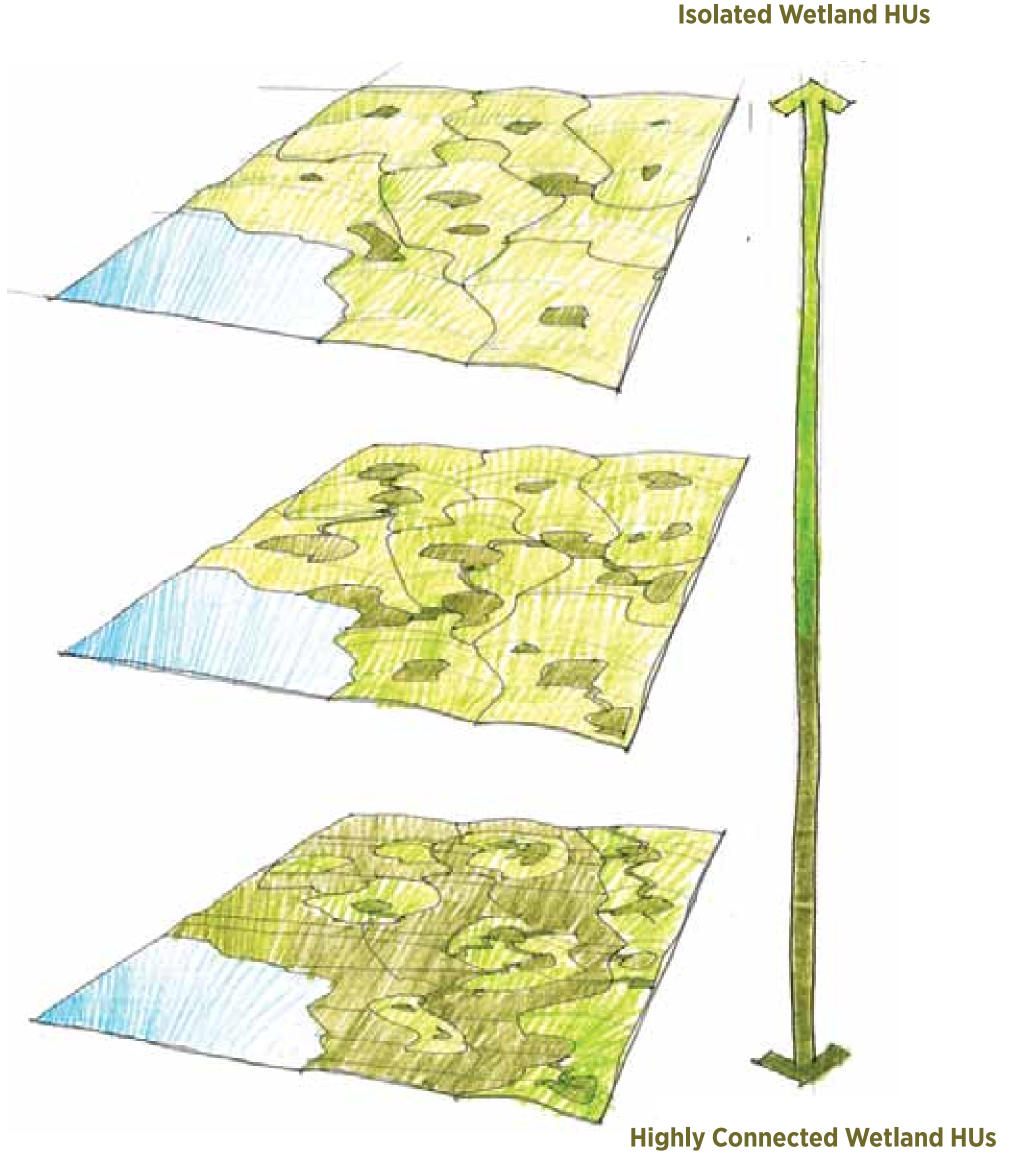
Small isolated Wetland HUs. The dominant water movement is from Wetland HU to Forestland HU. The landscape is dominated by the Forestland HU water balance with a net moisture deficit with large soil storage or groundwater recharge. Landscape scale flow is via "fill and spill" from Forestland HUs to Wetland HUs or to the open water at the bottom and this occurs infrequently (every two to three decades).

Middle:

Increasing proportion and connectivity of Wetland HUs. Redistribution of water from both Wetland HUs to Forestland HUs as well as to adjacent connected Wetland HUs (often via ephemeral draws). The landscape water budget is roughly balanced between the two HUs.

Lower:

Large expanses of well-connected networks of Wetland HUs. The dominant water movement is between connected adjacent Wetland HUs. The landscape is dominated by a wetland water balance with net moisture surplus, limited storage, and larger and consistent surface flow (runoff) at the landscape scale.



D.5.1.2 Landscape Influence on the Type and Direction of Hydrologic Connections Between HUs

KEY CONCEPT: THE TYPE OF HRA AND HU POSITION ON THE HRA INFLUENCES THE TYPE AND DIRECTION OF HYDROLOGIC CONNECTIONS BETWEEN HUS

The hydrologic connectivity between Forestland and Wetland HUs as well as between HRAs and landscapes is primarily controlled by the coarse scale surficial geology (the HRAs) and the climate (recall section C.1.6).

The generally observed direction of water redistribution and magnitude of hydrologic connectivity resulting from the contrast in water balance between Wetland and Forestland HUs (Section D.5.1.1) is further modified by the:

- Relative topographic position of the HUs in the HRA
- Nature of the HRA (fine-textured, coarse-textured, veneer-type)

The strength and direction, including reversals, of the hydrologic connection is determined by:

- The composition of the HRA (soil texture and arrangement of HUs)
- The climate cycles

Some of the ranges in water table configuration and type and direction of hydrologic connectivity between wetland and Forestland HUs on a range of HRAs are illustrated in Section D.1. Often, the water table does not follow the local topographic slope. Due to the potential influence of larger groundwater flow systems, especially in coarse-textured HRAs, the effective watershed boundaries and water table configurations are not reliably identified by surface topography. Rather, the hydrologic connectivity between HUs and the water table configuration within are determined primarily by the soil texture of the HRA deposits.

KEY CONCEPT: HRA TYPE AND POSITION INFLUENCE THE DISTRIBUTION OF HYDROLOGIC UNITS

Figure D.33 illustrates the influence of landscape geology (HRA) and topographic position on the distribution and connectivity of wetland and Forestland HUs and, hence, on the potential landscape water balance and runoff.

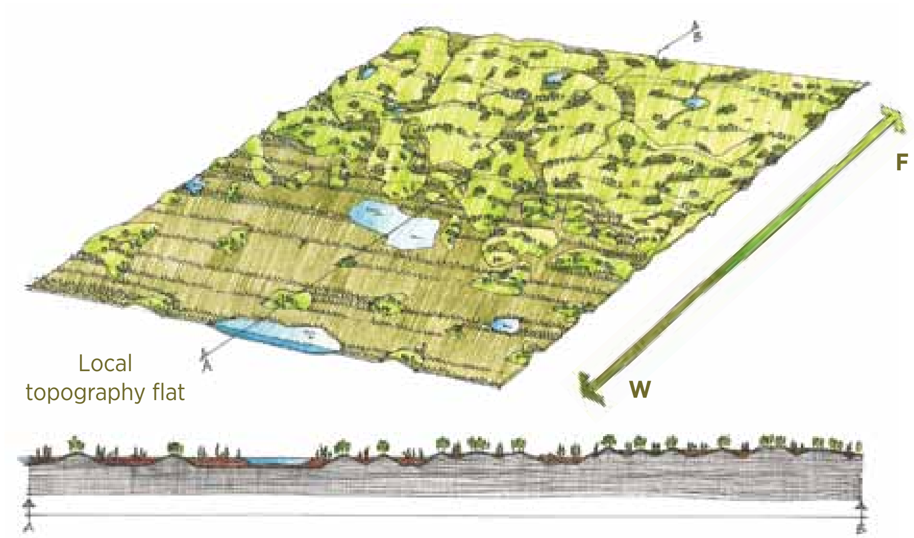
In **coarse-textured HRAs** regional topographic position controls Wetland HU distribution and connectivity. In coarse-textured HRAs Forestland HUs dominate on topographic highs, with smaller, isolated ("dimples") of Wetland HUs distributed throughout. The Wetland HUs in these locations are perched or isolated from the regional groundwater flow system.

The bottoms of large-flow regimes (regional topographic lows) in coarse-textured materials are characterized by expansive continuous networks of Wetland HUs with small, isolated islands or hummocks ("pimples") of Forestland HUs. These expansive wetland units in coarse-textured HRAs tend to be connected to large-scale regional groundwater flow systems and, so, are discharge areas with relatively constant water levels. The lower wetlands portions also receive increasing surface water from wetlands connected above. The small hummocks of forestland units can receive generous sources of water from regional groundwater.

In **fine-textured HRAs** there is also a similar gradient of wetland to Forestland HU distributions. However, the gradient is controlled more by local surficial topography and the connectivity to regional groundwater regimes is minimal. In fine-textured (clay rich) HRAs with hummocky terrain and variability in relief, small, isolated ("dimples") of poorly-connected wetlands occur. The primary direction of flow is from wetlands to forestlands. Wetland HUs become progressively more connected as one moves into the flatter areas. Flatter areas are comprised of expansive Wetland HUs with isolated ("pimples") of Forestland HUs. The dominant source of water for lower wetlands is other connected wetlands. The Forestland HUs receive localized sources of water from adjacent Wetland HUs.

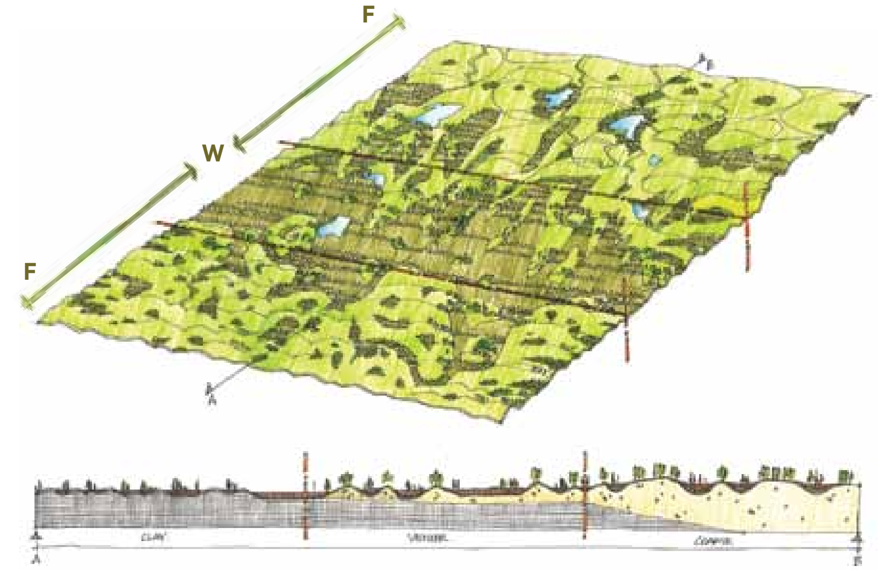
Veneer-type HRAs occur at the transition zone between coarse textured and fine textured HRAs. Isolated "perched" Wetland HUs can form throughout the HRA. Extensive networks of Wetland HUs form at the margin, and also wherever the overlying material thins or depressions intersect groundwater.

FIGURE D.33
Influence of HRA on Wetland and Forestland HU Distribution and Connectivity

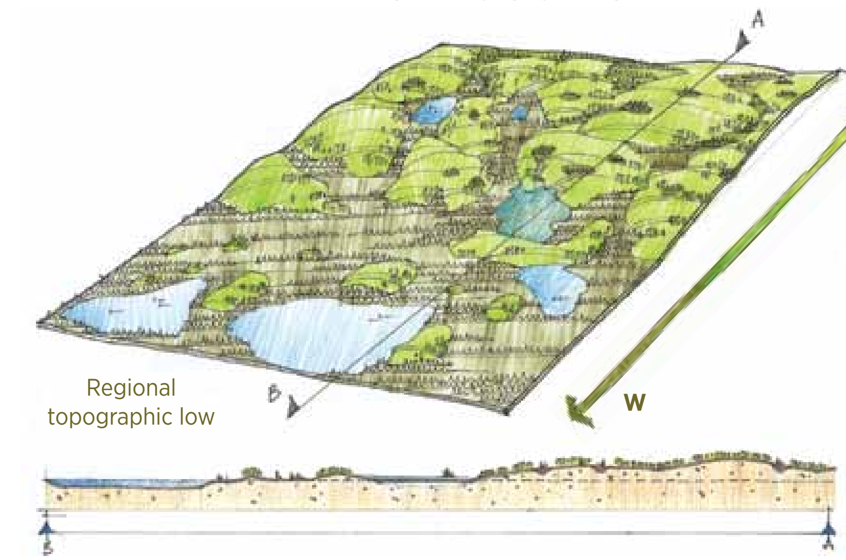


In fine-textured HRAs *local surficial topography*, controls wetland distribution and the connectivity to regional groundwater regimes is minimal.

Extensive Forestland HUs with “dimples” of Wetland HUs



In **veneer-type HRAs** the landscape patterns combine the gradients observed in both coarse-textured and fine-textured HRAs with wetlands dominating at the transition zone between.



In **coarse-textured HRAs**, *regional topographic position* controls wetland distribution and connectivity.

Expansive Wetland HU with “pimples” of Forestland HUs

D.5.2 Interfaces Between and Within HUs: Critical Interaction Points

The previous sections illustrated the processes of water flow and how landscape position, topography, material type (HRA), and stage of climate cycle determine the relative degree of hydrologic connectivity between Wetland and Forestland HUs and within Wetland HUs.

Knowledge of the locations, shape, and composition of HUs, and especially the dynamics of flow magnitude and direction across the interfaces between and within HUs, in turn improves understanding of the important hydrologic and biogeochemical role these zones play in determining water redistribution and water quality.

Water quality (transformation and movement of compounds of interest like nutrients) was a focus in several research projects linked to the hydrology research under the HEAD research program umbrella. Although the data collected were not synthesized as part of this report[4], the importance of the interfaces between hydrologic building blocks on both water redistribution and biogeochemical processes is introduced here.

KEY CONCEPT: THERE ARE TWO CRITICAL INTERFACES FOR HYDROLOGY AND BIOGEOCHEMISTRY IN THE BOREAL PLAINS

The complex and dynamic nature of water flow and hydrologic connectivity between and within HUs results in two critical interaction points

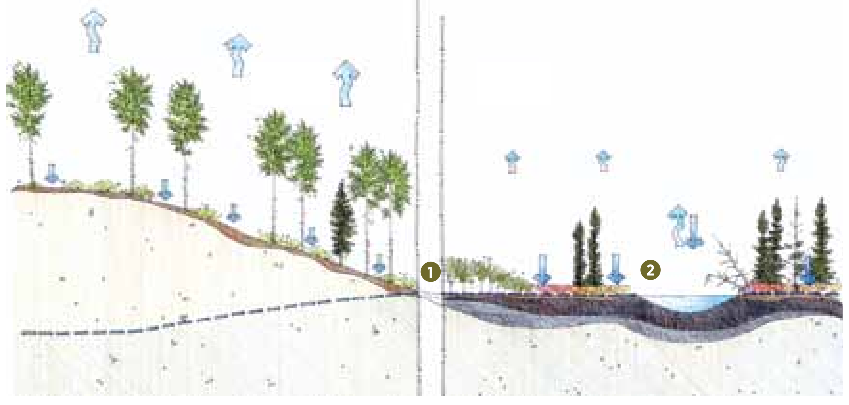
1. The wetland-forestland interface between the Wetland and Forestland HUs
2. The interface between the open water and the water's edge within the Wetland HU, which can be very dynamic and not always present

[4]*See Carmosini et al. (2003); Devito et al. (2000); Macrae et al. (2006); Macrae et al. (2005); Sass et al. (2008); Squires et al. (2006); Wray and Bayley (2007, 2008) for more detail on nutrient movement and cycling processes.*

FIGURE D.34
Hydrologic Interfaces Between and Within HUs

The two key interfaces of hydrologic and biogeochemical interaction in the Boreal Plains landscape are:

1. The interface *between* the Wetland and Forestland HU
2. The interface with open water *within* the Wetland HU



D.5.2.1 Details on Forestland-Wetland Interface

The interface between Wetland and Forestland HUs is the location of dynamic hydrologic (Section D.5.1.1) and biogeochemical interactions.

It is a zone of large water table fluctuations and complex flow paths resulting in:

- Soil redox conditions changing from oxic (dry/drained forestland) to anoxic (wet/wetland). This change in redox condition causes the rapid alterations in water chemistry observed as water moves across the interface
- Clays (if present) shifting from unfractured to fractured and from holding to recharging surface water to groundwater

Depending on the season or the year (i.e., climate condition), the gradient between the two sides of the interface can change and subsurface flow reversals may occur in response to precipitation cycles. Hence, climate cycles can influence the lateral extent of the effect of the interface in both the Wetland and the Forestland HU. This has important implications for the geochemistry of this interface.

Flow direction at this interface is often out of the Wetland HU and into the Forestland HU (recall Section D.5.1.1). The flow of water out of the Wetland HU into the Forestland HU is often via the aspen root "pipeline" (Section D.4.4). In aspen stands, this can extend the length and area of some interactions tens-of-metres into the Forestland HU.

It is only during wetting cycles, when the Forestland HU soil and geologic material water storage capacity is exceeded, that water flows (as runoff) into the Wetland HU from the Forestland HU. The wetland side of the interface can "wet up" seasonally in isolation, however, without engaging the adjacent Forestland HU or hill slope.

The shape of the interface zone (concave or convex) influences:

- The wetting cycle, drying cycle, and flow path (water table dynamics), and, therefore, the anoxic/oxic gradient
- Chemistry
- Vegetation communities and productivity

The effects of the shape of this interface merit further research.

D.5.2.2 Details on Open Water and Water's Edge Interface

Recall that within a Wetland HU, open water and, thus, the presence of the open water-water's edge interface, can be extremely dynamic. When open water is present in a Wetland HU, the open water-water's edge interface:

- Is relatively abrupt—on the order of one metre.
- May change (expand or contract) in extent and location in the Wetland HU as a function of climate.

The open-water edge, whether characterized as open water-layered Wetland HU or open water-Forestland HU, is the location of dynamic hydrologic and biogeochemical interactions. This is the interface where there can be a rapid change from oxic water (open water) to anoxic water (the water's edge). As a consequence, large geochemical and redox gradients are found in this area (P, N, S, and gases CH_4, CO_2).

Lake systems and open-water wetlands may need periodic flooding (one to two times every two to three decades) for long-term maintenance. As a result, these open-water systems usually undergo flow reversals at their edges at some time in the seasonal or annual climate cycles.

Open water level fluctuations and, hence, the zone of dynamic hydrologic and biogeochemical processes, vary depending on the arrangement of the Wetland HU and Forestland HU as shown in Figure D.35.

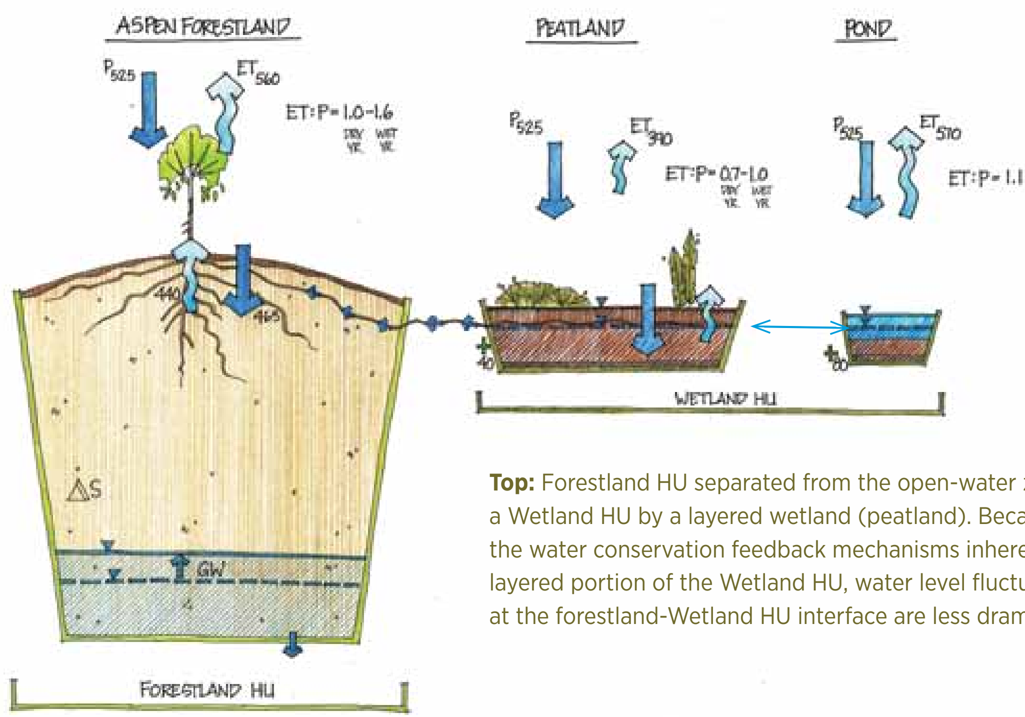
When a Forestland HU is in close proximity to the open-water zone of a Wetland HU, the open-water fluxes are dramatic and hence the interface between the two changes dramatically as well. This is because the open water loses substantial water to evaporation and also loses water to the adjacent Forestland HU (Section D.5.1.1). In these landscape configurations, a large external source of water is required to maintain the open water. Options for this external water supply are discussed in Section D.3.5, but in Boreal Plains systems open water is usually maintained through water supply from a network of connected Wetland HUs or by the presence of a large storage basin to hold the infrequent runoff from the adjacent Forestland HUs (Section D.3.4).

If the open water is directly surrounded by aspen Forestland HUs, then the potential area of interaction (and water demand) may be large. The perimeter to area ratio of open water to surrounding forest determines the forest water demand on the open water. Open-water depression wetlands that are too small will dry up rapidly. However, these ephemeral ponds or vernal pools can represent important water and nutrient sources for adjacent Forestland HUs.

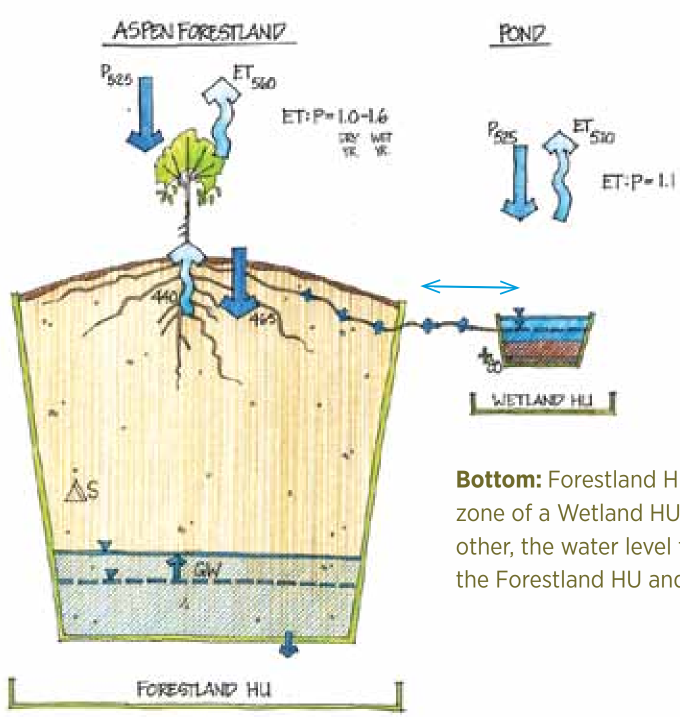
FIGURE D.35

Forestland-Wetland HU Arrangements Influencing Open-water Level Fluctuations

Shown are two forestland-Wetland HU arrangements which result in two different types of interfaces between the HUs. These different interfaces subsequently result in different open-water level fluctuations and hence different zones of dynamic hydrologic and biogeochemical processes.



Top: Forestland HU separated from the open-water zone of a Wetland HU by a layered wetland (peatland). Because of the water conservation feedback mechanisms inherent in the layered portion of the Wetland HU, water level fluctuations at the forestland-Wetland HU interface are less dramatic.



Bottom: Forestland HU in close proximity to the open-water zone of a Wetland HU. With two water sinks adjacent to each other, the water level fluctuations at the interface between the Forestland HU and the Wetland HU are dramatic.

D.5.3 Hydrologic Connectivity: Implications for Landscape Reconstruction

In reconstruction efforts the proportion of HUs, and how they are positioned and connected on HRAs, along with the arrangement of HRAs in the landscape, will influence:

- The emergence and sustainability of the range of ecological communities (terrestrial and aquatic) that characterize the Boreal Plains; this has implications for achievement of equivalent capability goals
- The quantity, quality, and timing of water flow in the reconstructed landscapes on all scales—from small ponds and wetlands on individual dumps to end-pit lakes

DESIGN CONSIDERATION: TYPES OF HYDROLOGIC CONNECTIVITY

The type of hydrologic connectivity and, hence, landscape performance (including vegetation community development and water quality and quantity moving through the landscape), can be designed or anticipated to some extent by understanding and configuring:

- The soil texture of the "building blocks" (HRAs and HUs)
- The relative position of the building blocks in the landscape and the types of interfaces separating the building blocks
- The vegetation communities on each building block
- How climate cycles (seasonal, decadal, and multi-decadal) change the type, strength, and direction of hydrologic connection in the types of building blocks

DESIGN CONSIDERATION: USE OF MULTIPLE SCALES OF HYDROLOGIC BUILDING BLOCKS AND EXTENT OF CONNECTIVITY TO MODERATE THE INFLUENCE OF CLIMATE CYCLES ON LANDSCAPE WATER REDISTRIBUTION

By designing for multiple scales of hydrologic connectivity between Wetland and Forestland HUs and across HRAs it should be possible to provide the dual hydrologic functionality required to accommodate the large wet events and extended dry periods typical of the Boreal Plains region. In this way the designer can have increased confidence in the ability of the reconstructed landscape to:

- Respond to wet periods and events by storing and transmitting moderate amounts of water in or through landscape features and by enhancing evaporative losses
- Sustain forest and wetland diversity and vigour through dry cycles

This may be accomplished by creating Wetland HUs of various sizes and of various degrees of isolation across the landscape, recalling that the effective surface-water catchment area for the entire landscape, in most years, is the total area of connected Wetland HUs which includes ephemeral draws.

The designer should also consider the number and extent of ephemeral draws compared to other types and sizes of designed drainage systems connecting Forestland and Wetland HUs.

DESIGN CONSIDERATION: THE *ARRANGEMENT* OF WETLAND AND FORESTLAND HUS ON HRAS INFLUENCES LANDSCAPE-SCALE HYDROLOGIC CONNECTIVITY AND WATER REDISTRIBUTION

By delineating and planning for the arrangement and connectivity of HRAs and HUs a reconstructed landscape water balance can be quantified or managed. Landform shape and position, soil layering, and vegetation selection are important factors.

The particular tendency of the HRA for surface or subsurface flow connectivity should be understood and designed for at initiation of landscape construction to provide appropriate hydrologic function prior to designing HUs. The HUs can be arranged on the HRAs (on the landforms) to enhance or optimize the probability of achieving those goals. If the general hydrologic tendencies of the HRAs are not considered early in the design process, it is possible to modify those tendencies later on. That is, it is possible to modify the amounts of vertical flow (storage/groundwater recharge) versus lateral surface or near-surface flow (runoff) by building different ratios of wetland to Forestland HUs. However, more effort (resources) will have to be expended to overcome the predominating control of the HRA material type if that is necessary.

Once HRAs have been identified, it is possible to enhance or diminish an HRA's water balance and flow characteristics according to seasonal or long-term climate cycles or to change the relative amounts of fresh water available for runoff to open-water systems. This may be achieved by building and arranging hydrologic units in various sizes and configurations and with different degrees of connectivity, with relatively more surface water generated in landscapes dominated by Wetland HUs and relatively more water retained in Forestland HU-dominated landscapes. There will be a natural tendency towards certain Wetland-Forestland HU distributions and water quality as a function of the connectivity to regional groundwater regimes for each type of HRA (see Figure D.33).

For example, Wetland HUs built in higher topographic positions in coarse-textured HRAs will likely be characterized by fresher water than those placed lower down in the flow regime. Wetland HUs in higher positions in the flow regime on coarse-textured HRAs can only be created if certain layering is present (clay lenses, for example, as discussed in Section D.3.3.1). These Wetland HUs are perched, and so may experience more water-level fluctuations. Those placed lower in the regime are fed by regional groundwater and often have a steadier water level, but may be affected by adverse water chemistry.

It is possible and necessary to build both Forestland HUs and Wetland HUs in reconstructed landscapes. However, there are trade-offs at the landscape scale that must be taken into account between landscapes that consistently produce large amounts of fresh surface water versus those dominated by forests (Figure D.36). This is because some building blocks in the landscape behave as water sources, while others are sinks. Forestland HUs and open-water portions of Wetland HUs are water sinks in this landscape, while layered Wetland HUs are water sources. Their relative proportions and their degree of connectivity in the landscape will strongly influence water redistribution at all scales. Designing expansive Forestland HUs in watersheds adjacent to open waters (e.g., end pit lakes) requires careful consideration of periodicity and magnitude of all water sources for each of these units within the context of the long-term moisture deficit. Interspersing Forestland HUs with Wetland HUs will likely improve the vigour of the Forestland HUs. Greater proportions and connectivity of Wetland HUs is likely required to generate substantial and consistent water flows.

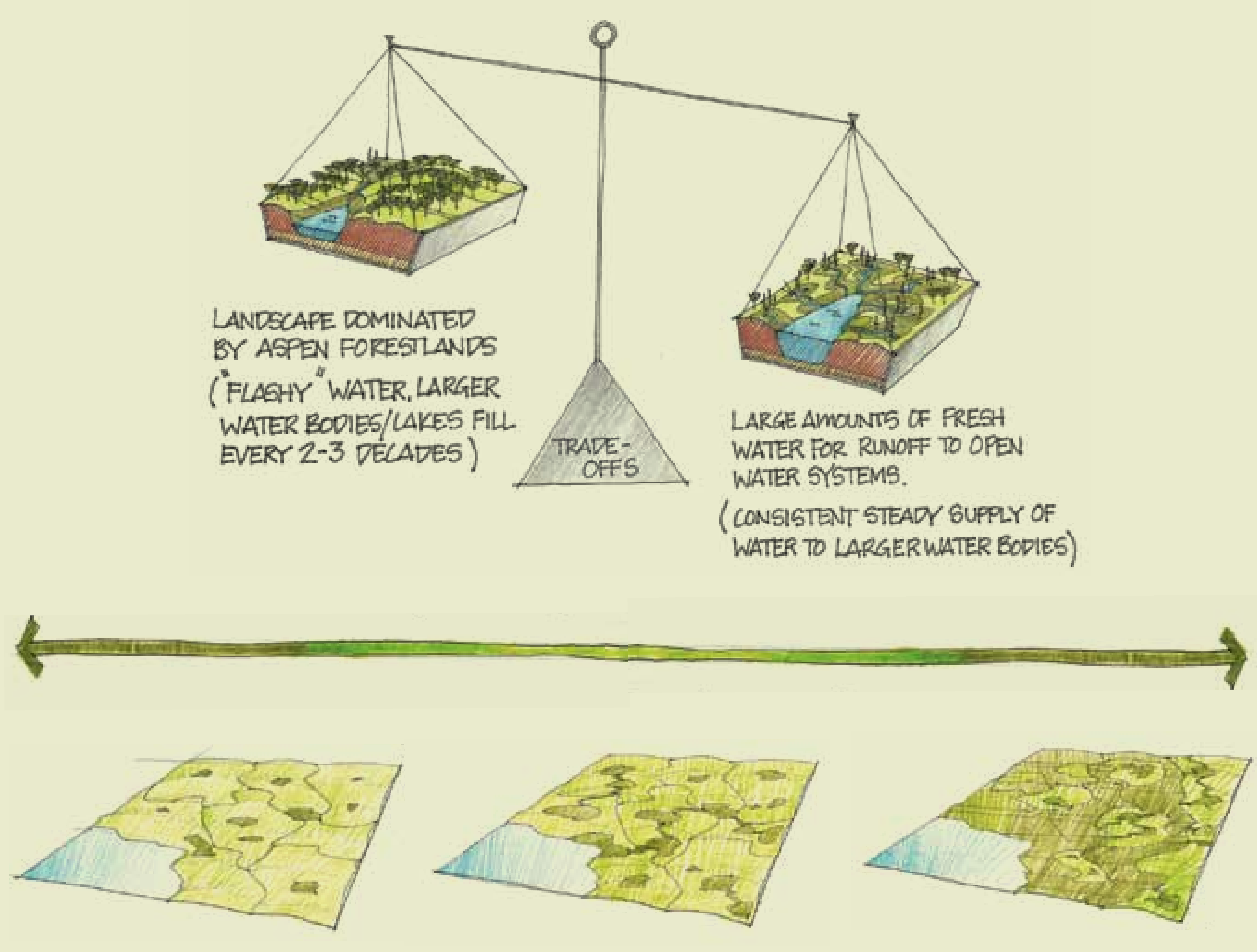
DESIGN CONSIDERATION: HU AND HRA INTERFACES

The interfaces between and within HUs and HRAs require extra consideration by the designer. While more research is required to characterize and quantify the effects of various reconstructions, the results of the research synthesized in this report suggest that the design configuration of these zones will strongly influence both the geochemistry (water quality) of water flowing through the reconstructed landscape and water-level fluctuations in open-water systems.

FIGURE D.36

Tradeoffs and Spectrums

Landscape-scale water redistribution goals will be achieved only through appropriate incorporation of hydrologic connectivity into a landscape. Shown (top) are the trade-offs to be assessed when designing Wetland and Forestland HU proportions and distributions. In reality, landscapes will likely require features from both ends of the balance and, as a result, the designer can consider a spectrum (bottom) of HU arrangements and connectivity to meet the identified goals.



Example Applications: Using the Conceptual Model for Water Balance Calculations and Planning

E

Table of Contents

E

Example Applications: Using the Conceptual Model for Water Balance Calculations and Planning

The data compiled and the concepts developed in this research can be used for a variety of applications. This chapter shows how to:

1. Approach calculation of a water balance along with a numerical representation of how climate and geology interact to affect that balance (Sections E.1 and E.2)

2. Plan a landscape using the conceptual model (Section E.3)

As emphasized throughout this document, understanding the water balance for a soil, landform, or landscape, and how the balance varies through time, is central to anticipating water redistribution and, ultimately, to successful reconstruction design or management. Section E.1 outlines the steps for calculating a water balance for a hydrologic building block and provides detailed explanations regarding how the numbers in Section E.2 were calculated.

In Section E.2 "order of magnitude" example values for water balance components for the two HUs (Forestland and Wetland) of the Boreal Plains are presented and compared for coarse-textured or fine-textured HRA contexts. The water balances for these hydrologic building blocks are also shown for various climate conditions given a specific topographic position. It is hoped that this numerical illustration will provide the designer with an improved understanding of vegetated landscapes on the Boreal Plains—specifically, how climate and geology interact to affect the water balance.

Section E.3 describes how the conceptual model underpinning the new approach to the water balance can be used to inform a modified approach to landscape design. The section also suggests what a landscape planning or design process might look like in light of the findings arising from the research.

E.1

Calculating a Water Balance for an HU: Steps and Explanations for the Numerical Water Balance Example in E.2

In this section, the series of steps that should be considered when calculating a water balance are outlined. The potential numerical values for a water balance for the two types of HU (Wetland and Forestland) on different HRAs under different antecedent moisture conditions are illustrated in Section E.2. Under each step discussed in this section, the rationale behind the values illustrated in Section E.2 is described.

WATER BALANCE STEP 1: CONSIDER THE ANTECEDENT MOISTURE CONDITIONS (INTERACTION OF CLIMATE AND GEOLOGY) (FIGURE E.1)

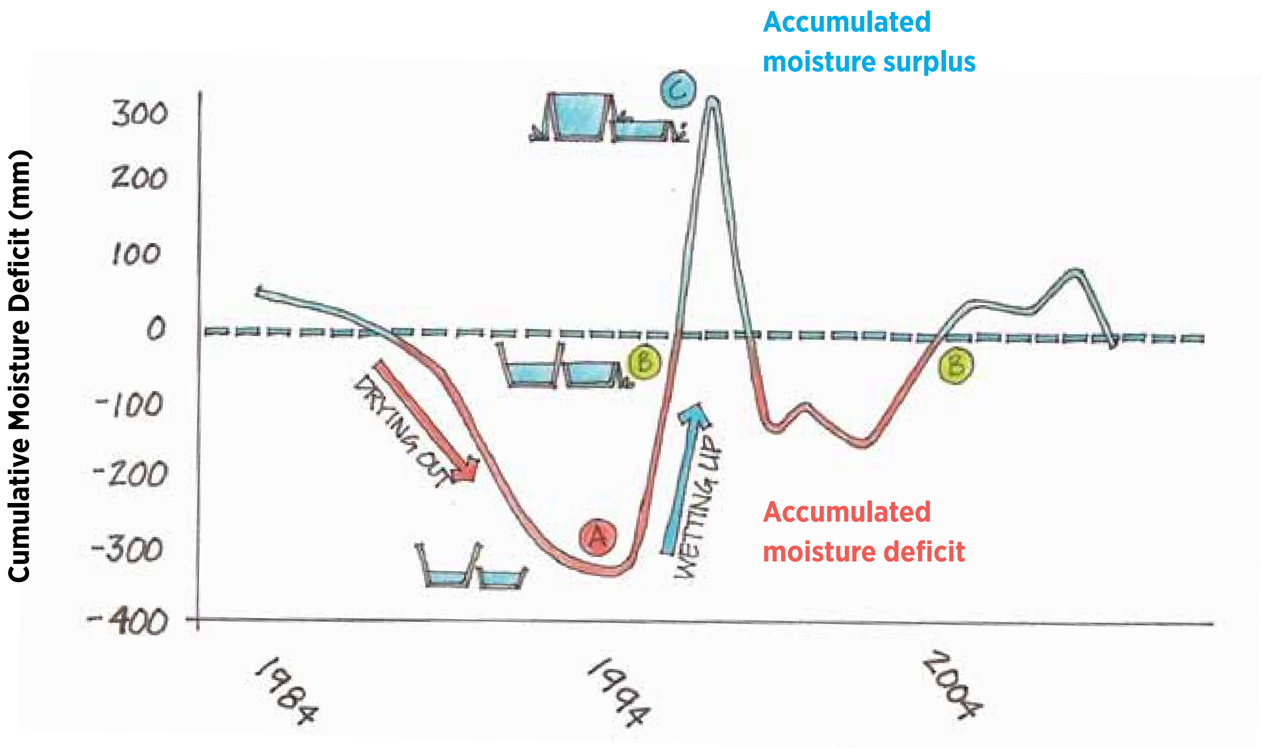
Review Section C.1.6. The relative magnitude of the water balance components in any particular year is a function of the climate cycles. Evaluating the cumulative moisture deficit or surplus (CDYrM) may be helpful in understanding the antecedent moisture conditions and, hence, the relative changes in water balance components that might be expected. For the example in Section E.2, typical magnitudes for water balance components for a "shallow bucket" at Point A and Point C on the graph are presented.

For Wetland HUs, a "dry" antecedent condition does not mean all of the areas of the Wetland HU are dry or empty—there is almost always some water in the Wetland HU (Section D3). Also recall that a Wetland HU can be isolated or networked. In either case, the issue of scale of the Wetland HU must be considered in the next steps.

For the example water balance in Section E.2, Figure E.10, we are assuming "dry" antecedent conditions are very dry with maximal water storage space available in the HU or HRA. The "wet" antecedent conditions are—in the example in Section E.2, Figure E.11—similar to the landscape water "buckets" being essentially full with little water storage space left in the HU or HRA, as illustrated by points A and C on Figure E.1.

FIGURE E.1
Water Balance Step 1:

Consider antecedent moisture conditions. Refer to Section C.1.6. for details.



WATER BALANCE STEP 2: DETERMINE WHICH HU THE WATER BALANCE IS BEING CALCULATED FOR AND ON WHAT HRA TYPE IT IS SITUATED (FIGURE E.2)

Review Section D. Appropriate delineation and characterization of the hydrologic building blocks (HRAs and HUs) are essential prior to calculating a water balance. These building blocks may be uncorrelated with topographically defined watershed boundaries.

For the example in E.2, we are calculating water balances for the following:

1. Forestland HUs on fine-textured HRAs and coarse-textured HRAs (veneer-type HRAs are not represented here)
2. Wetland HU on any HRA type.

WATER BALANCE STEP 3: DEFINE WHAT TOPOGRAPHIC POSITION AND/OR REGIONAL GROUNDWATER POSITION THE HU IS IN (FIGURE E.3)

Review Section C2.1. Topographic position and the position within the regional groundwater system of an HRA or HU will influence the values of incoming runoff and groundwater (R_{in} and GW_{in}). For the example in Section E.2, we are assuming the HUs for which the water balance is being calculated are in topographic highs or regional groundwater recharge areas (i.e., R_{in} and GW_{in} are both equal to zero).

FIGURE E.2
Water Balance Step 2:

Determine which HU the water balance is being calculated for and on what HRA type it is situated.

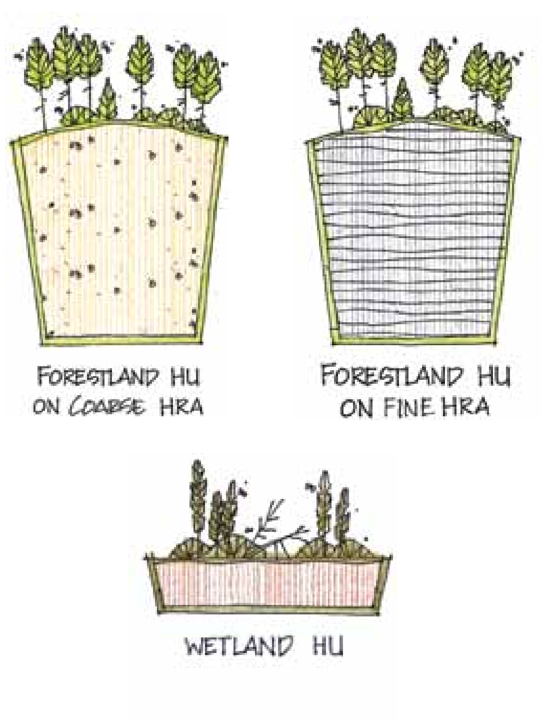
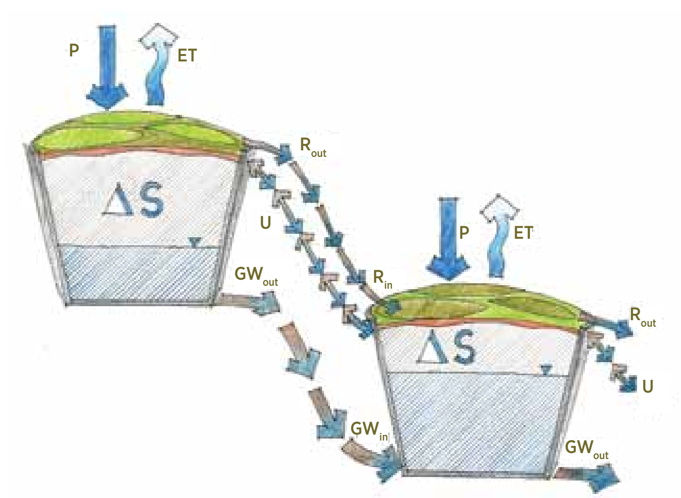


FIGURE E.3
Water Balance Step 3:

Define what topographic position and/or regional groundwater position the HU is in.



WATER BALANCE STEP 4: ESTIMATE THE AVAILABLE WATER STORAGE FOR THE UNIT IN QUESTION (GIVEN ANTECEDENT MOISTURE CONDITIONS) BASED ON THE HU TYPE AND THE TEXTURE OF THE HRA (FIGURE E.4)

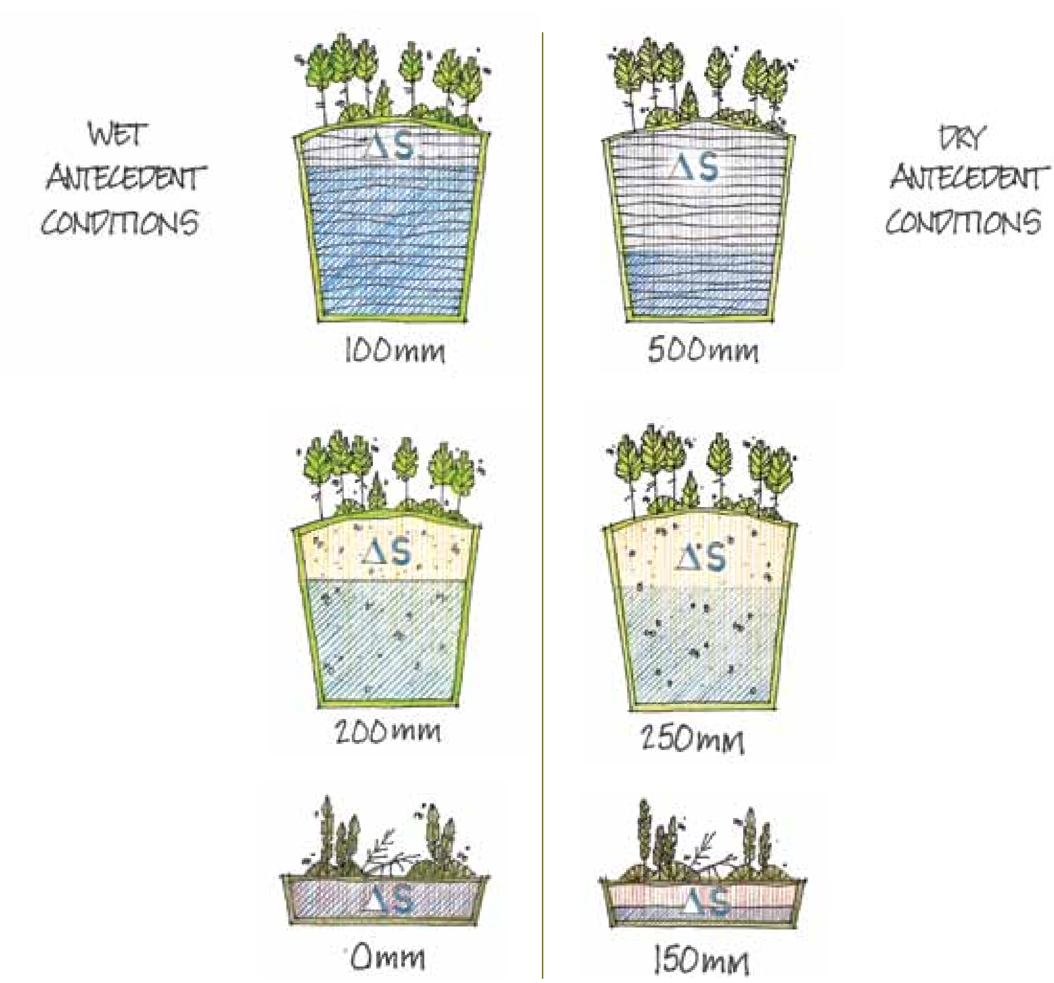
Review Section D. Different HUs or collections of HUs on an HRA have different water storage capacities, as represented here and throughout the document by deep buckets (large water storage) or shallow buckets (small water storage). The size of the bucket and the antecedent moisture conditions affect the available water storage value for the year or season the water balance for the unit is being calculated for.

Available water storage (S), is the maximum available space/storage that the HU or HRA can hold and is a function of the antecedent moisture, the HU type, and the texture of the HRA for Forestland HUs.

For the example water balance in Section E.2, we assume a depth of storage (D_{wt} = depth to water table) and a storage capacity for each HU. Also, the values reported for S are based on depth integration (i.e., there is more storage capacity at the top of the unit than at the bottom, but the value used represents an average).

FIGURE E.4
Water Balance Step 4:

Estimate the available water storage for the unit in question (given antecedent moisture conditions) based on the HU type and the texture of the HRA.



WATER BALANCE STEP 5: FOCUS ON STORAGE AND CALCULATE CHANGE IN SOIL STORAGE BASED ON MEASURED OR INFORMED ESTIMATES OF THE OTHER COMPONENTS OF THE WATER BALANCE EQUATION (FIGURE E.5)

The next steps described (Steps 5a-5e) address individual components or variables in the water balance equation. The water balance in the Boreal Plains landscape is generally dry (Section C.1) and small changes in magnitudes of the terms in the water balance make the difference between the landscape "wetting up" or "drying out."

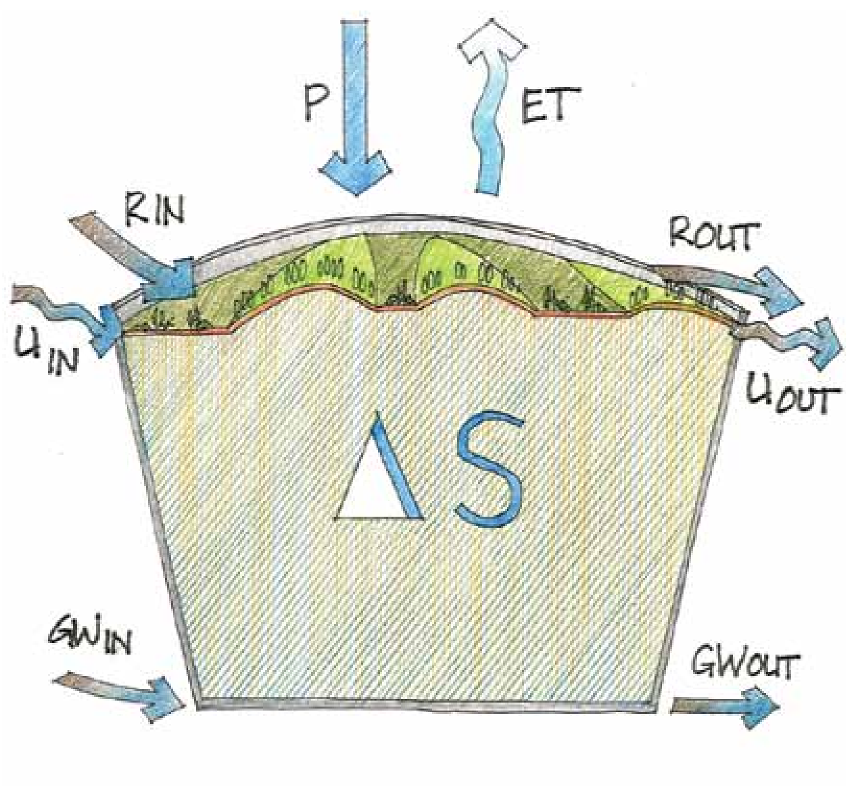
In this research, independent measures of each of the components of the water balance equation were made, including ΔS. For the example in Section E.2, the values reported/calculated reflect the typical values (order of magnitude) measured in the research study sites both on both an absolute and relative basis.

FIGURE E.5
Water Balance Step 5:

Focus on storage and calculate change in storage based on measured or informed estimates of the other components of the water balance equation.

ΔS Change in storage
P Precipitation
ET Evapotranspiration
R Runoff
GW Groundwater
U Uplift

Subscripts in and out represent movement of water into or out of a system.



$$\Delta S = P - ET + (R_{in} - R_{out}) + (GW_{in} - GW_{out}) + (U_{in} - U_{out})$$

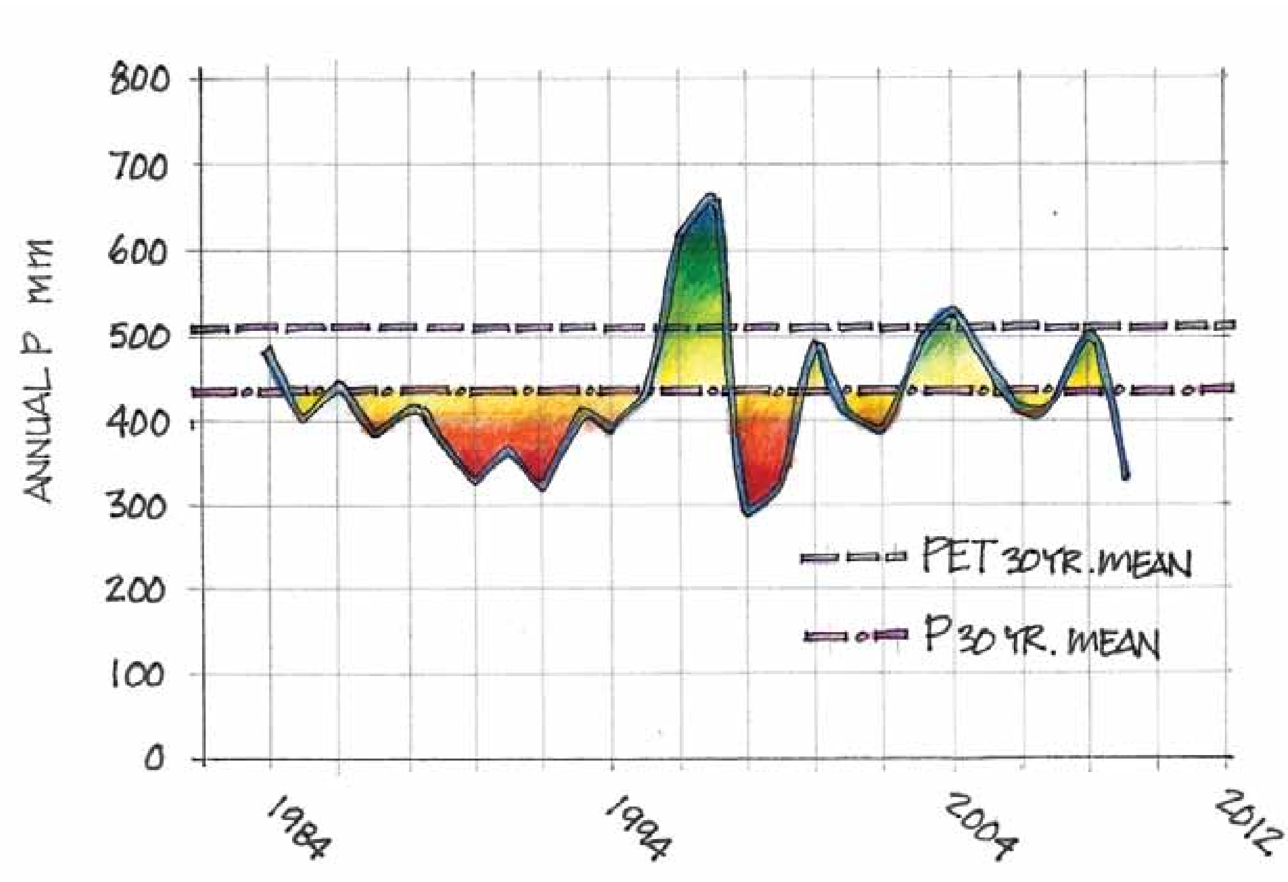
WATER BALANCE STEP 5A: ESTIMATE OR MEASURE THE PRECIPITATION FOR THE YEAR IN QUESTION (FIGURE E.6)

Recall that a core concept in the new conceptual model is that there is no year that is average. For the example in Section E.2, we use bulk annual precipitation values in combination with an explicit recognition of the climate context in which the precipitation arrives (wet antecedent or dry antecedent moisture conditions) to show the impact of long-term climate trends.

When calculating the water balance for an HRA or HU it will be necessary to conduct sensitivity analyses based on probabilities of receiving precipitation during the summer or other times of year (see Section C.1.2). For brevity, this step was omitted in the example in Section E.2. But for the cases here we assumed a bulk annual precipitation of 350 millimetres for a "dry" year, 450 millimetres for a "mesic" year, and 650 millimetres for a "wet" year. These bulk precipitation numbers are based on measurements from several locations on the Boreal Plains. The values for the wet year are those for an extreme wet cycle based on historic data for URSA, and the dry year values are for an extreme dry cycle based on historic data for URSA.

FIGURE E.6
Water Balance Step 5a:

Estimate or measure the precipitation for the year in question.



WATER BALANCE STEP 5B: ESTIMATE OR MEASURE THE EVAPOTRANSPIRATION FOR THE HU AND YEAR IN QUESTION (FIGURE E.7)

Review Sections D.3 and D.4. Evapotranspiration is one of the most important terms in the water balance equation, and the data collected over ten years of research are some of the most important numerical values obtained. Variability in the evapotranspiration value is of utmost importance in the water balance. Evapotranspiration varies enough between HU types to cause the surplus of water required to maintain wetlands in the Boreal Plains region which is dominated by a long-term moisture deficit. The values used in the example in E.2 fall within the range of magnitudes for evapotranspiration observed for the different HU types in the study areas.

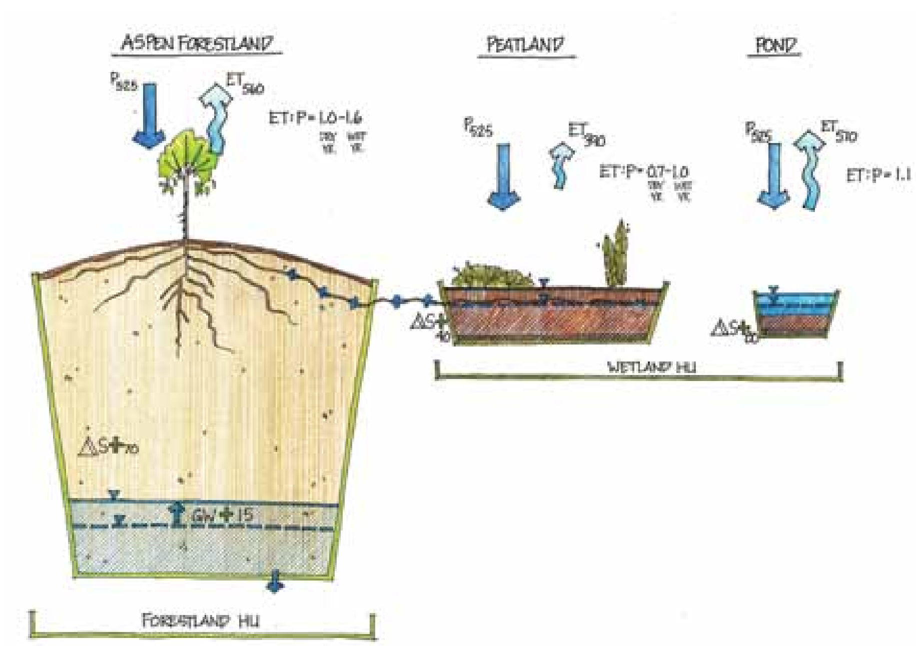
The evapotranspiration values used in the examples in Section E.2 are variable. In addition to reviewing Section D, the following material describes reasons for variability in this critical water balance component.

Evapotranspiration values for Forestland HUs are substantially higher than those of Wetland HUs (Section D). Evapotranspiration values for Forestland HUs vary substantially with soil moisture levels. How well the forest grows is directly linked to evapotranspiration. Growth is also a function of whether or not the forest was water-stressed during the previous year (dry antecedent moisture or wet antecedent moisture), and of whether or not sufficient moisture is provided in the year in question (which is a function, in turn, of precipitation levels the year the water balance is being calculated for, plus the texture of the HRA).

- In a dry year preceded by dry years, evapotranspiration drops, as the plants cannot transpire water they cannot access.
- In an average year, evapotranspiration goes up but the plants are still experiencing a moisture deficit (ET < P).
- In a wet year, evapotranspiration for a Forestland unit is high, but not maximal, and varies based on antecedent moisture.

FIGURE E.7
Water Balance Step 5b:

Estimate or measure the evapotranspiration for the HU and year in question.



Why would evapotranspiration not be maximal in a wet year? This is because it matters when and how these large volumes of water are received by the ecosystem (Section C.1). Wet years are often characterized by high intensity summer storms preceded by high snow packs. This type of moisture can exceed the capacity of the forest floor to accept it, and so can run off. Thus, in wet years, not all water from precipitation is available to plants. But plants require water every day of the growing season and will tap into other sources (U_{in}) between rains and early in the season before the soil "buckets" fill.

Coarse-textured materials cannot supply water to the plant roots quickly enough. Often, the excess water received in wet years drains past root zones to form groundwater recharge. Hence, evapotranspiration on coarse-textured HRAs is slightly lower than fine-textured HRAs.

Evapotranspiration values for Wetland HUs also vary substantially with soil moisture levels, but the following points should be noted (Section D.3):

- Evapotranspiration is less than precipitation for Wetland HUs, which means these units are a source of water in the landscape, except when open water is present.
- Evapotranspiration does not vary as much across HRA types for Wetland HUs as it does for Forestland HUs. Regardless of the HRA type on which a Wetland HU is found, these HUs are characterized by high water tables, minimal water table fluctuation, and similar vegetation. These attributes, together, result in evapotranspiration being low and relatively non-variable for Wetland HUs across all HRA types.

A component of evapotranspiration is the "new" term, U, reported in this water balance equation. U stands for "uplift" and represents water moving into or out of an HU via the aspen root "pipeline."

While actual values of U were not measured in research synthesized for this report, extensive evidence was compiled that demonstrated that aspen roots "pump" water out of Wetland HUs (Section D.4). This is a physical manifestation of the hydrologic connectivity discussed in Section D.5.

The U value is considered as "additional" to the measured evapotranspiration terms since it is speculated that without this water source, coarse-textured materials would drain incoming water more rapidly than plants could take it up. Often the excess water received in wet years drains past the root zone to form groundwater recharge. Without additional water input to the Forestland HUs, the plants will be more stressed and evapotranspiration will drop. As well, without this output from the Wetland HUs, dry-down would not occur because of the water-conserving properties of these units.

The ratio of Forestland HU U_{in} to Wetland HU U_{out} is a function of either:

a) The perimeter to surface area ratio of the Wetland HU (if the water balance is being calculated for an HU)
b) The ratio of the amount of Forestland HU to Wetland HU in an HRA (if the water balance is being calculated for an HRA).

If a Wetland HU is too small relative to the surrounding Forestland HU, it will dry out because the forestland can access or use all the water via the aspen root "pipeline." In this example we assume the Forestland HU is twice the size of the Wetland HU. Thus, it becomes evident that even when calculating the water balance for an individual HU one must consider its context with respect to the other HUs.

For the example water balance in Section E.2 it is assumed that evapotranspiration values for Forestland HUs reflect mature aspen stands. In Forestland units, U_{out} is always zero and in Wetland HUs, U_{in} is always zero.

WATER BALANCE STEP 5C: ESTIMATE OR MEASURE RUNOFF FOR EACH UNIT FOR THE YEAR IN QUESTION BASED ON THE POSITION OF THE UNIT IN THE LANDSCAPE

We must consider water running "into" (R_{in}) a unit or HRA as well as water running "off" (R_{out}). The magnitude of terms R_{in} and R_{out} are a function of the:

- Location of the HU or HRA in the landscape
- Type of HU
- Type of HRA

For the examples in Section E.2 we assume the HUs for which the water balance is being calculated are in topographic highs and, in turn, R_{in} is thus assumed to be zero in all cases.

If the HU (Forestland or Wetland), or the HRA for which the water balance is being calculated is located in a topographic low or a regional groundwater discharge area, the R_{in} value can be very high.

For any unit in a low-lying topographic position, the R_{in} value is predominantly the R_{out} accumulated from the total area of linked Wetland HUs above the unit or HRA in most years (Sections D.4 and D.6). When Wetland HUs are isolated this value can be small; when they are highly networked this value is very large. Similarly, when lakes and streams are linked to highly networked Wetland HUs, the R_{in} for the lake or stream (often termed the "effective catchment area") is the total area of linked Wetland HUs above it during most years.

It is only every 20 years or so that the Forestland HUs in a topographic high contribute any R_{in} to lower lying units (Sections C and D.4).

Variability in this general trend is observed based on HRA type. For Wetland HUs in low topographic positions on coarse-textured HRAs, the R_{in} term is comprised of the:

- R_{out} accumulated from the total area of the linked Wetland HUs above it in most years
- R_{out} from the Forestland units above it once or twice every 20 years when in a regional groundwater discharge area
- The GW_{out} of the Forestland HUs "above" it in the groundwater system which becomes the R_{in} or GW_{in} for the Wetland HU in question in most years

For Wetland HUs in low topographic positions on fine-textured HRAs, the R_{in} is predominantly comprised of:

- R_{out} accumulated from the total area of linked wetland HUs above it in most years

and then once or twice every 20 years it also receives

- R_{out} from the Forestland HUs above it (runoff return periods for Forestland HUs in this region are on the order of 20 years—see Sections C and D.4)

For Wetland HUs on veneer-type HRAs, the R_{in} is:

- R_{out} accumulated from the total area of linked Wetland HUs above it in most years
- The R_{out} from the Forestland units above it once or twice every 20 years
- The GW_{out} of the Forestland units "above" it in the groundwater system which becomes the R_{in} or GW_{in} for the Wetland HU in question in most years

There is almost always some R_{out} for Wetland HUs even in low precipitation years preceded by dry antecedent conditions. This is because wetlands have a high water table and are typically frozen late into the year and any snowmelt or rain will run off the ice (Section D.3).

For the example water balance in Section E.2 it is assumed that the HUs in question were in topographic highs or in regional groundwater recharge positions. Therefore, $R_{in} = 0$ in all cases.

WATER BALANCE STEP 5D: MEASURE OR INFER GROUNDWATER TERMS (GW_{IN} AND GW_{OUT}) FOR THE YEAR IN QUESTION BASED ON THE POSITION OF THE HU IN THE LANDSCAPE AND THE TYPE OF HRA BASED ON ITS DOMINANT PARTICLE-SIZE CHARACTERISTICS (FIGURE E.8)

In Forestland HUs on fine-textured HRAs there is little, but always some, groundwater recharge (hence the use of GW_{out} = 1 millimetre in the example in Section E.2).

In Forestland HUs on coarse-textured HRAs there is substantial groundwater recharge (GW_{out}), the magnitude of which is a function of actual HRA particle-size characteristics, soil depths, and rainfall timing and intensity.

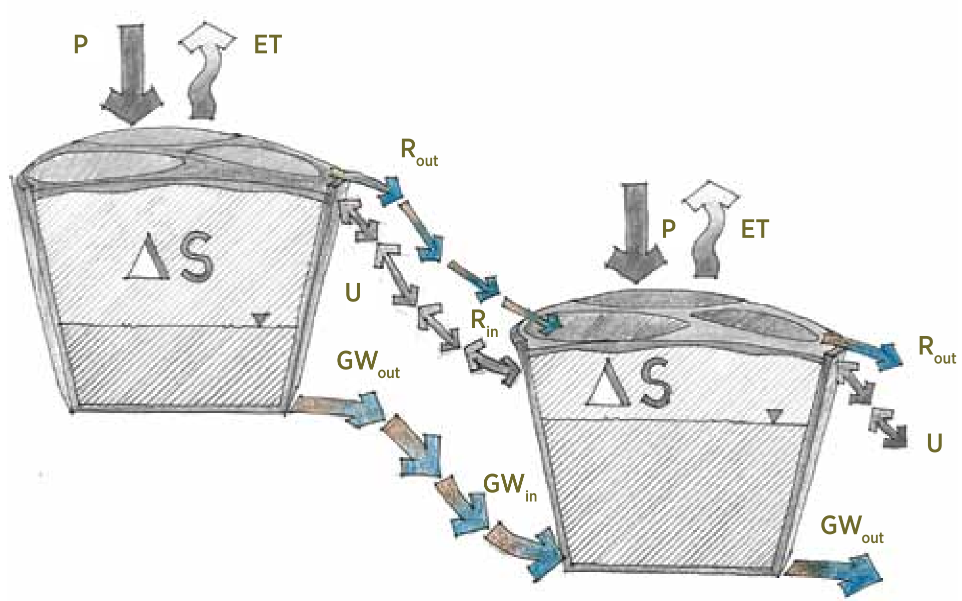
In Wetland HUs there is a small amount of GW_{out} but this is constrained by the Wetland HU characteristics (Section D.3).

It must also be noted that there will be time lags in the response of groundwater as a function of climate cycle and HRA type (Section C.1.6). This is particularly important when trying to calculate a "salt balance" in conjunction with a water balance. The interaction of climate cycles with the geology results in time lags in hydrologic response and, hence, time lags in flushing of compounds of interest. Consideration of antecedent moisture conditions is also important in Step 5d, but the length of time that one must "look back" is longer if one is trying to project the GW_{in} and GW_{out} terms and flushing for larger-scale systems.

For the example in Section E.2 it is assumed the HU is in a high topographic position, or high in the groundwater regime. Therefore, GW_{in} is always zero for both Forestland and Wetland HUs. However, in lower topographic positions or HUs lower in the groundwater regime, particularly in coarse-textured HRAs, GW_{in} can make a substantial contribution to the water balance of Wetland and Forestland HUs. The example in E.2 illustrates potential values for groundwater for two types of HRAs—fine- and coarse-textured.

FIGURE E.8
Water Balance Steps 5c and 5d:

Estimate or measure runoff and groundwater for each unit for the year in question based on the position of the hydrologic building block in the landscape and the type of HRA.



WATER BALANCE STEP 5E: RUN SENSITIVITY TESTS GIVEN VARIABLE PERIODICITY OF PRECIPITATION OR CLIMATE SCENARIOS (FIGURE E.9)

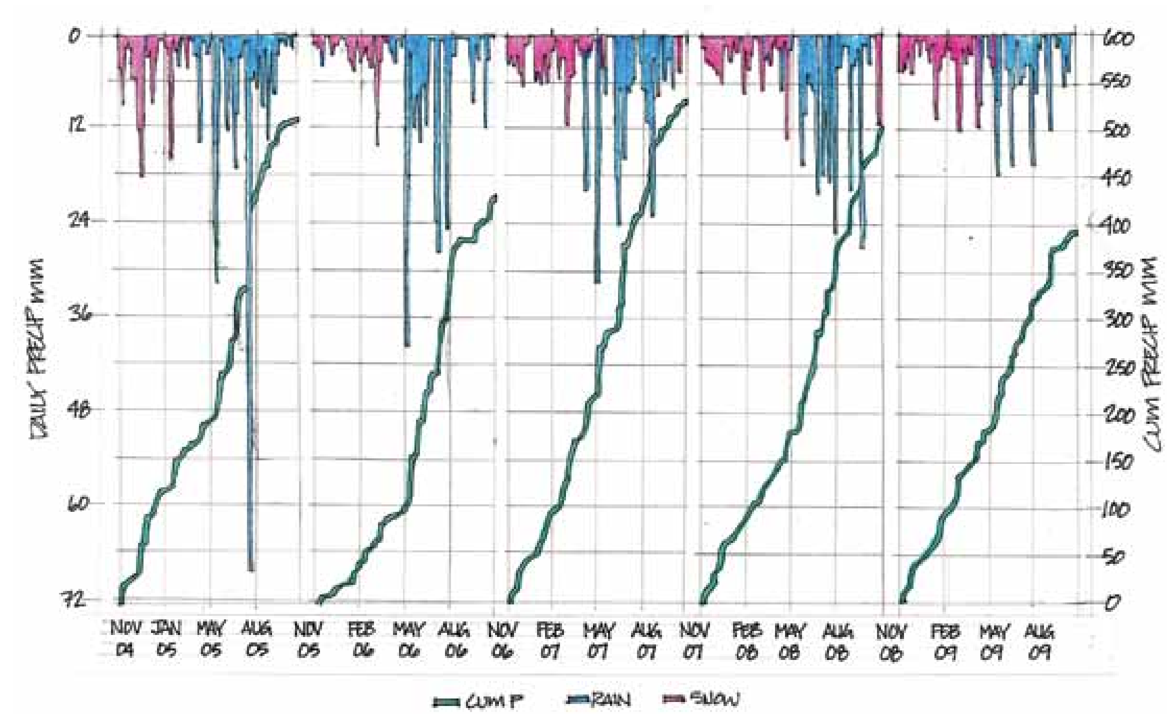
In general, the Boreal Plains region has characteristic rainfall patterns (small-size and low-intensity events) with most of the precipitation received in the summer growing season (season of highest evapotranspiration). Thus, most of the available precipitation is used by the plants. However, precipitation variability affects the water balance (Section C.1). When trying to understand historic hydrologic response it is helpful to know the periodicity of precipitation events since they affect how much water is available for moving around the landscape (thus affecting the water balance for each of the HUs) from one year to the next.

As a starting point for applying Step 5e, assume that a larger proportion of the moisture in the year being studied comes as large snowmelt or spring or fall rains (when there is no evapotranspiration) rather than during summer when evapotranspiration is at a maximum (the example in E.2). Then evaluate the converse situation, where minimal precipitation is received in the non-growing season.

For the example water balance in Section E.2 it is assumed that most moisture arrives during the summer. Sensitivity tests were not conducted for this example.

FIGURE E.9
Water Balance Step 5e.

Run sensitivity tests given variable periodicity of precipitation or climate scenarios. This graph illustrates the variability in volumes and distribution of precipitation over a sequence of years. This variability is important to consider when calculating water balances (Section C).



E.2

Hydrologic Building Blocks: Numerical Examples of their Water Balance Components as a Function of Position in the Climate Cycle

Figures E.10 and E.11 present "order of magnitude" example values for water balance components for the two HUs (Forestland and Wetland) of the Boreal Plains. The water balances are compared for when they reside on either a coarse-textured or a fine-textured HRA. Figure E.10 illustrates possible water balances for the HUs on the two types of HRAs under dry antecedent conditions, while Figure E.11 illustrates the potential water balance for the same HUs and HRAs under wet antecedent conditions. The arrangement of the illustrations in each figure is important: climate and antecedent moisture conditions must be considered first (left), followed by the geology (centre), with the results then informing the water balance (right).

The numbers reported here are examples. The actual and relative orders of magnitude of the numbers are based on results from the research. Numerical values for the components of the equation are reported to two significant figures and thus the equations may not balance exactly. The intent is to provide a sense of the relative changes in each component, and to provide the designer with an improved understanding of vegetated landscapes on the Boreal Plains—specifically, how climate and geology interact to affect the water balance.

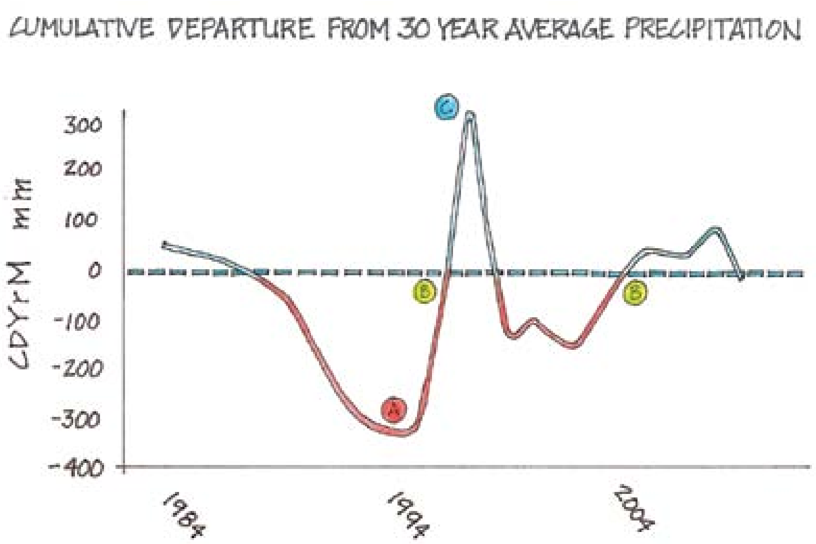
Recall that the water balance equation is:

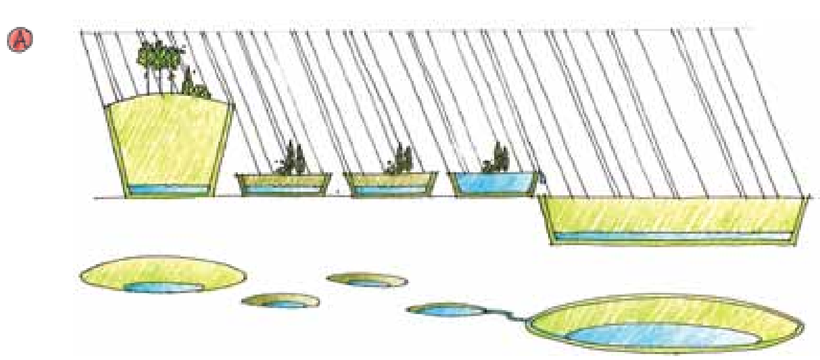
$$\Delta S = P - ET + (R_{in} - R_{out}) + (GW_{in} - GW_{out}) + (U_{in} - U_{out})$$

FIGURE E.10

Example water balances under DRY Antecedent Moisture Conditions

Starting Conditions

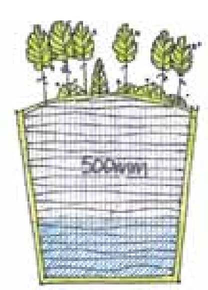




Wetland HU on any HRA: available water storage[5]:

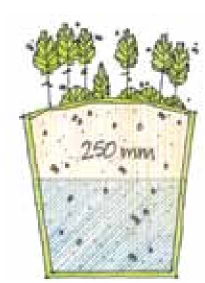
Assuming **0.5 m D_{wt}**, in a year preceded by dry antecedent moisture there is **300 mm/m of S_c**. Thus there is a ΔS_{max} of **~150 mm.**

Forestland HU on a fine-textured HRA: available water storage[5] :



Assuming 2.5 m Dwt, in a year preceded by dry antecedent moisture there is **~200 mm/m of S_c**. Thus there is a **ΔS_{max} of ~500 mm** (the bucket is empty).

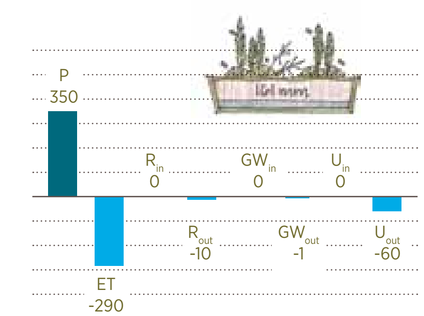
Forestland HU on a coarse-textured HRA: available water storage[5]:



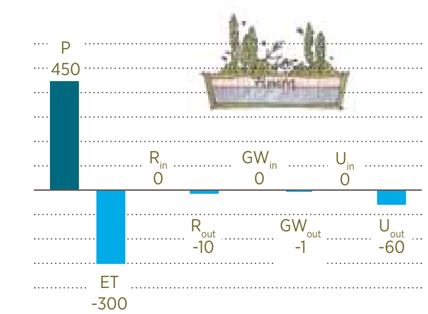
Assuming **2.5 m D_{wt}**, in a year preceded by dry antecedent moisture there is **~100 mm/m of S_c**. Thus there is a **ΔS_{max} of ~250 mm** (the bucket is empty).

Water Balance Numbers After Different Types of Years:
Recall that the water balance equation is: $\Delta S = P - ET + (R_{in} - R_{out}) + (GW_{in} - GW_{out}) + (U_{in} - U_{out})$

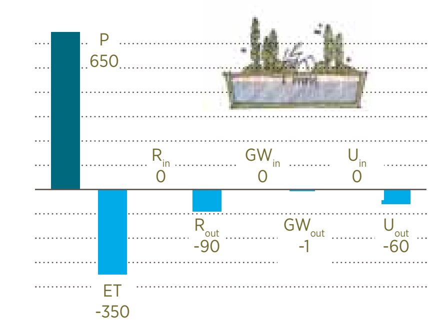
Dry year
$\Delta S = -11$ mm



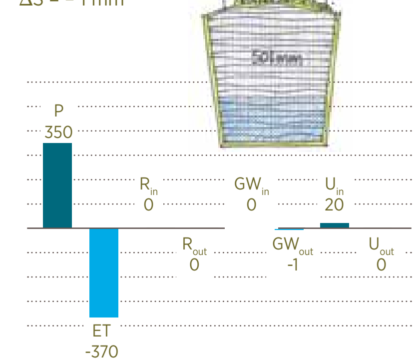
Mesic year
$\Delta S = +79$ mm



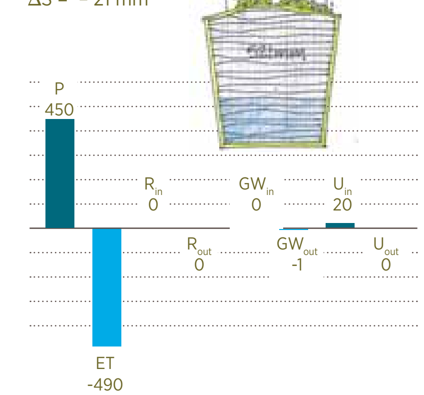
Wet year
$\Delta S = +149$ mm



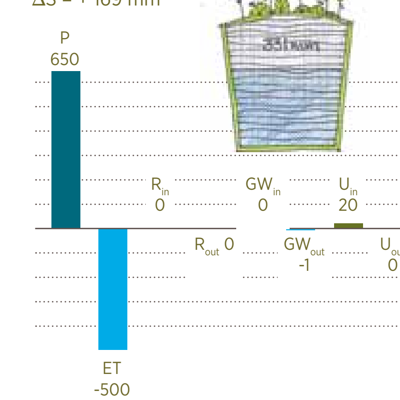
Dry year
$\Delta S = -1$ mm



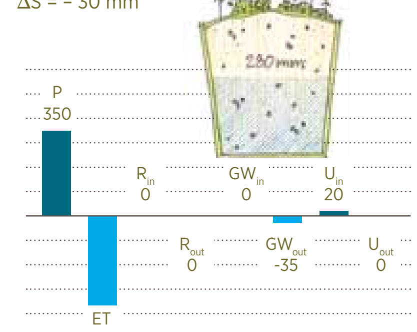
Mesic year
$\Delta S = -21$ mm



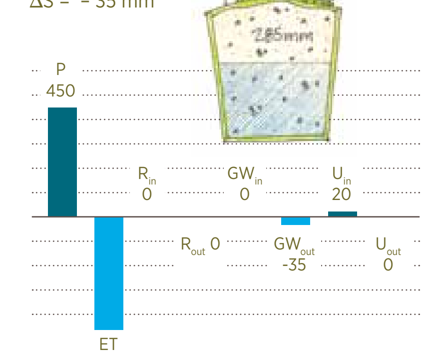
Wet year
$\Delta S = +169$ mm



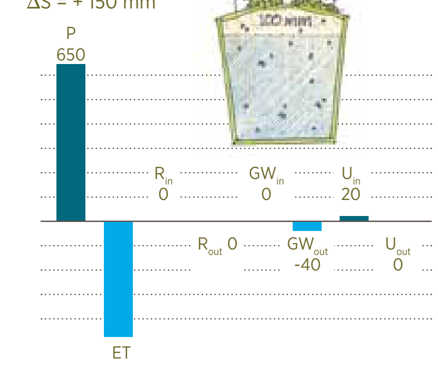
Dry year
$\Delta S = -30$ mm



Mesic year
$\Delta S = -35$ mm



Wet year
$\Delta S = +150$ mm

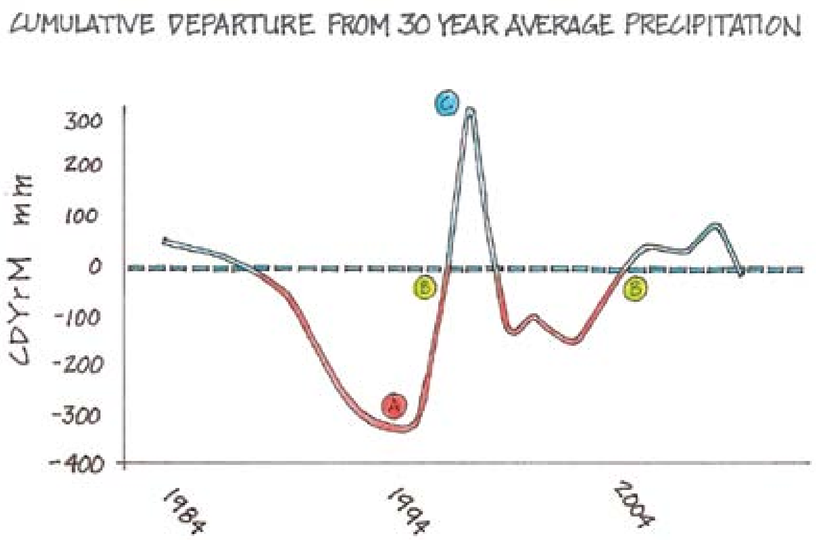


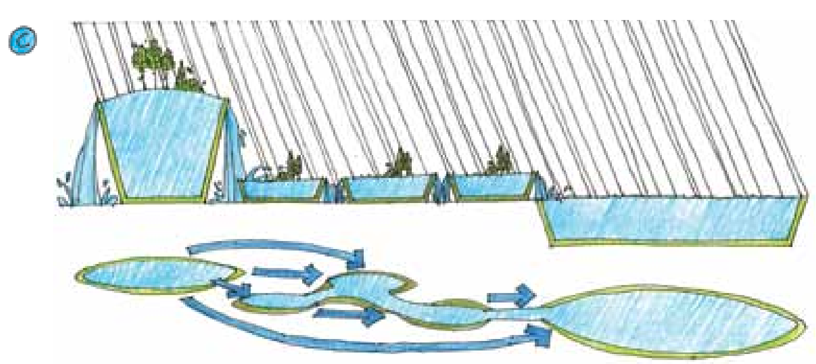
5 *$\Delta S_{max} = D_{wt} * S_c$ where:*
- *ΔS_{max} is the maximum available water storage in the HU (mm)*
- *D_{wt} is the depth to water table (m), and*
- *S_c is storage capacity (mm/m) for material above the water table. S_c is depth integrated because there is more storage capacity at the top, in the soil zone, compared to the parent material.*

FIGURE E.11

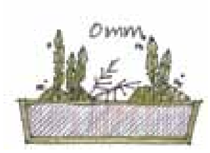
Example water balances under WET Antecedent Moisture Conditions

Starting Conditions



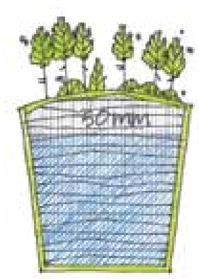


Wetland HU on any HRA: available water storage[6]:



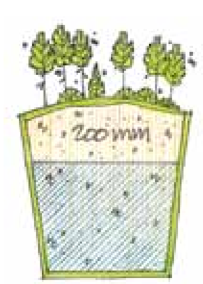
Assume **0.0 m D_{wt}**, in a year preceded by wet antecedent moisture. Although there is **~500 mm/m of S_c**. There is NO available water storage space (bucket is full).

Forestland HU on a fine-textured HRA: available water storage[6]:



Assume **0.5 m D_{wt}**, in a year preceded by wet antecedent moisture. There is **~100 mm/m of S_c**. Thus there is a ΔS_{max} of **~50 mm** (bucket is almost full).

Forestland HU on a coarse-textured HRA: available water storage[6]:

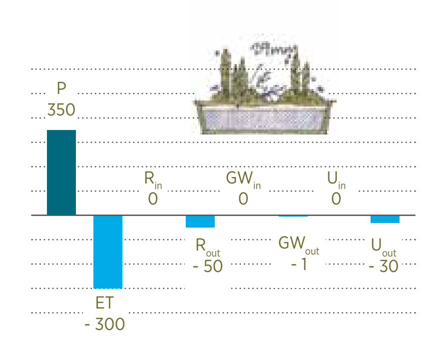


Assume **0.5 m D_{wt}**, in a year preceded by wet antecedent moisture. There is **~100 mm/m of S_c**. Thus there is a ΔS_{max} of **~50 mm** (bucket is almost full).

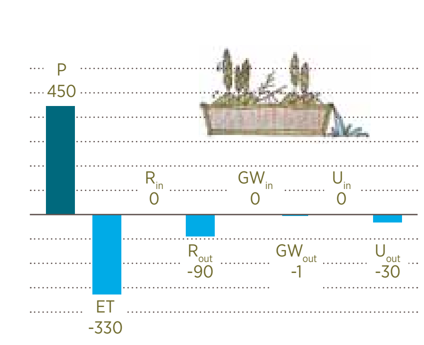
Water Balance Numbers After Different Types of Years:

Recall that the water balance equation is: $\Delta S = P - ET + (R_{in} - R_{out}) + (GW_{in} - GW_{out}) + (U_{in} - U_{out})$

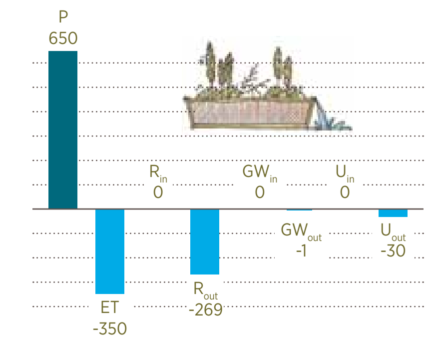
Dry year
ΔS = - 29 mm



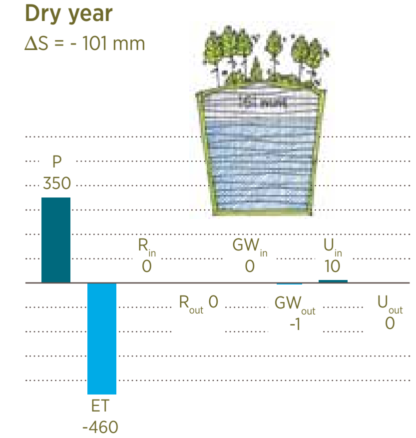
Mesic year
ΔS = 0 mm



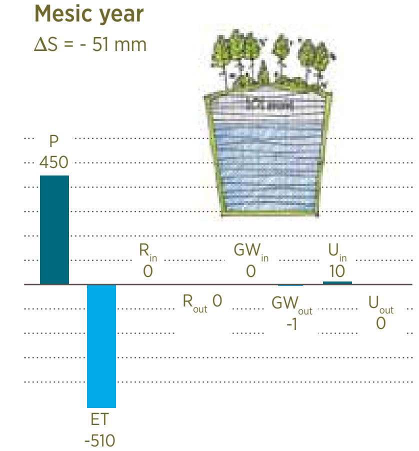
Wet year
ΔS = 0 mm



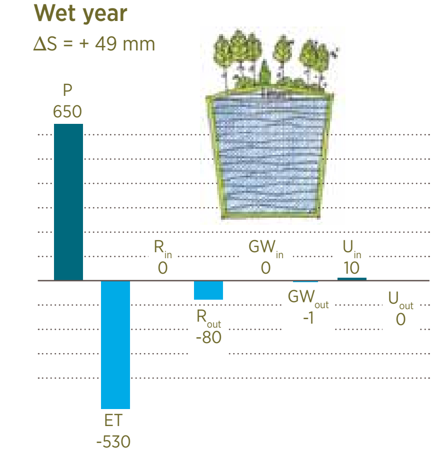
Dry year
ΔS = - 101 mm



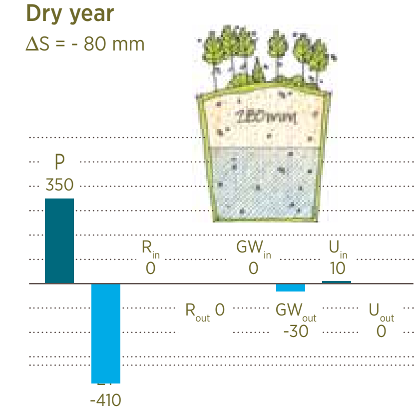
Mesic year
ΔS = - 51 mm



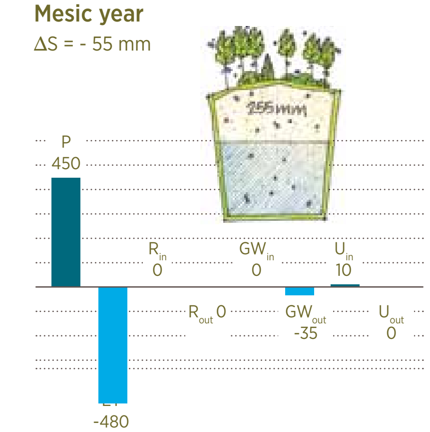
Wet year
ΔS = + 49 mm



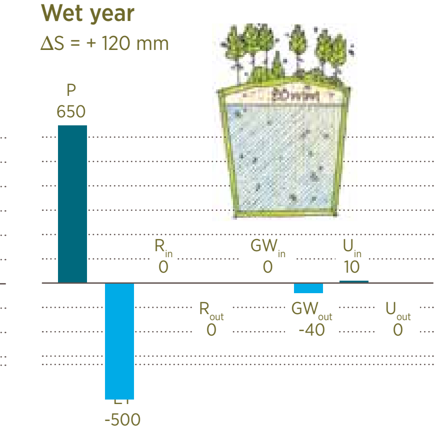
Dry year
ΔS = - 80 mm



Mesic year
ΔS = - 55 mm



Wet year
ΔS = + 120 mm



6 *$\Delta S_{max} = D_{wt} * S_c$ where:*

- *ΔS_{max} is the maximum available water storage in the HU (mm)*
- *D_{wt} is the depth to water table (m), and*
- *S_w is storage capacity (mm/m) for material above the water table. S_c is depth integrated because there is more storage capacity at the top, in the soil zone, compared to the parent material.*

E.3

Using the Conceptual Model: Designing a Reconstructed Landscape

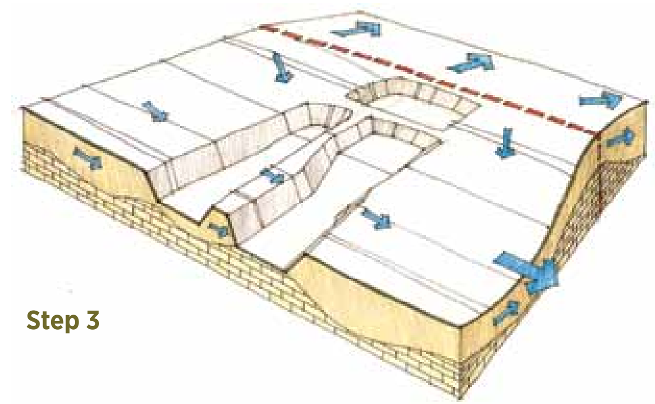
The new conceptual model for water flow in Boreal Plains landscapes can be applied to reconstructed systems. There are several factors to consider when attempting to understand the source and flow path of water at any point in a landscape or when designing water fluxes at specific locations in the reconstructed landscape. This research indicates that these factors must be addressed in a hierarchical order[7].

The hydrology of a system (on any scale, from soil to landform to landscape) can best be understood if each of the factors is considered in sequence.

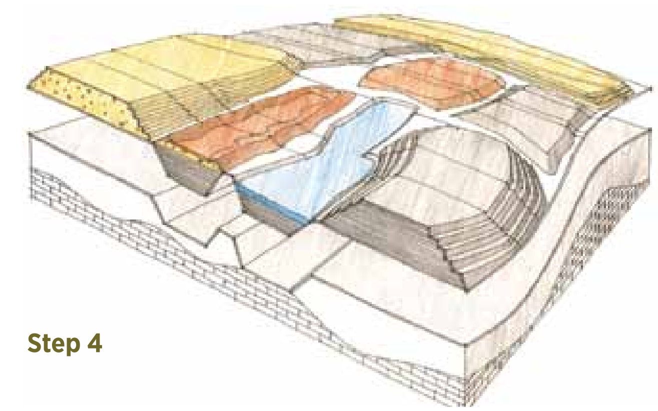
In this section, the core framework for broad scale classification of hydrologic building blocks developed from the research is interpreted for use in reconstructed landscape design by adapting the original hierarchical table[1] into a series of steps (Table E.1). Also incorporated in the "steps" are the other learnings arising from more recent phases of the research around water balances in Boreal Plains landscapes, which are analogues to the reconstructed systems. Figure E.12 is an illustrated flow chart of the suggested sequence.

[7]This hierarchical classification first appeared in Devito et al. (2005) to generalize dominant controls on water cycling and indices to define effective hydrologic response areas. It is applicable in the Western Boreal Forest, but is also applicable across continents, and is valuable when comparing results from other studies elsewhere in the region or in Canada. The items in the table should be used in the specified order when developing a conceptual framework to determine the dominance of specific components of the hydrologic cycle, and to determine the scale of interaction for a particular scenario.

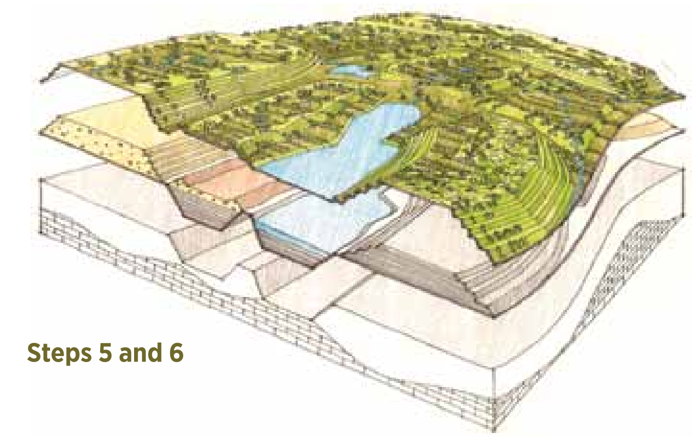
FIGURE E.12
Using the Conceptual Model to Design a Reconstructed Landscape



Step 3



Step 4



Steps 5 and 6

Recheck water balance for each HRA, landscape ← **Recheck water balance given HU selections** ← **Recheck water balance**

STEP 1 →

Climate
Explicitly recognize the overriding influence of climate.

STEP 2 →

Water Demand
Determine how much water is needed and the required residence times in different parts of the landscape through time.

STEP 3 →

Post-mining, Pre-reconstruction Surface
Determine the landscape or regional scale water "outlets" or collection points in the post-disturbance landscape. This will determine the scale of water flow systems feeding the "outlets" or collection points (e.g., streams, lakes) in question.

STEP 4 →

Macro-scale Drainage and Hydrologic Response Areas (HRAs).
Steps 4a and 4b identify the new macro-scale drainage system and or the first of the hydrologic building blocks (HRAs).

a. Identify the new macro-scale drainage system and/or assemble the "new" surficial geology (the reconstructed landforms) based on material type and hydrologic tendency. Identify the first of the hydrologic building blocks—the HRAs.
b. Determine how much and when water is needed for each HRA. Considering the hydrologic tendencies for each HRA, calculate the water balance through time for the HRA and the landscape. Determine if those balances meet the landscape-scale water volume, water quality, and timing requirements defined in Step 2

STEP 5 →

Hydrologic Units
Identify the appropriate ratio of HUs (the second type of hydrologic "building block") to overlay on each HRA.

STEP 6

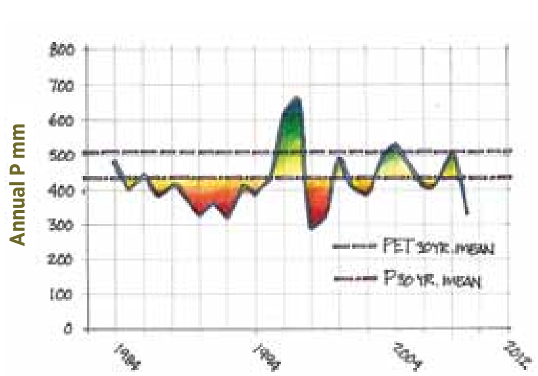
Arrangement and Connectivity of HUs
Build and connect the HUs at a range of scales on each landform.

a. Determine the appropriate arrangement and connectivity of HUs and assemble a network of Wetland and Forestland HUs at the meso- and micro-scale considering water delivery required through time for each HRA and for the landscape.
b. Construct the Wetland and Forestland HUs on each HRA incorporating the required features (e.g., clay lenses, active layers, soil depths and characteristics, proximities of HUs as discussed in Sections D.2 to D.5) as a function of location in the drainage system to enable water storage and transmission as per goals stipulated.

↓

STEP 7

Monitor to track recovery
Anticipate trajectory at reclamation certification. This step is unique to the design process.



Step 1

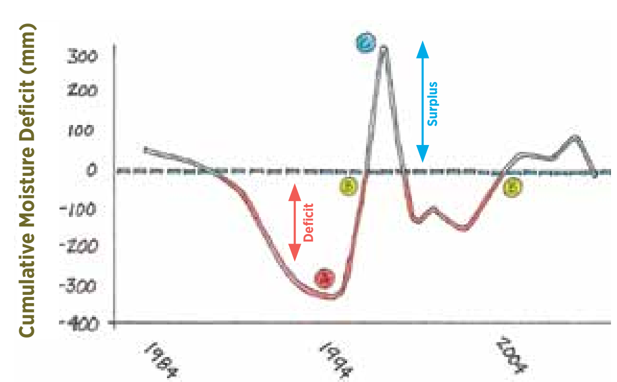


TABLE E.1

Using the Conceptual Model in the Design of a Reconstructed Landscape—How the Steps Link to the Hierarchical Factors Controlling Hydrologic Behaviour

Step	Summary of Step	Factor	Range of Factors		Scale
1	Explicitly recognize overriding influence of climate.	**A** Climate	**Dry, arid to sub-humid** • Runoff (R) poorly correlated with precipitation (P) • Storage or uptake dominates • Tendency for vertical flow	**Wet, humid (P > PET)** • Runoff (R) closely correlated with precipitation (P) • Runoff dominates • Tendency to lateral flow	**Continental to local** 1,000's of km to 10's of m
2	Determine how much water is needed, and the required residence times for water in different parts of the landscape through time.	There is no related factor. This step is unique to a design and reconstruction process			
3	Determine the landscape or regional scale water "outlets" or collection points in the post-disturbance landscape by evaluating post-mining, pre-reconstruction surfaces.	**B** Geologic material not disturbed by mining i.e., post-mining, pre-reconstruction surface	**Permeable bedrock** • Intermediate to regional flow systems • Lack of topographic control on direction of local flow • Vertical flow dominates in surface substrate	**Poorly permeable bedrock** • Characterized by local and predominantly surface flow • Topographic control on direction of local flow • Lateral flow dominates in surface substrate	**Continental to regional** 1,000's of km to 100's of km
4	a. Identify the new macro-scale drainage system and/or assemble the "new" surficial geology (reconstructed landforms) based on material type and hydrologic tendency. b. Determine how much water is needed, and when, for each hydrologic response area (HRA).	**C** Reconstructed Landforms or Hydrologic Response Areas (HRAs)	**Deep substrates** • Intermediate to regional flow systems **Coarse texture** • Vertical flow • Deeper sub-surface flow **Spatially heterogeneous deposits** • Complex groundwater systems • Groundwater flow modelling important	**Shallow substrates** • Local flow most probable **Fine texture** • Lateral flow • Depression storage, surface/shallow sub-surface flow **Spatially homogeneous deposits** • Simple groundwater flow systems • Surface flow modelling important	**Regional to local** 100's of km to 10's of m
5	Identify the appropriate ratio of hydrologic units (HUs) to overlay on each hydrologic response area (HRA)	**D** Soil Type and Depth	**Forestland mineral soil** • Sub-surface flow dominates • Slow flow generation (matrix flow), and macropore flow **Storage** • Deeper with larger water storage potential **Transpiration** • Deep roots access stored water • Actual ET ≥ PET	**Wetland organic soils** • Return flow, surface overland flow pathways dominate • Quick flow generation (return/saturation overland flow) **Storage** • Shallower with small water storage potential • Lower specific yield of organics and compression leads to saturation **Transpiration** • Shallower roots limit access to stored water • Actual ET < PET	**Local to regional** Metres to 1000's of m
6	a. Determine the appropriate arrangement and connectivity of HUs and assemble a network of these at the meso and micro scale. b. Construct the Wetland and Forestland HUs on each HRA incorporating the required features as a function of location in the drainage system	**E** Topography and Drainage Network	**Gentle slope** • Disorganized, inefficient drainage networks • Large groundwater recharge • Small, variable runoff yield	**Steep slopes** • Organized, efficient drainage networks • Small groundwater recharge • Large, uniform runoff yield	**Local to regional** 10's of m to 1,000's of m
7	Monitor to track the recovery trajectory and to anticipate the trajectory at reclamation certification.	There is no related factor. This step is unique to the design and reconstruction process			

STEP 1: EXPLICITLY RECOGNIZE THE OVERRIDING INFLUENCE OF CLIMATE

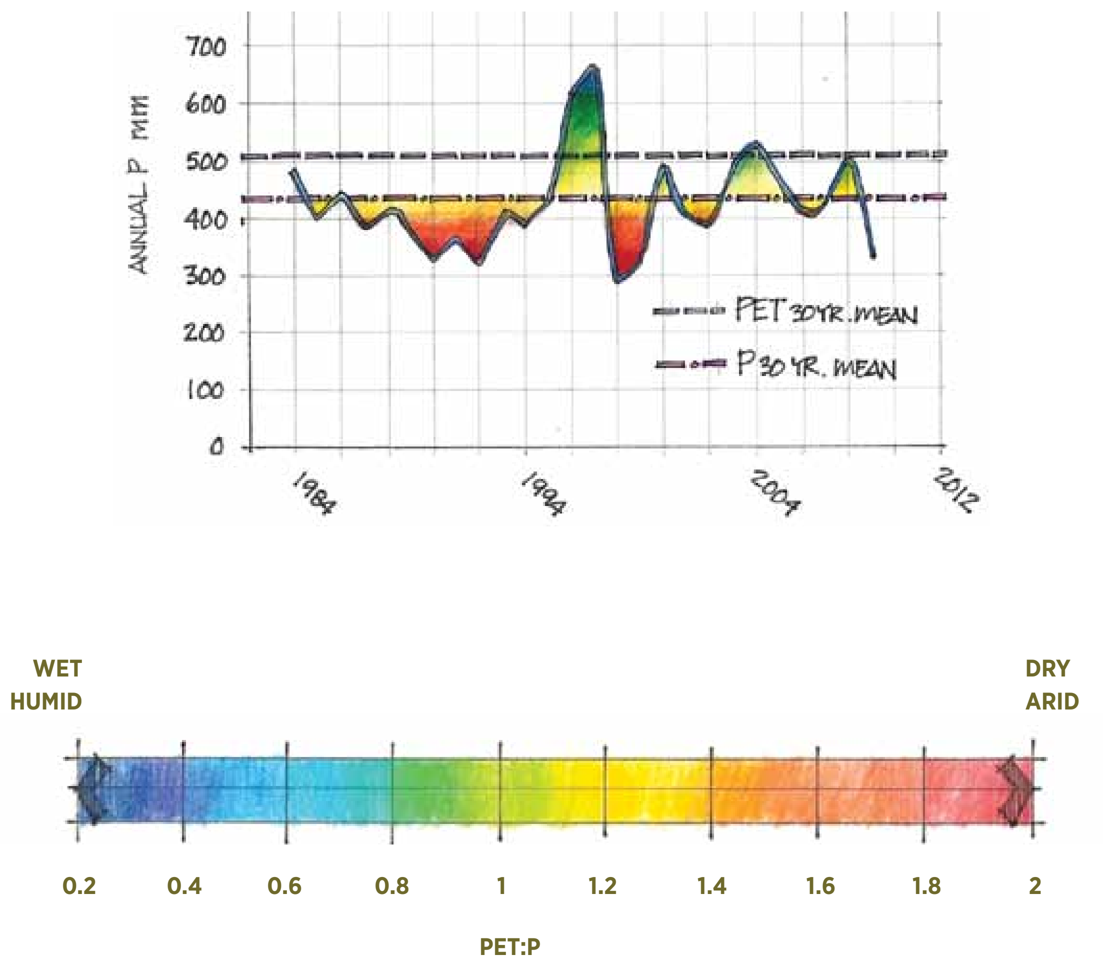
This step is related to Factor A in Table E.1.

In the oil sands region the climate is typified by a long-term potential water deficit, coupled with pronounced annual and decadal water input cycles (Section C.1.2 and C.1.3).

This frames the overarching design goal to effectively store and supply water to ecosystems through the extended drought cycles and to transmit water effectively in the periodic wet cycles—that is, to re-establish hydrologic functionality or equivalent capability.

FIGURE E.13
Using the New Conceptual Model Step 1:

Explicitly recognize the overriding influence of climate.



STEP 2: DETERMINE HOW MUCH WATER IS NEEDED AND THE REQUIRED RESIDENCE TIMES IN DIFFERENT PARTS OF THE LANDSCAPE THROUGH TIME

This step is unique to the reconstructed landscape design process—that is, it was not found in the original table (Devito *et al.* 2005), which was developed for natural systems.

Understanding how much and what quality of water is required and where and when it is needed (locally and regionally) both during operations and through closure, forms the basis for the next steps. There are trade-offs to be considered given identified short- and long-term eco-hydrologic goals. Landscapes dominated by Forestland HUs will produce less fresh surface water, with runoff return periods of greater than 20 years, while landscapes dominated by highly networked Wetland HUs will produce more consistent fresh surface water for annual runoff.

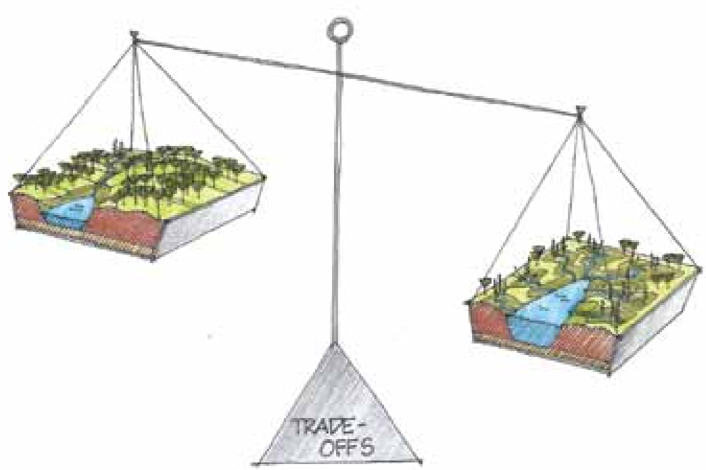
Understanding the water balances for the range of landscape components (HRAs and HUs), as well as for the integrated final landscape through time, is essential to understanding where on the recovery trajectory a reconstructed landform or landscape is at any given point in time. It is necessary to continually "check back" on the water balances after each of the subsequent steps to confirm if the eco-hydrologic goals can or are being met (see flow chart, Figure E.12)

As examples, goals might include:

- Shorter-term: An appropriate balance of fresh water and process-affected seepage water entering the end pit lake to optimize water-treatment processes
- Longer-term/broader scale: Water of sufficient quantity and quality received on the required cycles to meet both ecological goals of 1) white sucker and canvas back duck habitat in X hectares of wetlands, streams, and lakes including the completed end pit lake and 2) X hectares of productive, diverse boreal forest

FIGURE E.14
Using the New Conceptual Model Step 2:

How much water? Where? When?



STEP 3: DETERMINE THE LANDSCAPE- OR REGIONAL-SCALE WATER "OUTLETS" OR COLLECTION POINTS IN THE POST-DISTURBANCE LANDSCAPE. THIS WILL DETERMINE THE SCALE OF WATER-FLOW SYSTEMS FEEDING THE "OUTLETS" OR COLLECTION POINTS (E.G., STREAMS, LAKES) IN QUESTION.

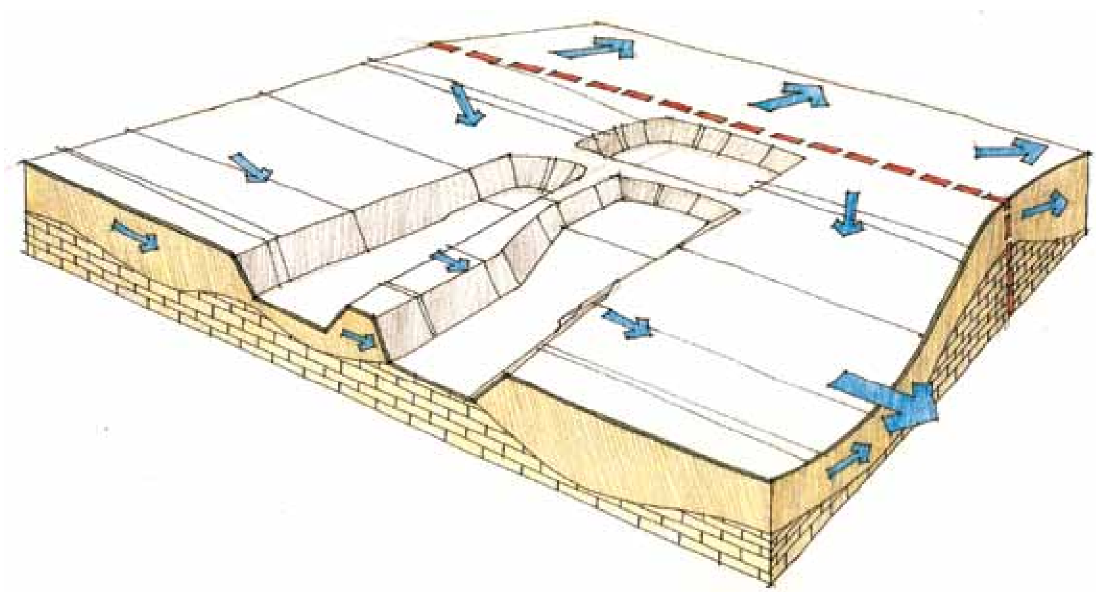
This step is related to Factor B in Table E.1.

In the original framework, Factor B was "bedrock." For the purposes of landscape reconstruction, the "bedrock" in this step, which defines large regional-scale flow, is the geologic material not disturbed by mining over which the "new" surficial geology (HRAs and HUs) will be assembled. In some cases, it may be glacial materials; in other cases, it may be limestone or oil sand. Understanding the topography and character of the geologic material not disturbed by mining defines regional flow and will help in understanding the reconstructed groundwater systems.

FIGURE E.15

Using the New Conceptual Model Step 3:

Determine the landscape- or regional-scale water "outlets" or collection points in the post-disturbance landscape. This will determine the scale of water-flow systems feeding the "outlets" or collection points (e.g., streams, lakes) in question.



STEPS 4A AND 4B: IDENTIFY THE NEW MACRO-SCALE DRAINAGE SYSTEM AND/OR IDENTIFY THE FIRST OF THE HYDROLOGIC BUILDING BLOCKS—THE HRAS

These steps are related to Factor C on Table E.1.

a. Identify the new macro-scale drainage system and/or assemble the "new" surficial geology (the reconstructed landforms) based on material type and hydrologic tendency. Identify the first of the hydrologic building blocks—the HRAs.

The reconstructed landforms, or subsections of them, are considered to be HRAs and can be grouped based on material type (coarse: sands, fine: clays, veneer).

By defining the HRAs in the reconstructed landscape, and ensuring a focus on understanding the water storage capacity of each one, the dominant hydrologic tendencies for the HRAs and, hence, for the landscape, can be understood for the next stages of design. Ideally, HRAs are arranged in the reconstructed landscape based on knowledge of their water transmission properties so that landscape water quality and quantity goals, through time, are met.

The arrangement of the HRAs in the reconstructed landscape (the macro-scale drainage system of streams, rivers, and lakes) should be considered in light of the objectives outlined in Step 2.

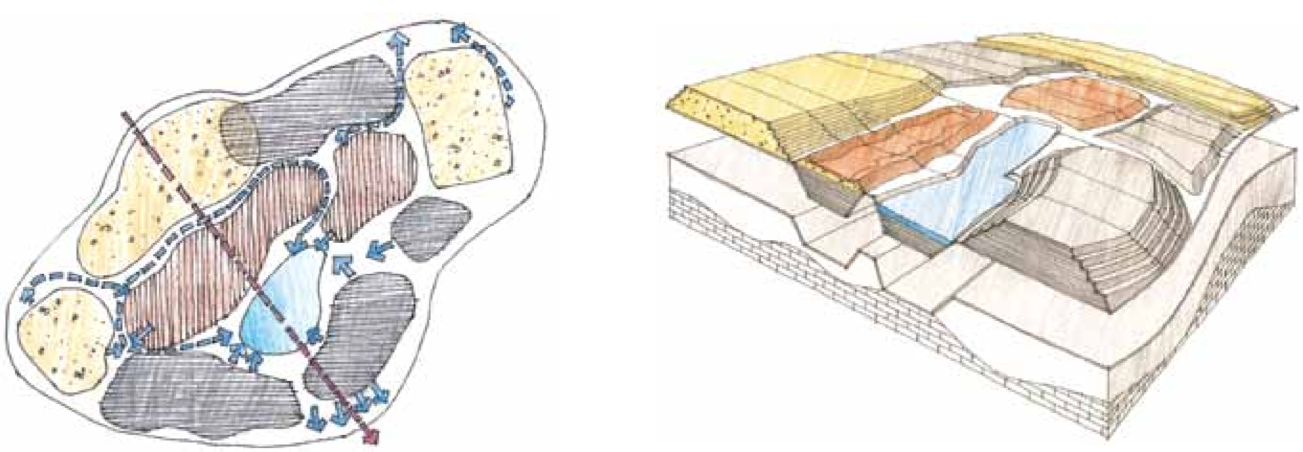
Explicitly consider, too, connections between the HRAs and, if possible, attempt to include a range of HRA size and scales of connectivity while accounting for landscape-scale water requirements. Note that the degree of linkage of this system to the micro- and meso-scale Wetland HUs (Step 6) will strongly influence periodicity and volumes of flow in the macro-scale drainage system.

FIGURE E.16

Using the New Conceptual Model Step 4a:

Identify the new macro-scale drainage system and/or identify the first of the hydrologic building blocks—the HRAs

Legend:
yellow = coarse-textured HRA
gray = fine-textured HRA
orangey/brown= veneer-type HRA



b. Determine how much and when water is needed for each HRA. Considering the hydrologic tendencies for each HRA, calculate the water balance through time for the HRA and the landscape. Determine if those balances meet the landscape-scale water volumes, water quality, and water timing requirements defined in Step 2.

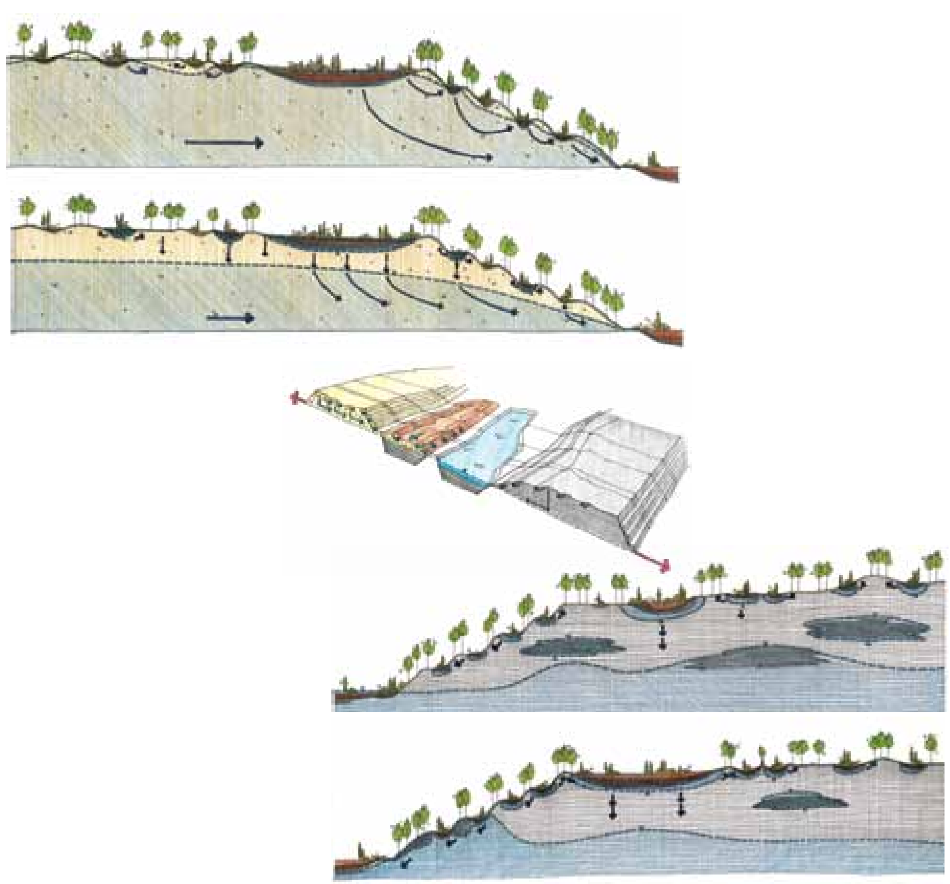
To meet landscape-scale goals, the individual and accumulated water balances for each of the HRAs must be determined. Each HRA type will have a predominant tendency for certain kinds of flow (surface flow or groundwater recharge). Ideally the hydrologic tendencies of each type of HRA will be understood early in the design phases so that the HRAs (landforms or subsections of them) can be arranged in the landscape to generally meet the stated spatial and temporal eco-hydrologic goals as defined in Step 2.

The HUs are then arranged on the HRAs (the landforms) to optimize the probability of achieving those goals (Step 5). If the general hydrologic tendencies of the HRAs are not considered early in the process, it is possible to modify them later on. That is, it is possible to modify the amounts of vertical flow (storage/ groundwater recharge) rather than lateral-surface or near-surface flow (runoff) by building different ratios of Wetland to Forestland HUs (Step 5). However, more effort will have to be expended to overcome the predominating control of the HRA material type, if that is necessary.

FIGURE E.17

Using the New Conceptual Model Step 4b:

Determine how much and when water is needed for each HRA, taking into consideration the predominant hydrologic tendencies for each HRA.



STEP 5: IDENTIFY THE APPROPRIATE RATIO OF HUS TO OVERLAY ON EACH HRA

Step 5 is related to Factor D on Table E.1

There are two types of HU on the Boreal Plains: Wetland HUs and Forestland HUs. Soils, vegetation, and soil-vegetation-atmosphere interactions (the dryness index) are unique to each. Wetland HUs are generally water "sources," except when open water predominates, while Forestland HUs are generally water "sinks" (Sections D.3 and D.4). It is possible to manage water distribution by managing the relative proportions of Wetland to Forestland HUs.

Selection of surface soils, vegetation type, and management of vegetation are functions of the Forestland and Wetland HU goals, which are linked back to the HRA goals (Step 4b) and the overarching landscape goals (Step 2).

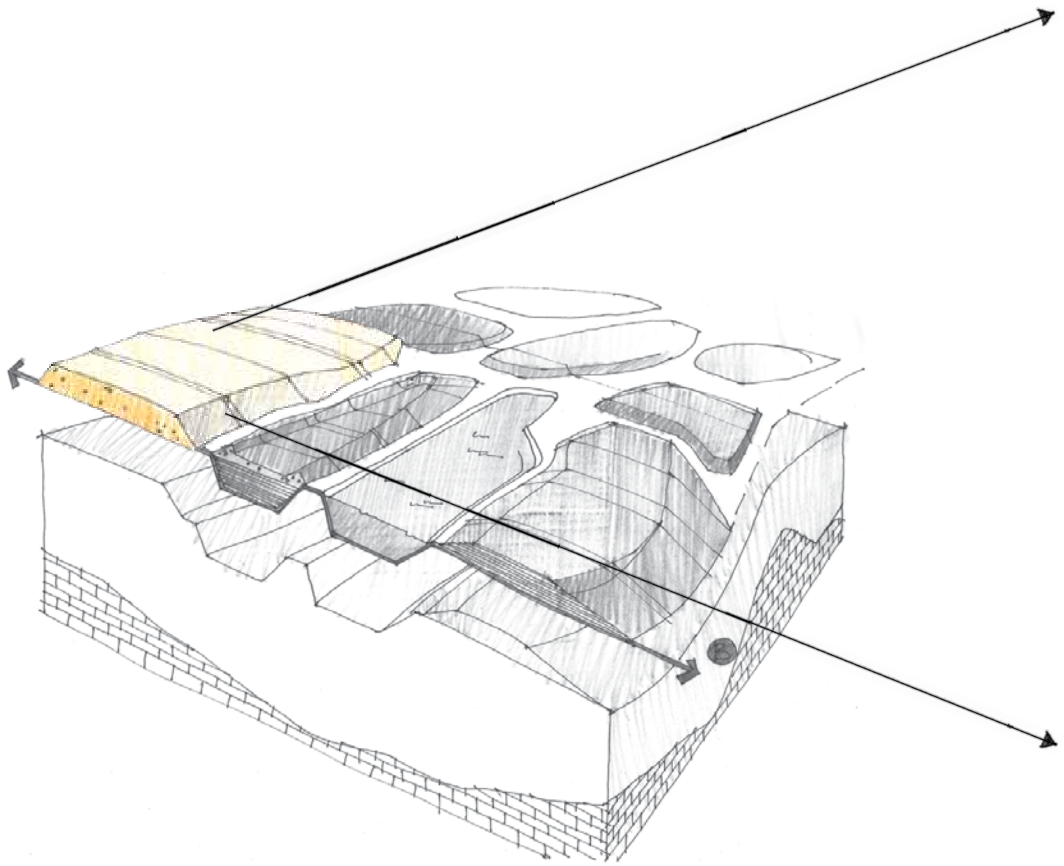
The appropriate ratio of Wetland:Forestland HUs is determined by considering the goals outlined in Step 4b and from water balance calculations for the individual and aggregated HUs for each HRA. Recall from Step 4b that although, Wetland and Forestland HUs can be created on any HRA, the hydrologic tendencies of the HRA will control the level of effort required to create the HUs. For example, it is possible to create perched Wetland HUs and, hence, "create" more surface water on coarse-textured HRAs; however, more effort will be needed to create sufficient and suitable layers (Section D.3.5) to offset the tendency of the coarse-textured HRA to have vertical drainage.

During design or when trying to understand the recovery trajectory of a reconstructed landscape it is important to conduct water balance sensitivity analyses to assess the effects of variable precipitation and antecedent moisture conditions on the chosen HUs (individually and cumulatively). See Section E.1 and E.2 for the steps and for example calculations.

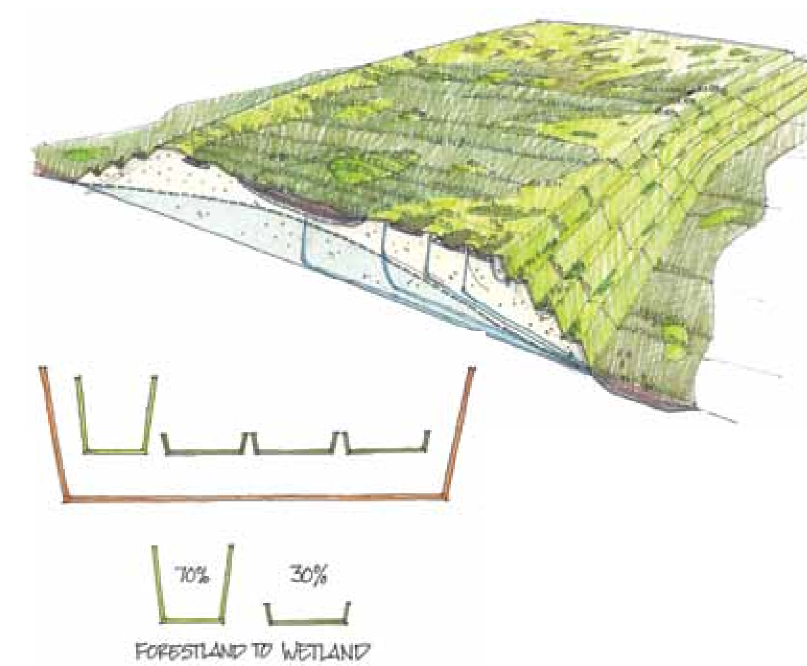
FIGURE E.18

Using the New Conceptual Model Step 5: Determine the Appropriate Ratio of Wetland to Forestland HUs to Overlay on each HRA

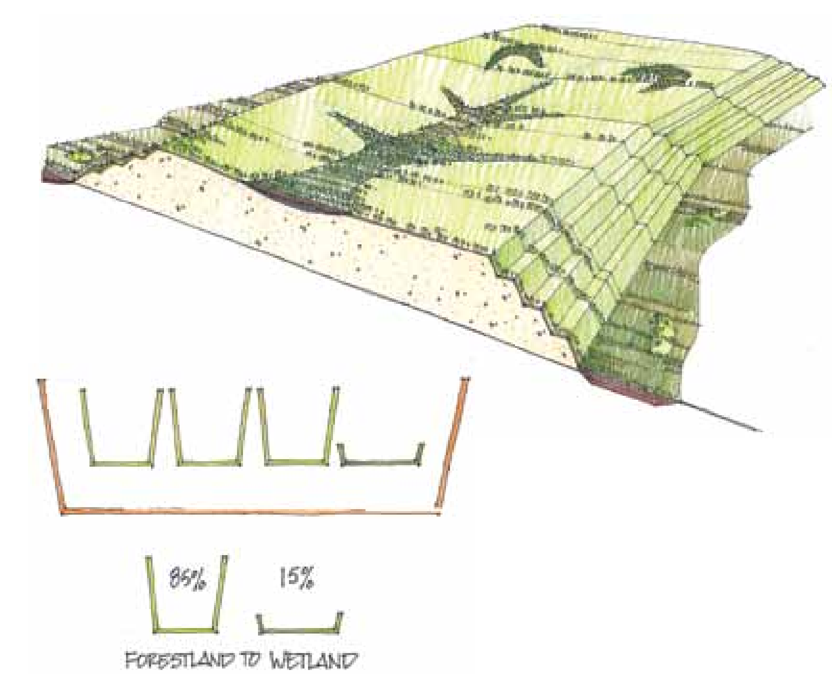
Step 5 is determined by calculating the water balance through time for each type of HU arrangement. By evaluating various proportions and distributions of Wetland:Forestland HUs on each HRA, against the water delivery goals through time, the appropriate ratio of HUs can be estimated.



Goal 1:
Abundant fresh surface water (consistent annual fresh runoff).
X m^3 of fresh water per year



Goal 2:
Substantial water storage and ground water recharge with large amounts of water delivered once or twice every 20-30 years.



STEP 6A AND 6B: BUILD AND CONNECT THE HUS AT A RANGE OF SCALES ON EACH LANDFORM

Steps 6a and 6b are related to Factor E on Table E.1.

a. Determine the appropriate arrangement and connectivity of HUs and assemble a network of Wetland and Forestland HUs at the meso- and micro-scale considering water delivery required through time for each HRA and for the landscape.

For scenarios where large amounts of surface water are desired from an HRA, connect the micro- and meso-scale Wetland HUs to the macro-scale Wetland HUs that comprise the macro-scale surface water drainage network. For scenarios when a dominance of forest and water retention is preferred, build minimal connectivity between the micro- and meso-scale wetland HUs. Recall from Section D.4 that even in forestland dominated landscapes, Wetland HUs are likely required to maintain the forests through the typically extended drought cycles. However, these Wetland HUs do not necessarily have to be connected to each other (see Section D.5). The degree of connectivity required is partially defined by the goals set out in 4b.

b. Construct the Wetland and Forestland HUs on each HRA incorporating the required features (e.g., clay lenses, active layers, soil depths and characteristics, proximities of HUs as discussed in Sections D.2 To D.5) As a function of location in the drainage system to enable water storage and transmission as per goals stipulated.

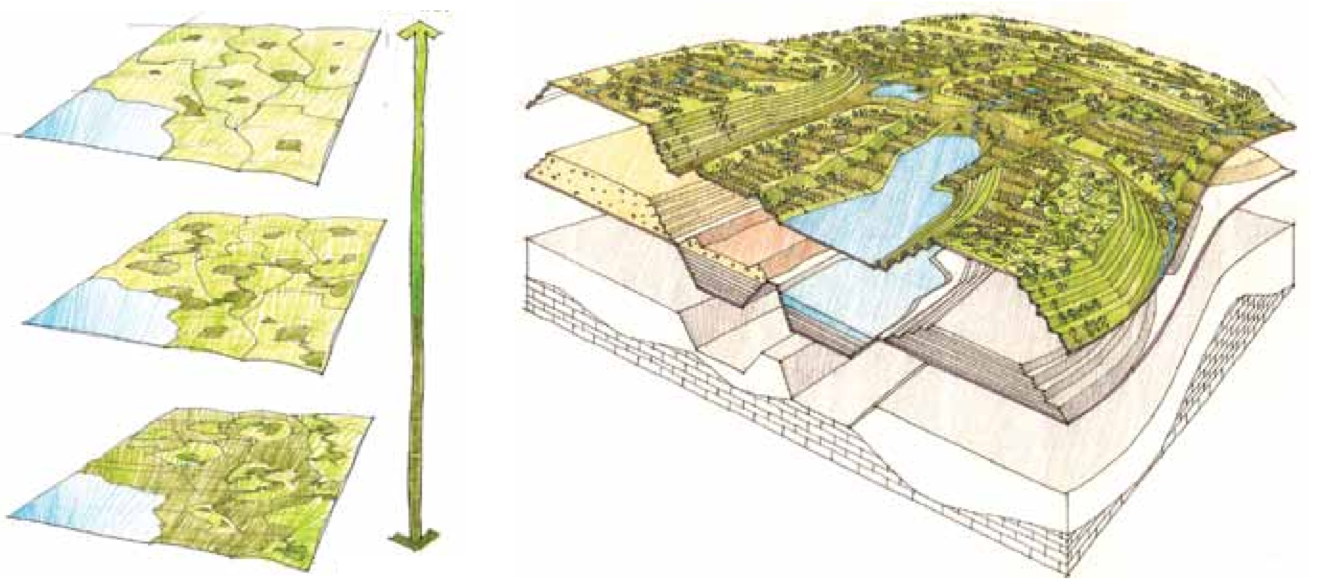
Per the process in Step 5 regarding the level of effort required to establish various HUs as a function of the HRA on which they are found, a similar consideration must be made here when considering the location of the HU in the topographic sequence. For example, creating a Wetland HU in a high topographic position on a sand-textured HRA may require use of a clay layer and additional mulch layer (see Section D.3.5) compared to building one in a regional groundwater discharge area where groundwater inputs dominate the water balance. Again, note the emphasis on considering the water balance for each HU in each landscape scenario under given climate cycles.

STEP 7: RECHECK THE WATER BALANCE FOR THE LANDSCAPE TO CONFIRM IT MEETS THE SPECIFIED GOALS, THROUGH TIME GIVEN CLIMATE PROBABILITIES AND MONITOR THE RESULTS

This step is unique to the reconstructed landscape design process.

Monitor to track the hydrologic recovery trajectory and to anticipate that trajectory at reclamation certification.

FIGURE E.19
Using the New Conceptual Model Step 6: Build and Connect the HUs at a Range of Scales on Each Landform



Publications

F

Publications

Note to reader: The research program with which each publication was associated is referred to at the end of the citation in brackets.

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As a professional courtesy, the academic authors would appreciate being notified as to how and where their work is being used, cited and implemented. An email with particulars to Kevin.Devito@UAlberta.ca or Carl.Mendoza@UAlberta.ca is sufficient.