Formation and maintenance of permanent perched wetlands in the Boreal Plain of Western Canada

by

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Abstract

Key words: wetland hydrology, peatlands, perched, sub-humid, autogenic, negative feedbacks, isolated, water generation, wetland reconstruction

The Boreal Plains Ecozone is characterized by a moisture deficit climate, as regional precipitation is less than potential evapotranspiration. Perched peatlands situated 20 m above regional groundwater have been identified as common features across the landscape in the Utikuma Region Study Area (URSA) in north central Alberta. How does an apparently isolated permanent perched wetland maintain saturated conditions in a sub-humid climate? Research was conducted at Pond Catchment 19 in the URSA on a perched wetland complex in a topographically high landscape position. Alternative hypotheses were evaluated by examining the wetland water budget and geologic setting. Results confirmed the study site to be an autogenic wetland, isolated from allogenic water sources. Wetland precipitation was greater than evapotranspiration. A clay rich confining layer underlies the wetland, maintaining the perched water table; the adjacent upland forest is consistently unsaturated. Autogenic processes maintaining wetland conditions were tested by examining increased precipitation, decreased evapotranspiration and low storage. Snow accumulation and through fall data indicated that decreased wetland interception compared to adjacent forest positively impacted the wetland water budget. Shading and sheltering, prolonged ablation, persistence of frozen soil, deep peatland water table and water isotopic signatures inferred decreased wetland evapotranspiration. Low storage in the margin swamp and decomposed lower peat promoted frequent saturation through rapid water table response, leading to consistent soil anoxia. This research highlights the importance of autogenic processes and soil textural layering in maintaining a permanent isolated wetland in a regional moisture deficit. Radiocarbon dating of basal organics indicated the peatland initiated ~4000 years ago in a climate similar to present. Peat appeared to advance northward over the next 2000 years, via the process of paludification. Since the study perched wetland does not rely on ground or surface water inputs, it may be implied that similar wetlands could be constructed in any landscape position. Incorporating perched wetlands into watershed reconstruction could provide an important fresh water source for headwater streams and surrounding forest vegetation.

Dedication

To my parents and partner Joshua,

I could not have completed this degree without you.

Thank you for everything.

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Chapter One – Conceptualization of permanent perched wetlands in the sub-humid Western Boreal Plain: Literature review and hypotheses generation

1.0 Background and problem statement

The Boreal Plain (BP) Ecozone extends across Western Canada, and is characterized by a sub-humid climate (precipitation, P < potential evapotranspiration, PET) (Winter and Woo, 1990; Marshall et al., 1999). Hydrological pathways through this landscape are complicated by thick heterogeneous Quaternary glacial deposits (Fenton et al., 2013), low relief topography and a water deficit climate (Devito et al., 2005a). Poorly integrated drainage networks promote wetland formation. The BP contains vast tracts of peatlands (Vitt et al., 1995), wetlands defined by organic matter > 0.4 m thick (National Wetlands Working Group, 1997), which provide valuable ecosystem services (Vitt et al., 2000). Peatlands are major carbon stores, playing a significant role in the global carbon budget (Frolking et al., 2011). The sub-humid climate of the BP highlights the need to understand both external (allogenic) sources and internal (autogenic) processes maintaining peatlands.

In the BP, precipitation (P) and evapotranspiration (ET) are dominant fluxes in the peatland water budget (Ferone and Devito, 2004; Thompson et al., 2015; Riddell, 2008). Since annual P < PET in this ecozone, allogenic sources have been assumed for peatland formation (Price et al., 2010). However, peatlands form in a range of geologic settings across the BP (e.g., Ferone and Devito, 2004; Smerdon et al., 2005; Hokanson et al., 2016), with varying connectivity to groundwater, dependent upon landscape position and texture of underlying glacial deposits (Winter, 2001). These glacial deposits can be classified into Hydrologic Response Areas (HRAs), wherein each HRA exhibits specific soil storage potential and water transmission properties (Devito et al., 2012). Recent research at the Utikuma Region Study Area (URSA) describes peatland – groundwater interactions across three major glacial deposits (HRAs) within the BP: coarse textured glacio-fluvial outwash, fine textured disintegration moraine, and fine textured glacio-lacustrine plain (Ferone and Devito, 2004; Devito et al., 2005a; Thompson et al., 2015; Hokanson et al., 2016; Plach et al., 2016). Along the transition zone between two HRAs (outwash and moraine), perched peatlands situated 20 m above regional groundwater have been identified (Riddell, 2008). The term ‘perched’ is applied to hydrologic systems that form above underlying groundwater, separated by an unsaturated zone (Meinzer, 1923). Previous work suggests perched peatlands are isolated from local ground and surface waters, functioning in a delicate balance between P and ET (Riddell, 2008).

Runoff and shallow groundwater contributions to downslope wetlands are limited in the BP due to the presence of deep, heterogeneous glacial deposits. Hillslope hydrology is controlled by soil water storage and dominated by vertical movement (infiltration and ET), limiting runoff and sub surface lateral flow (Devito et al., 2005b; Redding and Devito, 2008; Redding and Devito, 2010). Water movement between adjacent hillslopes and wetlands diverges from traditional downslope flow paths, as water tables (WT) are often inverse to topography (Ferone and Devito, 2004; Devito et al., 2005a; Thompson et al., 2015; Riddell, 2008). Perched peatlands may be hydrologically isolated from adjacent hillslopes and may be entirely dependent upon autogenic processes to maintain wetland conditions.

Contrasting conceptualizations of water movement and accumulation across different HRAs on the BP have been presented by Devito et al. (2012), and Ireson et al. (2015). According to one model, perched peatlands cannot exist without allogenic sources (Ireson et al., 2015). Ireson et al. (2015) describe the relative positions of groundwater, forests and wetlands within fine versus coarse-textured glacial deposits. ET is presented in relation to wetland and forest type. Ireson et al. (2015) conceptualize high ET from both bog and fen peatlands, high ET in aspen forests and low to moderate ET in pine and black spruce forests respectively. They assume rates of ET to be constant. Isolated, perched peatlands are unlikely to form according to this conceptualization, as high evaporative losses from the wetland require ground or surface water inputs to maintain saturation. If perched peatlands are isolated, and $P < ET$, then the question arises: how do these wetlands exist?

Devito et al. (2012) utilize storage, geology and climate variation to explain the hydrologic cycle in the BP, employing HRAs with specific configurations of Hydrologic Units (HUs; e.g., wetland, pond, forested upland), which control landscape storage potential and ET. Perched wetlands are conceptualized in regions with fine-textured overlying coarse-textured material, wherein a shallow fine-textured layer facilitates a perched WT. Devito et al. (2012) also present ET losses as non-static within peatlands and directly linked to fluctuations in the decadal climate cycle. For example, peatlands have high ET losses during wet periods when the WT is proximal to the surface. During drier periods, when the WT falls below the surface, peatlands function to conserve water (Waddington et al., 2015). Under this conceptual model, isolated perched peatlands with $ET \leq P$ could form in a sub-humid climate.

Large-scale landscape disturbance in the BP of Western Canada has occurred as a result of open pit mining at the Athabasca oil sands (AOS). Watershed scale reclamation is underway in an effort to restore the land to equivalent capability post-mining (Price et al., 2010; Pollard et al., 2012). Current literature suggests that an ongoing source of allogenic ground or surface water is a requisite for fen peatland reconstruction (Price et al., 2010; CEMA, 2014). However in the AOS, contamination of groundwater from salt and hydrocarbons associated with mine tailings used in landscape reconstruction present a major impediment to reclamation (Quagraine et al., 2005; CEMA, 2014). Because perched peatlands appear isolated from potentially contaminated groundwater (Riddell, 2008), incorporating them into watershed reconstruction could provide an alternative method for building wetlands.

Perched, isolated peatlands occupy one extreme within the spectrum of peatland types, the opposing extreme being those dependent on groundwater sources (Clymo, 1983). Perched peatlands may be more susceptible to climate change, as they are dominated by climatic fluxes (P and ET), as opposed to groundwater (Thompson et al., 2015; Riddell, 2008). However, perched peatlands may have autogenic negative feedbacks that function to increase resilience to disturbance (Waddington et al., 2015). For example, peatlands reliant upon ephemeral groundwater were found to be more susceptible to deeper burning from wildfire compared to isolated peatlands with no groundwater connections (Hokanson et al., 2016).

There is a need to examine the formation and maintenance of perched peatlands in the BP by quantifying the relative importance of local allogenic water sources to autogenic wetland feedbacks in an apparently isolated wetland, located in a topographically high landscape position. These findings can be used to conceptualize peatland formation in sub-humid climates to better inform designs for reconstructing similar systems in the AOS, and to predict perched peatland resilience to disturbance such as wildfire and climate change. Wetland geologic setting is combined with a water budget approach to generate multiple working hypotheses in response to the research question: What maintains a permanent perched wetland complex on a topographic high in the sub-humid BP? The balance of Chapter 1 will:

a) describe the thesis objectives and study framework (Section 2.0);
b) provide a short review on perched wetland hydrology (Section 3.0) and introduce the water budget approach (Section 4.0)

c) present alternative hypotheses and review potential processes operating within and around a perched wetland to maintain saturated conditions, by following the conceptual flow chart in Figure 1.5 (Section 5.0).

2.0 Thesis objective and format

The overall objective of this thesis is to present a conceptual framework to explain how a permanent perched wetland on a topographic high maintains itself in sub-humid conditions, by evaluating four alternative hypotheses for BP perched wetland formation:

1) allogenic wetland with no confining layer
2) allogenic wetland with confining layer
3) autogenic wetland isolated from allogenic inputs
4) relic peatlands formed by allogenic inputs, and maintained through autogenic processes.

My thesis is presented as three individual research papers. Chapter Two addresses hypotheses 1 - 3 (Figures 1.2 – 1.4) from the perspective of water budget and wetland geologic setting. Chapter Three focuses on autogenic processes influencing climate (P and ET) and internal wetland flow paths, addressing the question: where and how is excess water generated, and how is it distributed within a perched wetland? Chapter Four addresses hypothesis 4, relic peatland formation, through carbon dating of macrofossils (e.g., Bauer et al., 2009) within peatland and margin swamp organics. Chapter Five summarizes the alternative hypotheses for wetland formation and the hydrologic processes maintaining wetland conditions. An updated conceptual flow chart is presented for perched wetland formation and maintenance in the sub-humid BP. Implications and future research questions related to wetland reconstruction and vulnerability of these systems to disturbance such as wildfire, climate change, and anthropogenic activity are also discussed.

3.0 Perched wetland hydrology

Perched systems are any saturated water bodies such as lakes, rivers, streams, or wetlands containing a perched WT. Textural layering within a soil profile can give rise to a capillary or hydraulic barrier (Li et al., 2013), impeding infiltration, and facilitating perched WT. A hydraulic barrier is a low permeability layer present in the soil profile. Capillary barriers impede flow during infiltration when a fine-textured layer overlies a coarse-textured one. Conversely, capillary barriers to evaporation arise through a coarse-textured layer overlying a fine-textured layer (Li et al., 2013).

Perched wetlands occur across North America, presenting as vernal pools (Brooks and Hayashi, 2002; Zedler et al., 2003; Cable-Rains et al., 2006), prairie potholes (van der Kamp and Hayashi, 2009), glacial outwash lakes (Rosenberry, 2000), arctic ponds (Walker and Harris, 1976) and peatlands (Riddell, 2008). Vernal pools and prairie pothole wetlands typically overlay substrates of low permeability, resulting in a hydraulic barrier (Cable-Rains et al., 2006; van der Kamp and Hayashi, 2009). Local flow systems develop, largely influenced by vegetation (e.g., inverted summer flow from willow rings at prairie potholes; Meyboom, 1966), and confining layer (CL) morphology (Riddell, 2008). Perched water may be discharged to downgradient systems like streams (von der Heyden and New, 2003; O'Driscoll and Parizek, 2003) via horizontal flow paths (Driese et al., 2001), or contribute to regional groundwater through depression focused recharge (Winter and Rosenberry, 1995). Among these systems, prairie pothole hydrology is well understood (e.g., Meyboom, 1966; Hayashi et al., 1998; van der Kamp and Hayashi, 2009). There is, however, a gap in the literature on the hydrologic role of other perched wetlands

(Cable-Rains et al., 2006; Riddell, 2008), particularly in the sub-humid BP where there is extensive peatland coverage (Vitt et al., 2000).

Perched wetlands with ephemeral water bodies form in drier climates, where annual P << PET, but where P is in seasonal excess, e.g., winter rains or snow melt (Cable-Rains et al., 2006; van der Kamp and Hayashi, 2009). It could be assumed that the sub-humid climate of the BP (P < PET) would only support ephemeral, rather than permanent perched wetlands. It is not clear how these permanent perched wetlands maintain themselves, with no apparent groundwater contributions (e.g., Ireson et al., 2015). This study aims to address the gap in the literature by examining a perched wetland complex consisting of a peatland surrounded by treed margin swamp in a topographically high landscape position. Due to their apparent isolation, perched wetlands on topographic highs offer an ideal setting to differentiate the influence of allogenic (upland contributions) from autogenic processes (internal wetland feedbacks) in maintaining wetland conditions. Peatland margin swamps are ubiquitous features across the BP landscape, but their hydrologic role is not well understood (Dimitrov et al., 2014). The role of margin swamps as buffers of water loss, in receiving peatland water, or as generators of perched groundwater to adjacent peatlands, and the influence of shading, wind protection, and peatland negative feedbacks on permanent perched wetland maintenance in sub-humid conditions have not been documented.

4.0 Water budget approach: requirements for wetland development

A water budget approach can be used to determine the relative importance of water fluxes entering and leaving a wetland. The general equation for the budget is:

$$inputs - outputs \pm \Delta S = 0 \tag{1.1}$$

where ΔS is change in wetland storage. To maintain permanent wetland conditions, inputs must be greater than or equal to outputs. The water budget equation for a perched wetland is:

$$\Delta S = (Pnet - AET) - (So + Go + Seepage \pm UGW) + (Si + Gi) \tag{1.2}$$

where $Pnet$ is net precipitation (P net) which equals total precipitation minus interception, AET is actual evapotranspiration, So is surface water out, Go is groundwater out, $Seepage$ is vertical drainage beneath the wetland, UGW is unsaturated groundwater flow, Si is surface water into the wetland, and Gi is local groundwater from adjacent hillslopes into the wetland. Since the wetland is perched, deep groundwater input is assumed zero. For perched wetlands to exist in a sub-humid climate they require Si and or Gi, or wetland $Pnet>AET$ coupled with low soil water storage to offset climate deficit and water outputs.

4.1 Role of a confining layer

An impermeable layer present beneath a wetland will limit water budget outputs (So, Go, $Seepage$), holding water within the wetland. A confining layer (CL) is defined as a lithological barrier impeding infiltration (e.g., hydraulic or capillary barrier; Li et al., 2013). A hydraulic barrier CL is typically a clay rich layer of glacial till with hydraulic conductivity ranging from 10^{-8} to 10^{-10} ms^{-1} (Rosenberry and Winter, 1995; Hayashi and van der Kamp, 2009; Devito et al., 2005b). Lower decomposed peat and clay rich silt could also function as a CL, as hydraulic conductivity of these materials ranges from 10^{-7} – 10^{-8} ms^{-1} (Riddell, 2008). Decomposed peat, silts and clays exhibit higher holding capacity than coarser grained material such as sand (Lund, 1959; Boelter, 1969). Therefore, these finer textured soils could maintain a perched WT through low permeability and high holding capacity. An alternative CL is unsaturated coarse material overlain by finer textured material resulting in a capillary barrier to infiltration (Li et al., 2013).

The presence of a CL beneath the wetland would decrease soil water storage and $Seepage$ beneath the wetland, facilitating a perched WT (Li et al., 2013; Riddell, 2008). When a CL is present, the wetland requires lower inputs (Gi, Si) to maintain saturated conditions if P < AET. For perched wetlands to be autogenic systems, and not reliant on allogenic sources, a CL must be present. Lack of a CL beneath an isolated wetland would result in greater groundwater outputs; permanent wetland formation would be unlikely.

5.0 Literature review of potential processes maintaining a perched wetland

5.1 Allogenic wetland formation

The water budget equation (Eqn. 1.2) represents a perched wetland in a topographically high landscape position, restricted to local allogenic water from adjacent hillslopes. If wetland P < AET, the wetland must be allogenic, dependent on external sources of water to overcome the climate moisture deficit. Allogenic perched wetlands could form with (Figures 1.3 and 1.5, hypothesis 2) or without (Figures 1.2 and 1.5, hypothesis 1) a mineral CL. This section assesses each allogenic hypothesis by first reviewing the literature on BP hillslope runoff and lateral flow, then relating potential mechanisms of allogenic water generation to the topographically high landscape position of the study perched wetland.

5.1.1 Hypothesis 1: No confining layer

For allogenic formation of a perched wetland with no CL (Figure 1.2 and 1.5, hypothesis 1) to be viable, high Si and or Gi are required, as outputs ($So, Go, Seepage$) will also be high. This hypothesis is consistent with the current paradigm of constructing peatlands that receive water from adjacent hillslopes (e.g., Price et al., 2010) and coincides with traditional hillslope hydrology. However, the potential to generate runoff and shallow groundwater flow is limited within BP uplands due to the high soil storage capacity of deep heterogeneous glacial deposits (Redding and Devito, 2008, 2010; Devito et al., 2005b). Uplands tend to be hydrologically disconnected from wetlands and dominated by ET losses and infiltration. Soil water storage capacity is exceeded approximately once every 20 years, during which a hydrological connection between upland and wetland is established (Devito et al., 2005b; Redding and Devito, 2008). Studies have found that lateral flow generation in Luvisolic aspen-dominated uplands is uncommon without a CL (Whitson et al., 2004; Devito et al., 2005b; Redding and Devito, 2010), except at the base of hillslopes (Thompson et al., 2015). If the hillslope lithology of adjacent perched wetlands is composed of silts and or sands, allogenic wetland formation on a topographic high is unlikely, as the high storage capacity would not promote frequent (>1 in 20 years) lateral flow to offset wetland water outputs. However, if the perched wetland formed in a wetter climate, when P > ET, adjacent hillslope soil water storage could fill and supply allogenic water to the wetland (See Section 5.3 Relic peatland formation and Figure 1.5).

5.1.2 Hypothesis 2: Confining layer under wetland

If there is a CL present beneath the perched wetland, $Seepage$ and soil water storage are reduced. In this hypothesis, wetland P can be less than ET, as allogenic inputs, Si and or Gi, are only required make up the climate deficit, since other wetland outputs are low (Figures 1.3 and 1.5, hypothesis 2).

Confining layer under hillslope

The presence and morphology of a CL within the adjacent hillslope could promote lateral flow (Gi) and interflow (lateral movement of water through vadose zone; Dingman, 1994) into the wetland (Figures 1.3 and 1.5). The requisites for producing lateral flow are high antecedent moisture conditions, where soil water storage above the CL is at capacity, followed by events of

15 - 20 mm, with rain intensity > saturated hydraulic conductivity of the CL (Redding and Devito, 2010). The enabling mechanism for lateral flow is transmissivity feedback, which requires a CL proximal to the surface (Buttle, 1994; Redding and Devito, 2010). Transient perched aquifers can occur above the CL during rain events. Water is laterally displaced along preferential flow paths within the upper horizons. Lateral flux increases with increased aquifer thickness, and an increased proportion of high permeability layers (e.g., sands). Flow paths resulting from this feedback are local, occurring within 50 m of a stream or wetland (Buttle, 1994).

For transmissivity feedback to be viable as an external source of water to perched wetlands, a CL must extend from the wetland through the upland, allowing preferential flow paths to develop during wet conditions. If the CL is too deep, high soil water storage will prevent frequent saturation, thus preventing transmission of groundwater to adjacent perched wetlands (e.g., Redding and Devito, 2010). This depth is determined by texture (fine vs. coarse) above the CL. In the AOS for example, a constructed fen wetland was designed to receive water from the local adjacent hillslope via a shallow (3 m) sand aquifer (Price et al., 2010; Pollard et al., 2012). A geosynthetic clay liner or CL was placed beneath the sand to promote lateral flow downslope. Shallow local groundwater is generated above the CL within the high porosity sand veneer, discharging water to the constructed fen wetland (Price et al., 2010). Similar layering in the adjacent uplands could generate water to a perched wetland, and a flow-through system could form subject to the morphology of the CL beneath the wetland and adjacent hillslope. The wetland in turn could transmit flow downslope (Spence et al., 2011), creating flow-through conditions described in hypothesis 2 (Figure 1.3). In this hypothesis, wetland ET can exceed P, as wetland conditions are maintained through allogenic local groundwater, Gi. In spring, high moisture conditions following snowmelt could satisfy storage capacity, depending on fall antecedent moisture conditions and winter snowpack (Redding and Devito, 2011). However, in the BP there is only a 1.1% chance of rain storms >20 mm in May, the amount of P required to initiate lateral flow once storage is filled (Redding and Devito, 2010). These results suggest that even with a CL, perched wetlands may not rely on local allogenic groundwater.

An alternative mechanism for allogenic water is near surface runoff over ice, creating Si for a perched wetland (Figures 1.3 and 1.5). Snowmelt runoff is limited within the BP, as infiltration dominates over runoff (Whitson et al., 2004; Devito et al., 2005b; Redding and Devito, 2011). Snow water equivalence (SWE) in the BP is low compared to other forested regions in North America (Golding and Swanson, 1978; Troendle and Leaf, 1980), accumulating 100 mm on average (Marshall et al., 1999, Pomeroy et al., 1997). The development of concrete frost increases potential for near surface runoff by creating a barrier to infiltration, decreasing storage capacity. In spring, snowmelt coupled with concrete frost and low evaporative demand could promote high surface moisture conditions on BP hillslopes and generate water to adjacent perched wetlands (Whitson et al., 2004; Redding and Devito, 2011).

Soil texture and aspect play an important role in the development of concrete frost. South facing slopes with open canopies (e.g., jack pine forest) undergo periodic melting and refreezing throughout most winters, facilitating formation of concrete frost. This process is reduced on north facing slopes due to decreased solar radiation. Increased solar radiation on south facing slopes increases melt rate, while concrete frost impedes infiltration. This creates a barrier to flow, and near surface runoff is generated when snowmelt exceeds rate of infiltration (Redding and Devito, 2011). Studies have concluded that maximum runoff occurs when concrete frost layers are connected (Winter and Rosenberry, 1995; Redding and Devito, 2011). For example, in prairie pothole wetlands, snowmelt runoff over frozen soil provides the main flux of water to the wetland, filling depression ponds (Winter and Rosenberry, 1995). Texture of glacial till (silts and clays) surrounding BP perched wetlands may be similar to prairie potholes, and could promote formation of a concrete frost CL and consequent generation of near surface runoff during snowmelt, providing allogenic water to the wetland in the form of Si (hypothesis 2, Figures 1.3a and 1.5). However, studies in BP aspen forests (which surround perched wetlands) have shown low antecedent fall moisture from high summer ET and low periodic melting and refreezing compared to open jack pine stands (Redding and Devito, 2011). These factors suggest formation of concrete frost in adjacent aspen hillslopes is unlikely. In the BP, the most probable location for concrete frost development is within ephemeral draws (Devito et al., 2012; Devito et al., 2005b). The margin swamp of the perched wetland complex shares characteristics with ephemeral draws. If concrete frost develops in the swamp, near surface runoff over ice may be generated to the peatland or adjacent upland edge in a manner similar to runoff observed in ephemeral draws (Devito et al., 2005b).

Confining layer under base of hillslope

If there is a CL under the adjacent hillslope base, flow may be generated through groundwater ridging (Figures 1.3b and 1.5) (Riddell, 2008). Groundwater ridging typically occurs in foot slopes and valley bottoms where the capillary fringe is near the surface (Gillham, 1984; Buttle, 1994). Groundwater ridging generates shallow groundwater inputs from the upland to the wetland. Silt rich soils have low porosity and readily draw water from the saturated zone via capillary forces, creating capillary fringes > 1 m (Gillham, 1984). Infiltration of event water from snowmelt or rain converts the tension-saturated capillary fringe to phreatic water. The result is a rapid rise in the WT, increasing hydraulic gradient and seepage face, thereby enhancing water flux into the down gradient system (Gillham, 1984; Buttle, 1994).

The subdued topography around a perched wetland in a topographically high landscape position is conducive to groundwater ridging at the base of upland hill slopes (Thompson et al., 2015; Riddell, 2008). Local clay-rich layers extending into the upland forest edge could maintain a perched WT. If silt is present above the CL, a large capillary fringe will develop above the WT (Gillham, 1984). High intensity events may trigger a rapid rise in WT, and preferential flow may then occur from the base of the upland to the wetland. Groundwater ridging presents an alternative mechanism for allogenic wetland formation (hypothesis 2, Figures 1.3b and 1.5). In this process, wetland P can be less than ET, as sufficient Gi is generated through groundwater ridging during rain events, offsetting the moisture deficit. This process would have a greater impact in smaller wetland systems, as the perimeter to area ratio of small systems is high.

5.2 Autogenic wetland formation: hypothesis 3

The water budget equation for an autogenic isolated perched wetland is:

$$\Delta S = (Pnet - AET) - (So, + Go + Seepage \pm UGW) \pm residual\ error \tag{1.3}$$

For wetland conditions to be maintained in an autogenic system, $Pnet > AET$, and the difference must exceed the sum of So, Go, $Seepage$, and UGW. Given the sub-humid climate and small difference between $Pnet$ and AET, a CL beneath the wetland is required to maintain the perched WT, and to decrease wetland water loss. Consequently, the interaction between P and ET controls the wetland water budget. Autogenic feedbacks associated with wetland storage, P funneling, moss structure, sheltering and ice could function to increase P and or decrease ET, reducing the climate deficit and generating excess water within an isolated perched wetland (hypothesis 3, Figure 1.4). Section 5.2 will explore processes impacting P and ET within a perched wetland complex (peatland surrounded by margin swamp) and how excess water could be generated and distributed through internal wetland flow paths (hypothesis 3, Figures 1.4 and 1.5).

5.2.1 Increased precipitation

This section describes alternative mechanisms to offset the climate water deficit by decreasing the amount of P required to maintain wetland conditions through low soil water storage or by increasing P net over the wetland.

Precipitation – storage feedback

A CL beneath a perched wetland limits storage; the wetland requires lower amounts of P to satisfy storage capacity and maintain saturated conditions. The presence of peat in perched wetlands could further influence P – storage dynamics. Water movement within peat is governed by soil physical properties controlling the function of water retention, specific yield, and hydraulic conductivity (Boelter, 1969). These physical properties are controlled by the degree of organic matter decomposition, which is in turn determined by bulk density and fibre content. Degree of decomposition ultimately controls pore size. Undecomposed peat has large pores, and pore size decreases with increased decomposition. As a consequence, peat is composed of two distinct layers (Ingram, 1978): the active layer is the upper, undecomposed peat, with low bulk density, high fibre content and large pores. It is frequently aerated, and functions to regulate the WT due to high storage and specific yield (Boelter, 1969; Ingram, 1978). The active layer exhibits high hydraulic conductivity and low water retention, and transmits water rapidly. The lower decomposed layer behaves inversely to the upper layer. It has high bulk density, low fibre content and small pores. Persistent saturated conditions create anoxia. Due to small pore size, the lower decomposed peat displays low saturated hydraulic conductivity, which reduces water movement, maintaining the WT (Ingram, 1978).

The active peat layer in perched peatlands could shed excess water to margin swamps during wet periods (Figure 1.4). When the WT drops into the lower peat layer, high water holding capacity would maintain the WT. Further, the low specific yield and storage of decomposed peat would cause frequent and rapid WT rise into the base of the active layer following even small rain events, maintaining permanent wetland conditions. This is evidenced in the WT depth - decomposition negative feedback (Waddington et al., 2015): a prolonged dry period, typical of the BP, causes a drop in the WT, breaking the capillary fringe. The smaller pores of decomposed peat exhibit higher water retention and lower hydraulic conductivity, resulting in reduced drainage, thus maintaining the WT. In addition, smaller pores have lower storage capacity. When water is added to the system, the WT rises quickly due to low specific yield, restoring saturated conditions in the active peat layer (Morris et al. 2011; Swindles et al. 2012).

Increasing P over wetland through funneling and wind

Tree density, species and height can influence winter interception and net P (Pomeroy et al. 2002). The vegetation height within perched wetland complexes is substantially lower than surrounding forest. This gap in forest canopy over perched wetlands could increase net winter precipitation through preferential funnelling of snow. Golding and Swanson (1978) studied snow accumulation in varying gap treatments and adjacent undisturbed forest near Rocky Mountain House, Alberta. They found that snow accumulation and SWE was greater within the gaps when compared to the adjacent jack pine stands. This was attributed to lower interception within the gap, discontinuity in canopy structure causing snow to settle in the gap, and increase in wind speed and turbulence in forest openings, resulting in redistribution of snow. A relationship existed between gap diameter and tree height (d:h). Maximum snow accumulation in the gap occurred when the gap diameter was 2 – 3 d:h (Golding and Swanson, 1978). Similar studies have shown an increase in gap SWE when compared to uncut forest (Golding and Swanson, 1986; Ellis et al., 2013).

There is limited understanding of snow accumulation in peatland dominated landscapes (Whittington et al., 2012). Since snow accounts for 25% of total P in the BP (Pomeroy et al., 1997), snow accumulation and melt could play a considerable role in the wetland water budget by increasing P during a period of low ET. Whittington et al. (2012) investigated snow accumulation across a transect consisting of five peatland types in the James Bay Lowlands of central Canada. It was found that bogs with medium to high density tree cover accumulated the most snow, while snowmelt remained consistent across the five types.

Wind can also affect snow distribution (Elder et al., 1991). Snow accumulates where wind decelerates, and erodes in areas of accelerated flow. Across areas with a long fetch like the James Bay Lowlands, stands of black spruce function as ‘snow fences’, trapping blown snow. A comparison of snow dynamics between a harvested and adjacent undisturbed treed peatland found a significant difference in SWE, wherein the undisturbed peatland accumulated more SWE (Ketcheson et al., 2012). This was credited to wind; the treed portion of the bog trapped snow that was transported from the harvested portion (Ketcheson et al., 2012).

The above processes can be monitored around a perched wetland complex to determine whether snow accumulation is greater within the peatland, margin swamp or adjacent upland forest. Increased snow accumulation on perched wetlands through funneling, lowering interception, and wind dynamics could prove integral in providing excess water through increased P.

5.2.2 Decreased evapotranspiration

Perched wetland ET could be affected by protection and shading from adjacent forest, ice, and peatland negative feedbacks. These processes could decrease wetland AET relative to P net and offset the moisture deficit of the sub-humid climate. Understanding controls on wetland ET is critical for conceptualizing autogenic perched wetland formation and maintenance in the BP (hypothesis 3, Figures 1.4 and 1.5).

Sheltering and shading

Forest surrounding a perched wetland could decrease ET through sheltering and shading. Rate of ET depends on energy available at the surface and vapour pressure deficit (VPD) (Robinson and Ward, 2000). A taller upland forest canopy decreases wind speed over the wetland by increasing aerodynamic resistance. Humid air may then stagnate over the wetland as a result of lower turbulence, decreasing VPD and wetland ET. Shading of the wetland by adjacent forest would decrease surface temperature and energy available for evaporation (Kettridge et al., 2013). For example, wetlands sheltered by tall trees may decrease AET and winter sublimation as much as 30%, compared to more open sites (Petrone et al., 2007).

Snowmelt is controlled by vegetation density or winter leaf area index, which influences energy available for ablation (Boon, 2009). Mature stands have been found to attenuate radiation, decreasing snowmelt as canopy density increases (Pomeroy et al., 2002). Average snowmelt rates are greater in clear-cut than in conifer forested environments due to greater shortwave radiation inputs (Winkler et al., 2005). A study examining a transect of peatlands in the James Bay Lowlands observed uniform melt rates between sites, attributed to the relatively open canopy. Rate of snowmelt in harvested peatland was double that of adjacent forested peatland, with total melt period 17 days shorter in harvested peatland (Ketcheson et al., 2012). In small, perched peatlands on the BP, sheltering and shading from adjacent forest and tree canopy over the wetland may protect perched wetlands from sublimation loss and reduce the rate of snowmelt, similar to the forested peatland described in Ketcheson et al. (2012). A prolonged snow pack in the wetland compared to adjacent forest would shorten the duration of ET and conserve water within the wetland.

Persistence of ice

For much of the year, peatlands in the BP are frozen (Brown et al., 2010). Ice lenses can persist into high summer because of the insulating properties of peat and snow (Kershaw and Gill, 1979; Laberge and Payette, 1995). Similar to conditions seen in droughts, near-surface ice lenses can affect capillary rise in peat. Surface moisture decreases, provoking a decline in evaporation (Waddington et al., 2015). Further, transpiration rates within peatlands are influenced by ice, particularly within black spruce, the prevalent tree cover on the bog peatlands in the BP (Kettridge et al., 2014). Root density in a peatland is limited to the top 20 cm of the soil profile (Steele et al., 1997). Ice lenses maintain lower temperatures within this zone, decreasing stomatal conductance and lowering metabolism, which combine to greatly reduce water loss through transpiration (Goodine et al., 2008). For example, temperatures below 7.5℃ decrease stomatal conductance in spruce, due to water limitation caused by increased water viscosity (Delucia, 1986). Peatlands defrost from the surface downward. AET is lower than PET until the rooting zone is thawed (Goodine et al., 2008). This mechanism could function to preserve water within perched peatlands.

Persistence of ground ice was found to regulate ET in a BP peatland (Brown et al., 2010). Impermeable ice lenses controlled WT position by trapping water near the peat surface, promoting lateral flow and high surface moisture conditions (Brown et al., 2010). This action resulted in an early season peak in evaporation from high surface moisture. Within perched wetlands, ice could enhance surface evaporation by maintaining high WT positions, while reducing transpiration due to freezing temperatures in the rooting zone.

Peatland feedbacks: structure and species cover

Studies of peatland hydrology have determined that a number of autogenic feedbacks affecting ET occur as a result of the specific structure of peat and surface mosses (e.g., Kettridge et al., 2013; Kettridge and Waddington, 2014; Waddington et al., 2015). Autogenic peatland feedbacks may reduce or enhance WT depth. The relative influence of these feedbacks on lowering wetland ET may be essential in maintaining a perched isolated peatland within a sub-humid climate.

Sphagnum mosses dominate northern peatlands and have been identified as the principle peat-forming plant (Kuhry and Vitt, 1996; Price and Whittington, 2010). Since mosses are non-vascular, water flows by capillary forces between fascicles in sphagnum (Hayward and Clymo, 1982). Water can also be transmitted through hyaline cells (intercellular spaces), which are able to withstand matric potential of up to -100 cm of water (Price and Whittington, 2010). Feathermoss is another common moss in treed bogs, displaying higher surface resistance to evaporation than sphagnum (Brown et al. 2010; Kettridge et al., 2013). Feathermoss physiology differs from sphagnum, as it lacks structures to efficiently pull water via capillary forces (Kettridge et al., 2013). The relative cover of feathermoss versus sphagnum on perched peatlands may affect peatland ET.

The WT depth-afforestation feedback (Waddington et al. 2015) consists of three components: transpiration and interception, shading and evaporation, and aerodynamics. The first component involves trees or shrubs encroaching onto non-forested peatlands, causing a positive drying trend due to greater root uptake of water (Landhausser et al., 2003), resulting in a lowering of the WT and an increase in the oxic zone, promoting vascular plant growth. This feedback may be mitigated by species composition and tree cover. For example, Stritesky and Humphreys (2012) found that the treed portion of a bog had lower total ET than the non-treed area. This was attributed to lower stomatal conductance in black spruce. Secondly, the afforestation feedback alters shading and evaporation. Increased tree cover creates shading, reducing available energy for evaporation (Kettridge et al., 2013). This reduction in energy greatly reduces moss evaporation, counteracting the increase in transpiration from trees (Kettridge et al., 2013). The shading effect of trees can also change moss communities. Feathermoss was found to outcompete sphagnum when the canopy was over 80% (Bisbee et al., 2001). Since feathermoss has a greater resistance to evaporation than sphagnum (Kettridge et al., 2013), higher proportions of feathermoss on a peatland may provide a negative feedback to drying. The third component of WT depth-afforestation feedback involves the aerodynamic effect of trees (Waddington et al., 2015). When tree density increases, aerodynamics of the peatland canopy become smoother, decreasing turbulence and subsequently evaporation, providing a further negative feedback to drying. Since many perched peatlands are treed (Riddell, 2008), low stomatal conductance of black spruce, prevalent feathermoss cover and high tree density could provide negative feedbacks to water loss.

Moss surface resistance and albedo feedback (Waddington et al., 2015) may be critical in reducing WT drawdown during prolonged dry periods in peatlands. Surface moss becomes resistant to evaporation when the WT drops below a threshold depth (Hayward and Clymo, 1982). The ability of moss to conduct water upward via capillary forces, dependent upon species and surface structure, is limited and eventually broken, thus decreasing evaporation (Price, 1991). When near surface peat dries, matric potential declines and evaporation is further reduced (Kettridge and Waddington, 2014). An experiment on peat surface resistance revealed a step shift from 50 s/m to 1000 s/m when the WT dropped to 30 cm depth, shutting down evaporation (Kettridge and Waddington, 2014). Further supporting these results, field studies have found surface tension increased with increased WT depth (Lukenbach et al., 2015, 2016). During an extended dry period, moss capitulum were shown to lighten in colour, increasing albedo and lowering energy available for evaporation, providing an even stronger negative feedback to drying (Waddington et al., 2015).

In a review of peatland autogenic processes in continental peatland systems, Waddington et al. (2015) noted that the negative feedbacks greatly outnumbered the positive, suggesting peatlands function to conserve water. Negative feedbacks may work simultaneously to maintain wetland conditions in perched peatlands by decreasing AET within moisture deficit conditions characteristic of the BP.

5.2.3 Within wetland flow paths

If perched wetlands are autogenic systems and wetland P > ET, how is excess water generated and redistributed within the wetland? Permanent perched wetland complexes are comprised of a peatland and margin swamp (Riddell, 2008). These two components may have contrasting hydrologic functions. The following section reviews the hydrologic role a peatland and swamp could play within the context of an autogenic wetland. Potential mechanisms for internal wetland flow generation and resulting flow paths are discussed (Figure 1.4).

Hydrologic role of peatlands

The hydrologic role of peatlands changes through wet and dry periods (Verry et al., 1998; Spence et al., 2011; Gracz et al., 2015). The role of peatlands in either mitigating or generating runoff is subject to contrasting explanations. Spence et al. (2011) found that Boreal Shield peatland hydrology changes in response to high and low flow, undergoing periods of storing, generating and transmitting water. Landscape position influences relative amounts of surface and groundwater entering peatlands (Spence et al., 2011). The hydrologic function of peatlands situated lower in the landscape on the Boreal Shield is to receive and transmit water, rather than to generate. Glen and Woo (1997) concluded that peatland runoff during low flow is controlled by autogenic processes. This is supported by Gracz et al. (2015) who found that an Alaskan peatland underlain by glacio-lacustrine and poorly sorted till deposits generated 55% of streamflow during drought periods, suggesting watersheds with a higher proportion of peatlands are more resilient to drought. Studies in a variety of hydrogeologic settings found that low flow during dry periods increased in proportion to percentage of peatlands (Panu, 1988; Ackroyd et al., 1967; Newson, 1980; Brandesten, 1988; Gracz et al., 2015; Devito et al., *In press*). The role of BP peatlands in generating, storing and transmitting water appears dependent on landscape position and HRA, and connectivity to adjacent HUs, rather than topography (Ferone and Devito, 2004; Plach et al., 2016; Hokanson et al., 2016). Whether perched peatlands function as water sources or sinks is governed by their relative isolation from local allogenic water inputs.

Flow reversals in peatlands have been observed in response to wet and dry conditions (Devito et al., 1996; Ferone and Devito, 2004). During an extended dry period, surface peat is subject to change in hydraulic head due to evaporative losses, resulting in lower hydraulic head on the surface compared to the interior of the peat (Devito et al., 1996). Higher hydraulic head in the peatland centre directs flow outwards. A reversal occurs during wet periods; water is directed from the wetland edge toward the centre. Similar subsurface flow patterns may develop within perched peatlands in response to wet and dry periods.

A study conducted in the URSA examined shallow groundwater exchange between pond-peatland complexes in fine textured glacial till (Ferone and Devito, 2004). During dry periods, the peatland received water from the pond. During wet periods a reversal occurred, wherein peatland water levels rose above the adjacent pond, generating flow. In contrast, autogenic perched wetlands are not reliant upon pond water during drought periods. However, during wet periods water may be directed from the peatland to margin swamp, similar to flow observed in pond-peatland complexes (Ferone and Devito, 2004).

Flow can occur over ice lenses in peat during spring melt and early summer (e.g., Quinton et al., 2009, Figure 1.4). Frozen peat at the active layer base can prevent infiltration and direct flow laterally though the high porosity undecomposed peat active layer (Brown et al., 2010). This shedding of water during spring melt in perched peatlands could provide water to the margin swamp and adjacent upland forest. The hypothesis of an autogenic wetland capable of self-generation is supported if both surface and groundwater flow directions are from peatland → margin swamp → upland forest (Figure 1.4).

Hydrologic role of peat margin swamps

The hydrological function of peatland margins, specifically the lagg (margin swamp), is poorly understood (Whitfield et al., 2005; Dimitrov et al., 2014; Langlois et al., 2015). Laggs form along the peripheries of ombrotrophic bogs and are defined as wet zones with fen characteristics, due to the influence of both bog and mineral water (Hobbs, 1986). Langlois et al. (2015) described laggs in the New Brunswick Lowlands of two types: confined and unconfined.

Confined laggs occur in topographic depressions between bog and mineral forest. Unconfined laggs are adjacent to flat or down-sloping mineral forest. Confined laggs have higher water levels, pH and electrical conductivity than unconfined, which is attributed to the topography and contribution of water from adjacent hillslopes. Confined laggs receive water from both bog and forest, whereas the sole source of water in unconfined laggs is the bog (Langlois et al., 2015). Though understudied, lagg and bog margins appear to play a dominant role in wetland maintenance. For example, the hydraulic conductivity in bog margins decreases rapidly with depth, slowing water movement from bog to lagg (Langlois et al., 2015), promoting water conservation within the bog (Price, 2003). Further restricting water loss is a mineral layer of low hydraulic conductivity beneath the lagg (Langlois et al., 2015).

Perched peatland margin swamps may function as confined or unconfined laggs, receiving water from both peatland and adjacent hillslopes, subject to topography and presence of hillslope water (Langlois et al., 2015). Since the margin swamp can represent almost half of a total wetland area, understanding the hydrologic role of the swamp relative to the peatland is key. For instance, during wet periods, the peatland could shed water to the adjacent swamp (Figure 1.4), facilitating an expansion of peat through paludification, the process of converting upland forest to peatland (Lavoie et al., 2005). As part of this process, soils typically undergo podsolization to form placic horizons (iron pans), a result of downward transport of iron. This process decreases soil permeability, increases surface moisture, and facilitates the growth of peat forming mosses (Klinger, 1996). During dry periods, the margin swamp or lagg could conserve wetland water through the presence of low conductivity layers (Langlois et al., 2015). Dimitrov et al. (2014) modelled the ecotone (margin swamp) between upland forests and peatlands in the BP. They reported that hillslope water flowed through the margin swamp into the peatland. This study presents an alternative flow path between margin swamp and peatland, wherein the swamp transmits to, rather than receives water from the peatland. Another alternative for the hydrologic function of the swamp involves self-generation of water (Figures 1.4 and 1.5). If silt overlies the CL in the margin swamp, groundwater ridging could occur during rain events (Gillham, 1984; Buttle, 1994), directing water toward the peatland and adjacent upland. Groundwater ridging in the swamp would create a buffer to peatland water loss, generating excess water and assisting in paludification. The function of margin swamps on maintenance and expansion of perched peatlands is a current gap in the hydrologic and peatland development literature.

5.3 Hypothesis 4: Relic peatland formation

High WT from a historically wetter climate (P > PET) could cause groundwater to intersect the surface and facilitate development of peat due to saturated conditions. The wetland could form through local allogenic hillslope contributions (described in Section 5.1), as a wetter climate could fill hillslope storage, increasing Gi, and Si to the wetland (Figures 1.2 and 1.5). Following a drop in the regional WT to current levels (e.g., 20 m below ground surface), the lower decomposed peat layer could function as a CL and maintain perched WT due to low hydraulic conductivity (or capillary break), inhibiting $Seepage$ beneath the wetland. The water deficit from sub-humid conditions could be offset by autogenic processes impacting P, ET and storage, as laid out in Section 5.2 (Figure 1.4). Further, if BP perched peatlands are relic (formed when P > PET), then the age of the centre and edge of basal peat should be similarly old, as expansion is no longer plausible due to lack of allogenic contributions.

If the wetland is still expanding under current sub-humid conditions, basal peat in the centre should be the oldest, becoming younger towards the peatland margin. A study in central Saskatchewan on the transition zone between upland forest and peatland showed basal peat was oldest at the peatland edge (3800 calendar years before present), becoming younger towards the upland forest (800 calendar years before present; Bauer et al., 2009). In Bauer et al. (2009), these transition zones had a maximum accumulation of 1.5 m of peat, similar depth to that measured in perched peatlands (Riddell, 2008). In addition, Bauer et al. (2009) determined that at all points analyzed, peat initiation occurred via paludification. Another peatland located in the BP central mixed wood sub region of Alberta was found to originate through paludification around 3400 years before present in a climate similar to present (Schweger and Hickman, 1989; Kubiw et al., 1989). The authors speculated landscape scale paludification took place in the boreal region following the mid-Holocene warm period which ended approximately 4000 years ago. In a study of basal peat from 90 sites in Alberta, it was determined that the oldest peatlands in the study area are between 7,000 and 8,000 years old (Halsey et al., 1998). Climate records indicate that modern climatic conditions originated approximately 3000 - 4000 calendar years before present (Vance et al., 1983). If basal peat in a perched peatland is older than 4,000 years, this peatland may be relic, having formed under historic climatic conditions. If the age is younger, then these peatlands are hypothesized to form under current conditions through paludification, showing increasing age in basal dates toward the peatland centre. Radiocarbon dating of basal peat should provide an indication of how and when the peatland formed.

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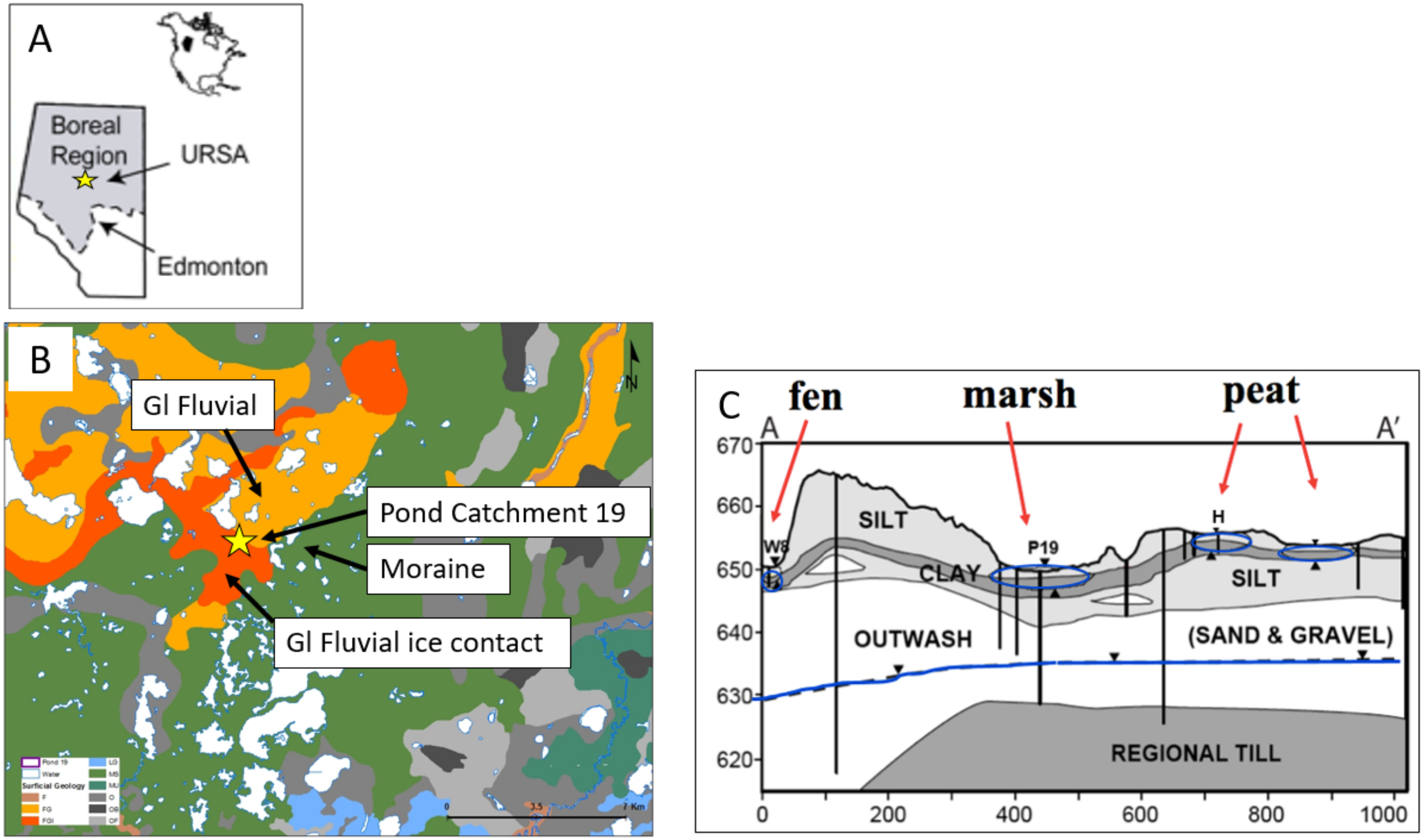


Figure 1.1: a) location of URSA within the Boreal Plain Ecozone b) Surficial geology of the URSA showing Pond Catchment 19 c) cross section of Pond Catchment 19 showing fine silts and clay over coarse material, with regional water table contained in outwash sediment and perched water tables forming in overlying fine textured substrate. The study perched wetland complex on a topographically high setting is denoted by 'H', and Pond 19 by 'P19'. Vertical axis is in m above sea level, horizontal is distance in m. Adapted from Riddell (2008).

Eqn. $S = (P - ET) - (So + Go + UGW + \text{seepage}) + (Gi + Si)$

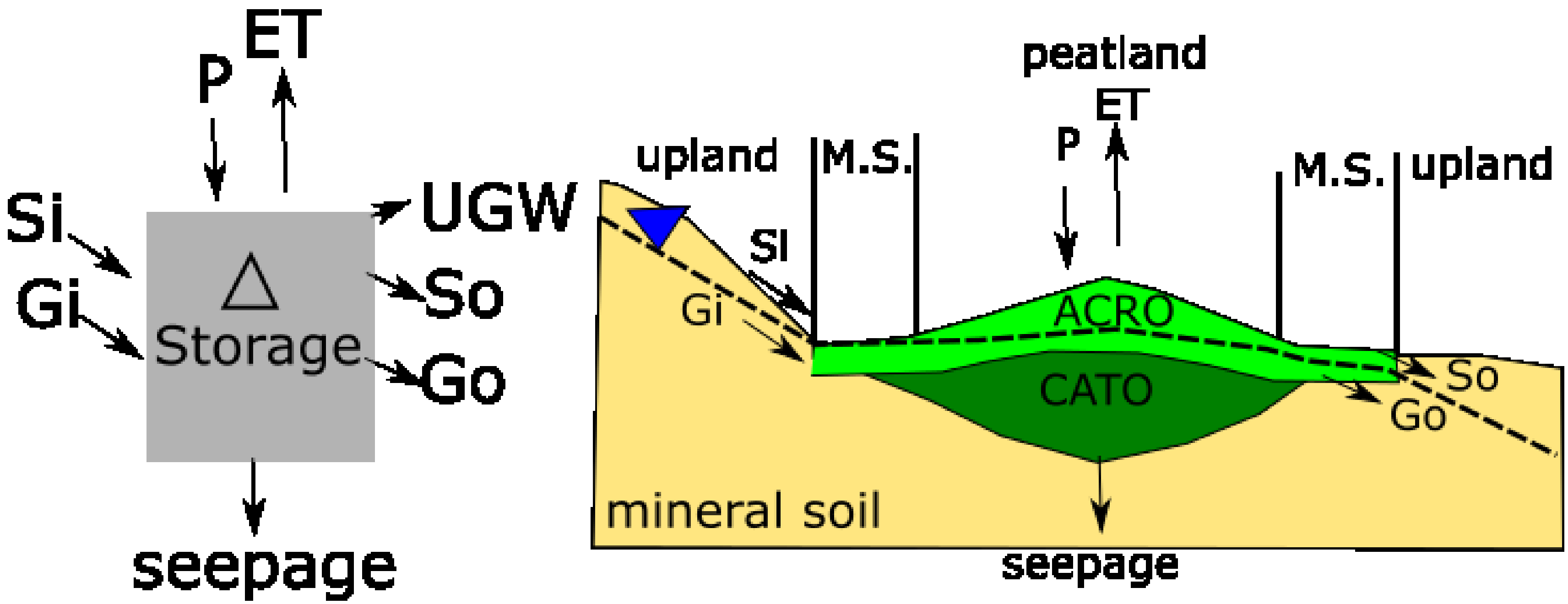


Figure 1.2: Hypothesis 1: allogenic wetland formation without a confining layer (CL). M.S. denotes margin swamp. ACRO is acrotelm, and CATO is catotelm peat.

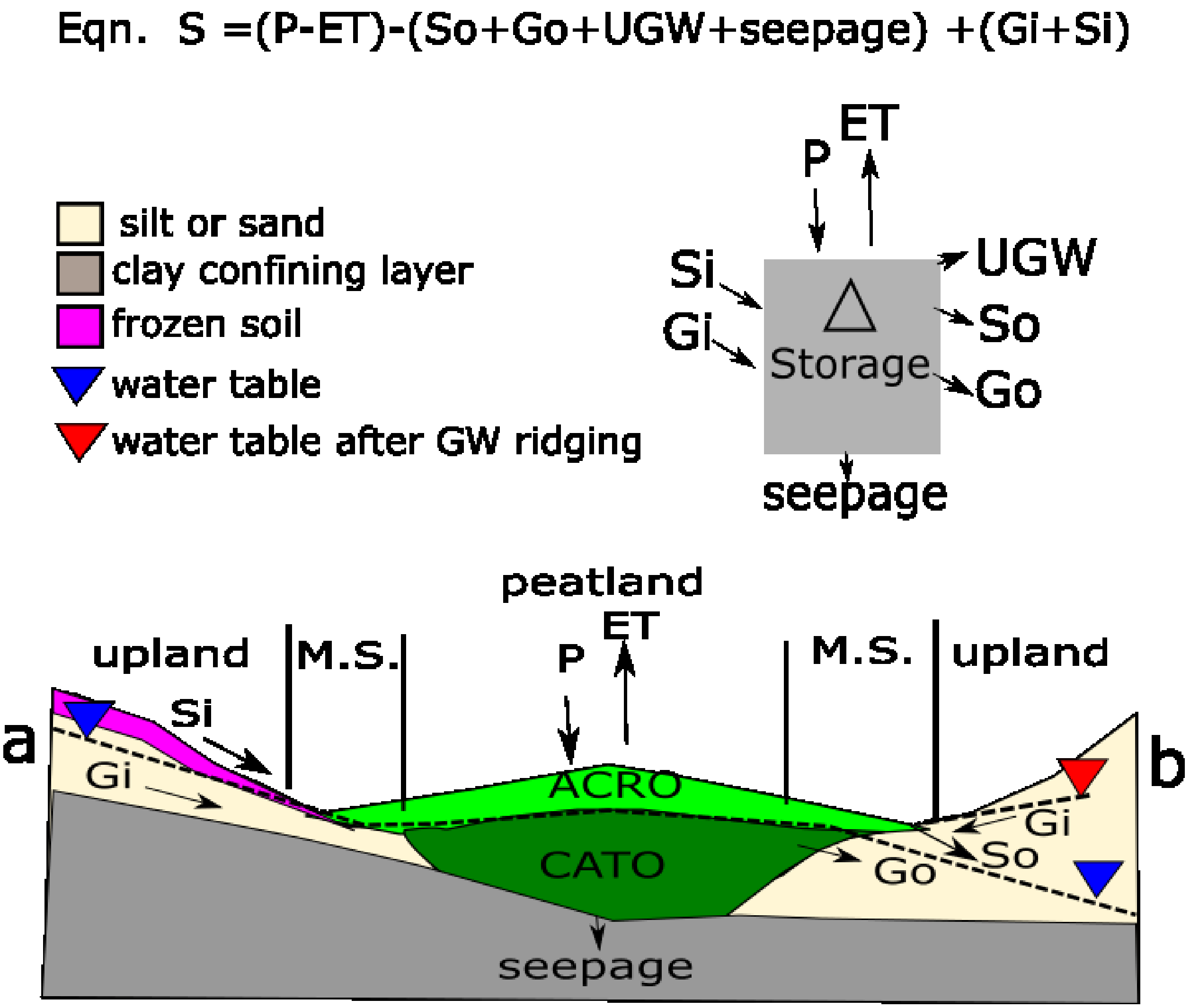


Figure 1.3: Hypothesis 2: allogenic wetland formation with a confining layer (CL). Requires lower ground and surface water inputs due to decreased seepage through CL. (a) represents entire hillslope contributions from surface (frozen soil) and groundwater (shallow CL beneath hillslope) b) groundwater ridging in hillslope base. M.S. denotes margin swamp.

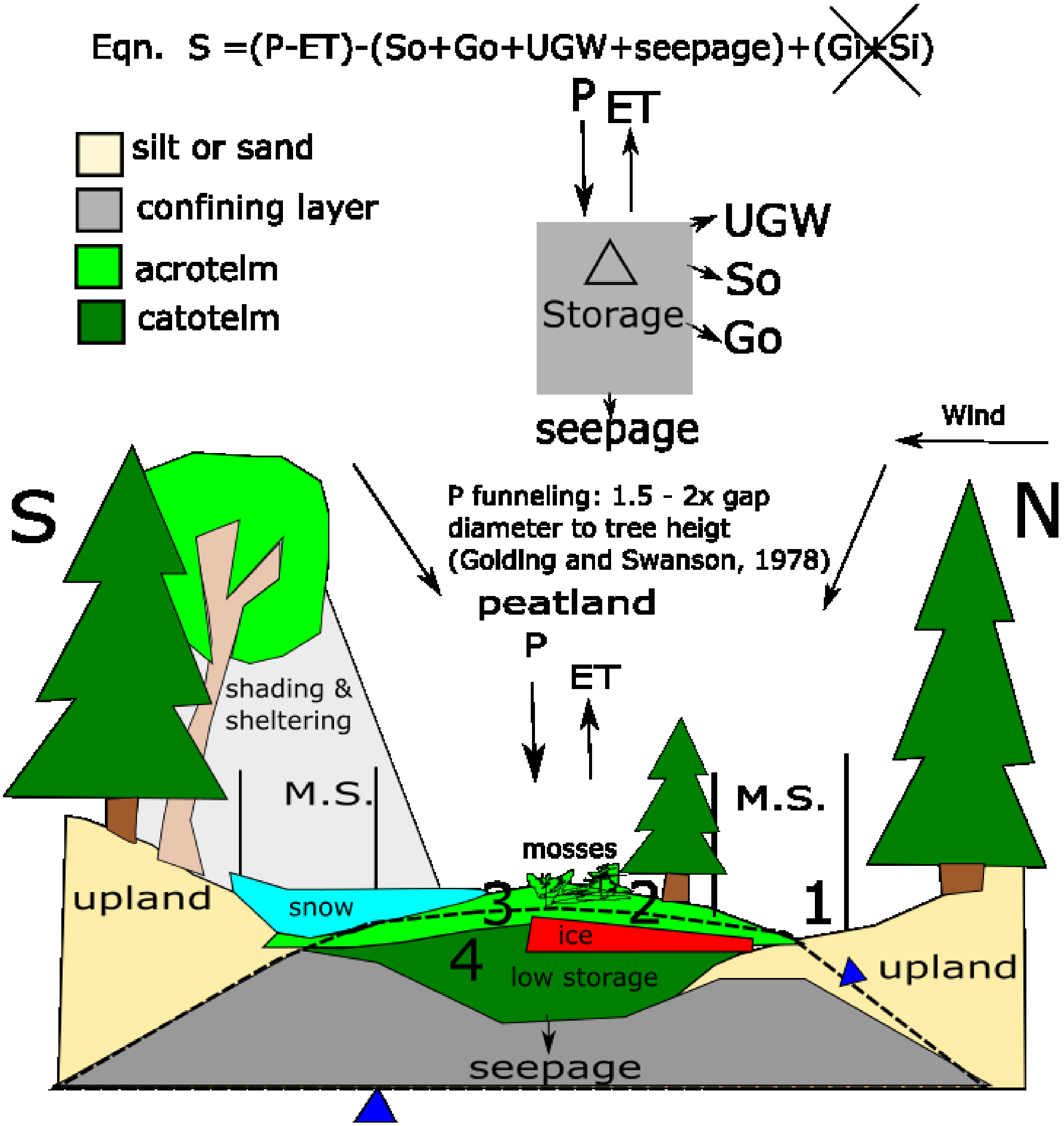
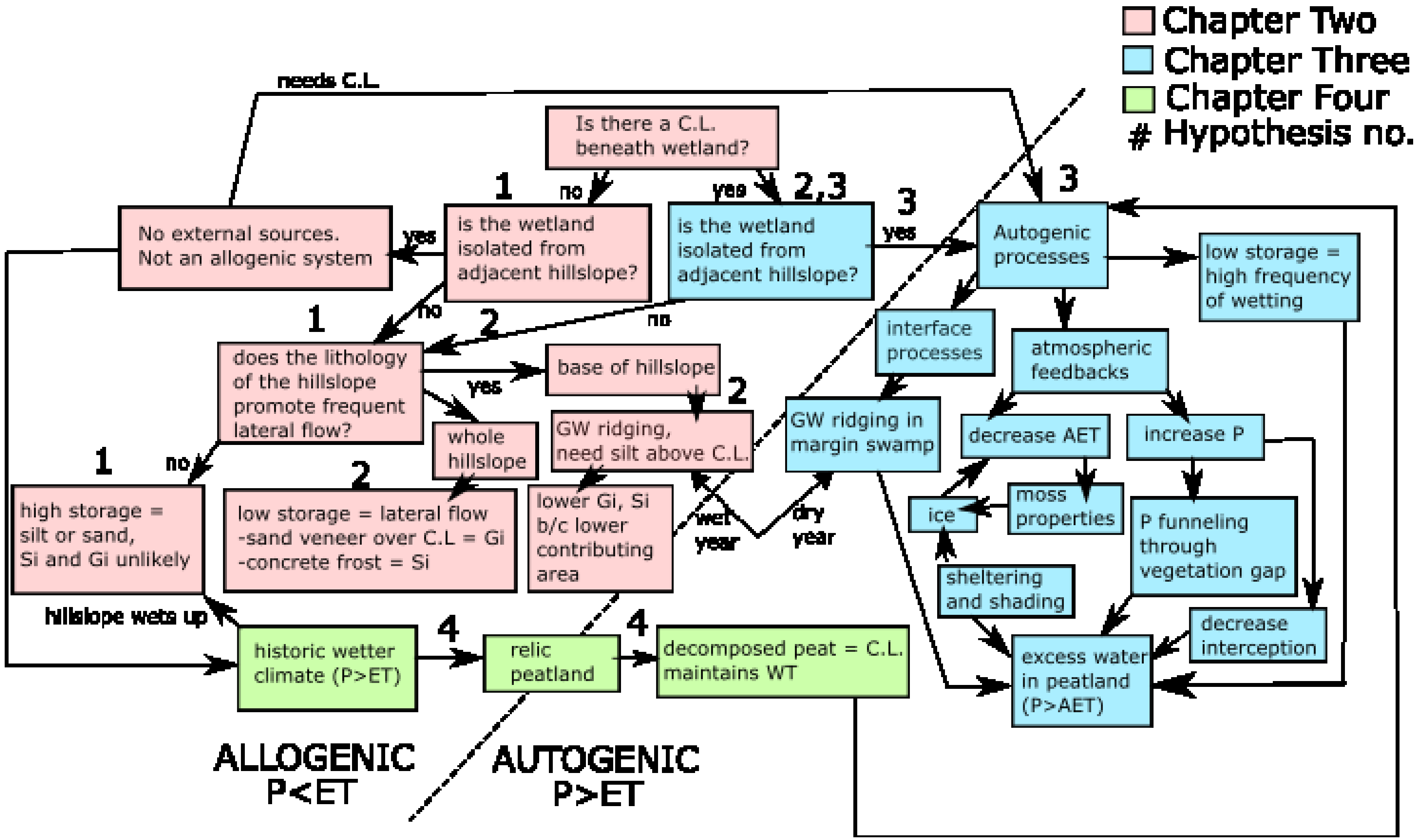


Figure 1.4: Hypothesis 3: autogenic wetland processes and flow paths for wetland maintenance. Water budget requires P > ET and low outputs. Wetland dependent on autogenic processes such as shading/sheltering, moss properties, snow, P funneling and low storage. Potential flow paths are: (1) Groundwater ridging in swamp (swamp to peatland), (2) flow over ice (peatland to swamp), (3) flow through acrotelm (peatland to swamp), and (4) lateral flow through catotelm. M.S. denotes margin swamp.



C.L. = lithological barrier impeding flow
e.g. clay rich soil

Figure 1.5: Conceptual model flow chart for the formation and maintenance of permanent perched wetlands in the sub-humid Boreal Plain.

Chapter Two: Water budget and geologic setting of a perched wetland complex in the sub-humid Boreal Plain

1.0 Introduction

Permanent perched peatlands have been identified 20 m above regional groundwater in the sub-humid Boreal Plain (BP) of Alberta. These peatlands occur in basins and topographic highs and appear isolated from external (allogenic) ground and surface waters (Riddell, 2008). The hydrologic function of perched peatlands in the BP is unclear. Perched peatlands may not require groundwater, and could function as autogenic systems, capable of generating water (Riddell, 2008). Further, the presence of margin swamps encircling perched peatlands is a feature ubiquitous in the BP landscape (Dimitrov et al., 2014). The role these ever-present margin swamps play in peatland maintenance and expansion is currently unknown. The sub-humid climate and apparent hydrologic isolation of permanent perched wetlands raise fundamental questions in respect of their ongoing existence. This paper tests alternative hypotheses in response to the research question: How does a permanent perched wetland on a topographically high landscape position maintain itself in sub-humid conditions?

The term 'perched' is applied to hydrologic systems that form above underlying groundwater, separated by an unsaturated zone (Meinzer, 1923). A wetland is a zone between aquatic and terrestrial defined by the WT at, near and above the surface long enough to promote hydric soils and hydrophytic vegetation growth (Mitsch and Gosselink, 2007). Perched wetlands typically overlay a confining layer (CL) which inhibits infiltration, and facilitates a perched water table (WT) (Cable-Rains et al., 2006; van der Kamp and Hayashi, 2009, Riddell, 2008). Confining layers form through contrasts in soil hydrologic conductivity, resulting in either a capillary or hydraulic barrier (Li et al., 2013).

Perched systems are widely distributed across North America, occurring as vernal pools (Brooks and Hayashi, 2002; Zedler et al. 2003; Cable-Rains et al., 2006), glacial outwash lakes (Rosenberry, 2000), shallow ponds (Walker and Harris, 1976; Peters et al., 2006), prairie potholes (Winter and Rosenberry, 1995; van der Kamp and Hayashi, 2009), and peatlands (Boelter and Verry, 1977; Dempster et al., 2006; Metcalfe and Buttle, 2001; Riddell, 2008). While prairie pothole hydrology is well understood (e.g., Meyboom, 1966; Hayashi et al., 1998; van der Kamp and Hayashi, 2009), there is a gap in the literature on the hydrologic role of perched wetlands (Cable-Rains et al., 2006), particularly in the BP (Riddell, 2008).

Perched wetlands in moisture deficit climates appear to rely on external sources of water. Perched wetlands and shallow lakes have been documented within large riverine floodplains (Fisher and Willis, 2000; Peters et al., 2006). These systems rely on allogenic (external) water sourced during flooding. For example, in the Peace-Athabasca Delta (PAD), high water conditions were found to recharge perched basins (Peters et al., 2006). Once filled, the water level in perched basins declined as evaporation exceeded precipitation (P). Peters et al., (2006) determined that with no allogenic inputs, perched pond water in a PAD basin 0.8 m deep endured 5 – 10 years before drying, subject to climate cycles.

Vernal pools are small depressional wetlands that fill and dry seasonally (Korfel et al., 2010). Similar to PAD perched basins, vernal pools also depend on externally sourced water such as snowmelt runoff, ephemeral streams and shallow groundwater to inundate pools. Perched vernal pools in central California form over low permeability claypans and duripans (Cable-Rains et al., 2006). From October to May ~96% of annual P occurs, charging vernal pools and creating perched aquifers. These vernal pools are part of a flow through system, receiving water from up gradient perched aquifers and discharging water to down gradient seasonal streams.

Prairie potholes exhibit a range of hydrologic connections. They may form part of longer flow systems or may be isolated and perched (e.g., Meyboom, 1966; LaBaugh et al., 1998; Hayashi and van der Kamp, 2009). Prairie potholes typically overlay a substrate of low hydraulic conductivity containing the WT and consist of an ephemeral pond encircled by riparian wetland vegetation. Local flow systems develop both into and out of the wetland, governed by season (e.g., Meyboom, 1966). In spring, groundwater mounds form beneath the base of prairie potholes from snowmelt runoff, creating ephemeral ponds. Flow is directed both laterally and vertically as the groundwater mound slowly dissipates. In summer, regional evapotranspiration (ET) greatly exceeds P (van der Kamp and Hayashi, 2009), and the ponds dry. Prairie potholes, perched PAD basins, and vernal pools rely on allogenic water originating outside the wetland.

Perched peatlands forming above regional groundwater have been documented in wetter climates (P > PET) such as southern Ontario, northern Manitoba and Minnesota (Boelter and Verry, 1977; Dempster et al., 2006; Metcalfe and Buttle, 2001). Fine-textured material beneath these perched peatlands decreases seepage, maintaining the WT. In northern Manitoba, Metcalfe and Buttle (1999) noted small disconnected perched peatlands. These peatlands were isolated from allogenic surface and ground water, receiving water through P.

To maintain permanent wetland conditions in a climate deficit region such as the BP, perched peatlands require either allogenic sources (local ground or surface water) and or autogenic (within wetland) processes to increase P relative to ET. On BP hillslopes, sub surface lateral flow generation and runoff are limited (Devito et al., 2005b; Redding and Devito, 2010), unlike other documented perched wetlands (e.g., prairie potholes, Winter and Rosenberry, 1995). This is accounted for by the high storage capacity of deep glacial deposits and subdued landscape topography typical of the BP (Devito et al., 2005b; Thompson et al., 2015). In light of this, perched peatlands may not depend on local allogenic ground or surface water from adjacent hillslopes, suggesting autogenic feedbacks may play a dominant role in maintaining wetland conditions.

In continental peatlands, Waddington et al. (2015) found that negative feedbacks relating to water conservation outnumbered positive, implying that peatlands function to conserve water. There are several ways that autogenic peatland feedbacks relating to the structure of peat and surface mosses could function to enhance or reduce WT depth in continental peatlands (Waddington et al. 2015). For example, moss becomes resistant to evaporation when the WT drops below a threshold depth of ~30 cm (Hayward and Clymo, 1982; Kettridge and Waddington, 2014), causing a hydrologic disconnect between peatland surface and WT (Price, 1991). This could allow isolated peatlands to store snowmelt and rain water and hold it through the summer months via decreased evaporation. Moss species and tree density also influence surface evaporation on peatlands (Kettridge et al., 2013). A higher proportion of feathermoss relative to sphagnum moss cover decreases surface evaporation, as feathermoss has a greater resistance to evaporation than sphagnum (Brown et al. 2010; Kettridge et al., 2013).

Further autogenic processes associated with low wetland storage (Rodriguez-Iturbe, 2000), P funneling (Golding and Swanson, 1978), sheltering and shading by adjacent trees (Petrone et al., 2007), and ice in the rooting zone (Steele, 1997) could function to increase P and or decrease ET, reducing the climate deficit and generating excess water in a perched peatland.

In the Athabasca oil sands (AOS), watershed scale reconstruction is underway in an effort to restore the land to equivalent capability post-mining (Devito et al. 2012). The current paradigms feature wetlands constructed low in the landscape, receiving water from local hill slopes (Price et al. 2010; Rooney et al. 2012). However other work has shown that in the BP water does not necessarily follow traditional downslope flow paths (Ferone and Devito, 2004; Devito et al. 2005a; Riddell, 2008). In the AOS, contamination of groundwater from salt and hydrocarbons associated with mine tailings used in landscape reconstruction may present a major impediment to reclamation (Quagraine et al., 2005). Since perched peatlands appear isolated from potentially contaminated groundwater (Riddell, 2008), incorporating perched peatlands into watershed reconstruction could provide an important fresh water source for headwater streams and surrounding forest vegetation. Constructing perched peatlands on topographic highs presents an alternative landscape position and contrasting hydrologic function to peatlands constructed in low lying areas (e.g., Sandhill and Nikanotee fens, Pollard et al., 2012).

Peatlands form in a range of geologic settings across the BP with varying degrees of connectivity to groundwater, dependent upon landscape position and Hydrologic Response Area (HRAs; e.g., Ferone and Devito, 2004; Smerdon et al., 2005; Hokanson et al., 2016), defined as landforms with similar permeability and water transmission properties. For example, peatlands forming in coarse-grained material such as sand or gravel are typically connected to deeper groundwater flow paths, and rely on groundwater to maintain saturation, as seepage beneath the wetland is high (Smerdon et al., 2005; Hokanson et al., 2016). Other peatlands in the BP form over fine-grained material such as silt and clay and are associated with local rather than intermediate groundwater flow paths (Ferone and Devito, 2004; Hokanson et al., 2016). Seepage is much lower beneath such peatlands (Ferone and Devito, 2004; Riddell, 2008). However, during wet periods in the climate cycle, these peatlands may be ephemerally connected to large groundwater flow systems (e.g., Hokanson et al., 2016).

Numerous small permanent peatlands occur on topographically high landscape positions in the BP (Hokanson et al., 2016; Lukenbach et al., 2016), inferring relative isolation from adjacent hillslopes and limited groundwater connectivity. Little is known of the function of these peatlands with respect to carbon storage and forest diversity, or their susceptibility to the changing climate (Riddell, 2008). Perched peatlands may be constructed in any landscape position, and may function to generate water to surrounding ecosystems (Riddell, 2008). The margin swamp surrounding the peatland may play a role in maintenance and development of isolated peatlands through paludification. The potential function of negative autogenic feedbacks on continental peatland resilience has been recognized (e.g., Waddington et al., 2015), but not quantified within a water budget study.

In this paper, a water budget approach is taken to assess the relative importance of allogenic sources and autogenic wetland feedbacks in maintaining permanent perched wetlands in sub-humid conditions. A small perched wetland located on a topographic high presents an ideal locus to assess inputs and outputs, as this wetland is likely to be isolated. The following questions are posed:

a) Does the wetland depend on any allogenic sources i.e., adjacent upland hillslopes or ephemeral groundwater connections?
b) What is the role of a confining layer in permanent wetland maintenance (Chapter One Figure 1.5)?

Three alternative hypotheses for wetland maintenance are evaluated, from perspectives of water budget and geologic setting:

a) Allogenic wetland with no confining layer: high seepage, requiring high surface and or local groundwater inputs to offset $P < ET$ deficit (Chapter One Figure 1.2)

b) Allogenic wetland with confining layer: decreased seepage, requiring less surface and or local groundwater to offset P < ET deficit (Chapter One Figure 1.3)

c) Autogenic wetland with confining layer: requiring wetland P > ET and low outputs (Chapter One Figure 1.4).

2.0 Site description

The study site is 370 km north of Edmonton in north central Alberta within the Utikuma Region Study Area (URSA, 56°6'N, 116°32'W, Figure 2.1). The URSA is located in the Mid-Boreal Uplands Ecoregion of the BP Ecozone (Ecological Stratification Working Group, 1996), and the central mixed wood sub region within the Boreal Forest ecoregion of Alberta (Natural Regions Committee, 2006). The climate is sub-humid; average annual PET (518 mm) exceeds average annual P (486 mm) (Environment Canada, 2003). Winter and Woo (1993) and National Ecological framework (Marshall et al., 1999) place the URSA in a moisture deficit region. Air temperature ranges from -14.6 ^{0}C (January) to 15.6 ^{0}C (July) (Environment Canada, 2003), with winter snow averaging < 25% (100 mm; Pomeroy et al., 1997) and the majority of rainfall occurring in June, July and August as convective storms (Devito et al., 2005b). Water surpluses (regional P >> PET) occur approximately every 20 years (Devito et al., 2005b; Mwale et al., 2009). Surficial geology of the area is characterized by three geomorphic landforms: hummocky coarse-textured glaciofluvial deposits, fine-textured, low relief glaciolacustrine deposits, and hummocky fine-textured stagnant ice moraine deposits (Fenton et al., 2013). These glacial deposits overlie siltstone and shale bedrock of the Upper Cretaceous Smoky Group (Prior et al., 2013), and range from 60 to 120 m in thickness (MacCormack et al., 2015).

A previous study (Riddell, 2008) described perched wetlands situated on a topographic high within the URSA (Pond Catchment 19; Figure 2.1b), on the transition zone between a stagnant ice moraine to the east (fine textured) and a glaciofluvial deposit to the west (coarse textured) (Fenton et al., 2003; Ferone and Devito, 2004; Smerdon et al., 2005; Figure 2.1b). Observation wells installed within the transition zone showed perched WT approximately 20 m above regional groundwater, with meters of unsaturated sediment between perched and deep ground WT. Riddell (2008) concluded a 2 - 3 m thick clay rich clogging layer < 2 m below the ground surface was responsible for maintenance of perched WT and the presence of wetlands (Figure 2.2b).

This paper reports additional findings within Pond Catchment 19 (2.3 km^2) in the URSA (Figures 2.1b and 2.2*)*. The catchment comprises a shallow pond-marsh complex (Pond 19, 1.7 ha), an ephemeral draw connected to the pond (0.7 ha), and peatlands of varying size (0.24 - 1.75 ha) (Figure 2.2a). Research focuses on perched wetland H (Figure 2.2), a 0.49 ha complex containing a peatland encircled by margin swamp on a topographically high landscape position within Pond Catchment 19. Perched wetland H occupies a flat hilltop approximately 3 m above the ephemeral draw and Pond 19. Topography is saddle-like in the northwest and east, with a closed, irregularly shaped catchment and no flow outlet. The topographic catchment is approximately 0.8 ha; the majority of the catchment area is in a narrow zone to the north and to the south and southeast (Figure 2.3). Elevation differences between upland hillslopes and perched wetland H are up to 2.4 m, with a maximum slope of only 0.03. The catchment was visually delineated using 0.2 m contours derived from a digital elevation model in ArcMap V.10.4.

In perched wetland H, the peatland is classified as coniferous treed basin bog (Canadian Wetland Classification System, National Wetlands Working Group, 1997), or as a wooded bog (Alberta Wetland Classification System; ESRD, 2015). The margin swamp is classified as a hardwood treed peat margin swamp (National Wetlands Working Group), or a deciduous wooded swamp (ESRD, 2015). The peatland has an approximate area of 0.24 ha, and has accumulated up to 1 m of peat. The surrounding swamp area is 0.25 ha, with 0.2 m depth of organics. Mineral soils in the swamp and beneath the peat are Gleysols, while upland soils are classified as Grey Luvisols. The forest canopy encircling the wetland complex consists of aspen (*Populous tremuloides,* ~20 m) and stands of white spruce (*Picea glauca,* 20 – 30 m) in the north, east, and south portions of the wetland. Dominant wetland vegetation comprises paper birch (*Betula papyrifera,* ~ 10 m), alder (*Alnus*), and willow (*Salix*) in the margin swamp, and stunted black spruce (*Picea mariana,* 3 - 4 m) with bog birch (*Betula pumila*) in the peatland. The surrounding forest is taller than wetland trees, resulting in a gap in the forest canopy over the wetland. Peatland understory vegetation comprises Labrador tea (*Rhododendron groenlandicum*), leatherleaf (*Chamaedaphne calyculata*), cloud berry (*Rubus chamaemorus*) and bog cranberry (*Vaccinium oxycocco*). Hummocks and hollows in the peatland are dominated by sphagnum (*magellanicum, fuscum, angustifolium*) and feathermosses. Microtopography variations across the peatland are 0.3 m vertically and 1 m horizontally between hummocks and hollows. Onsite mapping, soil coring, and aerial imagery provided for accurate wetland delineation. Wetland – upland boundaries at perched wetland H were identified by observed vegetation changes between margin swamp and upland species and presence of wetland (hydric) soil. Boundaries were also determined by measuring depth and decomposition of organic soil horizons to distinguish between peatland and swamp, and swamp and upland forest.

3.0 Methods

3.1 Water budget

Perched wetland H consists of a peatland and margin swamp, so the wetland boundary was defined as the outside edge of the margin swamp (Figure 2.3). The water budget equation for the whole wetland is:

$$\Delta S = (Pnet - AET) - (So + \ Go + Seepage \pm UGW) + (Si + Gi) \pm residual\ error$$

(2.1)

where $Pnet$ is net precipitation (total precipitation minus interception), AET is actual evapotranspiration, So is surface water out, Go is groundwater out, $Seepage$ is vertical drainage beneath wetland, UGW is unsaturated groundwater flow, Si is surface water into wetland, and Gi is local groundwater from adjacent hillslopes. As the wetland is perched some 20 m above regional groundwater, deep groundwater input is assumed negligible. Water budgets were calculated for the hydrologic year 1 November 2014 - 31 October 2015. Each component was estimated for the winter-spring season (1 November 2014 - 30 April 2015) and summer-fall season (1 May 2015 - 31 October 2015), then totaled to account for the full hydrologic year. The following sections describe methods employed to estimate components of the water budget.

3.2 Precipitation

Precipitation (P) in the open was measured adjacent Pond 19 using a tipping bucket rain gauge (Jarek Tipping Bucket Rain Gauge, Geoscientific Ltd., Vancouver, Canada; Figure 2.2a). Another tipping bucket was installed in the peatland canopy gap at wetland H (HOBO Rain Gauge Datalogger, Onset Computer Corporation, MA, USA) April 2015 - October 2015 in the peatland centre. Precipitation was considered to be snow if mean daily temperature was < 2°C. At both Pond 19, wetland H, and wetland S8 a bulk rain gauge was installed in the open area adjacent the meteorological (MET) towers (Figure 2.2) during the snow-free period late April - October 2015, and measured weekly to twice-monthly to validate tipping bucket measurements. Bulk precipitation measurements were collected at Pond 19 by weighing a P bucket monthly November 2014 - October 2015, and were also used to validate total P. Monthly winter snow surveys during the same time period measured snow depth, ice depth and snow water equivalence (SWE) across perched wetland H (Figure 2.3 from A-A'). Monthly snowboard snow depth and SWE measurements were taken adjacent Pond 19 and in the centre of wetland H beside the tipping buckets. Peak winter snowpack at perched wetland H was measured prior to spring melt on 13 March 2015 and 4 March 2016, using star-shaped transects throughout the wetland and adjacent forest (see Chapter Three), similar to Golding and Swanson (1978). These transects provided spatial snow depth point data for peatland (604 pts/ha) and margin swamp (557pts/ha) (Golding and Swanson, 1978). Representative spot SWE were also measured around the wetland on 13 March 2015 (n = 83) and 4 March 2016 (n = 134). Snow depths were converted to SWE using a linear regression between snow depth and SWE from the spot data. Spatially weighted average SWE was found for peatland and swamp using the spatial cell declustering method (declus.exe, Deutsch and Journel, 1992). Winter interception was estimated using total precipitation minus peak spatially averaged snow accumulation in the wetland, assuming winter interception included both vegetation interception and sublimation. Winter interception % was calculated for both peatland and swamp. A weighted average (48% peatland, 52% swamp) was used to estimate total wetland winter interception % for the entire wetland for the winter period (1 November 2014 - 30 April 2015).

Summer interception was estimated using through fall hand gauges placed beneath the dominant vegetation zones, and spaced evenly around the wetland and adjacent forest: peatland (n = 10), margin swamp (n = 3), aspen forest (n = 2) and white spruce stands (n = 2). Stem flow was assumed a negligible component of interception in the peatland (Price et al. 1997), but assumed to be 5% in the birch margin swamp from measurements conducted on a nearby catchment (Pond Catchment 40-43, Mika Little-Devito and Kevin Devito, unpublished data). Average P net for the snow-free season within the peatland and margin swamp was determined using total P values, average through fall rain gauge estimations of interception, and stem flow when applicable, i.e., in margin swamp. Proportion of canopy, edge and gap determined from the peak winter snow survey were employed to calculate spatially weighted average interception for the peatland i.e., 50% gap, 30% black spruce edge, and 20% black spruce canopy. Margin swamp and peatland average interception were weighted by area to total wetland average interception. P net for the snow-free period (1 May 2015 - 31 October 2015) was total P minus wetland average interception. For annual P net, winter and snow-free periods were summed.

3.3 Evapotranspiration

Potential evapotranspiration (PET) at Pond 19 was measured during the open water period 11 May 2015 - 12 October 2015 using a Class A evaporation pan at the south end of the pond. For most of this period the pan was submerged, similar to Ferone and Devito (2004) and Smerdon et al., (2005). Another evaporation pan was placed in the centre of wetland H on the peat surface 27 May 2015 - 10 October 2016. A pressure transducer (Solinst Levelogger model 3001, Solinst Canada Ltd.) on the pan bottom recorded continuous water levels for comparison with discrete manual measurements taken every two weeks. Water levels in the pans were maintained to within 15 cm of the top of the pan. A 0.9 correction coefficient was applied to Pond 19 pan following Smerdon et al. (2005) and Riddell (2008).

Actual ET in the peatland was estimated using a plastic bucket lysimeter (area = 0.18 m^2) filled with a 30 cm depth peat monolith, similar to Van Seters and Price (2001) 15 June 2015 – 10 October 2015. The monolith was representative of the dominant surface vegetation, containing both sphagnum and feathermoss groundcover with a Labrador tea shrub layer. The bucket containing the peat was perforated, and another bucket placed beneath. Both buckets were weighed weekly to twice-weekly; water in the bottom bucket was assumed to be drainage. Twice-monthly soil moisture measurements taken in the lysimeter and adjacent peat showed similar measurements. The WT remained below the base of the lysimeter over the course of study.

A MET tower placed in the open area beside the evaporation pan measured air temperature (^{0}C, HOBO U23-001 data logger), relative humidity (%, HOBO U23-001 data logger), wind speed (m s^{-1}, Young wind and direction monitor model 03002-5, R.M. Young Company, Michigan, USA), wind direction (0-360^0), and net radiation (Wm^{-2}, NRlite net radiometer, Kipp and Zonen, The Netherlands) at 2 m height. Radiometer malfunctions for April 2015 required that data be gap filled from the MET tower at wetland S8, 340 m southeast of perched wetland H (Figure 2.2). A linear regression was employed between the two tower sites using data from May to August 2015. Soil moisture (θ, m^3m^{-3}) was measured using a time-domain reflectometry (TDR) probe (CS616, Campbell Scientific Inc., Utah, USA) installed vertically into peat; the TDR averaged volumetric water content (VWC) over 30 cm. Additionally, soil temperature probes (107 temperature probes, Campbell Scientific Inc., Utah, USA) were installed at 2, 5, and 15 cm below ground adjacent the TDR probe. All sensors (except HOBO U23-001) were connected to a

Campbell Scientific CR1000 data logger. Instruments were scanned every 30 seconds, and averaged at half-hour intervals. All sensors except the TDR probe were installed late August 2014. The soil moisture TDR probe was installed early July 2015. In conjunction, manual soil moisture measurements were estimated from bi-monthly PR2 probe measurements (PR2/6, Delta-T Devices Ltd., Cambridge, UK) taken 10 m from the TDR probe, interpolating between measurement dates for April through June 2015. Ground heat flux (Qg, Wm^{-2}) was estimated with the calorimetric method (Oke, 1987), employing ground temperature profiles and heat capacity values of peat under varying moisture contents (Brown et al., 2010, Sutherland et al., 2014). Mean daily ground heat flux was shown to be 1 to 2 magnitudes below net radiation (Brown et al., 2010; Brutsaert, 1982).

PET was estimated using the Thornthwaite (1948), Hamon (1963), and Priestley-Taylor (Priestley and Taylor, 1972) models. The Thornthwaite (1948) method is a temperature-based empirical monthly calculation based on average monthly temperature (Riddell, 2008):

$$PET = 1.6 \times \left[\frac{10T_a}{I}\right]^a \tag{2.2}$$

$$I = \sum_{12}^{1} \left(\frac{T_a}{5}\right)^{1.5} \tag{2.3}$$

where PET in mm/month, T_a is average monthly air temperature in °C, I is annual heat index, and a is equal to $(0.49 + 0.0179I + 7.71 * 10^{-5}I^2 + 6.75 * 10^{-7}I^3)$. To compare temperature-based PET methods, Hamon (1963) PET was calculated using the model from Rao et al. (2011):

$$PET = 0.1651 * L_{day} * \rho_{sat} \tag{2.4}$$

$$\rho_{sat} = \frac{216.7 * e_s}{T + 273.3} \tag{2.5}$$

$$e_s = 6.108 * e^{\frac{17.26*T}{T+273.3}} \tag{2.6}$$

where PET is daily PET (mm), L_{day} is daytime length from sunrise to sunset in hours (e.g., 13.2 hrs of daylight on 2 April 2015), ρ_{sat} is saturated vapour density at daily mean air temperature T (°C) and e_s is saturated vapour pressure (mbar) at a given temperature. The Hamon (1963) estimation was expected to provide similar results to the Thornthwaite (1948) method (Federer and Lash, 1983).

The Priestley-Taylor equation for PET is a radiation-based method employing net radiation (Q*) and temperature to estimate equilibrium evapotranspiration (PET_{EQ}), which assumes that air moving over a homogenous, well-watered surface becomes saturated (Slatyer and McIlroy, 1961; Dingman, 1994). Evapotranspiration reaches a state of equilibrium under these conditions (Priestley and Taylor, 1972). PET_{EQ} was calculated as in Brown et al. (2010):

$$PET_{EQ} = \frac{\Delta}{\Delta+\gamma} * (Q^* - Q_G) \tag{2.7}$$

where Δ is slope of saturated vapour pressure curve in kPa^0C^{-1}, γ is psychrometric constant in kPa^0C^{-1}, Q* is net radiation in Wm^{-2}, and Q_G is soil heat flux in Wm^{-2}. PET_{EQ} is related to PET via the Priestley-Taylor coefficient, α, defined as (Priestley and Taylor, 1972):

$$\alpha = 1.26 = \frac{PET}{PET_{EQ}} \tag{2.8}$$

where PET is potential evapotranspiration, defined as the ET rate when neither energy nor moisture is limiting (Priestley and Taylor, 1972). Equilibrium is rarely achieved, therefore alpha greater or less than 1.26 represents AET. Given the scope of this research, literature values were used for alpha. An alpha factor of 0.69 was developed from a riparian peatland complex at the URSA with similar WT (50 – 80 cm below the surface), moss and shrub area, located 3.8 km from the perched study site (Petrone et al., 2007). Alpha was determined by relating PET_{EQ} to AET through Eqn. 2.8, where AET is used instead of PET, via the Bowen ratio energy balance (Petrone et al., 2007). In a similar study at the same riparian peatland complex, a time-series of alpha values was generated for early green (JD 121-158), green (JD 158-218), and late green (JD 219-280) for 2005 and 2006 snow-free seasons (Brown et al., 2010). AET was determined via eddy covariance, and related to PET_{EQ}. Alpha values for the northwestern site reported in Brown et al. (2010) were deemed most similar to perched wetland H, namely 0.87 for early green, 0.79 for green, and 0.77 for late green. The alpha values from Petrone et al. (2007) and Brown et al. (2010) described above were applied to provide a range of estimated AET at perched wetland H for comparison with measured AET (lysimeter) and the peatland evaporation pan.

3.4 Saturated zone

3.4.1 Soil stratigraphy

Shallow soil stratigraphy across the perched wetland and adjacent upland was assessed along north-south and east-west transects (Figure 2.3 A-A’, B-B’). Exploratory and well/piezometer boreholes were cored using 1” or 2” bucket augers approximately every 5 m. Soil texture was classified in the field with a rub test (Thien, 1979). Field texture was paired with soil types developed from particle-size analysis (Riddell, 2008), and combined with survey data recorded with an autolevel (Top Site TIA 16673 Astor Precision Equipment Co. Ltd., China). Borehole and well locations, were used to create cross-sections of shallow soil stratigraphy.

3.4.2 Hydrometric measurements

A network of wells (n = 29) and piezometers (n = 14) was installed around the perched wetland summer 2014 and 2015 to characterize the local groundwater flow regime (Figure 2.3). Transects extending from the peatland centre were employed to assess the perched WT across the peatland, margin swamp and upland forest. Wells were constructed with slotted 2” PVC pipe wrapped in well sock and inserted into pre-drilled boreholes. The void between well casing and borehole wall was filled with silica sand. Well depth was determined by soil texture, with deeper wells installed to top of CL (up to 2 m) and shallow wells installed to 0.5 m, to intersect perched WT. Piezometers were installed using 1” PVC pipe wrapped in well sock and bottom screened for 0.2 – 0.3 m. Wells were developed by purging water following installations. For installations above the CL it was necessary to back-fill with silica sand, then seal with bentonite clay above the screen. Piezometers installed within the clay CL were drilled to top of clay, then driven down to a depth slightly greater than the length of the screen to create a seal. A similar technique was used for piezometers within the peatland: a borehole was drilled to top of decomposed peat; the piezometer was then driven down the approximate length of the screen to seal. Regional groundwater levels were recorded using deep piezometers (25 - 27 m), constructed of 1.5” PVC pipe and 1.5 m screens which had been installed below the regional WT 2001 - 2003 (Riddell, 2008). All well and piezometer locations were given unique identifiers: site-equipment-equipment depth, e.g., 81-Wsh-50.

Manual WT measurements were made in all wells and piezometers summer from 2014 to spring 2016. Wells and piezometers were measured monthly November 2014 - March 2015. During the snow-free season, manual water level measurements were taken weekly to twice monthly 2014 to 2016, and with increased frequency following storms. At each site, water level, depth to ice, depth of rust, and depth of standing water (if present) were recorded. Electrical conductivity of ground and surface water was also recorded (TLC meter, Solinst Canada Ltd., ON, Canada). In addition, automated pressure transducers (Solinst level logger model 3001; HOBO U20 water level data logger, Onset, MA, USA) were installed April 2015 at six key wells in the peatland, margin swamp and upland, and corrected for atmospheric pressure with a barologger (Solinst barologger model 3001, Solinst Canada Ltd., ON, Canada). Saturated hydraulic conductivity values for CL and lower peat (60 - 100 cm) were estimated using slug tests conducted in 9 piezometers within wetland H (n = 5 clay layer, n = 4 lower peat) (Hvorslev, 1951). These supplemented hydraulic conductivities for 20 piezometers at adjacent perched wetlands within Pond Catchment 19 (Riddell, 2008).

3.4.3 Shallow groundwater flow

Saturated flow of perched groundwater was estimated using Darcy's Law (Freeze and Cherry, 1979):

$$Q = -KA\frac{dh}{dL} \tag{2.9}$$

where Q is discharge (m^3s^{-1}), K is saturated hydraulic conductivity (ms^{-1}), A is cross-sectional area of seepage (m^2), and $\frac{dh}{dL}$ is hydraulic head gradient. In the peatland no channeling was observed, so groundwater was assumed to be lost through lateral seepage. To account for the diplotelmic structure of peat, lateral groundwater flux was calculated through two flow tubes, assuming Dupuit-Forcheimer flow (Freeze and Cherry, 1979; Ferone and Devito, 2004). The first tube was defined by thickness of acrotelm (0-35 cm); the second by thickness of catotelm above the CL at the peatland margin. Hydraulic conductivity of the lower peat from slug tests was employed for the catotelm. When a WT was present in the acrotelm, saturated hydraulic conductivity was applied from Ferone and Devito (2004). The resulting flow out of the acrotelm and catotelm was summed. The saturated flow from swamp to upland was estimated with values of hydraulic conductivity from Riddell (2008) and from Hvorslev slug tests at Pond Catchment 19. The flow tube depth was defined by ground surface to top of CL. A geometric mean of 10^{-7}

ms^{-1} was used for the heterogeneous mineral soil above the CL. Lateral gradients for peatland → swamp and swamp → upland were estimated via (Freeze and Cherry, 1979):

$$Lateral\ gradient = \frac{dh}{dL} \tag{2.10}$$

where dh is the difference in water level between two wells, and dL is the lateral distance between wells. Shallow groundwater flow out of the peatland and margin swamp was averaged across the north, south, east and west transects of the wetland using spot water levels. A half-distance interpolation was employed to gap fill between measurement dates, and flow was converted to mm/year by applying total area of the wetland. To account for uncertainties, groundwater flow under maximum and minimum flow conditions was calculated over the entire hydrologic year.

Seepage beneath perched wetland H was estimated applying piezometer data above and within clay from Darcy's law (Eqn. 2.9) using the vertical hydraulic gradient (Freeze and Cherry, 1979):

$$Vertical\ gradient = \frac{dh}{dZ} \tag{2.11}$$

where dh is water level difference between two layers, and dZ is distance between mid-screen point of piezometers. Vertical hydraulic conductivity of the CL is less than horizontal due to anisotropy in soil structure (Freeze and Cherry, 1979). Accordingly, an estimate of $1x10^{-11}$ ms^{-1} was applied for vertical hydraulic conductivity through the CL (Riddell, 2008).

3.4.4 Surface water

Surface water, electrical conductivity and depth to ice in the wetland and adjacent upland were mapped during peak water levels in spring 2015, spring 2016 and summer 2015. This was undertaken using geographic markers, e.g., well sites, recording depth and extent of saturation. Saturation was determined from either the presence of standing water or gravimetric water emitted when soil was placed under pressure (Devito et al., 2005b). Maps were digitized for each period, and % saturation for upland, swamp and peatland determined.

3.5 Vadose zone

3.5.1 Unsaturated groundwater flow

A transect of pits equipped with soil moisture probes and tensiometers was installed along the transition zone from wetland edge to upland forest (Figure 2.3). These pits followed changes in soil water content and unsaturated flux of perched groundwater from wetland to surrounding forest (Riddell, 2008). Installation of instrumentation followed Hayashi et al. (1998), with three pits installed 2 m apart. Depths ranged from 0.4 – 1.0 m below ground; sensors were installed every 0.2 – 0.3 m. Both soil moisture probes (GS-1 soil moisture sensor, Decagon Devices, WA, USA), and tensiometers (MPS-2 dielectric water potential, Decagon Devices, WA, USA) were inserted into the undisturbed pit wall. The pit was backfilled to maintain soil layering and density. Measurements were recorded hourly with an EM50 digital data logger (Decagon Devices, WA, USA), 30 May - 1 November 2015. Lateral and vertical gradients were established across the wetland margin applying both soil tension (unsaturated hydraulic head) and wetland water levels. Rooting depth was estimated using soil tension observations. Unsaturated hydraulic conductivity (K_{unsat}) was estimated from soil texture (silt loam) and VWC applying the Carsel and Parrish (1988) equation. K_{unsat} for minimum, maximum, and average rooting zone VWC (25 cm depth) was thus determined. Darcy's law was employed to estimate unsaturated groundwater flux out of the perched wetland. Total volumetric flux was determined by multiplying rooting zone depth and wetland circumference. Unsaturated flow was assumed uniform around the wetland. Flow under average conditions was used for the water budget; maximum and minimum estimates were used in the error for unsaturated groundwater flow.

3.5.2 Soil water storage

Soil moisture access tubes (1 m) (PR2/6, Delta-T Devices Ltd., Cambridge, UK) were installed in a hummock and hollow near the peatland centre (site 81), and in a margin swamp hollow (site 87) August 2014. These point measurements were considered representative of perched wetland soil moisture (Rodriguez-Iturbe, 2000). Discrete measurements using PR2-6 soil moisture probes were taken at the end of August 2014 and assumed representative for 1 November 2014 measurement due to similar WT depths. Measurements were collected twice-monthly May - October 2015. At each access tube, two measurements were taken by rotating the probe 180˚ between readings, then averaging the readings. Soil moisture was recorded in millivolts (mV) every 10, 20, 30, 40, 60 and 100 cm. Soil specific calibrations were required for peat soil (Figure A.1b), as the PR2 factory calibration (Delta-T Devices Ltd., Cambridge, UK) gave VWC readings > 100%. The mineral polynomial factory equation for mV to VWC was used for silt and clay soils, since field data matched well with this calibration (Figure A.1b). Depth integrated soil water storage over 1 m was calculated for each time period and measurement at each access tube, similar to the calculation of unsaturated storage in Spence and Woo (2006):

$$S_{Z_2-Z_1} = \theta[z_2 - z_1] \tag{2.12}$$

where S is soil water storage from soil depth z_1 and z_2 (mm), θ is soil moisture (m^3m^{-3}), z_1 is soil depth 1 (mm) e.g., 0 mm below ground and z_2 is soil depth 2 (mm), e.g., 150 mm below ground. Soil water for each storage interval, e.g., 0-150 mm below ground, was summed from 0-1000 mm to calculate total soil water storage (e.g., 0-150 mm + 150 – 250 mm + 250 – 350 mm + 350

– 500 mm + 500 – 800 mm + 800 – 1000 mm below ground) in the 1 m soil column. Changes in storage between time intervals for peatland and margin swamp were calculated for two time periods: 1 November 2014 – 30 April 2015 and 1 May 2015 - 31 October 2015.

3.6 Error estimates for the water budget

Estimated errors for the water budget were calculated using minimum, maximum (Devito, 1995) and calculated budget components. Precipitation estimates can exhibit large error estimates (15 - 30%) due to gauge placing, spacing and interpolation techniques (Winter, 1981). On an annual basis, error estimates of precipitation are typically around 5 % (Winter, 1981). Since P falls predominantly as convective storms in the BP (Mwale et al., 2009), spatial variability in P is expected to be high. However, at Pond Catchment 19, hand gauge placements are < 300 m apart, so associated P error is anticipated to be lower than ± 20 % (Winter, 1981; Devito et al., 1989). Total P error was estimated using independent open gauge measurements at Pond19 (site 15), H (site 95), and S8 (sites 53 and 126) MET towers (Figure 2.2). Errors in interception were assumed to be ± 25 %, a conservative estimate according to Crockford and Richardson (2000).

Errors associated with energy based approaches for AET on lakes are 10 – 15% (Winter, 1981). Uncertainty estimates of ± 20% were commonly applied in other budget studies (Lafleur, 1992; Spence et al., 2011; Barr et al., 2012). Evaporation pans are used as a direct measurement of lake evaporation (Winter, 1981). The evaporation pan placed on the surface of wetland H was assumed to represent the maximum amount of ET from wetland H. The minimum AET for the wetland was determined using an alpha value of 0.69 applied to the wetland P-T PET_{EQ} estimate (Petrone et al., 2007). These minimum and maximum estimates were combined with the median estimate (alpha values applied to P-T PET_{EQ} from Brown et al., 2010) to estimate variance in wetland AET. The resulting error estimates for AET were deemed sufficient to capture the potential range of ET at perched wetland H.

Uncertainty in groundwater estimates can be greater than 100% (Winter, 1981). This study employed methods similar to Devito (1995), wherein minimum and maximum groundwater flow were calculated by applying lowest and highest flow in L/day over the entire study period. Variance was estimated using calculated, minimum and maximum values.

The magnitude of total error for the budget was estimated using the least squares method described in Winter (1981) and LaBaugh and Winter (1984), subsequently employed by Devito et al. (1989), Devito and Dillon (1993) and Devito (1995). Total standard deviation for the budget is estimated by:

$$S_{Total}^2 = S_P^2 + S_{Int}^2 + S_{AET}^2 + S_{Gin}^2 + S_{Gout}^2 + S_{UGW}^2 \tag{2.13}$$

where S_{Total} is 1 standard deviation of total error, and S^2 is variance. This equation does not include stream flow or runoff as these components were not observed at study wetland H. It was assumed that measurement errors were independent, so covariance terms were not applied in Eqn. 2.13; ± 1 standard deviation (mm) is presented for a) each term in the budget and b) the total budget (inputs – outputs).

4.0 Results

4.1 Site characterization

4.1.1 Soil stratigraphy

Perched wetland H is underlain by an unfractured, unoxidized blue-grey silty clay, approximately 3 m thick (Figure 2.4). This clay layer occurs directly beneath the peatland, at approximately 1 m depth. Depth to clay in the margin swamp varies from 0.65 m in the west and east, to 1 m in north and south. Thin, heterogeneous soil layers were identified above the clay layer: silt with fine sand, silt loam, silty clay loam, and fine sand with clay interbedded with fine sand. These soil textures extend into the adjacent upland. Depth to clay in the upland decreases to 1.5 m in the south and east; to >2 m in the north and west (Figure 2.4). Silty clay beneath the upland is oxidized and light grey in colour, containing fractures and fine roots. The silt loam - silt clay loam layers along the peatland – swamp boundary show heavy rust mottling, and contain rust nodules up to 1 cm in diameter.

Peat accumulation ranged from 0.45 m along the peat margins (site 27) to 1 m in the centre (site 81). The margin swamp accumulated 0.2 m of organics. Organic soil in the peatland consists of active, or undecomposed peat and lower, decomposed peat, creating a diplotelmic structure (Figure 2.4). Von Post measurements in undecomposed peat ranged from H1 - 4 (0.3 – 0.45 m thickness), with the majority between H2 - 3. Decomposed peat ranged from H6 - 10 (0.4 – 0.7 m thickness); most were between H8 and 9. Swamp organics were 0.17 m thick, with Von Post measurements from H2 - 5. Example photographs of soil cores from peatland centre, edge and margin swamp are included in Figure A.3a - e.

Saturated hydraulic conductivity (K_h) measurements for dominant wetland soil textures are summarized in Table 2.1. Surface organics, LFH (litter-fibric-humic) and active peat displayed the greatest K_h, with values ranging from 10^{-4} – 10^{-5} ms^{-1}. Lower decomposed peat, silt loam, and silt clay loam presented similar K_h values, ranging from 10^{-7} – 10^{-8} ms^{-1}. Fine sand with silt and fine sand with clay interbedded with fine sand showed K_h values of 10^{-5} and 10^{-6} ms^{-1} respectively. The geometric mean of soils above the clay layer was 10^{-7} ms^{-1}. The silty clay – clay layer beneath the wetland showed an average K_h of 10^{-9} ms^{-1} and was therefore assumed to function as a CL, capable of maintaining the perched WT.

4.1.2 Water table configuration

A laterally discontinuous WT terminating at the wetland border with unsaturated adjacent uplands was observed across all transects at perched wetland H (Figure 2.4). The regional WT was consistently measured 22 m below the surface (site 03-P13) throughout the study period (Figure 2.12), implying approximately 19 m of unsaturated soil between perched and regional WT. Consistent with this observation, dry (2 m+ deep) wells and piezometers were noted within the adjacent upland > 5 m from the wetland edge, inferring an inverted perched WT beneath the wetland (Figure 2.4). No water was observed in upland wells > 5 m from the wetland edge. These data suggest the perched WT is contained by a shallow CL <1.5 m from the surface, namely the silty clay and lower decomposed peat (Figure 2.4). The lateral extent of perched groundwater across the wetland varied by moisture condition. During wet periods the saturated zone extended to the wetland edge; in dry periods, the WT terminated at the peatland edge, and the margin swamp dried (Figure 2.4).

4.2 Wetland inputs and outputs

Wetland inputs and outputs for the 2014 – 2015 hydrologic year are shown in Table 2.3. Sections 4.2.1 – 4.2.5 present each budget component in more detail; Section 4.3 summarizes the water budget.

4.2.1 Precipitation and interception

Total annual P for hydrologic year 1 November 2014 – 31 October 2015 in the perched wetland was 391±7 mm (Table 2.3, Figure 2.5), 20 % below the long-term average for the URSA (Figure 2.6). A similar below average trend was observed when comparing total P at wetland H to 30 year averages at two nearby Environment Canada weather stations - Red Earth Creek (448 mm) and Peavine (471 mm) (Figure 2.5). The decadal climate cycle showed a wetting trend to 2013, after which the wettest spring in over 10 years occurred in 2014. However the 2014-2015 hydrologic year displayed a two-year cumulative departure from the long term mean of -131 mm (Figure 2.6). Although 2014 – 2015 hydrologic year exhibited below average annual P, snow fall was above average (>100 mm, Pomeroy et al., 1997), approximately 36% of total P (144 mm, Figure 2.5). On 5 May 2015, 18% of total snowfall (26 mm) recorded in 2014 – 2015 hydrologic year occurred in a single event. The balance of P (250 mm, 65% of total P) was rain, between May and early October 2015. During the 2015 snow-free season, there were only 6 rain events exceeding 10 mm/day (Figure 2.5). Below average rainfall due to low frequency of summer storms in the second half of the hydrologic year resulted in below average annual P.

Average winter interception for the water budget was found to be 22 mm 1 November 2014 – 30 April 2015 using estimated interception rates of 15% from 2016 snow survey (Table 2.2 and Figure 2.7). Snow surveys revealed high spatial variability in snow accumulation within the peatland, accounted for by black spruce canopy, black spruce edge and peatland openings. Average winter interception in the peatland was 9%. Snow accumulation in the margin swamp was less variable; average winter interception was 21% (Table 2.2).

Rain through fall estimates in the snow-free period 2015 showed similar trends to snow interception. Estimates of interception varied spatially in the wetland (-5 to + 57%), resulting in a spatial average of 6% in the peatland and 10% in the margin swamp (Table 2.2). Average interception for the total wetland 1 May 2015 - 31 October 2015 was 8%, or 20 mm (Table 2.2). Total P (391±7 mm) and interception (42±10) resulted in a P net of 349±17 mm for the 2014 – 2015 hydrologic year (Table 2.3).

4.2.2 Evapotranspiration

Estimates of cumulative PET using Hamon, Priestley-Taylor (P-T), and Thornthwaite models were 383, 421, and 514 mm respectively for the 2014-2015 hydrologic year. The Thornthwaite estimate (514 mm) was ~ 25% greater than P-T and Hamon estimates, which were within 10% of one another. All PET estimates approximately equalled or exceeded total wetland P (391 mm), reaffirming the climatic moisture deficit characteristic of the sub-humid BP (Marshall et al., 1999). Evaporation pan measurements for the hydrologic year were 374 mm and 325 mm for Pond 19 and perched wetland H respectively (Figure 2.7). Total wetland AET using P-T method 1 April – 31 October 2015 was estimated at 272 mm, applying alpha values that varied with greening from Brown et al. (2010), compared to 231 mm using an alpha value of 0.69 (Petrone et al., 2007). The peatland weighing lysimeter showed 256 mm of water loss, and was within 5% of the above P-T literature estimates, confirming that alpha values from Brown et al. (2010) were suitable for application in the water budget equation. Minimum (231 mm), maximum (325 mm), and median (272 mm) estimates of AET resulted in an error estimate of ± 39 mm. All wetland AET estimates were below P net (349 ± 17 mm) (Table 2.3, Figure 2.7).

4.2.3 Groundwater and surface water

Lateral hydraulic gradients and corresponding electrical conductivity (EC) values between margin swamp and upland edge wells for the north, south, east and west transects of the wetland are depicted in Figures 2.8 and 2.9. All gradients were negative or zero, indicating that flow was directed from the margin swamp toward the upland, even during the wettest periods (2013 and spring 2014, Figure 2.8). EC values were similar in margin swamp (25 - 125 μS/cm) and upland (40 - 250 μS/cm), confirming that dilute margin swamp water was present in upland edge wells

(Figure 2.9). Upland wells > 5 m from wetland edge remained dry, so no water samples were obtained.

In the 2014 – 2015 hydrologic year, groundwater flow above the CL from margin swamp edge to adjacent upland forest ranged from 0 – 0.75 L·day^{-1}. Groundwater flow out of the wetland only occurred during wet periods, i.e., following snowmelt and after summer storms. Total flux out of the swamp for the hydrologic year was 8 mm. When applied to the entire wetland (peatland + swamp), the flux decreased to 3 mm (Table 2.3). Groundwater flow under maximum moisture conditions for the hydrologic year 2014 – 2015 was 17 mm; 0 mm under minimum flow conditions. Absence of a WT in adjacent upland wells for the majority of the year, and small K_h ($5x10^{-7}$ ms^{-1}) measurement are consistent with the relatively small flux observed.

Vertical seepage calculations through the CL revealed large vertical gradients (average = 0.91) between lower peat above the CL (0.7 m depth) and within the CL (1.35 m depth; Figure 2.4). Vertical hydraulic conductivity (K_v) for the CL was estimated at 10^{-11} ms^{-1}, resulting in < 1mm/year of $Seepage$. Observed unsaturated sand beneath the wetland implies the presence of both capillary and hydraulic barriers, restricting vertical water loss beneath the wetland (Figure 2.4; Riddell, 2008).

During peak flow May 2015, only 4% of the total wetland surface was saturated. The peatland surface showed 2% surface saturated area (SSA). SSAs were confined to hollows near the peatland edge and in the margin swamp. 7% of the swamp was saturated, and numerous depressions contained pools of standing water. There was no evidence of surface flow between pools, and SSAs were not connected. No SSAs were observed in the adjacent upland forest, indicating a lack of surface water movement from forestland to wetland (Table 2.3).

4.2.4 Unsaturated flow

Hydraulic head distributions from water level and tensiometer data suggest that lateral flow converges at site 122 (edge wetland pit) in the aspen rooting zone, 0 - 0.5 m below ground. Lower soil moisture measurements at site 122 compared to sites 133, 121, and 123 at 0.2, 0.3 and 0.4 m depths respectively support the premise of vertical water loss through suction at site 122 (Figure 2.10, Figures A.4 and 5). At this “hot spot”, water appears to originate from both the wetland and adjacent aspen forest (Figure 2.10). 0.6 m below ground at 121 and 123, high soil moisture and soil tension indicate gradients directed both up and down, indicating a boundary zone between suction and recharge. In the upland pits (sites 121, 123), recharge dominates between the 0.6 and 0.97 m tensiometers. Decreasing soil moisture below 0.6 m points to lack of a WT in the unsaturated upland forest. During the 2014-2015 hydrologic year, UGW was invariably directed across the wetland – upland interface from the margin swamp (site 87) to the edge of adjacent the upland forest (site 122) (see Figure 2.10 and Figure A.5).

The unsaturated hydraulic conductivities for a silt loam at maximum, average, and minimum, soil moisture were estimated to be 7 x 10^{-8} ms^{-1}, 1.6 x 10^{-9} ms^{-1}, and 1.5 x 10^{-12} ms^{-1} respectively (Carsel and Parish, 1988). Soil moisture measurements were taken from within the rooting zone (0.2 m depth) at the wetland – upland boundary (113) (Figure 2.10). Total UGW flux out of the wetland was ~1 mm/year under average soil moisture conditions for both silt and silt loam texture (Table 2.3). Unsaturated groundwater flow under maximum soil moisture conditions was 2 – 4 mm/year for silt loam and silt respectively; ±2 mm was applied as error for the budget equation. These data indicate that UGW, though directed away from the wetland, represented a minimal portion of the wetland water budget during the 2014 - 2015 hydrologic year.

4.2.5 Soil water storage

Cumulative change in soil water storage for a 1 m column in the peatland and swamp was +20 mm ±25% and +22 mm ±25% respectively for the 2014-2015 hydrologic year (Table 2.3). Total soil water stored in the peatland hollow was estimated at 617 mm and 638 mm on 1 November 2014 and 31 October 2015 respectively. Total soil water storage for the swamp was 311 mm for 1 November 2014 and 336 mm on 31 October 2015. Water table depths on 1 November 2014 were 78 and 117 cm for peatland and swamp respectively; WT depths on 31 October 2015 were 68 cm in the peatland and 73 cm in the swamp. The 1 m soil column contained both saturated and unsaturated soil above the CL. Total soil water ranged from 650 mm – 738 mm in the peatland, compared to 310 – 474 mm in the margin swamp. The TDR probe (0 - 0.3 m) in the peatland centre plotted similar values to discrete PR2 data from the peatland when plotted over the same depth. These results corroborate soil water storage findings employing PR2 probes in 1 m access tubes.

4.3 Water budget summary

Residual error for the water budget was 50 ± 53 mm. Overall, there was a small increase in storage (21 ± 5 mm), large water increase following spring melt, and subsequent loss over the growing season (Table 3.1 and Figure 2.7). Precipitation was the only input to the water budget for the 2014 – 2015 hydrologic year, demonstrating that wetland H is an autogenic wetland. Net P over the wetland exceeded all outputs. Primary water loss was AET, followed by interception (Int); groundwater out ($Go, UGW, Seepage$) were < 10 mm. No overland flow (So) out of the wetland was observed.

Precipitation and ET were the dominant fluxes in the budget, with total wetland $Pnet$ (349 mm) 77 mm greater than AET (272 mm; Table 2.3). Total groundwater out (Go) of the wetland (measured from margin swamp to upland edge) was estimated at 3 mm/yr. $Seepage$ through the wetland base was measured as negligible (<1 mm/yr), as K_v of CL was estimated at 10^{-11} ms^{-1} (Table 2.3). Unsaturated groundwater (UGW) flow was directed away from wetland edge (Figure 2.10), resulting in ~1 mm/yr UGW loss out of wetland peripheries based upon average moisture content (Table 2.3).

In Table 2.3 data are divided into two time periods: 1 November 2014 – 30 April 2015 (winter) and 1 May 2015 – 31 October 2015 (snow-free). Net precipitation was greater than AET in winter, and 17 mm less than AET during the snow-free period. During the winter period Go was 1 mm, compared to 3 mm in the snow-free period. Total inputs were 93 mm larger than outputs at the end of the winter period, substantiating the observed increase in storage (+96 mm) for the winter period (Table 2.3). This trend reversed during the snow-free period when outputs were 22 mm greater than inputs and soil water storage decreased by 75 mm. Residual errors for winter and snow-free periods were 3 and 53 mm respectively (Table 2.3).

4.4 Wetland – forestland interactions

The water budget for this study was completed during a dry period in the climate cycle. The following sections (4.4.1 and 4.4.2) will assess the impact of data from the period 2004 – 2016 on the matter at hand: Is the wetland isolated, or does it receive allogenic groundwater in wetter periods of the climate cycle?

4.4.1 Detailed study period: 2014 – 2016

Radial flow was observed from the wetland centre to the upland from 2014 to 2016. Water levels indicated flow directions were always from peatland centre → margin swamp → upland edge → unsaturated upland (Figure 2.11). An exception to this pattern was noted when small low gradient flow reversals occurred between peatland edge and margin swamp (e.g., sites 27 and 97) during spring melt and rain events > 10 mm. Excepting these relatively small reversals, observed flow was directed from peatland to swamp (Figure 2.11).

Continuous hydraulic head and spot water levels for peatland centre (site 81), edge (site 27), margin swamp (sites 87 and 97) and adjacent upland (site 86) are presented in Figure 2.11b for the 2014 - 2015 hydrologic year and spring 2016. Data indicate that during spring melt, the north margin swamp (site 97) wetted up by 1 April in 2015 and 2016, followed by the peatland edge (27). The west swamp (site 87) wetted up a week later than the north (site 97) during the 2016 spring melt. The peatland remained frozen until 11 April 2015 and 7 April 2016. During both years, the deep peatland well (site 81-Wdp screened 0.5 – 0.8 m below ground), remained dry for approximately one week after the shallow well (site 81-Wsh 0-0.5 m screen) showed water. This was attributed to local perching of snowmelt water within the peat active layer, caused by an ice barrier preventing infiltration. The upland well (site 86) did not record a WT during the study period.

For both 2015 and 2016, the highest water levels in the wetland were recorded mid to late May (Figures 2.4 and 2.11), following snowmelt and subsequent to a precipitation event 30 mm or greater. Concurrently, the margin swamp water levels rose above the ground surface for 1 to 2 weeks in both years, and pools of standing water formed. In the peatland, no surface water was observed, but the WT did rise to within 10 cm of the hollow surface (Figure 2.11). Following peak water levels in 2015, both swamp and peatland WT declined through June, accounted for by leaf out, and absence of P events >5 mm. Mid July - early September 2015, ET demand and several rain events >10 mm produced a variable WT for both peatland and swamp. In fall 2015, the WT fell slowly and were frozen or dry mid-November 2015 - early April 2016 (Figure 2.11).

4.4.2 Long term trends

Trends similar to those described above were noted in the historic spot water level data from 2004 – 2016 (Figure 2.12) along the transect from sites 03-P13 (upland) to 27 (peatland edge). Flow direction for shallow perched groundwater was always directed from peatland edge (site 27) → swamp (sites 29,30) → upland edge (site 31) (Figure 2.12). The shallow to intermediate depth wells and piezometers at site 03-P13 remained dry throughout the study period, which covered both wet (2007, 2008, 2013, spring 2014, 2016) mesic (2004, 2005, 2006, 2011, 2012) and dry (2009, 2010, 2015) years of the decadal climate cycle (Figures 2.6 and 2.12). Peaks in the two-year cumulative departure from the mean were +140 mm in 2008 and +126 mm in 2013, when precipitation was ~50 mm above the mean for 2+ consecutive years. During these periods of water surplus (e.g., 2013), groundwater flow remained from wetland to adjacent upland, indicating a lack of allogenic contribution to the wetland. During the period 2004 – 2016, depth to regional groundwater table remained constant at ~23 m below ground, exhibiting < 0.3 m fluctuations.

5.0 Discussion

5.1 Isolation from allogenic sources

Results show the wetland to be isolated, contrary to perched wetlands in drier climates such as PAD perched basins, (Peters et al., 2006) and prairie potholes (e.g., Winter and Rosenberry, 1995). This is one of the first known studies to document isolated peatlands in a water deficit climate such as the BP. Literature discussed below substantiates findings reported in this paper with respect to the absence of allogenic hillslope contribution from upland to wetland, and the isolation of perched wetland H. For these reasons, hypotheses a) allogenic wetland with no CL and b) allogenic wetland with CL are not supported by this study.

5.1.1 High storage in upland prevents lateral flow

The absence of a functioning CL proximal to the surface (<1 m) within adjacent upland hillslopes increases soil water storage, limiting near surface runoff potential from upland to wetland (Devito et al., 2005b; Redding and Devito, 2010). Deep heterogeneous glacial deposits surrounding perched wetland H originate from an ice contact, resulting in thin layers of fine textured silt, sand and clay (Fenton et al., 2013). In the BP, uplands tend to be hydrologically disconnected from wetlands, with uplands dominated by ET losses and infiltration (Devito et al., 2005b). Soil water storage capacity is exceeded approximately once every 20 years, during which a hydrological connection between upland and wetland is established (Devito et al., 2005b; Thompson et al., 2015).

It has been shown that lateral flow generation in Luvisolic aspen-dominated uplands similar to those surrounding perched wetland H is uncommon without a CL proximal (<1 m) to the surface, as soil storage cannot readily reach field capacity (Whitson et al., 2004; Devito et al., 2005b; Redding and Devito et al., 2010), except at the base of hillslopes (Thompson et al., 2015). This is supported by Carrera-Hernandez et al. (2011), who conducted unsaturated groundwater modelling in BP forests. In loam soil when the WT originated 4 m or greater from the surface (as is the case in the forest surrounding perched wetland H) in the last 100 years, the WT rose to a maximum height of 2 m from the surface (Carrera-Hernandez et al., 2011). This suggests that upland hillslopes adjacent the wetland are not subject to frequent saturation. Hydrologic data from adjacent upland wells (2 – 5 m deep) are consistent with the literature; all wells > 5 m from wetland edge remained dry throughout this and a previous study period, i.e., 2004 – 2016, indicating a lack of allogenic water contribution to perched wetland H during the last 12 years.

In 1997 the two-year cumulative departure from the mean was +479 mm resulting in runoff coefficients of 52% on BP hillslopes (Devito et al., 2005b). 1997 climatic conditions were indicative of a >1 in 25-year surplus (Redding and Devito, 2008). Hillslope runoff in 1997 (assuming P = 650 mm) from the topographic catchment (0.8 ha) surrounding perched wetland H (0.45 ha) could have been up to 117 mm, assuming a runoff coefficient of 50 % (Devito et al., 2005b). During the 1997 water surplus, wetland soil water storage was likely also at capacity, functioning to transmit water to the adjacent upland (Devito et al., 2012). My research demonstrates that the adjacent upland is unlikely to provide sufficient water to the wetland through lateral flow generation or groundwater ridging, except approximately every 25 years (Devito et al., 2005b; Redding and Devito, 2008), during which wetland storage is already filled and allogenic water is not a requirement.

5.1.2 Potential for ground water ridging at hillslope base

Silt-rich soils overlying the CL at the upland – wetland edge are conducive to groundwater ridging, as capillary fringes >1 m can form in silt (Gillham, 1984; Buttle, 1994). In a previous study at wetland S8 (Figure 2.2), groundwater ridging in the upland base/margin swamp edge lasting 1 – 5 days was observed following rain events >10 mm, which directed groundwater back into the peatland (Riddell, 2008). In perched wetland H, continuous monitoring of wells at the hillslope base during the snow-free season of 2015 through spring 2016 determined that groundwater levels in the upland were never above those in the wetland, although several storms >20 mm occurred. Though wetlands H and S8 are both perched, they are in different landscape positions; S8 in an isolated basin and wetland H on a relatively flat topographic high. Given these differences, the steeper hillslope at wetland S8 may be more conducive to groundwater ridging than the shallow slopes adjacent wetland H. It is recognized that the study period examined aligns with a drier than average portion of the regional climate cycle. It is worthy of note however, that spot water levels from the peak of the previous wet cycle (2013 and spring 2014) revealed flow directed from wetland edge (30) to the hillslope (31), an indication that groundwater ridging from the hillslope base is unlikely to provide water to the study wetland.

5.1.3 Near surface runoff over frozen soil

Near surface runoff over frozen soil as opposed to lateral groundwater flow is an alternative mechanism for generating allogenic water to the wetland, and is common in parkland and prairie landscapes (Winter and Rosenberry, 1995; van der Kamp and Hayashi, 2009). However snowmelt runoff is limited in the BP, as winter infiltration dominates over runoff (Redding and Devito, 2011). Concrete frost layers are a requisite for significant runoff. The formation of impermeable concrete frost is unlikely without high fall moisture content (Whitson et al., 2004; Redding and Devito, 2011). Several researchers have concluded that maximum runoff occurs when concrete frost layers are connected (Winter and Rosenberry, 1995; Redding and Devito, 2011). For example, snowmelt runoff over frozen soil is critical in supplying water to depression ponds in prairie potholes during spring melt (Winter and Rosenberry, 1995). In BP hillslopes, concrete frost was shown to develop as a consequence of melting and refreezing in the upper mineral soil (Redding and Devito, 2011). Redding and Devito (2011) found the least concrete frost development on hillslopes with closed canopies and limited southern aspect, similar to those surrounding perched wetland H. Data from springs 2015 and 2016 indicated that hillslopes adjacent wetland H did not develop concrete frost layers, as depth to frost table was highly variable and often > 30 cm. Further, all snow in the upland appeared to infiltrate, as continuous soil moisture data along the upland – wetland interface showed no surface saturation, confirming lack of near surface runoff.

5.2 Role of wetland confining layer

To maintain the WT, a CL of low permeability clay (hydraulic barrier, Li et al., 2013) overlying unsaturated sand (capillary barrier, Li et al., 2013) underlies wetland H, exhibiting hydrostratigraphy similar to other perched wetlands documented in the literature (Metcalfe and Buttle, 2001; Cable-Rains et al., 2006; van der Kamp and Hayashi, 2009; Riddell, 2008) (Figure 2.4). The CL functions to inhibit vertical seepage (van der Kamp and Hayashi, 2009; Riddell, 2008) and wetland storage capacity, thereby maintaining the WT (Riddell, 2008). Vertical flow through the CL was estimated to be <1 mm/yr, and considered a negligible component of the water budget. Depth to CL increased to ~ 1.5 m in adjacent uplands and showed obvious fractures, indicating vertical drainage through this layer, similar to fractured clay till observed at prairie potholes (e.g., Winter and Rosenberry, 1995; Hayashi et al., 1998; van der Kamp and Hayashi, 2009). It has been shown that the dominant groundwater exchange between pond and riparian margin of prairie pothole wetlands occurs through a higher conductivity fractured till layer called the transmission zone (van der Kamp and Hayashi, 2009). The transmission zone is underlain by unfractured, low conductivity clay till functioning as a CL. Following inundation of prairie pothole ponds, flow is directed out of the wetland through the transmission zone above the CL in a manner similar to flow observed between the peatland and margin swamp of perched wetland H (van der Kamp and Hayashi, 2009). Unlike prairie potholes, perched wetland H does not have a fractured transmission zone above the CL in the riparian (margin) swamp. Material above the swamp CL is fine textured, functioning to decrease lateral flow out of the wetland, compared to the more rapid transmission of water from wetland centre to riparian edge reported at prairie potholes (van der Kamp and Hayashi, 2009).

5.3 Wetland – forestland interactions

During the 2014 – 2015 hydrologic year, minimal groundwater exited the wetland through lateral flow (3 mm). This can be attributed to the low hydraulic conductivity of soil above the CL; the geometric mean K_h was 10^{-7} ms^{-1}. A WT in the upland edge (within 5 m of perched wetland H) was only present during high flow periods such as spring melt and following summer storms > 15 mm. Low EC values indicated that this water was sourced from the wetland, supporting observed hydrologic flow paths away from the wetland, indicated by negative gradients. The presence of unsaturated uplands provides a barrier to lateral flow from the wetland periphery, as K_{unsat} decreases rapidly with decreased soil moisture content (Dingman, 1994).

Unsaturated ground water flow was always directed out of the wetland during 2015, driven in part at least by upland forest vegetation through AET demand (Lubczynski, 2009). Perched wetlands appear to function as water sources for surrounding upland vegetation, e.g., aspen accessing water from the wetland periphery (Riddell, 2008). While measured unsaturated groundwater flow through the soil was low (~1 mm) (Table 2.3), the upland forest may be pulling water through extensive root systems characteristic of aspen stands (Lubczynski, 2009). An estimate of lateral unsaturated flow from wetland S8 was between 31 and 43 mm (Riddell, 2008). These data suggest lateral flow from perched wetland H may be an order of magnitude higher than calculated, which could make up the residual in the water budget. Since the water budget measurements were obtained during a dry year, UGW losses during a wet year are likely to be higher, closer to data reported in Riddell (2008).

In summary, the ground and surface water outputs of the wetland budget were low for the 2014 - 2015 hydrologic year (Table 2.3), an indication that the perched wetland functions to conserve water by limiting $Seepage$, So, Go, and UGW. Perched wetland H is an autogenic system (hypothesis 3, Chapter One Figure 1.4) with low outputs. P must be greater than AET to balance the water budget.

5.4 Atmospheric controls

Precipitation and ET are the dominant components in the perched wetland water budget (Table 2.3). Previous researchers have assumed that ground or surface water is required to form and maintain wetland conditions since wetlands in the BP are in regional moisture deficit (e.g., Price et al., 2010; Rooney et al., 2012; Nwaishi et al., 2016). This study shows that perched wetland H is an isolated, autogenic system in which wetland P is greater than AET, creating the water surplus required for maintenance of wetland conditions.

5.4.1 Increased wetland precipitation

The 2014 - 2015 hydrologic year saw 20% below average P. In spite of these dry conditions, the wetland was able to maintain a water surplus, meaning that autogenic feedbacks occurred to increase wetland P relative to ET. One such process may involve preferential funneling of snow or rain, resulting in an increase in P. The vegetation height within perched wetland complexes is substantially lower than surrounding forest, creating a gap. A study by Golding and Swanson (1978) found that snow accumulation and SWE were greater in clear cut gaps than in adjacent jack pine stands. This was attributed to lower interception within the gap, discontinuity in canopy structure causing snow to settle in the gap, and increase in wind speed and turbulence in forest openings, resulting in redistribution of snow (Golding and Swanson, 1978). The gap in the forest canopy over the wetland could cause preferential funneling of snow and rain into the wetland.

5.4.2 Decreased wetland evapotranspiration

Evapotranspiration losses at perched wetland H were estimated at 272 mm for the 2014 - 2015 hydrologic year. This ET estimate is 17 % lower than the estimated AET of 328 mm at wetland

S8 for 2006 (Riddell, 2008). Summer lysimeter measurements for wetland H and S8 were both ~ 250 mm. Riddell (2008) attributed lower lysimeter ET to prolonged ice within the wetland, extending well into June. Prolonged ice in the peatland rooting zone (0 - 20 cm depth; Steele, 1997) was also observed in wetland H, suggesting that ice may decrease AET through decreased transpiration rates (Goodine et al., 2008).

Petrone et al. (2007) attributed lower ET rates in peatlands to protection and sheltering of surrounding forest. In their study, the lower alpha value obtained (0.69) from the riparian peatland complex in the BP corresponds with lower AET through sheltering and protection, and deeper WT depths within the peatland (Petrone et al., 2007). The forest structure surrounding perched wetland H may function to decrease energy available at the surface, lowering evaporation rates. A comparison of data collected at the Pond 19 evaporation pan with that from the peatland evaporation pan at wetland H highlights the disparity in energy available for evaporation between open exposed systems (Pond 19) and closed protected systems (wetland H). The Pond 19 evaporation pan followed P-T PET, an indication that Pond 19 was evaporating close to potential and paralleling results at Pond 19 in a previous study (Riddell, 2008). The peatland evaporation pan showed 15% (50 mm) lower PET estimates than those reported for Pond 19. The distinction between the two pans is confirmation of the key roles of shading and protection from wind on evaporation rates in isolated peatlands such as perched wetland H (Petrone et al., 2007; Kettridge et al., 2013).

Peatland evaporation decreases rapidly when the WT is below 40 cm (Hayward and Clymo, 1982). A lab experiment on peatland resistance to drought found a step shift in surface resistance when the WT dropped to 30 cm, shutting down evaporation (Kettridge and Waddington, 2014). Water table depths in perched wetland H were frequently greater than 30 cm from the surface from end of June through fall 2015, implying decreased ET losses during this period. Other studies have reported lowered alpha values coincident with deeper WT depths (Petrone et al., 2004; Van Seters and Price, 2001; Petrone et al., 2007). This relationship between deeper WT depth and lower surface evaporation aligns with lower AET estimates from perched wetland H.

The 2014 - 2015 hydrologic year saw a two-year cumulative departure from mean P of -131 mm (Figure 2.6). It is significant that during the course of a year characterized by below average regional moisture conditions, perched wetland H was shown to be in water surplus. Though the range in AET for perched wetland H is broad (231 - 325 mm), all estimates are below P net (349 mm), a further indicator that perched wetland H functions to decrease AET relative to P through autogenic feedbacks. Previous research supports my research in that peatlands in the BP exhibit a variety of negative feedbacks that function to reduce WT draw down and evaporation (Kettridge et al., 2013; Waddington et al., 2015). These negative feedbacks should be further investigated at perched wetland H, as they appear to be dominant controllers on autogenic wetland maintenance.

5.5 Possible errors in the water budget

Water budgets are important informers on the hydrological function of a system even though they contain errors (Winter, 1981). This study calculated all terms in the perched wetland budget (Eqn. 2.1). However, some components such as P net, AET and groundwater can have a large error associated with them. Errors in P were assumed to be < 20%, given the small spatial extent of the study site. Using an error estimate of 20% (Winter, 1981), P net could vary by ± 70 mm. Nearby Environment Canada stations at Red Earth Creek and Peavine measured 306 and 355 mm respectively over the 2014 – 2015 hydrologic year (http://agriculture.alberta.ca/acis/alberta-weather-data-viewer.jsp), which differ from the Pond Catchment 19 estimate by 20 and 8%

respectively. Assuming the lower error estimate (20%) for P net (349 – 77 mm) of 279 mm, AET estimates are still approximately equal to P, supporting the existence of a permanent isolated wetland, rather than an ephemeral system.

One of the most error prone components in the water budget lies in the measurement of AET. The relatively small area of perched wetland H precluded use of eddy covariance systems (LI-COR, 2016), one of the more accurate methods to measure AET (Scott, 2010). Instead, this study used several alternate methods to estimate AET, which resulted in a range 231 – 325 mm. P net (350 mm) is still approximately equal to AET when factoring in the uncertainty calculation of ±39 mm to the AET (272 mm) used in the water budget.

Groundwater flux is difficult to calculate given errors inherent to accurate hydraulic conductivity estimates (e.g., Surridge et al., 2005). All groundwater terms were orders of magnitude less than the dominant components of the budget, P and ET. Assuming all groundwater components were an order of magnitude greater than calculated, total water loss via *Go*, *UGW*, and *Seepage* was ~ 40 mm. Groundwater outputs from perched wetland H are low even after adjusting for such an error. The residual of the water budget (50 mm) may be covered by an overestimate of P, or under-estimation of outputs. Given the greater uncertainties in estimating outputs, it is more likely that AET and groundwater fluxes have been underestimated in the water budget, and make up the bulk of the residual error, rather than an underestimation of P.

5.6 Conceptualization of autogenic wetland maintenance

The water budget demonstrates that perched wetland H maintains saturated conditions by increasing P relative to ET, and minimizing sub-surface losses. Key to the maintenance of this wetland is a CL proximal to the surface, functioning in concert with negative feedbacks to decrease wetland AET relative to P.

Low soil water storage potential due to a shallow (<1 m) CL beneath the peatland and margin swamp infers that less P is required to maintain saturated conditions (Devito et al., 2005b; Devito et al., 2012; Riddell, 2008). For instance, during a rain event of 45 mm over three days (6,7,8 August 2015), the WT rose 0.6 m in the swamp, and 0.3 m in the peatland, saturating a portion of the swamp. These data indicate that an important feedback exists between low storage, precipitation and frequency of wetting.

The presence of peat above the CL also influences precipitation – storage dynamics. The active peat layer is the upper, undecomposed peat, with low bulk density, high fibre content and large pores. It is frequently aerated, and functions to regulate the WT because of high storage and specific yield (Boelter, 1969; Ingram, 1978). This layer exhibits high hydraulic conductivity and low water retention, transmitting water rapidly. The lower decomposed layer behaves inversely to the upper layer. It has high bulk density, low fibre content and small pores, creating persistent saturated conditions which produce anoxia. Due to small pore size, the lower decomposed peat has low saturated hydraulic conductivity, which reduces water movement, maintaining the WT (Ingram, 1978). The active peat layer in the perched peatland appears to shed excess water to the margin swamp during wet periods. When the WT drops into the lower peat layer, high holding capacity maintains the WT. Further, the low specific yield and storage of decomposed peat in perched wetland H could cause frequent and rapid WT rise into the base of the active layer following even small rain events, maintaining wetland conditions.

Soil texture and type (peat vs. mineral) and CL depth appear to control WT response and soil water storage. Understanding the hydrologic role of the swamp relative to the peatland is essential, since the margin swamp represents almost half the wetland area. During wet periods, the peatland appears to shed water through the active layer to the adjacent swamp. However, small flow reversals are observed between the peatland edge and swamp due to rapid response of the swamp WT compared to peatland (groundwater ridging). Groundwater ridging in the swamp (Gilham, 1984; Buttle, 1994) as a result of rapid WT rise could buffer peatland water loss, and was found to direct groundwater towards the adjacent upland. Peatland margin swamps receive water from the peatland and or adjacent upland (Dimitrov et al., 2014; Langlois et al., 2015). However swamp margins have not been documented as generators of water, as has been observed in this research. Consequently, the function of margin swamps in the maintenance and expansion of perched peatlands is a current gap in the hydrologic and peatland development literature.

6.0 Conclusion

A confining layer beneath the wetland maintains the perched water table at wetland H. Perched wetland H is hydrologically isolated from adjacent hillslopes, receiving no allogenic ground or surface water, unlike perched wetlands in drier climates (e.g., Cable-Rains et al., 2006; Peters et al., 2006) (Chapter One Figure 1.4). The uplands adjacent this wetland are consistently unsaturated, and the regional groundwater table is located ~20 m below the surface. During this study (2014 - 2016) and previous studies (2004 - 2013), groundwater flow was always directed away from the wetland. The water budget reveals low ground and surface water losses and wetland P to be greater than AET. Thus the wetland is an autogenic system, functioning to conserve water in a regional moisture deficit.

Future research should further investigate the role of autogenic processes that may be promoting permanent wetland conditions. Examples of future research topics include preferential funneling of P over the wetland, storage – P feedbacks in both peatland and swamp, decreased AET through sheltering/shading, moss properties and the effect of ice in the rooting zone. To investigate the formation of isolated perched peatlands in the BP, the hypothesis of relic peatlands formed in historically wetter climates should be tested in response to the question: can these peatlands actually form in sub-humid conditions? The presence of isolated perched peatlands implies a resilience to moisture deficit conditions, given their capacity to decrease wetland ET relative to P.

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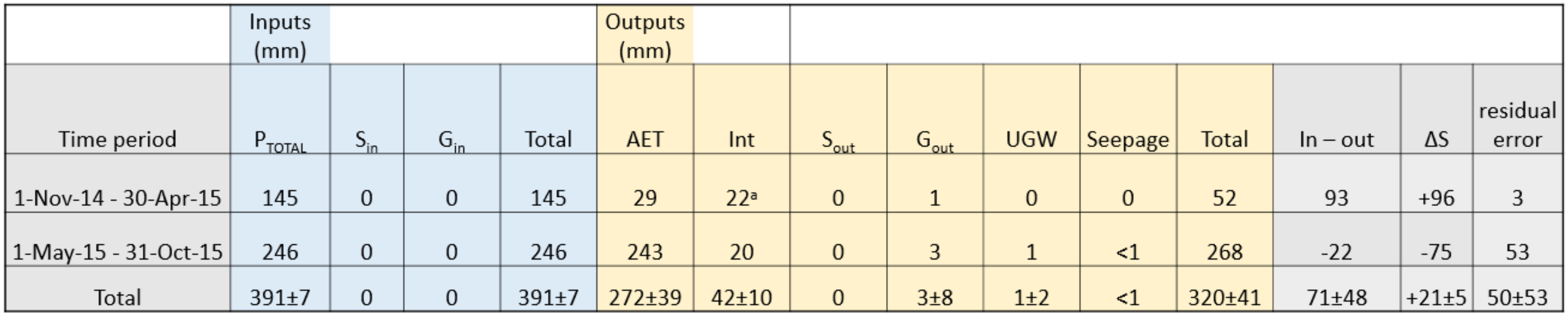
Table 2.1: Saturated hydraulic conductivity (K_h) with associated soil texture, source and method of measurement in Pond Catchment 19 (P19)

Soil type	Texture	Kh (m/s)	Source and Method
Organic	LFH forest floor	1E-04	Redding & Devito, 2010
Organic	Active peat H1-4	2E-05 – 5.5E-05	Calculated using Boelter, 1969; Ferone and Devito, 2004
Organic	Decomposed peat H6-10	4E-07	Hvorslev method at P19 catchment (n=3); Riddell, 2008 (n=4)
Mineral	Silt with fine sand	2.3E-06 - 4E-06	Hvorslev method at P19 catchment (n=1 in 19-40-P240); Smerdon et al., 2005 (n=3)
Mineral	Fine sand with clay interbedded with fine sand	1.3E-05 - 2E-05	Hvorslev method at P19 catchment (n=1 in 19-27-P120); Smerdon et al., 2005 (n>10)
Mineral	Silt loam to silt clay loam	6E-08	Hvorslev method at P19 catchment Riddell, 2008 (n>10)
Mineral	Silty clay to clay	3E-09	Hvorslev method at P19 catchment (n=4); Riddell, 2008 (n=5)

Table 2.2: Interception (Int.) percentages for peatland swamp and total wetland and interception amount in mm for the 2014-2015 hydrologic year. Interception estimation method for winter and snow-free periods is also summarized.

	Peatland **% Int. (amount in mm)**	**Swamp** **% Int.(amount in mm)**	**Total Wetland** **% Int. (amount in mm)**	**Int. estimation method**
1-Nov-14 to 30-Apr-15	9 (13 mm)	21 (30 mm)	15 (22 mm)	2016 peak winter snow survey (Total P – avg. peak SWE)
1-May-15 to 31-Oct-16	6 (15 mm)	10 (25 mm)	8 (20 mm)	2015 through fall hand gauges
Total hydrologic year amount interception	28 mm	55 mm	42 mm	---

Table 2.3: Water budget summary for 2014-2015 hydrologic year (1 November 2014 – 31 October 2014) divided into snow and snow free periods (1 November 2014 – 30 April 2015 and 1 May 2015 – 31 October 2015) for perched wetland H. Data are in mm/year. P_{TOTAL} *is total precipitation in the open,* $S_{in/out}$ *is surface water in/out,* $G_{in/out}$ *is groundwater in/out, Int is interception, UGW is unsaturated groundwater flow, Seepage is recharge beneath the wetland, and* ΔS *is change in soil water and depression storage in the wetland. The residual error is the portion of the budget that is not accounted for in the equation. See section 3.6 for methods on error estimation. ± after budget component is 1 standard deviation.*



	Inputs (mm)				Outputs (mm)									
Time period	P_{TOTAL}	S_{in}	G_{in}	Total	AET	Int	S_{out}	G_{out}	UGW	Seepage	Total	In – out	ΔS	residual error
1-Nov-14 - 30-Apr-15	145	0	0	145	29	22[a]	0	1	0	0	52	93	+96	3
1-May-15 - 31-Oct-15	246	0	0	246	243	20	0	3	1	<1	268	-22	-75	53
Total	391±7	0	0	391±7	272±39	42±10	0	3±8	1±2	<1	320±41	71±48	+21±5	50±53

[a] - interception during this time period assumed to include winter interception and sublimation

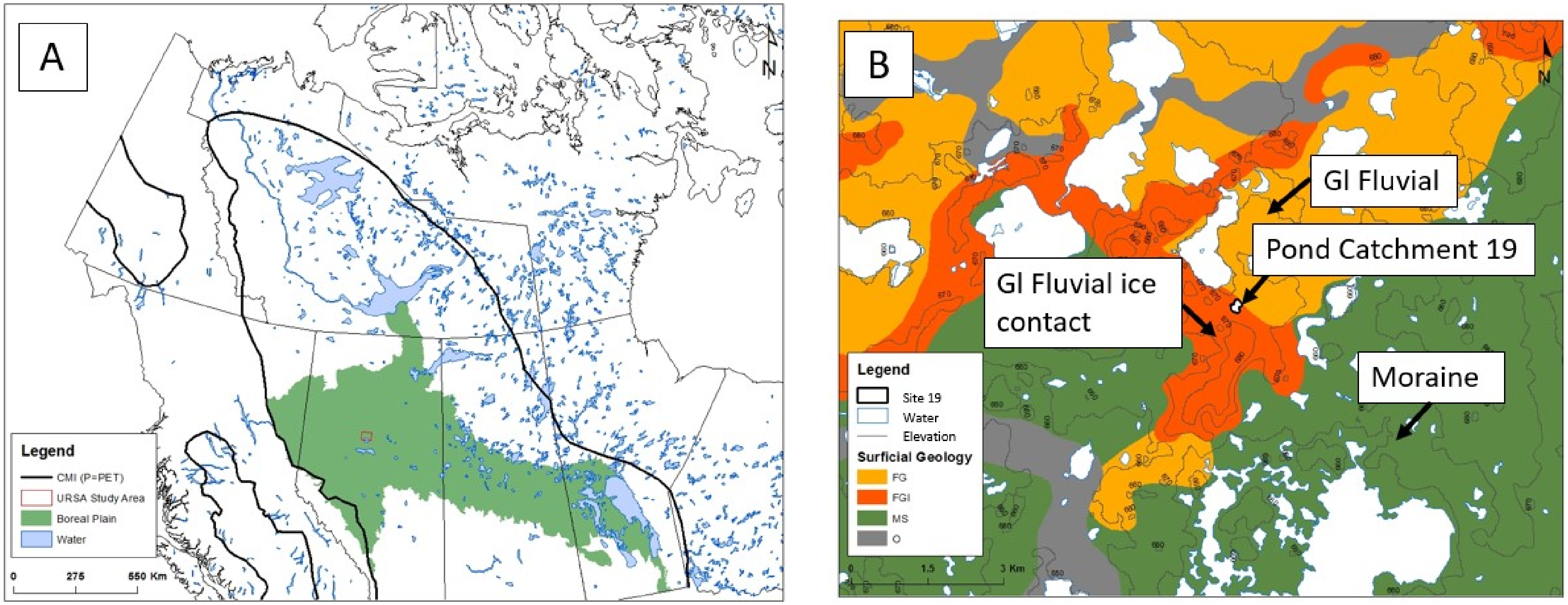


Figure 2.1: a) Location of the URSA within the Boreal Plains Ecozone. Black 'CMI' represents P=PET isoline modified from National Ecological Framework Penman and Thornthwaite estimates of P minus PET (Marshall et al., 1999). Corrected boundaries in the northeast and northwest using Winter and Woo (1993) and Wang et al., (2014) b) Inset of the Utikuma Region Study Area (URSA) surficial geology showing Pond Catchment 19 on the intersection of stagnant ice moraine (FGI) and glacial fluvial outwash plain (FG). Coordinates for panel b in lower right corner: 56˚01'49.81" N 115˚26'12.78".

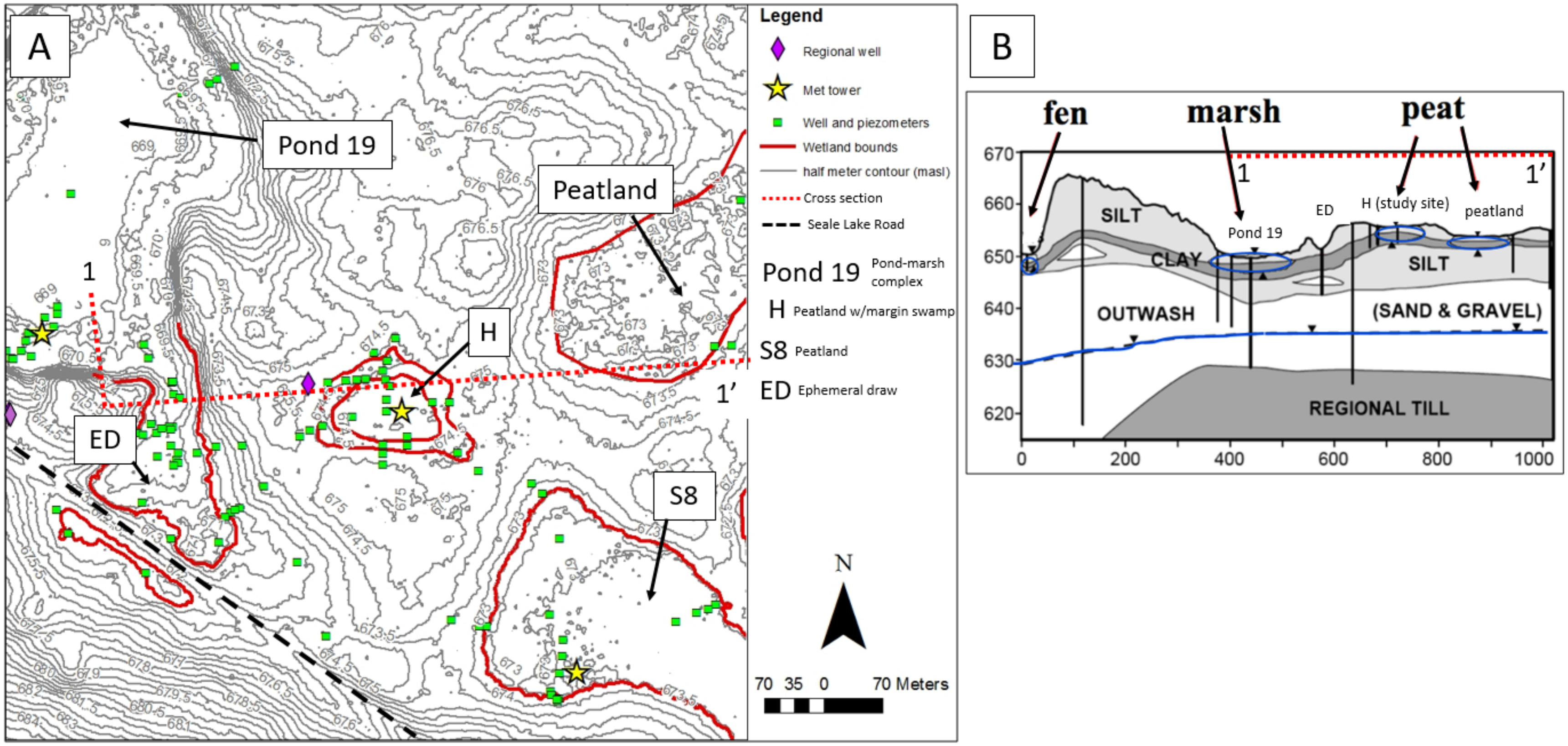


Figure 2.2: a) Plan view of Pond Catchment 19 with wetland labels and equipment locations. Wells and piezometers are < 5 m. b) Cross section of Pond Catchment 19 showing fine silts and clays over coarse material, with regional water table contained in outwash sediment and perched water tables forming in overlying fine textured substrate. The study perched wetland complex on a topographically high setting is denoted by 'H'. Vertical axis is m above sea level, horizontal axis is distance in m from start of transect (adapted from Riddell, 2008). 10x vertical exaggeration. Wetland H is at 56˚04'53.66" N 115˚32'06.02" W.

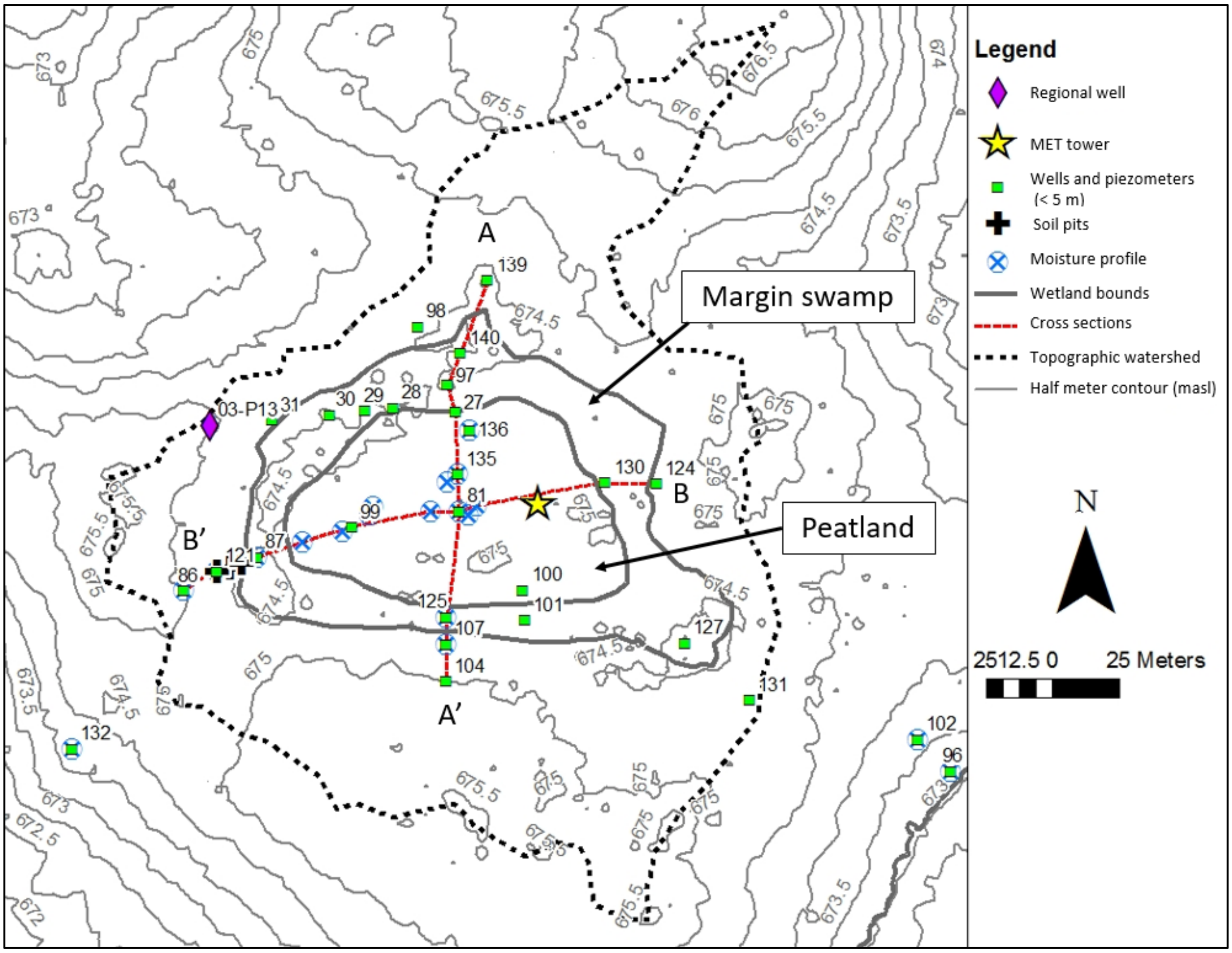


Figure 2.3: Plan view of perched wetland H with well and piezometers sites, location of regional groundwater well, meteorological tower (MET), and soil pits. Cross section locations: A-A' and B-B' and topographic watershed with 0.5 m contours are shown. The topographic watershed was delineated visually using 0.2 m contours.

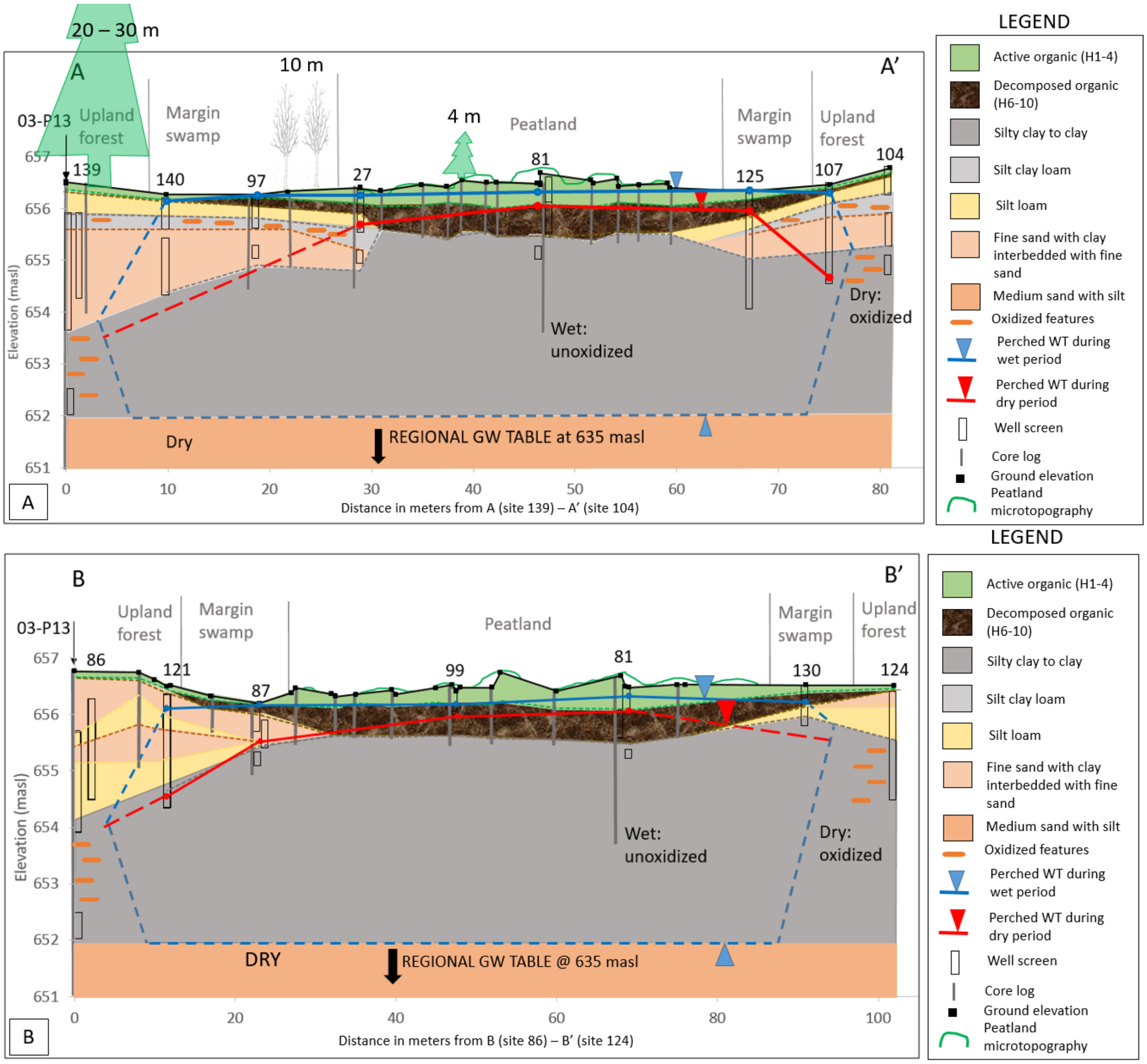


Figure 2.4 a) North-south from A-A' cross section (Figure 2.3) looking east at shallow (5 m) stratigraphy across the perched wetland b) East-west from B – B' (Figure 2.3) cross section looking north. Vegetation zones are labelled in grey, surface elevations in black, peatland microtopography in green. Dominant soil textures are described as active organics (H1-4), decomposed organics (H6-10), silt loam, silty clay loam with rust mottles, fine sand with clay interbedded with fine sand, and clay to silty clay. Water table with screens across perched wetland in wet period 20 May 2016 (blue) and dry period 13 July 2015 (red). Site 03-P13 is located 45 m SW of site 139, the ~same distance from the edge of the wetland. Tree heights relative to gap size are provided in panel a: upland forest (20-30 m), margin swamp (10 m) and peatland (3 - 4 m). Vertical exaggeration is 10x.

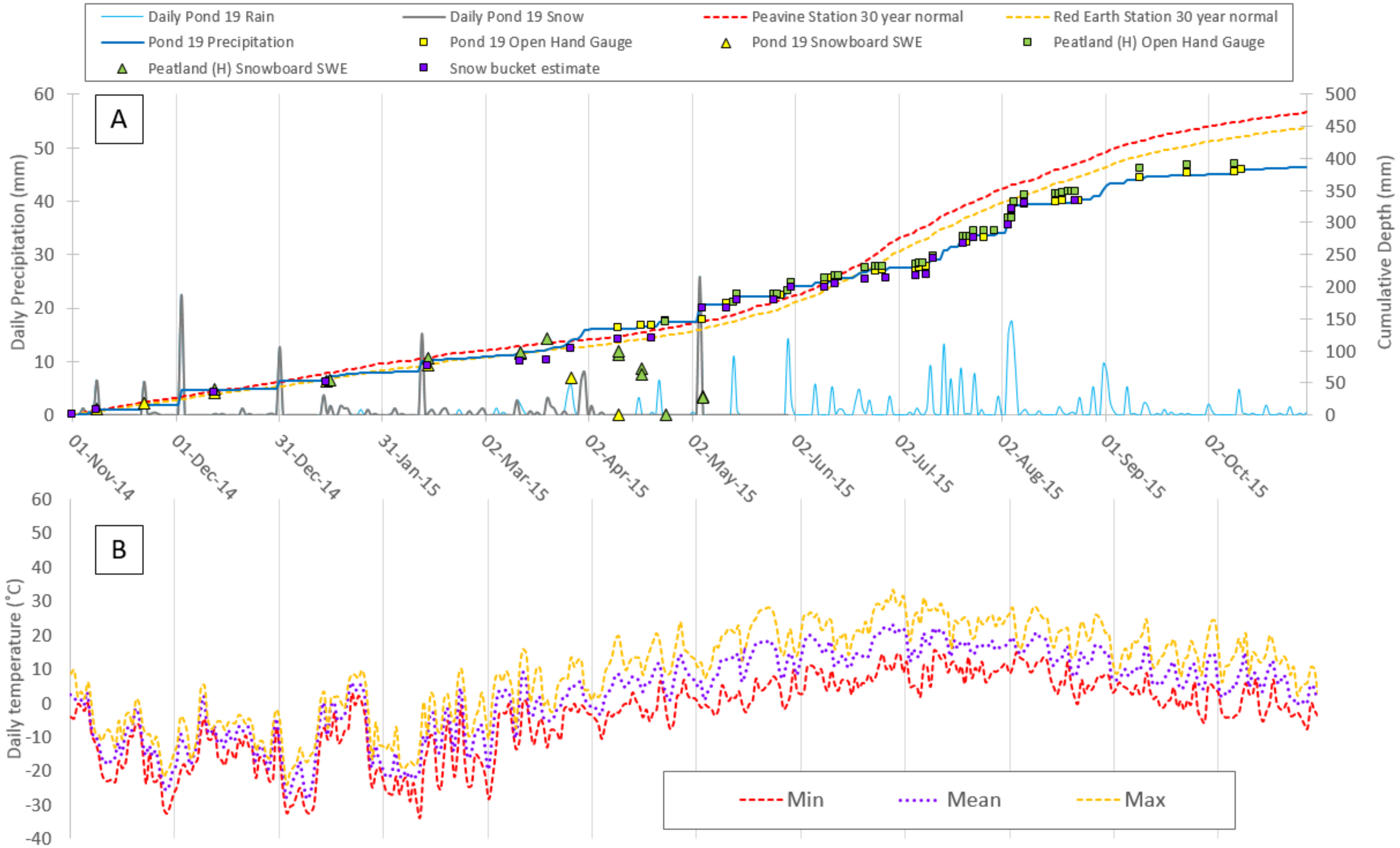


Figure 2.5: (a) Cumulative precipitation for Pond 19 (blue), with daily rain (light blue) and snow (grey). Long-term cumulative precipitation from nearby Environment Canada sites, Peavine (red) and Red Earth Creek (orange). Adjacent opening near Pond 19 (yellow) and peatland H (green) snowboard SWE and rain gauge cumulative depth. Snow bucket (P bucket) cumulative depth estimates shown in purple. Mean, maximum and minimum air temperatures shown in lower panel (b).

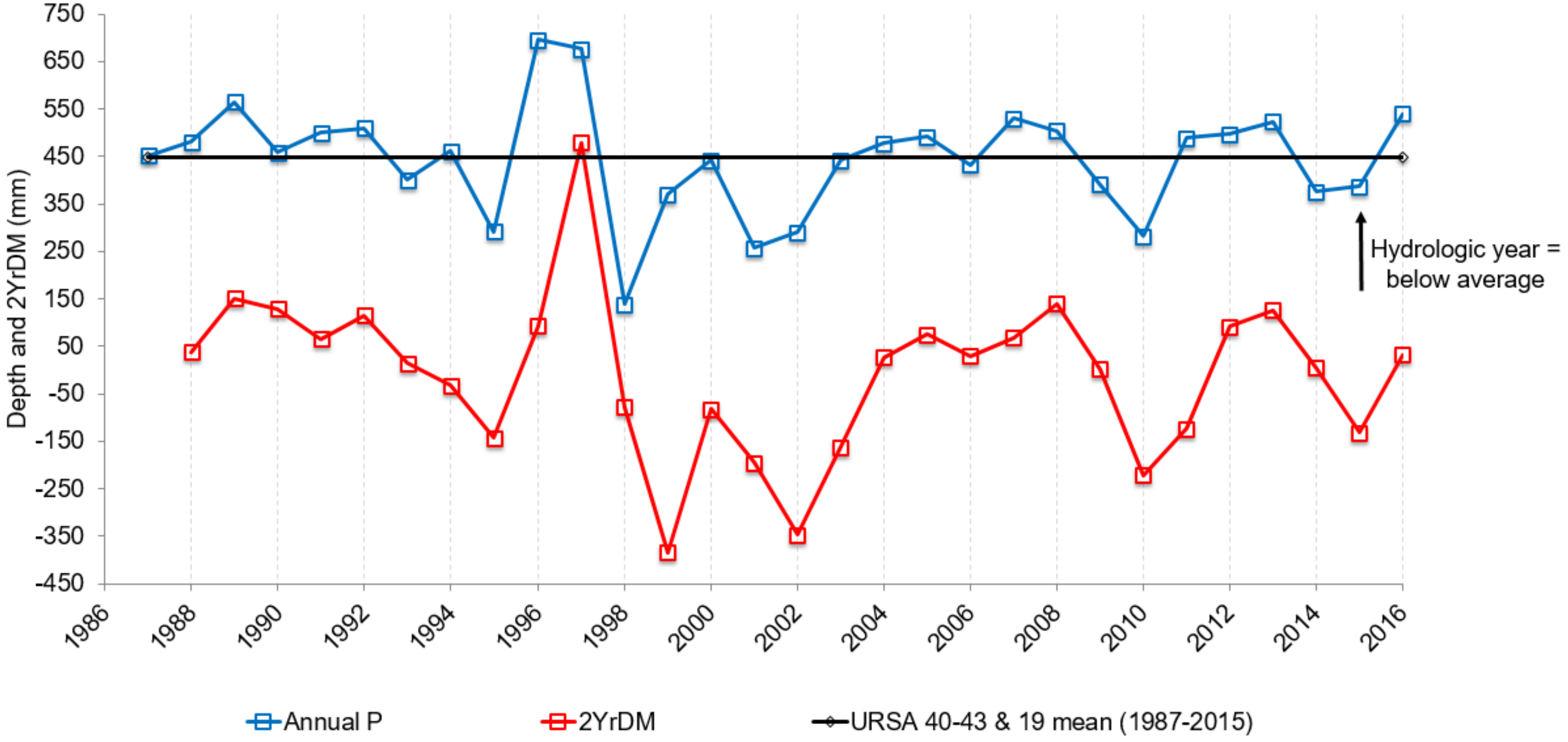


Figure 2.6: Annaul precipitation (annual P) for URSA Pond Catchments 19, 40-43 (1999-2016) and Red Earth Creek Environment Canada station (1986-1998) and 2-year cumulative departure from the mean (2YrDM) from 1987 -2016. 2014-2015 hydrologic year is considered a dry year at the end of a wet cycle. Mean annual P used was 447 mm 1984 – 2015 at Pond Catchments 40-43 and 19 in the URSA.

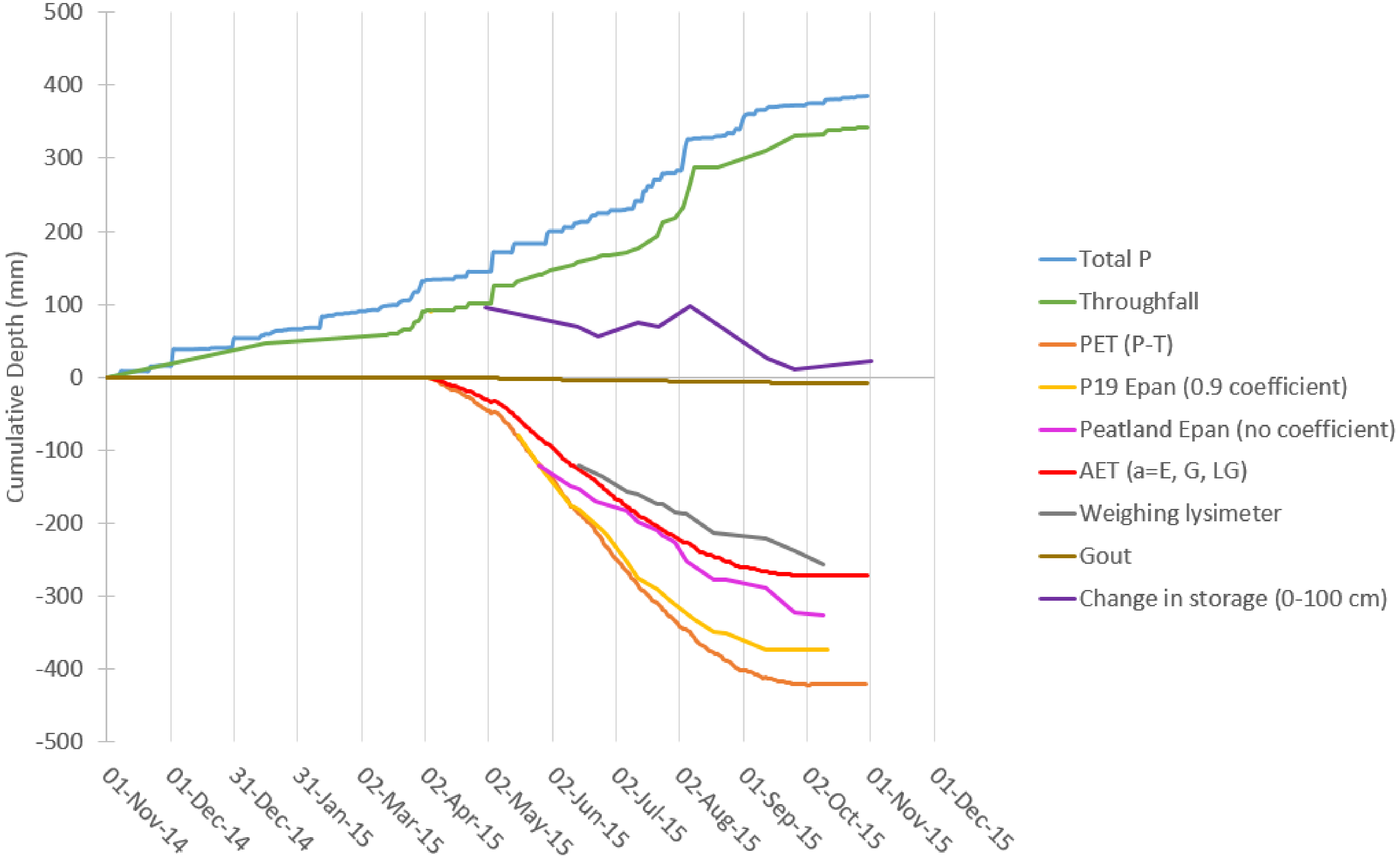


Figure 2.7: Cumulative depth in mm/year for the 2014-2015 water budget components of perched wetland H. P19 is Pond 19, Epan is evaporation pan, Gout is groundwater out (Go), and Change in storage is cumulative change in soil water storage over the 100 cm wetland soil profile.

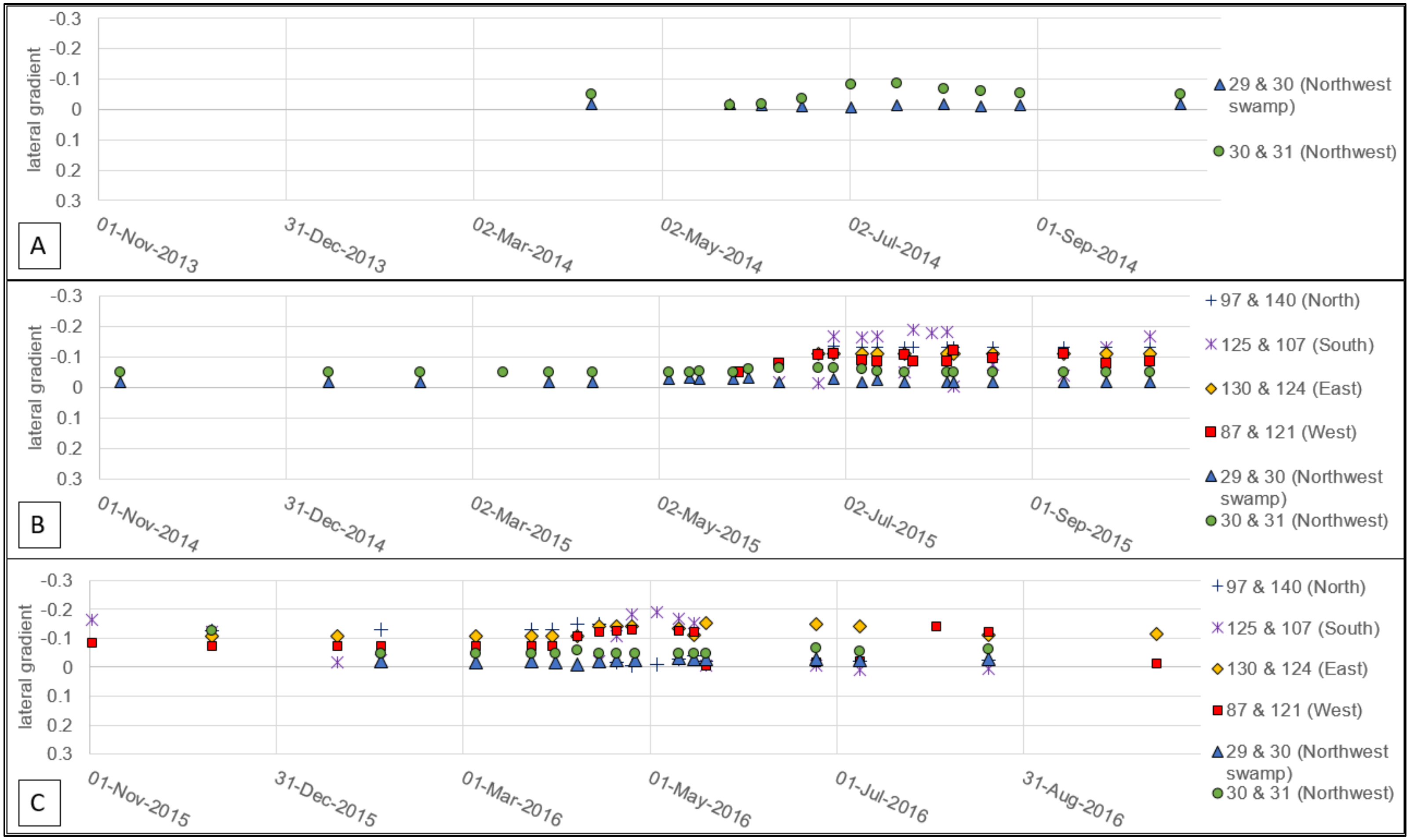


Figure 2.8: Lateral hydraulic gradient between margin swamp and adjacent upland at wetland H. Gradients were calculated even if the adjacent upland well was dry, and represent either minimum or actual gradients. All gradients calculated were negative or zero for 2014 (a), 2015 (b), and 2016 (c) hydrologic years indicating flow directed out of the wetland.

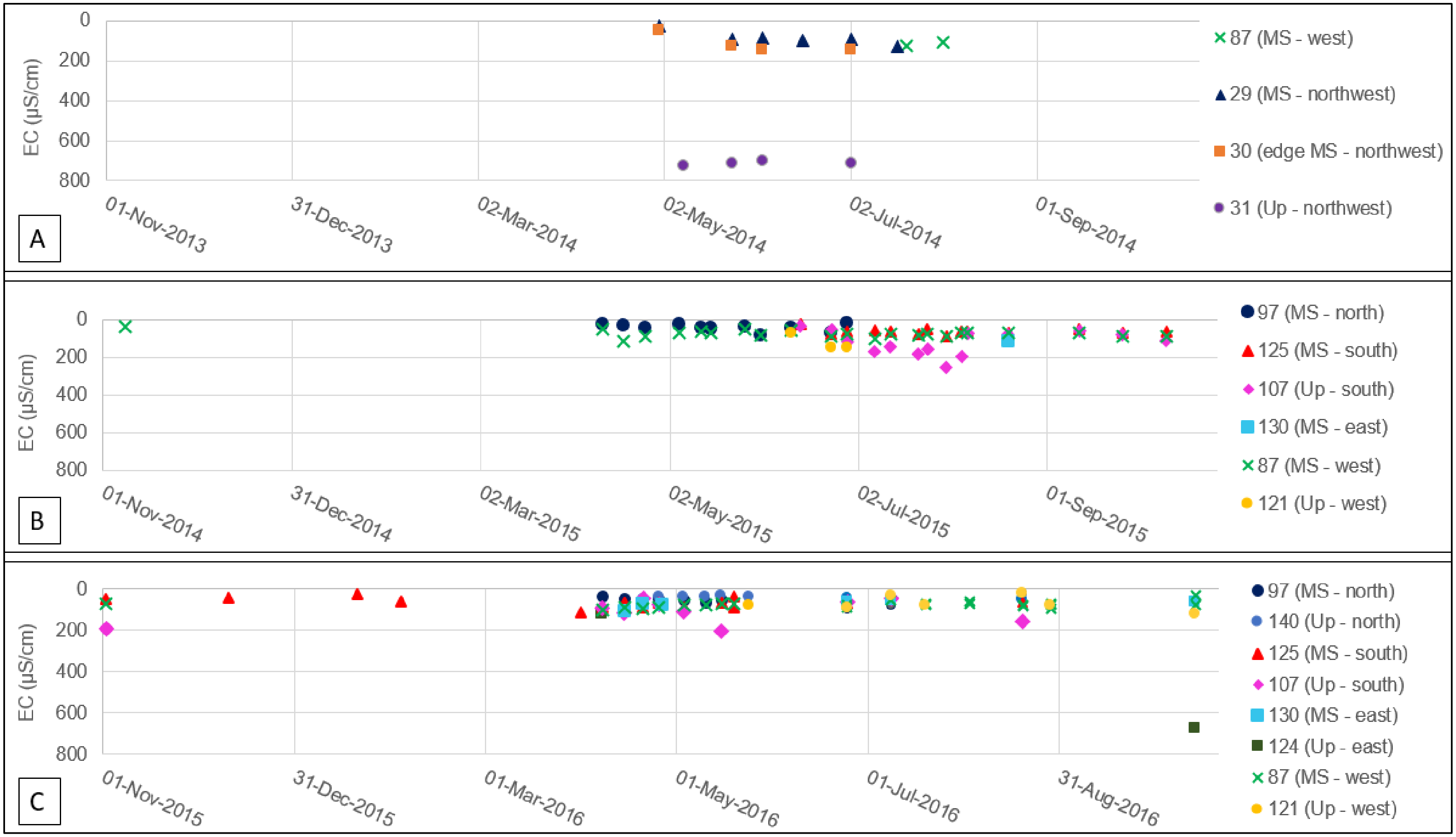


Figure 2.9: Electrical conductivity for margin swamp (MS) at wetland H and adjacent upland (Up) for (a) 2014 (b) 2015 (c) and 2016.

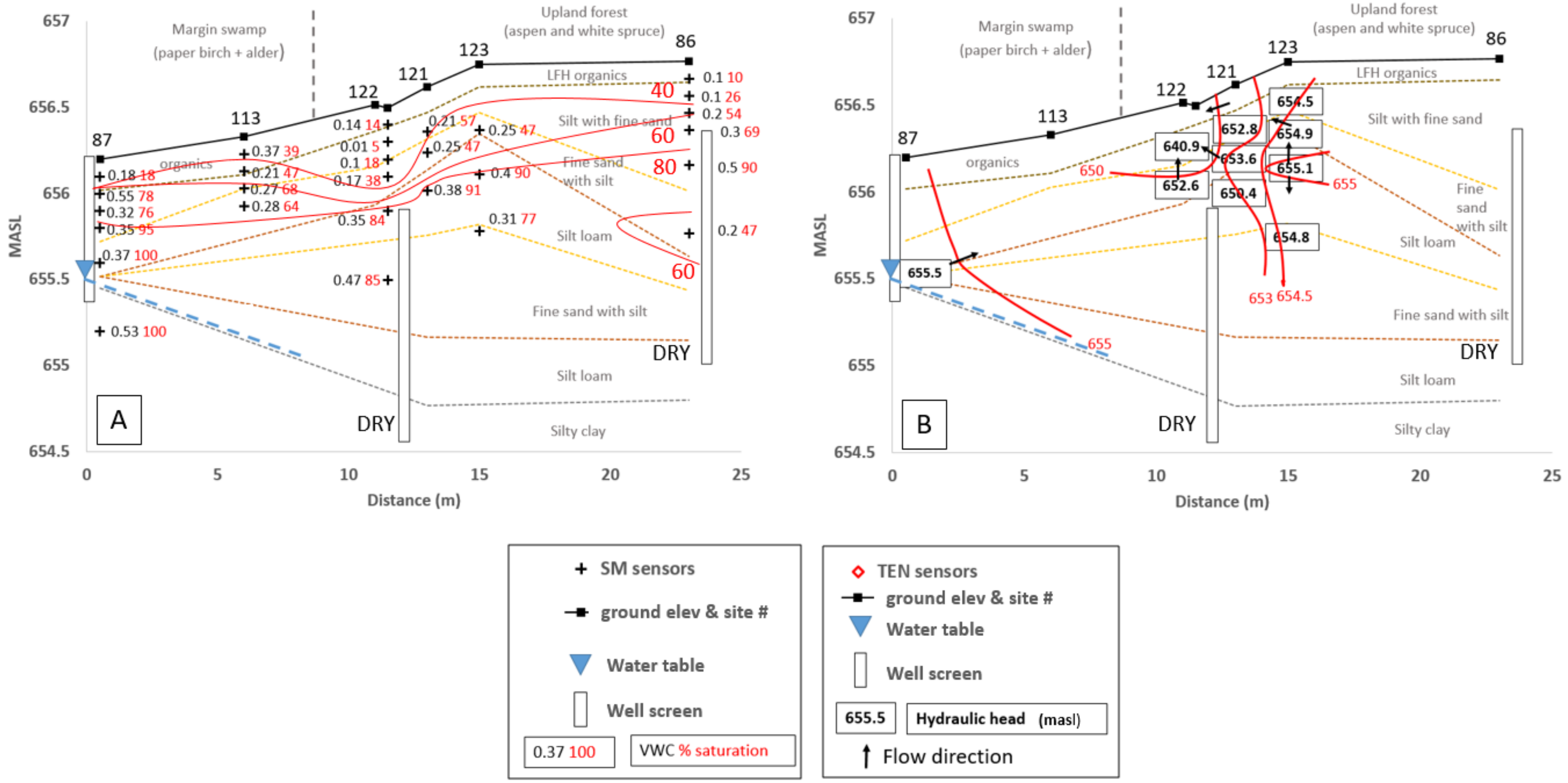


Figure 2.10: a) Soil moisture (Volumetric water content (VWC) and percent saturation) distribution across the wetland – upland interface and b) unsaturated hydraulic head (in masl) with hydraulic head distribution across the wetland – upland interface during dry conditions on 28 July 2015. Horizontal axis is distance from site 87 (Figure 3), and vertical axis is elevation in masl.

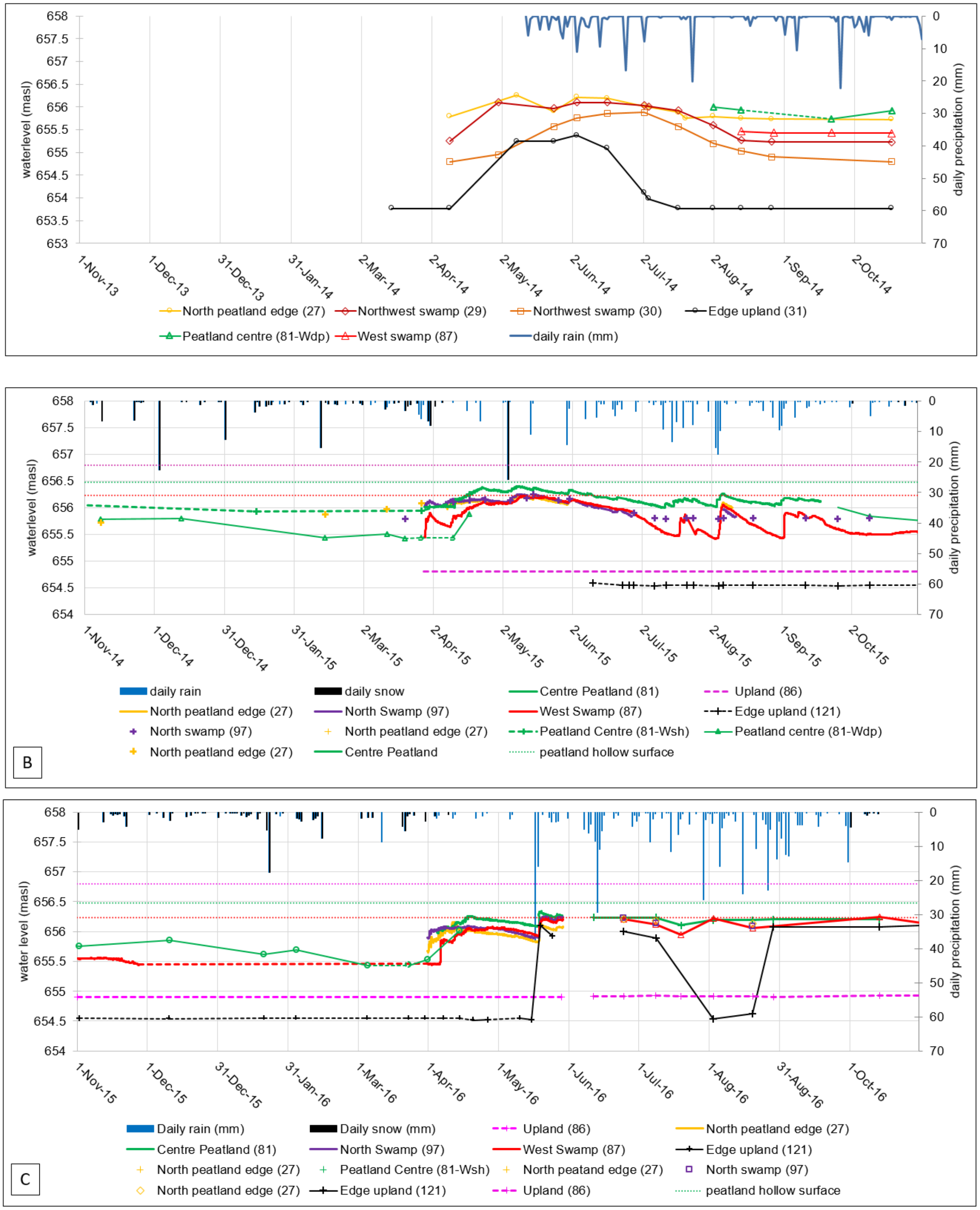


Figure 2.11: Water levels and daily precipitation for 2014, 2015 and 2016(a) 2014 water levels in peatland edge (site 27), swamp (sites 29, 30), and upland edge (site 31) (b) 2015 water levels (b) 2015 water levels in peatland centre, edge, margin swamp and adjacent upland (c) Same locations as 2015 but 2016 data. Flat and dashed lines indicate dry wells.

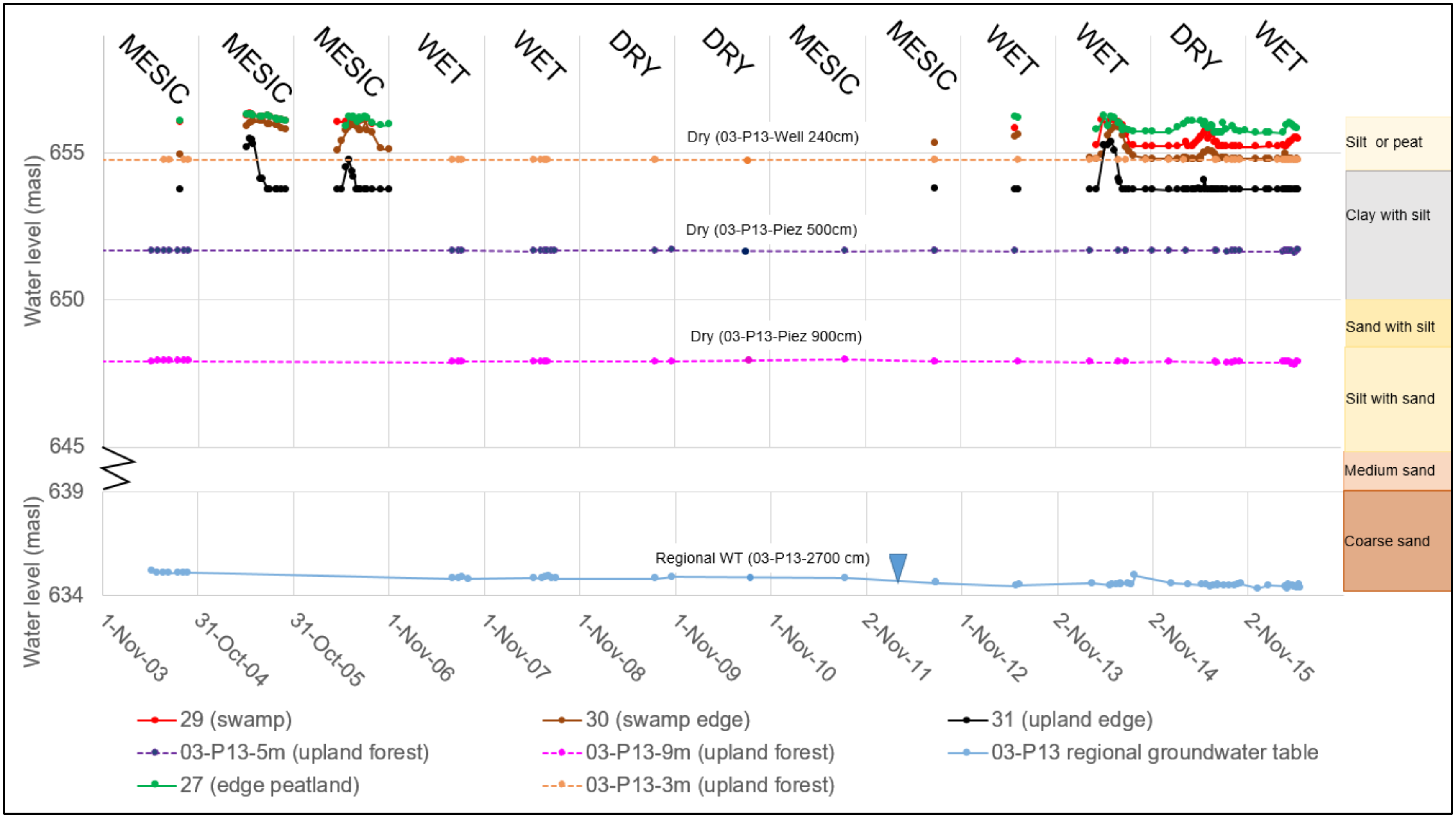


Figure 2.12: Historical spot water levels from 2003 – 2015 along transect sites 03-P13 → site 27. Water levels indicate flow from wetland to upland edge to upland for all spot measurements during this time period. Regional water table is 23 m below perched water table. Perched water is contained in silt or peat above the clay layer. Years are divided into moisture levels relative to long term mean: Dry, mesic and wet. Flat lines in the data indicate a dry well.

Chapter Three: Autogenic processes maintaining a permanent perched wetland: Nexus of soil layering, vegetation and climate interactions

1.0 Introduction

Isolated permanent perched wetlands occur within the sub-humid Boreal Plain (BP) of north central Alberta. These wetlands rely on a clay confining layer (CL) to maintain the perched water table (WT) (Chapter Two). Unlike perched wetlands in drier climates (e.g., Cable-Rains et al., 2006; Peters et al., 2006; van der Kamp and Hayashi, 2009), perched wetlands in the BP appear to be hydrologically isolated from adjacent hillslopes, receiving no allogenic ground or surface water (Chapter Two). The hydrologic isolation of perched peatlands in a sub-humid climate presents a new conceptual model for autogenic (e.g., Waddington et al., 2015), rather than allogenic (e.g., Ireson et al., 2015) wetland maintenance in a moisture deficit region. The question is: How does an isolated perched wetland maintain saturated or 'wetland' conditions in a sub-humid climate? The answer appears to be that wetland processes decrease actual evapotranspiration (AET) relative to precipitation (P), and decrease groundwater losses out of the wetland (Chapter Two). In this chapter, autogenic processes controlling the water generating potential of both the peatland and margin swamp are studied.

Understanding the hydrologic function of perched peatlands in the BP is important for peatland reconstruction in the Athabasca oil sands (AOS) (COSIA, 2014). Currently, in the AOS, watershed reconstruction is underway in order to restore the landscape to equivalent capability post-mining (Pollard et al., 2012). The current practice features constructed fen peatlands in low landscape positions, dependent on groundwater from adjacent hillslopes or larger groundwater flow systems (Price et al., 2010; Pollard et al., 2012; Rooney et al., 2012). However, perched peatlands maintained by autogenic processes may be constructed in any topographic position, because they do not rely on permanent ground or surface water connections (Chapter Two). Further, perched peatlands were found to generate fresh water to the surrounding ecosystem, a process that could impact adjacent forests and overall landscape productivity. Given their isolation from ground and surface water sources and their particular dependence on climate (P and ET), perched peatlands may be considered more susceptible than ground or surface water fed systems (Hokanson et al., 2016). However, it appears these isolated systems are maintained through autogenic processes which may function to increase their resilience to disturbance. Since P and ET are the dominant water budget components of perched peatlands (Riddell, 2008; Chapter Two), modelling changes in WT depth by employing projected climate changes to regional P and ET (IPCC, 2015) could provide indications of the response of BP peatlands to climate change (Thompson et al., 2015).

To assess the overall hydrologic function of perched isolated wetland complexes and potential role in constructed landscapes, it is useful to evaluate which autogenic processes dominate in controlling the water budget. In order to generate saturated conditions for wetland development (Mitsch and Gosselink, 2007), some or all of the following are required: increased wetland P compared to regional P (Golding and Swanson, 1978), decreased interception (Morris et al., 2003), decreased AET (e.g., Petrone et al., 2007), decreased soil water storage to promote frequently saturated soil (Devito et al., 2005b; Rodriguez-Iturbe, 2000; 2007), and resistance to wetland drainage (Chapter Two; Riddell, 2008; Langlois et al., 2015). The balance of this section will review these processes relating to P, AET and soil water storage.

Increased P on perched wetlands due to funnelling could prove integral in providing excess water in a moisture deficit climate such as the BP. Increased wetland P relative to regional P through funnelling may occur over the perched wetland complex, as the vegetation height in the wetland is substantially lower than surrounding forest. Studies in both experimental and natural settings found an increase of P in gaps compared to adjacent forest (Golding and Swanson, 1978; Golding and Swanson, 1986; Ellis et al., 2013). The gap in the canopy over perched wetlands could increase winter P through preferential funneling of snow, as concluded by Golding and Swanson (1978), who observed increased snow accumulation within clear cut gaps of varying diameter compared to adjacent undisturbed forest in the foothills of central Alberta. The effectiveness of the gap in collection of snow was a function of gap diameter and tree height (d:h), with maximum snow accumulation in gaps 2 – 3 d:h (Golding and Swanson, 1978). A similar study has shown maximum accumulation to occur at ~3 d:h (Troendle and Leaf, 1980). Based upon these findings, the diameter of perched wetlands compared to tree height in the adjacent forest structure may be a factor influencing total wetland P (the amount of P falling into wetland gap). The gap size could enhance total wetland P through funnelling, or decrease wetland P through interception effects of adjacent upland forest.

Another scale of interaction influencing P is vegetation present within the wetland. Soil characteristics and WT depth influence vegetation communities and structure (e.g., Lieffers and Macdonald, 1990; Macdonald and Yin, 1999), and their ability to intercept water (e.g., Dube et al., 1995). Since P and ET function in a delicate balance in sub-humid wetlands (Riddell, 2008), decreased interception and increased P net become important components in determining wetland water surplus (Chapter Two). It has been shown that greater P in clear-cut forest gaps is due in part to decreased interception (Golding and Swanson, 1978, Pomeroy et al., 2002). Gaps in the forest canopy were posited to increased pine forest water yield post-harvest (Golding and Swanson, 1978). In similar fashion, vascular vegetation on perched peatlands such as stunted black spruce, Labrador tea, and bog cranberry may promote lower interception than adjacent forest, increasing P net over the wetland. Across the BP, small wetlands with short and sparse vegetative cover may function to increase P net, offsetting higher interception rates observed in adjacent forests (e.g., Pomeroy et al., 2002; Morris et al., 2003). For example, a through fall study in northwestern Ontario reported that lower productivity black spruce stands (LAI = 1.6 m^2 m^{-2}) intercepted less P (12.5%) than more productive stands (LAI = 2.2 m^2 m^{-2}, 23 % interception) (Morris et al., 2003). The relative function of wetlands and adjacent forestland in respect of increased P net and wetland maintenance has not been studied in the BP.

Perched wetland AET could be affected by protection and shading from adjacent forest and wetland vegetation (Petrone et al., 2007; Kettridge et al., 2013), persistence of ice (Goodine et al., 2008; Brown et al., 2010), and peatland negative feedbacks relating to moss properties and WT depth (Kettridge and Waddington, 2014; Waddington et al., 2015). These processes could decrease wetland AET relative to P, offsetting the regional moisture deficit (Marshall, 1999; Devito et al., 2005a). Shading of the wetland by adjacent forest would decrease surface temperature and energy available for evaporation (Kettridge et al., 2013). Wetlands sheltered by tall trees may decrease AET as much as 30%, compared to more open sites (Petrone et al., 2007), an important factor in small wetlands (e.g., wetland H, Chapter Two). Decreased sublimation and prolonged snow on a perched wetland would extend the cold season and further reduce wetland AET. Average snowmelt rates are greater in open than in forested environments due to greater shortwave radiation inputs (Winkler et al., 2005), however, increased snowmelt in smaller open wetlands may be offset by sheltering and shading by adjacent forest, shorting the duration of ET over the wetland.

For much of the year, peatlands in the BP are frozen (Brown et al., 2010). Ice lenses can persist into high summer due to the insulating properties of peat and snow (Kershaw and Gill, 1979;

Laberge and Payette, 1995). In a manner similar to conditions seen in droughts, near-surface ice lenses can affect capillary rise. Surface moisture decreases, causing a decline in evaporation (Waddington et al., 2015). Further, transpiration rates within peatlands are influenced by ice, particularly rates measured within black spruce, the prevalent tree cover in BP peatlands. Root density in a peatland is limited to the top 20 cm of the soil profile (Steele et al., 1997). Ice lenses maintain lower temperatures within this zone, decreasing root activity (Steele et al., 1997) through decreased stomatal conductance and lowered metabolism, which greatly reduces transpiration (Goodine et al., 2008; Steele et al., 1997). Additionally, shallow ice lenses may increase surface saturation and evaporation early in the season due to standing water over ice, potentially offsetting the decrease in transpiration (Brown et al., 2010).

Research on peatland hydrology determined that a number of autogenic feedbacks affecting AET result from the specific structure of peat and surface mosses (e.g., Kettridge et al., 2013; Kettridge and Waddington, 2014; Waddington et al., 2015). Sphagnum mosses dominate northern peatlands and have been identified as the principal peat-forming plant (Kuhry and Vitt, 1996; Price and Whittington, 2010). Since mosses are non-vascular, water flows by capillary forces between fascicles in sphagnum (Hayward and Clymo, 1982). Water can also be transmitted through hyaline cells (intercellular spaces), which are able to withstand matric potential of up to -100 cm of water (Price and Whittington, 2010). Feathermoss is common in treed bogs or poor fens in the BP, displaying higher surface resistance to evaporation than sphagnum (Brown et al., 2010; Kettridge et al., 2013). Feathermoss physiology differs from that of sphagnum mosses, in that feathermoss lacks structures to efficiently pull water via capillary forces (Kettridge et al., 2013). The relative proportion of feathermoss to sphagnum on perched peatlands may influence ET rates.

The ability of moss to conduct water upward via capillary forces, dependent upon species and surface structure, is limited and eventually broken when the WT drops to a threshold depth, thus decreasing evaporation (Price, 1991). When near surface peat dries, the matric potential declines and evaporation is further reduced (Kettridge and Waddington, 2014). An experiment on peat surface resistance revealed a step shift in resistance from 50 sm^{-1} to 1000 sm^{-1} when the WT dropped to 30 cm depth, shutting down evaporation (Kettridge and Waddington, 2014). The threshold depth varies by species, and is hypothesized to be shallower in feathermoss than in sphagnum, given the lower evaporation rates of feathermoss (Brown et al., 2010). This mechanism, together with the other autogenic processes detailed above could affect climate components of the wetland water budget to preserve water within perched peatlands.

Soil textural layering, physical properties and antecedent moisture conditions in a wetland control soil water storage (Devito et al., 2005b; Devito et al., 2012), and the frequency of saturation following rain events (Rodriquez-Iturbe, 2000; Rodriquez-Iturbe et al., 2007). Low soil water storage capacity due to low porosity and specific yield promotes soil saturation with limited P inputs (Devito et al., 2005b). High frequency of wetting gives rise to high soil moisture, generating anoxia, thus promoting wetland conditions (Rodriguez-Iturbe, 2000). If a wetland maintains high moisture values in the rooting zone, resulting in anoxia near the surface, only water-tolerant and hydrophillic species can survive (Rodriguez-Iturbe, 2000; Rodriquez-Iturbe et al., 2007). A direct implication of low soil water storage capacity and high frequency of wetting in a wetland, is a system in which P may be equal to or less than AET, but in which wetland conditions are still maintained.

Soil textural layering within perched peatlands may give rise to complex flow paths and interactions between the peatland and margin swamp. The peatland active layer is the upper, undecomposed peat, with low bulk density, high fibre content and large pores (Boelter, 1969). It is frequently aerated, and functions to regulate the WT due to high storage and specific yield, and is able to rapidly transmit water (Boelter, 1969; Ingram, 1978). The lower decomposed layer behaves inversely to the upper layer. It has high bulk density, low fibre content and small pores resulting in low storage, high holding capacity and low conductivity (Boelter, 1969). The active peat layer in the perched peatland appears to shed excess water to the margin swamp during wet periods (Chapter Two). When the WT drops into the lower peat layer, high holding capacity maintains the WT and anoxic conditions (Boelter, 1969). Further, the low specific yield and storage of decomposed peat could provoke frequent and rapid WT rise into the base of the active layer following even minor rain events, maintaining permanent wetland conditions in the peat. These interactions could result in wetland flow paths from the peatland to swamp (Langlois et al., 2015). However, low relief between the peatland dome and margin swamp could also cause reversals wherein the margin swamp generates water to the peatland edge, similar to reversals reported in other systems (Devito and Hill, 1997; Fraser et al., 2001; Ferone and Devito, 2004). Alternatively, the margin swamp may maintain wetland conditions primarily through low storage and frequency of wetting. During wet periods, both peatland and margin swamp could generate water and facilitate peatland expansion through paludification (Lavoie et al., 2005). Whether paludification stops soil storage reaches a given capacity, or whether the wetland can transmit sufficient water into adjacent hillslope soils to continue expansion in a sub-humid climate is unknown.

The literature has affirmed the functional role of peatland margin swamps as receivers or transmitters of water from either the peatland or adjacent upland (Dimitrov et al., 2014; Langlois et al., 2015), but has not documented margin swamps as generators of water. Instead, research to date has concluded that margin swamps transmit water to downslope peatlands (Dimitrov et al., 2014) and conserve water in adjacent peatlands due to low hydraulic conductivity layers beneath the margin (Langlois et al., 2015). The hydrologic function of the margin swamp adds to the complexity of perched wetland maintenance, considering the potential of swamps to generate water and maintain wetland conditions through low storage. Further evidence of margin swamps as generators of water is discussed in Devito et al. (2005b; 2012). Ephemeral draws, which exhibit similar textural layering to margin swamps, were found to contribute a substantial portion of annual runoff in BP catchments (Devito et al., 2005b; Devito et al., *In press*).

This chapter will investigate the dominant processes controlling climate and frequency of wetting in an autogenic isolated wetland. Research related to P, AET and storage will provide insight on perched wetland maintenance in sub-humid conditions. These findings will inform on perched wetland reconstruction. In addition, this work aims to identify the relative roles of the peatland and the margin swamp in generating water, and to expand knowledge of the overall function of margin swamps. Two key questions emerge:

1) What are the dominant processes operating to increase the climate surplus over the wetland, since the wetland is autogenic with net precipitation (P net) > AET?
2) What is the interaction between soil water storage and P in the generation of excess water in the peatland and margin swamp?

In response to these research questions, the following hypotheses are tested:

a) Increase in total wetland P relative to regional P due to preferential funneling over wetland gap (Golding and Swanson, 1978)

b) Decrease in wetland interception and increase in wetland P net compared to surrounding forest (Golding and Swanson, 1978)

c) Decrease in wetland AET through shading and sheltering by adjacent forest (Petrone et al., 2007), ice in the rooting zone (Steele et al., 1997), and peatland internal feedbacks relating to moss properties and WT depth (e.g., Kettridge and Waddington, 2014)

d) Low storage caused by soil textural layering (Devito et al., 2005b) generating wetland soils through high frequency of wetting (Rodriguez-Iturbe, 2000). The wetland can exist with P net ≤ AET.

2.0 Site description

The study perched wetlands are located 370 km north of Edmonton, Alberta in the Utikuma Research Study Area (URSA, Figure 2.1a). The URSA is situated in the BP Ecozone of the western boreal forest, in the Mid-Boreal Uplands Ecoregion (Ecological Stratification Working Group, 1996), and is classified as central mixed wood in the Boreal Forest of Alberta (Natural Regions Committee, 2006). The climate is sub-humid; average annual P (486 mm) is less than potential evapotranspiration (PET, 518 mm) (Environment Canada, 2003; Winter and Woo, 1993; Marshall et al., 1999 Figure 2.1a). The majority of P falls as rain during convective storms in June, July and August (Devito et al., 2005b), and winter snow averages 100 mm (< 25 % of P; Pomeroy et al., 1997). Regional daily average temperature ranges from -14.6 ℃ in January to 15.6 ℃ in July. The climate undergoes decadal wetting and drying periods, with water surpluses (high runoff rates) occurring approximately every 20 years (Mwale et al., 2009). Hydrologic and biogeochemical studies in the URSA have been conducted across three common geomorphic landforms characteristic of the BP: hummocky coarse-textured glaciofluvial deposits, fine-textured, low relief glaciolacustrine deposits, and hummocky fine-textured stagnant ice moraine deposits (Fenton et al., 2013). These glacial features range from 60 – 120 m in thickness (MacCormack et al., 2015), and overlie shale and siltstone of the Upper Cretaceous Smoky Group (Prior et al., 2013).

The study site for this chapter is Pond Catchment 19 in the URSA, located on the transition zone between a stagnant ice moraine to the east (fine grained; Ferone and Devito, 2004) and a glaciofluvial outwash deposit to the west (coarse grained; Smerdon et al., 2005) (Figure 2.1b). Previous work has shown that regional groundwater is approximately 20 m below the ground in a sand aquifer, separated from the perched WT by meters of unsaturated zone (Riddell, 2008; Chapter Two, Figure 3.1b). Perched wetlands occur in this landscape when a clay CL is proximal (< 0.8 m) to the surface (Chapter Two). Pond Catchment 19 (2.3 km^2) contains several wetland forms (Figure 2.2a): a shallow open pond - marsh complex (Pond 19, 1.7 ha), an ephemeral draw connected to the pond (0.7 ha), and peatland - swamp complexes of varying size (0.45 – 1.75 ha). Chapter Two focused on perched wetland H (0.45 ha), a complex containing a peatland encircled by margin swamp, located on a Pond Catchment 19 topographic high (Figure 3.1a). Perched wetland H occupies a flat hilltop approximately 4 m above the ephemeral draw and wetland S8, and 6 m above Pond 19 (Figure 3.1b). Though this chapter focuses on perched wetland H, it also compares data from the Pond 19 meteorological tower (MET) and wetland S8, a 1.75 ha peatland – margin swamp complex located 300 m southwest of perched wetland H (Figure 2.2a).

The peatland in perched wetland H is classified as a coniferous treed basin bog by the Canadian Wetland Classification System (National Wetlands Working Group, 1997), and as a wooded bog by the Alberta Wetland Classification System (ESRD, 2015). The margin swamp is classified as a hardwood treed peat margin swamp (National Wetlands Working Group, 1997), and a deciduous wooded swamp (ESRD, 2015). The peatland (0.24 ha) in perched wetland H accumulates up to 1 m of peat in the centre, exhibiting a distinct diplotelmic structure (Figure 3.2). Acrotelm thickness ranges from 25 – 40 cm and catotelm from 40 – 70 cm. The margin swamp has a similar area of 0.25 ha, accumulating up to 20 cm of organic matter. A gleyed clay CL underlies the wetland, occurring 1 m beneath the peatland and at depths of 0.6 – 1 m in the swamp (Figure 3.2). This same CL increases to 1.5 to > 2 m depth in the adjacent upland, and contains root fractures and oxidized features. Dominant soil textures above the CL are silt loam, silt clay loam, and fine sand with clay (Figure 3.2). The canopy of the forest encircling the wetland complex consists of aspen (*Populous tremuloides,* ~20 m) and stands of white spruce (*Picea glauca,* 20 - 30 m) in the north, east, and south portions of the wetland (Figure 3.3). These trees are much taller than the dominant wetland vegetation which comprises paper birch (*Betula papyrifera,* ~10 m), alder (*Alnus*), and willow (*Salix*) in the margin swamp, and stunted black spruce (*Picea mariana,* 3 - 4 m) with bog birch (*Betula pumila*) in the peatland, creating a gap in the forest canopy over the wetland. Peatland understory vegetation comprises Labrador tea (*Rhododendron groenlandicum*), leatherleaf (*Chamaedaphne calyculata*), cloud berry (*Rubus chamaemorus*) and bog cranberry (*Vaccinium oxycocco*). Hummocks and hollows in the peatland are dominated by sphagnum (sp. *magellanicum, fuscum, angustifolium*) and feathermosses. Microtopography variations across the peatland are approximately 30 cm between hummocks and hollows.

The water budget for perched wetland H (Chapter Two) revealed that groundwater flow was always directed away from the wetland edge (margin swamp) to adjacent upland. Upland wells greater than 5 m from the wetland edge were dry (Figure 3.2). The perched WT was contained by a CL < 1 m from the surface. The sand layer beneath the CL was unsaturated (Figure 3.2). No surface flow was observed between the wetland and the upland.

Wetland S8 occupies a closed oblong basin, surrounded by shallow hillslopes (2 – 3 degrees), and exhibits similar margin swamp vegetation to wetland H (Figure 2.2a). In the S8 peatland a series of distinct vegetation zones extend from northwest to southeast: stunted black spruce, tamarack, bog birch, sedges and grasses. The adjacent upland forest is classified as mixed aspen woods. There is up to 2.5 m of peat in the centre of the peatland, decreasing in thickness toward the margin swamp (Riddell, 2008). During the snow free season, standing water was noted predominantly in the southeast portions of the peatland. Previous work at wetland S8 found similar stratigraphy to wetland H, with a CL proximal to the wetland surface, increasing in depth toward the upland (Riddell, 2008). Heterogeneous silt loam and fine sand was observed above the CL in the margin swamp and adjacent upland at wetland S8.

Pond 19 (Figures 3.1b and 2.2a), a shallow pond – marsh complex, is an open system with little protection from adjacent forest compared to the more sheltered wetlands H and S8. Pond extent has varied from 1.4 – 5.6 ha over the last 50 years (Riddell, 2008). Riparian vegetation consists principally of tall grasses; few alder and birch are present given extensive beaver activity. The wetland basin slope is 2.5 degrees, compared to slopes of 8 – 10 degrees in the adjacent upland (Riddell, 2008).

3.0 Methods

3.1 Climatic controls

3.1.1 Precipitation

Pond Catchment regional P in the open was measured adjacent the Pond 19 meteorological (MET) tower (Figure 2.2a) using a tipping bucket (Jarek Tipping Bucket Rain Gauge, Geoscientific Ltd., Vancouver, Canada) and bulk P bucket measured monthly 1 November 2015

- 31 October 2016. To compare snow accumulation at perched wetland H and S8 to Pond 19, SWE measurements (n = 3) were taken with a snow core on 5 March 2016.

Four dominant vegetation zones around the perched wetlands were identified: mixed aspen forest, white spruce stands, margin swamp and peatland (Figure 3.3). Snow surveys were conducted at peak snow accumulation in early March 2016 on adjoining wetlands of differing gap size (H = ~1.75 d:h, S8 = 3 - 4 d:h, gap diameter to tree height). Surveys at the smaller wetland, perched wetland H, were laid out as described in Golding and Swanson (1978); star-shaped transects centred at the wetland gap extending north-south, east-west, northwest-southeast and northeast-southwest (Figure 3.3). A similar transect plan was employed on the larger gap at wetland S8. Snow surveys extended north-south, east-west, and northwest-southeast (Figure 3.3). Depth of snow and depth to ice were taken at 2 - 3 m intervals on either side of the transect point at wetland H, and at 2 - 5 m intervals at S8. Sampling intensity at wetland H was 245 points/ha for upland forest (aspen and white spruce), 557 points/ha for margin swamp, and 604 points/ha for the peatland. S8 sampling intensity showed 92 points/ha for aspen forest, 130 points/ha for margin swamp, and 146 points/ha for peatland. Disparity in sampling intensities is due to the larger area of S8. At each point, vegetation zone (aspen, white spruce, margin swamp, and peatland) and canopy cover (canopy, edge canopy, gap) were recorded. Snow surveys for the two wetlands were completed within one day of each other, with no intervening precipitation, justifying direct comparison of data. Spot SWE measurements (n = 240, Figure 3.3) were completed concurrently with snow surveys in order to develop a relationship between SWE and snow depth. SWE was calculated gravimetrically, using volume of snow core and snow depth. Transect snow depths were converted to SWE using a linear regression from the spot SWE measurements. Spatially weighted average SWE was found for each vegetation zone by spatial cell declustering (declus.exe; Deutsch and Journel, 1992), as sampling intensity increased toward transect centres. Snow depth and SWE point data was imported into GIS software and interpolated using the kriging tool (default settings; ESRI 2011. ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute) to create SWE surface maps for each wetland. The Wilcoxon rank sum difference of means test was used to determine statistical significance between vegetation zones, i.e., peatland, swamp, aspen forest and conifer stands for each wetland as in Lundburg and Koivusalo (2003) and Ketcheson et al. (2012). Spatial averages from the snow survey were subtracted from regional estimates of total snowfall at Pond Catchment 19 to calculate the difference in SWE between regional and snow survey estimates among vegetation zones in wetlands H and S8.

Net rainfall for vegetation zones at wetland H was estimated using through fall hand gauges during the 2015 snow-free season (13 May – 12 October). Amount and percentage interception for peatland, margin swamp, aspen forest, and conifer stands were estimated by comparing through fall measurements to total rainfall during the same period. Total rainfall for Pond Catchment 19 was estimated using open hand gauges adjacent Pond 19, wetland H, wetland S8 MET towers and the tipping bucket adjacent Pond 19.

3.1.2 Evapotranspiration

Prolonged ablation and persistence of ice

Ablation in spring 2015 was assessed weekly from peak snow in mid-March to end of melt. Depth of snow, depth to ice, and depth of surface water were collected along the north-south transect every 2.5 m at wetland H (Figure 3.3). This transect extended through aspen forest, white spruce stands, margin swamp and peatland to facilitate assessment of snowmelt timing in each zone. A similar survey was conducted along a north-south transect at wetland S8 (Figure

3.3). Photos were taken in different vegetation zones in the wetland and upland forest throughout snowmelt to qualitatively compare snow cover (Figure A.6).

Peatland surface moisture

Surface soil moisture transects extending north-south and east-west (crosses on Figure 3.1) were monitored twice-monthly May - October 2015, and following rain events > 10 mm during the same period. Measurements were taken every 2.5 – 3 m with a soil moisture probe (Theta Probe ML2x soil moisture sensor, Delta-T Devices Ltd., Cambridge, UK), inserted to a depth of 6 cm. Transects covered peatland microtopography (hummock and hollow) and dominant surface cover (feathermoss, sphagnum, and bare), and extended through margin swamp, aspen and conifer forests. Surface soil moisture was taken coincident with ice depth, and depth of rust. Ice depth was measured with steel probes, determined when the probe hit resistance in the soil profile. Metal pin flags were employed to determine depth of rust below soil surface (Carnell and Anderson, 1986; Bridgham et al., 1991); rust was removed from flags after each measurement, and pin flags were left 2 - 3 weeks between measurements. Ice measurements throughout the spring and early summer enabled monitoring of distribution, depth and persistence of soil frost across the wetland. Soil redox condition is controlled by fluctuating water levels (Mitsch and Gosselink, 2007). A reducing zone (no rust), implies saturated wetland (hydric) soils.

Protection and sheltering: meteorological variables

A MET tower was installed in the open area at the peatland centre in wetland H (Figure 3.1). Air temperature and relative humidity probes (%, HOBO U23-001 data logger) were positioned 0.25 m above the peatland surface at the MET tower and in the margin swamp (site 87; Figure 3.1). Hourly data was recorded April – October 2015. An identical probe was placed 0.25 m above the surface of Pond 19 MET (Figure 2.2a), and measured over the same time interval for comparison with perched wetland H. Using daily minimum and maximum air temperatures and relative humidity (RH), daily vapour pressure deficit (VPD) was calculated for Pond 19 and wetland H. Daily average air temperature and RH were also determined for each site. Data was divided into early green (1 May 2015 – 7 Jun 2015), green (8 Jun 2015 – 6 Aug 2015), and late green (7 Aug 2015 – 7 Oct 2015) periods, to assess changes in variables throughout the growing season in open versus protected systems. Data were compared by applying the t-test (unequal variance) to determine if a significant difference existed between open (Pond 19) minus wetland H (peatland and swamp) compared to no difference (null hypothesis of zero) for air temperature, RH, and VPD within the early green, green, and late green periods.

Relative evaporation using isotopes

To assess evaporative signatures, water samples were collected from snow, surface waters, wells and piezometers within the peatland and margin swamp at perched wetland H for stable isotope analysis. Snow samples were collected for isotope analysis during March snow surveys in 2015 and 2016 according to vegetation zone around the wetland. Well and piezometer samples were collected with bailers (PVC bailers, Rice Engineering, Edmonton, AB, Canada). Sampling took place during spring melt 2015, 2016, early summer 2015, 2016, mid summer 2014, 2015 and fall 2014, 2015. Precipitation during the snow-free period was collected in an isotope collector based on the Palmex Rain Sample RSI (Gröning et al., 2012) at Pond 19 MET (Figure 2.2a) 2013 - 2015. Rain was sampled monthly 2013 - 2014, and twice-monthly 2015 - spring 2016 to establish a local meteoric waterline. Pond water from Pond 19 was sampled monthly during the ice free period 2014 - 2016 (May to October) to generate an evaporation line. Water samples were filtered using 0.45 µm membranes in the field, and stored in 2 ml glass vials with no head space to prevent further fractionation. Stable isotope ratios for hydrogen and oxygen were measured at the Biogeochemical Analytical Laboratory, University of Alberta. Water samples were run on the Picarro Cavity Ring-Down Spectroscopy L2130-i isotope analyzer. Results were quoted in per mil difference (‰), in relation to Vienna Standard Mean Oceanic Water (VSMOW). Analytical uncertainties were ± 0.1 ‰ for δ18O and ± 0.5 ‰ for δ2H.

3.2 Peatland and margin swamp interactions

3.2.1 Soil physical properties

In August 2015, soil profiles in both wetland and upland were sampled for bulk density. Samples were taken in the peatland (sites 81, 136, 138, 116, 27, 100), swamp (sites 87, 97) and upland (sites 86, 107, 121, 122, 123) (Figure 3.1). Soil depth profiles were 0.5 – 1 m deep, and samples of known volume were collected every 0.1 m. Samples were placed in sealed containers, and weighed prior to air drying. Samples were then oven-dried for 72 hr at 70°C, and reweighed post-drying. Bulk density was calculated using (Carter, 1993):

$$\rho_b = \frac{weight\ of\ oven\ dried\ soil}{volume} \tag{3.1}$$

where ρ_b is the dry bulk density in g cm^{-3}, weight of oven dried soil in g and volume of soil in cm^{3}.

Porosity was calculated using bulk density, and estimated particle density for wetland Redding and Devito, 2006) and upland (Redding et al., 2005) soils. Organic soils were given 1.53 – 1.55 g cm^{-3} particle densities depending on Von Post degree of decomposition and bulk density. Mineral soils were given particle density of 2.65 g cm^{-3}.

$$\Phi = 1 - \left(\frac{\rho_b}{\rho_s}\right) \tag{3.2}$$

where Φ is porosity, ρ_b is the dry bulk density in g cm^{-3}, and ρ_s is the particle density in g cm^{-3}.

3.2.2 Wetland hydrology

Flow regime, water table response and fluxes

A network of wells (n = 29) and piezometers (n = 14) was installed around the perched wetland in the summers of 2014 and 2015 to characterize the local groundwater flow regime (Figure 3.1). Transects extending from the peatland centre were employed to assess the perched WT across the peatland, margin swamp and upland forest. Wells were constructed with slotted 2" PVC pipe, wrapped in well sock and installed into pre-drilled boreholes. The void between well casing and borehole wall was filled with silica sand. Well depth was determined by soil texture, with deeper wells installed to top of CL (up to 2 m) and shallow wells installed to 0.5 m, to intersect perched WT. Piezometers were installed using 1" PVC pipe, wrapped in porous well sock to prevent clogging, and bottom screened for 0.2 – 0.3 m. For installations above the CL, it was necessary to back-fill with silica sand, then seal with bentonite clay above the screen. Piezometers installed within the clay CL were drilled to top of clay, and were then driven down to a depth slightly greater than the length of the screen to create a seal. A similar technique was used for piezometers within the peatland: a borehole was drilled to top of decomposed peat and the piezometer was then driven down the length of the screen to seal.

Manual WT measurements were made in all wells and piezometers throughout 2014, 2015, and 2016. Wells and piezometers were measured monthly November 2014 - March 2015. During the snow-free season (April – October), manual water level measurements were performed weekly to twice-monthly 2014 - 2016, and with increased frequency following storms. At each site water level, depth to ice, depth of rust, and depth of standing water (if present) were recorded. Electrical conductivity of ground and surface water was also recorded (TLC meter, Solinst

Canada Ltd., ON, Canada). In addition, automated pressure transducers (Solinst level logger model 3001; HOBO U20 water level data logger, Onset, MA, USA) were installed April 2015 at five key wells in the peatland (sites 81 27), margin swamp (sites 87, 97) and upland (site 86), and corrected for atmospheric pressure with a barologger (Solinst barologger model 3001, Solinst Canada Ltd., ON, Canada). WT response was estimated using a linear regression between rain inputs in the peatland centre (site 81) and margin swamp (site 87), similar to Devito et al., (2005b). Specific yield was calculated by dividing rainfall input (mm) by WT response (mm). Separate water budgets for the peatland and margin swamp were completed (Chapter Two).

Geochemical tracers for wetland flow paths

Precipitation, surface water and groundwater were sampled throughout 2014, 2015 and spring 2016. Precipitation was measured monthly employing a P bucket lined with clean polyethylene bags to capture rainwater, installed adjacent the Pond 19 MET (Figure 2.2a). Surface water was sampled from the margin swamp in early May 2015. Perched groundwater was collected fall 2014 - 15, spring melt 2015 - 16, and before and after summer rains in 2015 from select peatland (sites 81, 27, 125) and swamp (sites 97, 87) wells. Upland wells within 5 m of peatland edge were sampled when water was present (sites 107, 121). Precipitation samples were coarse filtered in the field through 750 μm membranes; ground and surface water were filtered through 250 μm membranes. *In situ* measurements of electrical conductivity and water temperature were taken using a temperature level conductivity meter (TLC, Solinst Canada Ltd., ON, Canada). Water samples were placed in contaminant free containers (Thermo-Scientific), and submitted to the Biogeochemical Analytical Service Laboratory, University of Alberta. Water was analyzed for dissolved organic carbon (DOC) by a TOC/N analyzer within 28 days of sample submission (Shimadzu 5000A TOC analyzer and TOC-V CPH with TMN unit), and calcium (Ca) by inductively coupled plasma – optical emission spectrometer (Thermo Scientific ICP6300). DOC and Ca were chosen based on bi-variate plots from a similar system described in Ferone and Devito (2004). Snow water chemistry was completed on samples taken in the dominant vegetation zones within wetland and surrounding forest March 2015 - 2016, together with survey and spot snow measurements during peak snow accumulation. Water was analyzed for DOC and Ca at the Biogeochemical Analytical Laboratory. End member chemistry of P (rain and snow) and groundwater (peatland and swamp) was combined with hydrologic data to interpret dominant wetland flow paths. Given the lack of upland groundwater adjacent wetland H, 2015 data for the 'URSA groundwater end member' was sampled from deep (sites 03-P14, P11) and local (site 40) groundwater at Pond Catchment 19, and local (sites 16-3 and 516) at Pond Catchment 16 and plotted for comparison with wetland H.

4.0 Results

4.1 Climatic controls

4.1.1 Increased precipitation

Funneling of precipitation: total wetland P versus regional P

The snow survey and through fall analyses did not support the preferential funneling of P (Tables 3.1 and 3.2), as peatland average SWE and through fall estimates at H and S8 were less than total snow and rain fall estimates for Pond Catchment 19. Further, although S8 SWE was slightly greater than H, indicating large gaps 3 - 4 diameter to tree height (d:h) may accumulate more snow, the difference between SWE at H and S8 was not significant ($p > 0.05$). Snow accumulation trends at S8 correspond with the prevailing northwest wind (Figure 3.3). At wetland H, no obvious trends between snow accumulation and wind direction were noted.

Maximum accumulation corresponded with gaps in the peatland black spruce canopy (Figure 3.3).

Average SWE in peatland openings were 2 – 3 mm more than the open Pond Catchment 19 regional estimate (79 mm) (Table 3.1). Average peatland SWE at H and S8 on 5 March 2016 was -8 mm and – 1 mm lower than total snowfall estimates for H and S8 respectively (Table 3.1). With respect to rainfall, peatland openings (228 mm) were estimated to funnel 11 mm more rain than the regional estimate for Pond Catchment 19 (217 mm) (Table 3.2). At H, average estimates of through fall for the whole peatland for 2015 (206 mm) were only 11 mm less than total regional rainfall estimate (217 mm) (Table 3.2).

Net precipitation: wetland versus forestland

At both H and S8 there was significantly more snow accumulation on average in the peatland (H = 71 mm, S8 = 78 mm) than the margin swamps (H = 62 mm, S8 = 65 mm) and mixed aspen forest (H = 59 mm, S8 = 67 mm), and lowest SWE in the conifer stands (H = 29 mm) ($p < 0.05$, Table 3.1). No difference was observed between mixed aspen forest and margin swamp in wetland H ($p = 0.195$) and S8 ($p = 0.35$). The highest variability in snow accumulation occurred in the peatland (Table 3.1), predominantly due to the relative effectiveness of interception in black spruce canopy, edges and peatland openings. The greatest SWE occurred in gaps, then black spruce edges; the lowest SWE was beneath the canopy (Table 3.1).

For the 2015 growing season, through fall in peatland H was 206 mm, or 9 mm and 78 mm greater than margin swamp (197 mm) and aspen forest (128 mm) respectively (Table 3.2). Comparing net rainfall in wetland and adjacent conifer stands showed > 150 mm more rain in the wetland (Table 3.2). During the 2015 snow-free season, interception percentages for wetland H were 5 and 9 % in the peatland and margin swamp respectively, compared to 41 and 80 % in the aspen forest and beneath the conifer stands respectively (Table 3.2).

4.1.2 Decreased evapotranspiration

Prolonged ablation

Protection and sheltering by the adjacent forest was hypothesized to prolong ablation and onset of wetland ET. In 2015, ablation in the peatland zone was prolonged 2 – 3 weeks compared to other vegetation zones at both H and S8 (Figures 3.4 and A.6). On 11 April 2015, patches of snow > 30 cm deep were noted throughout wetland H, with little or no snow observed in adjacent vegetation zones. By 25 April 2015, the only remaining snow was in the peatland at wetland H (Figure 3.4a and A.6), deepest in the southern edge, corresponding to areas of deepest SWE accumulation (5 March 2016; Figure 3.3). Similarly, at S8 large patches of snow (up to 38 cm deep) remained in southern portions of the peatland and swamp on 18 April 2015. By 18 April 2015 the northern peatland, margin swamp and aspen zones had no remaining snow (Figure 3.4b).

Persistence of ice

A frost table was measured from spring to early summer (April – June) 2015 and 2016 in the rooting zone of perched wetland H (Figure 3.5). The wetland rooting zone is defined as the top 20 cm of soil (Steele et al., 1997), as depth of rust data indicated that the oxic zone was ~ 20 cm in peatland and margin swamp hollows (Figure 3.7). Depth to ice data presented is from perched wetland H (Figure 3.5). Depth to ice in the peatland was < 10 cm below the surface during spring melt (April 2015 and 2016), and persisted within 20 cm from the surface until the middle of June 2015 and 2016 (Figure 3.5). Solid ice lenses within the top 40 cm of soil were measured until the end of June 2015 and 2016. Soil coring in southern portions of the wetland revealed patches of peatland ice until mid July 2015. In the margin swamp, ice depths decreased to < 10 cm during spring melt (Figure 3.5). Ice was present in the rooting zone (0 - 20 cm) until mid May 2015 and 2016, and occurred deeper in the soil column until the middle of June 2015. In the southern portions of the swamp, ice was recorded 38 cm below the surface mid July 2015 during exploratory soil coring. The upland forest adjacent wetland H showed ice depths near the surface during spring melt, but all ice was melted by mid May in both 2015 and 2016 (Figure 3.5).

Peatland surface moisture and water table depth

Previous studies of peatland ET highlighted low surface soil moisture and deep WT depth (> 30 cm below ground) as indicators of low evaporation rates (Kettridge and Waddington, 2013). Surface soil moisture measurements during the snow-free season were grouped by dominant surface cover (sphagnum, feathermoss and bare surface) and microtopography (hummock and hollow) in the peatland zone at wetland H, and divided into early green (1 May – 7 June), green (8 June – 6 August), and late green (7 August – 7 October) periods for 2015 to observe changes in soil moisture across the growing season (Figure 3.6a). Data indicated low moisture content across all surface types (Figure 3.6a); means ranged from 0.05 – 0.16 m^3m^{-3}. Soil moisture was higher in sphagnum than in feathermoss and bare surfaces. For all three covers, the average was higher in the early green compared to the green and late green periods (Figure 3.6a).

WT depth in the peatland centre hollow (site 81) at wetland H was 30 cm or greater from the end of June 2015 to early August 2015, and from mid-August through fall 2015, until the well was frozen (Figure 3.7). Shallow WT in early green period corresponded with higher soil moisture. Deeper WT depths (> 30 cm) corresponded with low surface moisture in green and late green periods.

Protection and sheltering: meteorological variables

Both PET (evaporation pan) and AET (272 mm) were lower at wetland H than at open Pond 19 (Chapter Two). The peatland evaporation pan (325 mm) was 50 mm lower in wetland H than at open Pond 19 evaporation pan (374 mm, Chapter Two). Both the peatland and margin swamp vegetation zones had higher % RH and lower air temperature than the open site (Pond 19, Figure 3.6). The margin swamp had higher RH and lower air temperature than the peatland at wetland H (Figure 3.6). Differences in temperature between peatland and swamp were only significant during the green period ($p < 0.05$).

Average RH was 8 – 11% greater in wetland H (peatland (60 – 90% RH) and margin swamp (90 % RH) than Pond 19 (60 – 80% RH) for early green, green, and late green periods ($p < 0.05$, Figure 3.6b). Air temperature averaged ~2°C cooler in both vegetation zones at wetland H (8 - 15°C) compared to Pond 19 (10 - 17°C); the difference was significant for entire growing season ($p < 0.05$, Figure 3.6c). VPD in the peatland (0.6 kPa) was higher than Pond 19 (0.5 kPa) in the early green period, but not significant. VPD between Pond 19 and peatland during the green period were similar (0.3 kPa), showing no significant difference ($p = 0.24$, Figure 3.6d). In the late green period, the trend shifted to lower VPD in the peatland (0.05 kPa) compared to the pond (0.2 kPa), resulting in a significant difference ($p < 0.05$). Large differences in VPD were observed in the margin swamp (~0 kPa) compared to open Pond 19; Pond 19 showed an average VPD 0.2 and 0.4 kPa higher in late green and green periods respectively. Differences were significant for both periods ($p < 0.05$, Figure 3.6d).

Relative evaporation using isotopes

Snow and rainfall δ ^{2}H and δ ^{18}O of P collected at Pond 19 MET were tightly clustered, resulting in an R^2 of 0.98 for the local meteoric water line (LMWL). The slope of the LMWL (7.19, Figure 3.8) was similar to the global meteoric water line (USGS, http://wwwrcamnl.wr.usgs.gov/isoig/period/o_iig.html). Aspen forest, peatland, swamp and conifer stand snow plotted on the LMWL -25 to -20 δ^{18}O (per mil) and -200 to -170 δ^{2}H (per mil), and were tightly clustered with Pond 19 snow samples. Water taken from Pond 19 displayed a distinct evaporative signature, resulting in an evaporation line with a slope of 4.7 and R^2 value of 0.99 (Figure 3.8). All ground and surface water samples from perched wetland H clustered within the central part of the LWML, as opposed to the pond evaporation line (Figure 3.8). To summarize the above findings, wetland H water demonstrated a precipitation rather than an evaporative isotopic signature.

4.2 Peatland and margin swamp interactions

4.2.1 Soil physical properties

Soil physical properties were expected to influence soil water storage and wetland WT response. In the organic soil (peatland), bulk density increased and porosity decreased relative to depth and degree of decomposition. There was low bulk density (0.04 – 0.07 g cm^{-3}) and high porosity (0.92 – 0.98) in 0 – 20 cm organic soils in the peatland, swamp and upland (Figure 3.9, Table A.1). There was a significant increase in bulk density and decrease in porosity along the transition from organic to mineral soil at 20 cm in the margin swamp and upland soil profile. From 20 – 80 cm depth below ground higher bulk density (>1.5 g cm^{-3}) and lower porosity (< 0.4) was observed in the margin swamp compared to adjacent upland soil. In contrast, the peatland displayed a gradual increase in bulk density to 0.28 g cm^{-3}, and gradual decease in porosity to 0.8 to a depth of 90 cm. At 100 cm, the transition from organic to mineral soil at the peat base resulted in a rapid increase in bulk density (0.5 → 1.45 g cm^{-3}), and decrease in porosity (0.8 → 0.5).

4.2.2 Wetland hydrology

Water table response and specific yield

Water table fluctuations were much more pronounced in the swamp than in the peatland. For example, a 45 mm rain event over three days in August 2015 generated a 0.62 m WT rise in the swamp (site 87) (Figures 3.7b and 3.10), 3x greater than the 0.23 m WT rise in the peatland centre (site 81) during the same period. Similarly, a dry period between 1 June and 12 July 2015 provoked a 0.65 m WT decline in the swamp, whereas the peatland WT decreased by 0.34 m. Figure 3.10a details the relationship between WT response and rainfall, highlighting that WT response to events in swamp mineral soil is at least two-fold that of the adjacent peatland active layer (Figure 3.10). Specific yield in swamp mineral soil was estimated to be between 0.05 and 0.10, compared to specific yield estimates in organic matter between 0.15 to 0.22, an indication that the storage capacity of the swamp is much lower than that of the upper peat layer (0 - 30 cm) (Figure 3.10b). No major draw down was noted in the lower peat layer (30 cm + depth, Von Post > 6) during the three years of detailed research in this paper (2014 – 2016) covering both wet and dry periods (Figure 3.7).

Seasonal trends

During snowmelt, the swamp wetted up on 1 April, one week before the peatland in both 2015 and 2016. Peak water level occurred in mid-May in 2014, 2015 and 2016, and resulted in standing water in the swamp but not the peatland (Figure 3.7b). In 2016, surface water was noted throughout spring, summer and fall. Following peak water levels in spring 2014 and 2015, both swamp and peatland WT declined throughout June, accounted for by leaf out, and lack of P events > 5 mm, while wet conditions in 2016 resulted in continually high water levels, given >100 mm more rain than 2014 or 2015 (Figure 3.7). From mid July to early September 2015, ET demand and several rain events > 15 mm generated a variable WT for both the peatland and swamp. During the same period in 2014, water levels decreased due to lack of rain events. In fall 2014 and 2015, all WT underwent a slow decline and were frozen/dry from mid-November to early April (Figure 3.7). Depth of the oxic zone (rust) 10 cm in the swamp, and 20 cm in the peatland until mid-summer each year, and did not exceed 30 cm in the peatland or swamp hollows during the 2014 – 2016 study period (Figure 3.7).

Wetland flow paths

Groundwater flow paths were consistently from center of the peatland to margin swamp, with lower gradients (close to zero, Figure 2.8) during wet periods in early 2014 and late 2016. Groundwater flow paths within perched wetland H are summarized in Figure 3.11. Radial flow occurred from peatland centre to swamp with low gradient flow reversals between centre (site 81) and southern portions of the peatland (site 125) during wet periods. Flow reversals with low gradients were also observed between the peatland edge and swamp (e.g., sites 27 and 97, 28 and 29; Figure 3.11). However, flow directions were consistently from the margin swamp to the adjacent upland, and most upland wells (2 - 5 m depth) > 5 m from wetland edge did not show a WT within 2 m of the surface during the study period (Figure 3.11). Regional groundwater remained 23 m below the surface for the entire study period (Figure 2.11).

Geochemical tracers for wetland flow paths

Geochemical tracers (Figure 3.12) were plotted for comparison with hydrological flow paths shown in Figure 3.11, and identification of potential sources. These geochemical data support hydrometric measurements, indicating flow from peatland → margin swamp → upland edge, and no water entering the wetland from local or deep groundwater (Figure 3.11). There was large separation in [Ca] between precipitation (<2 mgL^{-}1, rain and snow) and groundwater (>80 mgL^{-1}local and deep), but both end-members had similarly low [DOC] (Figure 3.12). Peatland water had moderate [Ca] (<15 mgL^{-1}) and elevated [DOC] (> 50 mgL^{-1}), a consequence of precipitation mixing with decomposed organic matter (Figure 3.12). The margin swamp surface water displayed a similar signature to peatland water. Swamp groundwater had similar [DOC] and slightly higher [Ca] (12 – 22 mgL^{-1}) compared to peatland water and precipitation (snow and rain) (Figure 3.12). Occasional water in the upland adjacent wetland H displayed similar [Ca] and [DOC] to margin swamp groundwater (3.12).

Water fluxes

Annual P for the 2014 – 2015 hydrologic year was below average compared to the long-term mean, because of below average summer rainfall (Chapter Two). P and AET are the dominant water budget components in the peatland and margin swamp (Table 3.3). Both peatland and swamp exhibit total P inputs (391 mm) > total outputs (320 – 336 mm), with AET estimates of 272 mm. The peatland (28 mm) has lower interception than the swamp (55 mm), but sheds excess groundwater to the swamp (19 mm). Higher interception in the swamp results in a lower P net, but groundwater in from the peatland compensates, and the swamp is able to generate water to the adjacent upland (8 mm). Cumulative change in water storage resulted in + 20 and + 22 mm for the peatland and margin swamp respectively.

During the winter – spring period (1 November 2014 – 30 April 2015), soil water storage increased by +60 and +131 mm in the peatland and margin swamp respectively, attributed to snowmelt filling storage, and the shedding of water from peatland to swamp. In the snow-free period (1 May 2015 – 31 October 2015), total inputs were less than outputs for both peatland (-39 mm) and margin swamp (-19 mm), attributed to higher AET and summer rainfall deficit, resulting in - 39 mm and - 109 mm storage changes in peatland and swamp respectively.

5.0 Discussion

5.1 Climatic controls

5.1.1 Increased precipitation

An increase in P net over the wetland compared to regional P due to funneling is unlikely a factor in wetland maintenance, because P net (both snow and rain), was not greater than the Pond Catchment 19 regional estimate. Peak snow accumulation did not differ significantly between wetlands H and S8, suggesting wetland gap size does not have an influence on snow accumulation in BP perched wetlands, contrary to other studies (Golding and Swanson, 1978). Decreased interception over wetland H due to gaps in the forest canopy allowed ~ 70 mm more P net to reach the surface than in the adjacent forest, indicating that lower wetland interception is an important autogenic process, especially in dry years such as 2015. Average SWE in perched peatlands was 10 – 20 mm greater than in the adjacent forest. This observation aligns with previous studies that found a similar increase in gap SWE compared to uncut forest (Golding and Swanson, 1978; Golding and Swanson, 1986; Troendle and Leaf, 1980; Ellis et al., 2013).

5.1.2 Decreased actual evapotranspiration

Perched wetland AET may be lowered through i) prolonged presence of ice and snow (Ketcheson et al., 2012; Steele et al., 1997), ii) protection and shading from adjacent forest (Petrone et al., 2007), and iii) peatland negative feedbacks relating to species composition and WT depth (Waddington et al., 2015). Understanding controls on wetland ET is critical for conceptualizing autogenic perched wetland formation and maintenance in the sub-humid BP.

Prolonged ablation

Results confirm that the peatland snowpack, particularly in wetland H, took up to three weeks longer to melt than the adjacent forest, shortening the duration of ET, thereby conserving water within perched wetlands. Snowmelt in forests is controlled in part by vegetation density or winter LAI (leaf area index, Pomeroy et al., 2002), which influences energy available for ablation (Boon, 2009). Mature conifer stands attenuate more radiation, exhibiting decreasing snowmelt as canopy density increases (Pomeroy et al., 2002). Ketcheson et al., (2012) concluded that rate of snowmelt in a harvested peatland was double that of an adjacent forested peatland; total snowmelt period was 17 days shorter in the harvested peatland. The relatively small gap at wetland H and proximity of conifer stands (20 – 30 m) provides effective shading of the wetland, therefore decreasing solar radiation inputs, especially on northern aspects (Pomeroy et al., 2002). The wetland gap also functions to increase snow accumulation (Section 5.1.1, e.g., Golding and Swanson, 1978). It may be concluded that when increased wetland snow pack combined with shading from adjacent forest, snow took longer to melt (Pomeroy et al., 2002; Winkler et al., 2005; Boon, 2009). Synergies may also exist among wind direction, accumulation, and ablation of wetland snow pack. For example, at the larger wetland S8, more snow accumulated in the southern portions of the wetland, correlating with the prevailing wind direction. During ablation, the southern portion of the wetland took up to two weeks longer to melt than the centre and northern portions. This may be attributed to decreased surface energy from shading, and or sheltering from wind by the adjacent forest (e.g., Petrone et al., 2007).

Persistence of ice

Lower available energy at the wetland surface in conjunction with thermal properties of peat impact the persistence of ice in the rooting zone and by extension transpiration rates, particularly rates measured in black spruce (Goodine et al., 2008). In the peatland and margin swamp at wetland H, ice was observed in the rooting zone (oxic layer of 20 cm depth) into early summer (mid June) in 2015 and 2016. Ice lenses function to maintain lower temperatures within this zone, decreasing stomatal conductance, and lowering metabolism, greatly reducing transpiration (Steele et al., 1997; Goodine et al., 2008). In contrast to the wetland, soil ice in the adjacent upland melted by mid-May. Shallow ice lenses imply transpiration rates in vascular vegetation in wetland H were reduced up to a month longer than surrounding aspen and spruce forest.

Near surface ice lenses can increase near surface moisture and decrease infiltration, thereby increasing surface evaporation, compensating for reduced transpiration (Brown et al., 2010). High WT in the wetland due to shallow ice may have increased evaporation rates in the early green period compared to the green and late green periods, particularly in the margin swamp, where standing water was recorded for ~ 2 weeks in May 2015 (Brown et al., 2010). However, surface soil moisture data during the early green period (May – June 2015) in peatland H showed low average VWC (<0.2), indicating the surface was unsaturated and not readily evaporating. Feathermoss was the dominant moss cover in the peatland, and due to its physiology is effective at reducing capillary rise, resulting in low evaporation rates even when the WT is shallow (Lukenbach et al., 2016).

Peatland surface moisture and water table depth

Deep WT depths in a peatland have negative impacts on evaporation (e.g., Kettridge and Waddington, 2014). Surface moss becomes resistant to evaporation when the WT drops to a threshold depth (Hayward and Clymo, 1982), and the ability of moss to conduct water upward via capillary forces, subject to species and surface structure, is limited and eventually broken (Price, 1991). When the WT dropped to 30 cm, an experiment found surface resistance increased from 50 sm^{-1} to 1000 sm^{-1}, shutting down evaporation (Kettridge and Waddington, 2014). For the majority of the growing season in 2015 the peatland WT in wetland H remained 30 cm or more below the surface. Low average soil moisture (VWC < 0.1) measured in peatland surface covers during the green and late green periods are indicative of lower surface evaporation and increased surface resistance, displaying similar values to those reported in Ketrridge and Waddington (2014). Surface soil moisture and peatland WT depth were consistent with lower peatland evaporation rates, similar to those observed in other studies (Price and Waddington, 2000; Petrone et al., 2007).

Protection and sheltering: meteorological variables

Sheltering and shading by the adjacent forest appeared to impact PET rates in wetland H by 15% (49 mm) when comparing evaporation pans at wetland H and open Pond 19 (Chapter Two). Petrone et al. (2007) found wetlands sheltered by tall trees resulted in a reduction of wind speed, and increase in humidity and aerodynamic resistance over the wetland, which functioned to decrease AET and winter sublimation by as much as 30% of PET. During the 2015 growing season, perched wetland H exhibited higher RH (8 – 11 %) than open Pond 19, attributed to decreased turbulence over the wetland from sheltering (Petrone et al., 2007; Waddington et al., 2015). In the margin swamp, the disparity was even more pronounced. The swamp had average

RH of 80 - 90%, a difference of up to 14 % greater RH than open Pond 19. Air temperature was ~2 ℃ cooler in the peatland and swamp than at open Pond 19 throughout the 2015 growing season. Reduction in surface air temperature observed at wetland H (treed bog) is explained by Kettridge et al. (2013), who concluded that wetland shading by trees decreased surface temperature and energy available for evaporation. In summary, meteorological variables such as RH and air temperature between open Pond 19 and protected wetland H appear to explain the observed differences in PET measured between the two sites, indicating protection and sheltering function to decrease wetland AET.

Relative evaporation using isotopes

Further support of decreased wetland AET through shading and sheltering, persistence of ice and snow, and high peatland WT depth was evidenced in the absence of isotopically enriched water in the wetland. All water samples from wetland H plotted on the LMWL rather than the Pond 19 evaporative line, indicating a distinct P isotopic signature. Since water from the perched wetland displays limited enrichment, it may be concluded that evaporation is low compared to adjacent Pond 19. Since AET is a dominant component of the wetland water budget, further work should be undertaken to quantify variability of ET throughout the season, and to determine how annual AET on isolated wetlands varies in response to water surplus and drought conditions characteristic of the BP.

5.2 Hydrologic role of peatland and margin swamp

5.2.1 Soil textural layering and physical properties control water table response

Margin swamp

The soil in the margin swamp has high bulk density and low porosity compared to the peatland and adjacent upland. A CL proximal (~0.5 m) to the surface gives rise to low soil water storage capacity in the swamp, resulting in low specific yields and rapid WT response, with limited P input (Devito et al., 2005b). For example, a rain event of 15 mm provoked a WT rise of 30 cm in the swamp, compared to 8 cm in the peatland. Even in a drier than average summer such as 2015, the rapid WT response of the swamp produced moisture conditions sufficiently high that the oxic zone rarely exceeded 20 cm. These data infer that the soil textural layering in the margin swamp generates wetland conditions through high frequency of wetting (Rodriguez-Iturbe, 2000), and further implies that unlike the peatland, the margin swamp may not require P > AET but rather low storage and rapid WT response to maintain wetland soils.

Peatland

The active layer in the peatland has contrasting soil physical properties to those of the margin swamp, namely high porosity and low bulk density, providing for high storage capacity in the top 30 cm of peat. The resultant hydrologic function is two-part: When the WT is present in this layer, response to rain events is mitigated, as the active peat has a high specific yield and saturated hydraulic conductivity (Boelter, 1969). Water is easily transmitted through this layer to the wetland edge. When the WT is below this layer, the active peat is unsaturated, creating a capillary break between the WT and surface, decreasing evaporation (Ingram, 1983). The peatland remains saturated due to the lower decomposed peat layer. This lower layer displays high holding capacity and low hydraulic conductivity (Boelter, 1969), maintaining the WT by decreasing both vertical and lateral seepage, observed during dry periods at wetland H (Price, 2003; Langlois et al., 2015). The low specific yield of decomposed peat enables the WT to rise rapidly into the active layer following a rain event (Boelter, 1969).

5.2.2 Internal water generation and flow paths

Geochemical data corroborates observed hydrological flow paths within the wetland. Flow is from the peatland centre to margin swamp. In the 2014-2015 hydrologic year, the peatland shed 20 mm to the margin swamp. The majority of this flow occurred during wet periods (5 - 9 L/day) when the WT was in the active layer. In contrast, during dry periods flow was approximately 0.05 L/day, a product of low lateral hydraulic conductivity (10^{-7} m s^{-1}) of decomposed peat. Ca – DOC bivariate plots revealed that swamp surface water (present May 2014, 2015, 2016) had a peatland groundwater signature, confirming water sourced from the peatland. Further, all swamp groundwater had similar [DOC] (> 50 mgL^{-1}) to the peatland, again signalling water flow from peatland to swamp.

Minor flow reversals occurred between the peatland edge and margin swamp. Continuous monitoring of water levels between northern peatland edge (site 27) and margin swamp (site 97) wells revealed frequent low gradient flow reversals throughout 2015 and 2016, with no clear relationship between wet and dry periods. For the entire study period WT differences were less than 10 cm between these two wells, indicating similar hydrologic response. Geochemical data showed mixed signatures between site 97 (north swamp) and site 27 (northern peatland edge) groundwater, a further indication of frequent low gradient flow reversals.

Internal flow paths in perched wetland H point to an autogenic system, capable of self-generation of water. During dry periods, low conductivity layers beneath the wetland promote water conservation. During wet periods, the peatland sheds water to the swamp, and the swamp generates and transmits water to the adjacent upland. To date, the literature has documented margin swamps as transmitters or receivers of water (Dimitrov et al., 2014; Langlois et al., 2015). However, perched margin swamps were shown to generate as well as transmit and receive water from the peatland, and exert a major influence in peatland water conservation (e.g., Langlois et al., 2015). As a result of soil textural layering, rapid WT response in the margin swamp could function as a buffer to peatland water loss by decreasing the hydraulic gradient between the peatland edge and swamp. Further, the margin swamp could function as a source of water to adjacent upland trees; trees could access swamp water rather than peatland water through roots at the wetland periphery (Lubczynski, 2009). During water surplus conditions in the climate cycle, the generating potential of the swamp could aid in peatland expansion through paludification. The margin swamp could be the first stage in paulidification. Before peat formed, the wetland may have been a swamp. The role of the margin swamp in perched peatland development and expansion is a current gap in the literature.

6.0 Conclusion

Perched wetland H is an autogenic wetland in the sub-humid BP, isolated from external ground and surface waters. Net P in the wetland was greater than AET, indicating that perched wetland H functions to conserve water in the water deficit climate (Chapter Two).

Snow accumulation and rainfall showed increased P net over the wetland relative to the adjacent forest due to decreased interception was an important autogenic processes functioning to increase wetland P. Snow accumulation in the wetland was 10 – 20 mm greater than in the adjacent forest and rainfall was up to 70 mm greater.

Decreased wetland AET caused by sheltering and shading afforded by adjacent forest prolonged ablation by 2 - 3 weeks in 2015. Air temperature was 2°C colder, and relative humidity 8 – 11% higher at perched wetland H than at open Pond 19, further evidence of lowered ET from shading and protection. Persistence of ice in the wetland rooting zone well into the growing season suggested lowered transpiration rates. WT depths > 30 cm and low surface moisture in the peatland promoted low surface evaporation. Surface and groundwater isotopic signatures from the peatland and margin swamp in perched wetland H support low ET, as all samples displayed a distinct P rather than evaporative isotopic signature.

Low storage in the swamp and lower decomposed peat controlled frequency of wetting and anoxic conditions. In the peatland, decomposed peat was always saturated due to high holding capacity of small pores. During wet periods, water was shed radially through the active layer to the peatland edge and margin swamp. The high bulk density and low porosity of underlying mineral soil resulted in low storage capacity in the swamp. Small specific yield in the swamp causes rapid WT rise with P inputs, and maintained anoxic wetland conditions even in dry summers. It is therefore probable that the margin swamp could maintain wetland soils with $P \leq AET$ if storage is low.

Autogenic processes and low storage are important in maintaining permanent wetland conditions in isolated systems in the sub-humid BP. Inclusion of internal processes functioning to decrease ET and low storage promoting frequent saturation may be requisites for successful reconstruction of isolated wetland systems. By generating water, the swamp appears to play a key role in wetland maintenance. Small, isolated systems may require margin swamps to function as buffers to upland forest influence, and aid in peat development and expansion. This work has shown isolated permanent wetlands in a sub-humid climate may not be as susceptible as previously indicated (Riddell, 2008), considering the influence of numerous autogenic processes operating to counter the regional moisture deficit.

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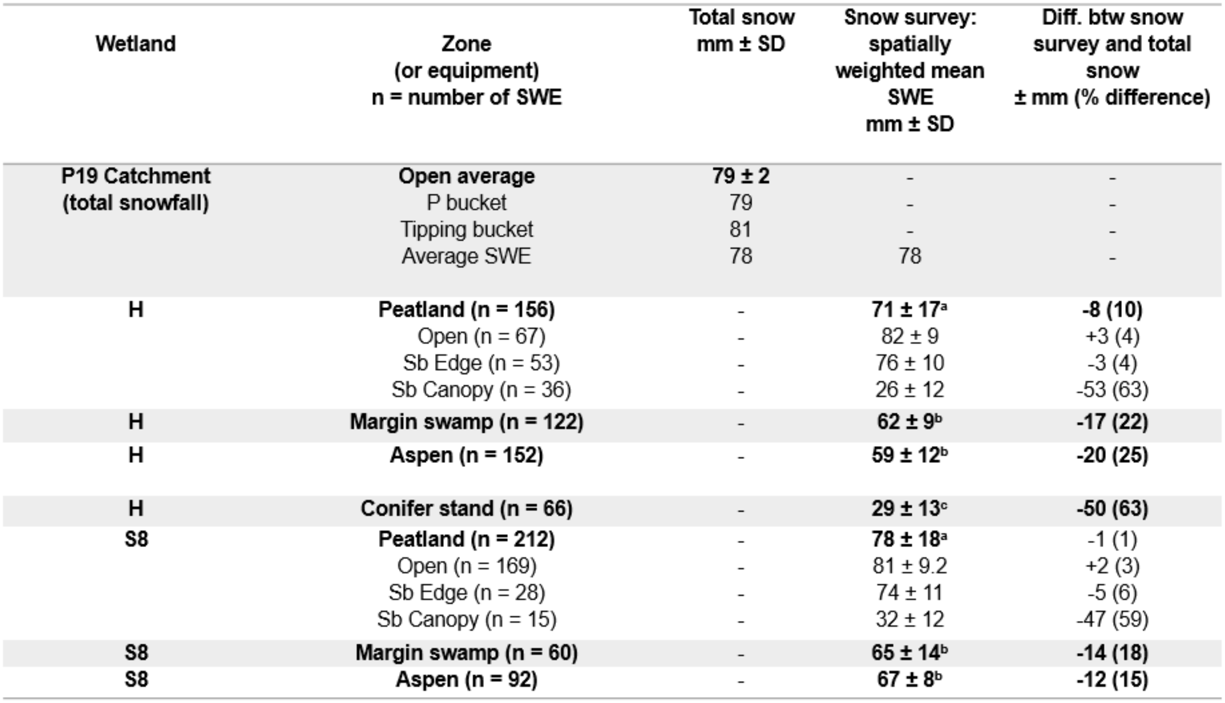
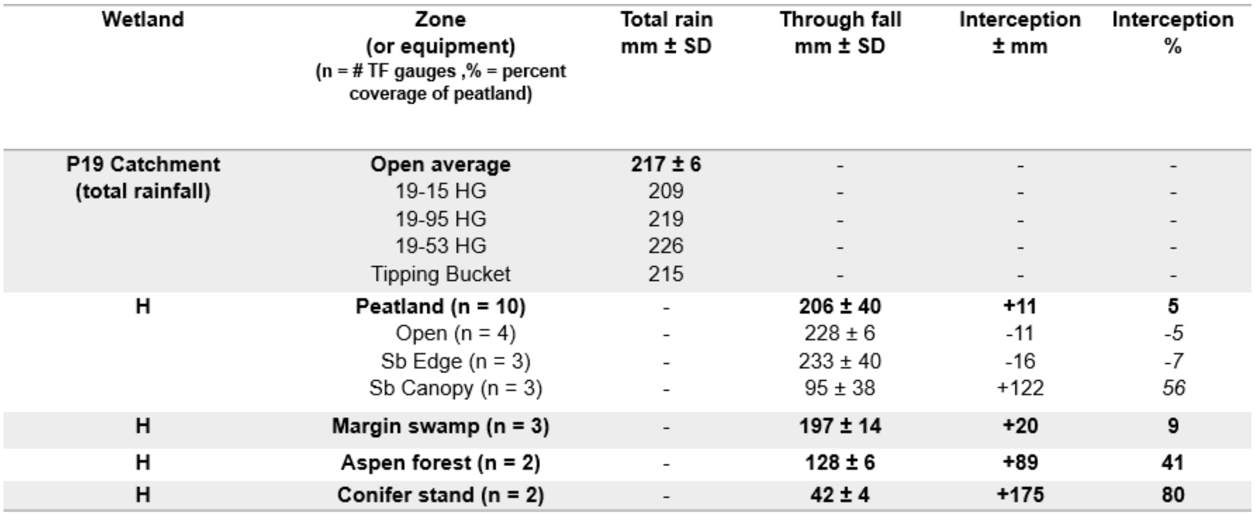
Table 3.1: Comparison of snow accumulation to total snowfall estimate (Pond Catchment 19) and comparison between dominant vegetation zone in wetlands H and S8 1 November 2015 - 5 March 2016. SWE is snow water equivalence in mm of water. Means with the same letter are not statistically significant at 5 % probability using the Wilcoxon rank sum test. Bold text represents vegetation zones for H and S8.



Wetland	Zone (or equipment) n = number of SWE	Total snow mm ± SD	Snow survey: spatially weighted mean SWE mm ± SD	Diff. btw snow survey and total snow ± mm (% difference)
P19 Catchment (total snowfall)	**Open average**	**79 ± 2**	-	-
	P bucket	79	-	-
	Tipping bucket	81	-	-
	Average SWE	78	78	-
H	**Peatland (n = 156)**	-	**71 ± 17^{a}**	**-8 (10)**
	Open (n = 67)	-	82 ± 9	+3 (4)
	Sb Edge (n = 53)	-	76 ± 10	-3 (4)
	Sb Canopy (n = 36)	-	26 ± 12	-53 (63)
H	**Margin swamp (n = 122)**	-	**62 ± 9^{b}**	**-17 (22)**
H	**Aspen (n = 152)**	-	**59 ± 12^{b}**	**-20 (25)**
H	**Conifer stand (n = 66)**	-	**29 ± 13^{c}**	**-50 (63)**
S8	**Peatland (n = 212)**	-	**78 ± 18^{a}**	-1 (1)
	Open (n = 169)	-	81 ± 9.2	+2 (3)
	Sb Edge (n = 28)	-	74 ± 11	-5 (6)
	Sb Canopy (n = 15)	-	32 ± 12	-47 (59)
S8	**Margin swamp (n = 60)**	-	**65 ± 14^{b}**	**-14 (18)**
S8	**Aspen (n = 92)**	-	**67 ± 8^{b}**	**-12 (15)**

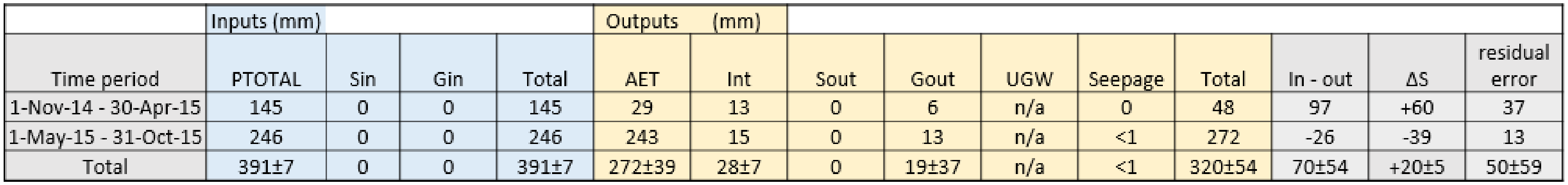
Table 3.2: Interception estimates at perched wetland H 13 May 2015 – 12 October 2015 in dominant vegetation zones within the wetland (peatland and margin swamp) and adjacent the wetland (aspen forest and conifer stands). Bold text represents vegetation zones around wetland H.



Wetland	**Zone (or equipment)** (n = # TF gauges ,% = percent coverage of peatland)	**Total rain mm ± SD**	**Through fall mm ± SD**	**Interception ± mm**	**Interception %**
P19 Catchment (total rainfall)	**Open average**	**217 ± 6**	-	-	-
	19-15 HG	209	-	-	-
	19-95 HG	219	-	-	-
	19-53 HG	226	-	-	-
	Tipping Bucket	215	-	-	-
H	**Peatland (n = 10)**	-	**206 ± 40**	**+11**	**5**
	Open (n = 4)	-	228 ± 6	-11	*-5*
	Sb Edge (n = 3)	-	233 ± 40	-16	*-7*
	Sb Canopy (n = 3)	-	95 ± 38	+122	*56*
H	**Margin swamp (n = 3)**	-	**197 ± 14**	**+20**	**9**
H	**Aspen forest (n = 2)**	-	**128 ± 6**	**+89**	**41**
H	**Conifer stand (n = 2)**	-	**42 ± 4**	**+175**	**80**

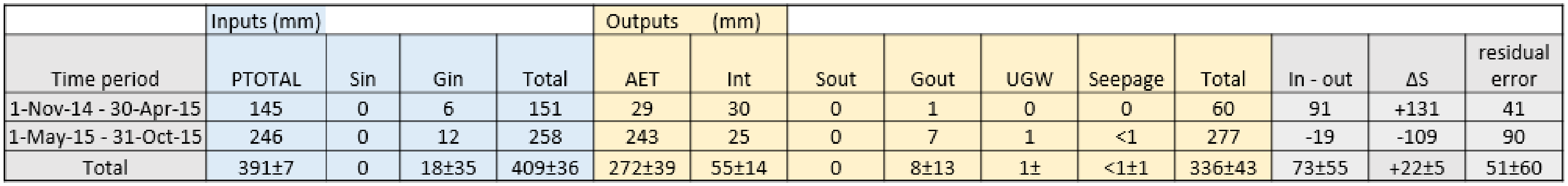
Table 3.3: Water budget components 1 November 2014 – 31 October hydrologic year for A) peatland and B) margin swamp. Uncertainties are presented as ± 1 standard deviation. See Chapter Two section 3.6 for error calculations.

A: Peatland



	Inputs (mm)				Outputs (mm)									
Time period	PTOTAL	Sin	Gin	Total	AET	Int	Sout	Gout	UGW	Seepage	Total	In - out	ΔS	residual error
1-Nov-14 - 30-Apr-15	145	0	0	145	29	13	0	6	n/a	0	48	97	+60	37
1-May-15 - 31-Oct-15	246	0	0	246	243	15	0	13	n/a	<1	272	-26	-39	13
Total	391±7	0	0	391±7	272±39	28±7	0	19±37	n/a	<1	320±54	70±54	+20±5	50±59

B: Margin swamp



	Inputs (mm)				Outputs (mm)									
Time period	PTOTAL	Sin	Gin	Total	AET	Int	Sout	Gout	UGW	Seepage	Total	In - out	ΔS	residual error
1-Nov-14 - 30-Apr-15	145	0	6	151	29	30	0	1	0	0	60	91	+131	41
1-May-15 - 31-Oct-15	246	0	12	258	243	25	0	7	1	<1	277	-19	-109	90
Total	391±7	0	18±35	409±36	272±39	55±14	0	8±13	1±	<1±1	336±43	73±55	+22±5	51±60

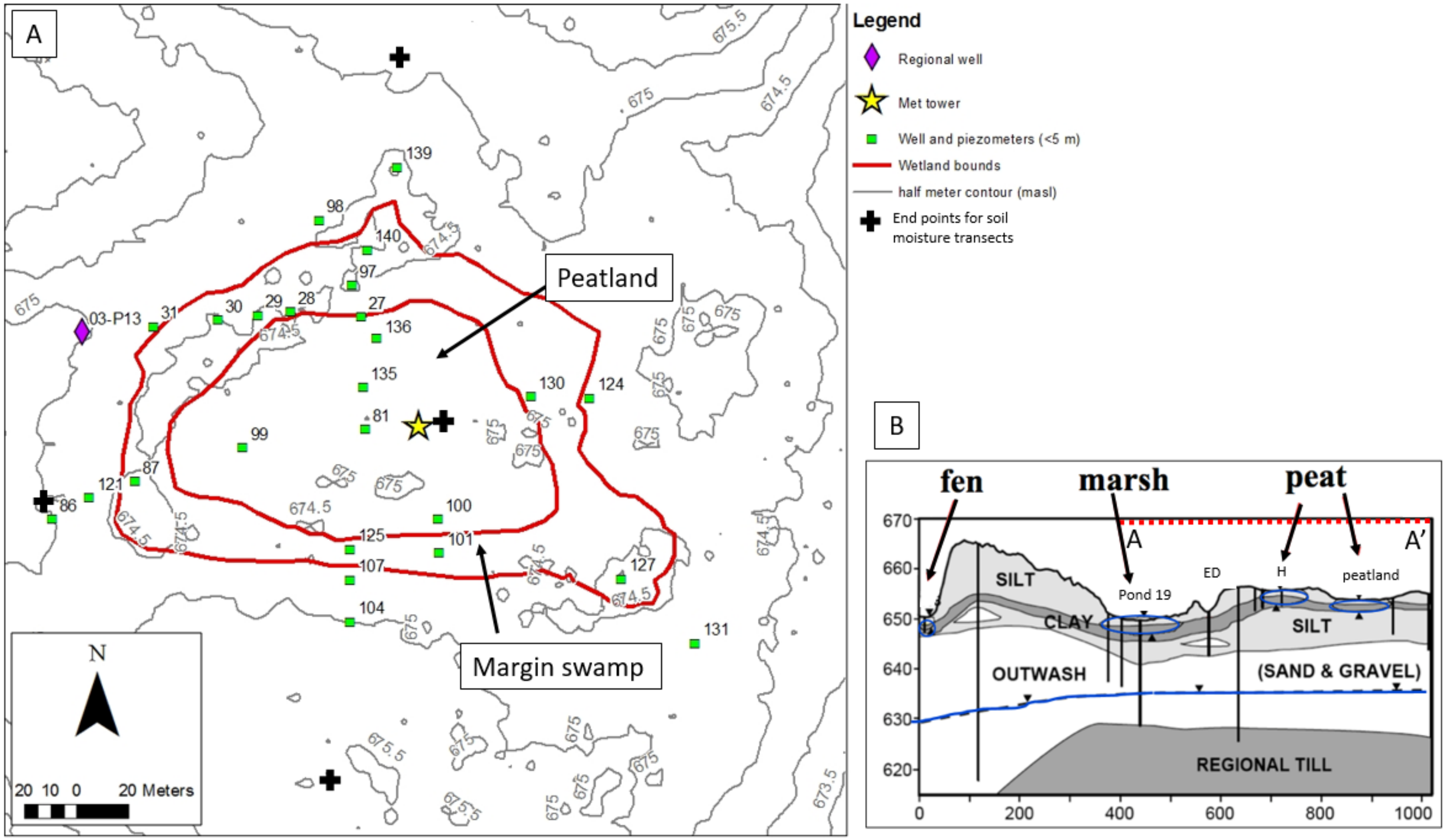


Figure 3.1: a) Perched wetland H site map containing wetland bounds, well and piezometer sites (< 5 m), meteorological tower, regional groundwater well and soil moisture transects (start and ends denoted by cross). Cross section in Figure 3.2 extends N-S from site 139 to 104 b) Cross section of Pond Catchment 19 showing silts and clays over coarse material with regional water table contained in outwash sediment and perched water tables forming in overlying fine textured substrate. The study perched wetland complex is on a topographically high setting, denoted by 'H' (adapted from Riddell, 2008). Vertical exaggeration is 10x. Wetland H is at 56˚04'53.66" N 115˚32'06.02" W in Google Earth.

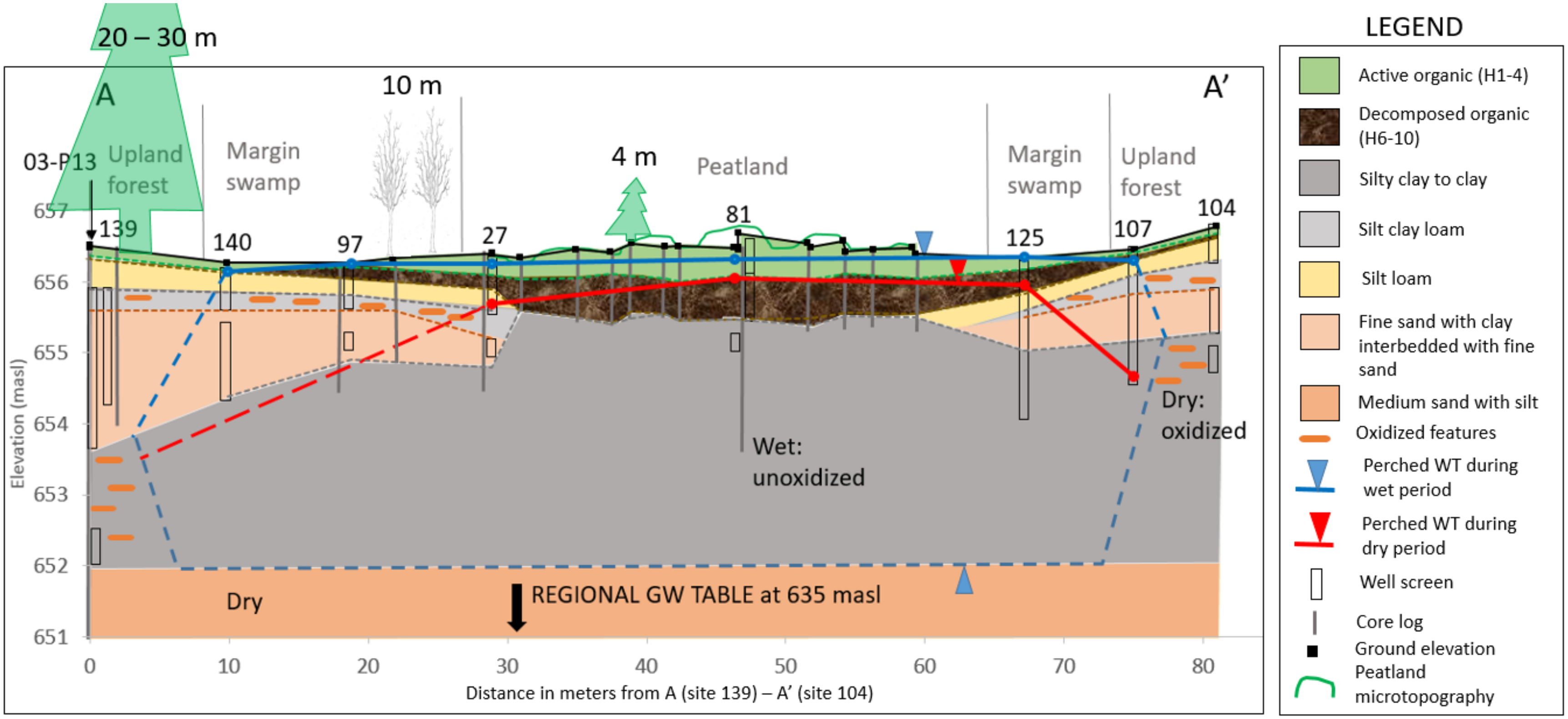


Figure 3.2) North-south cross section from sites 139 (A) to 104 (A’) (see Figure 3.1) across the perched wetland. Vegetation zones are shown in grey, surface elevations in black, peatland microtopography in green. Water table with screens across perched wetland for wet period (blue: 20 May 2016) and dry period (red: 13 July 2015). Site 03-P13 (regional groundwater well, Figure 3.1a) is located 45 m SW of site 139, the ~same distance from the edge of the wetland as site 139. Tree heights relative to gap size are provided: upland forest (20-30 m), margin swamp (10 m) and peatland (3 - 4 m).

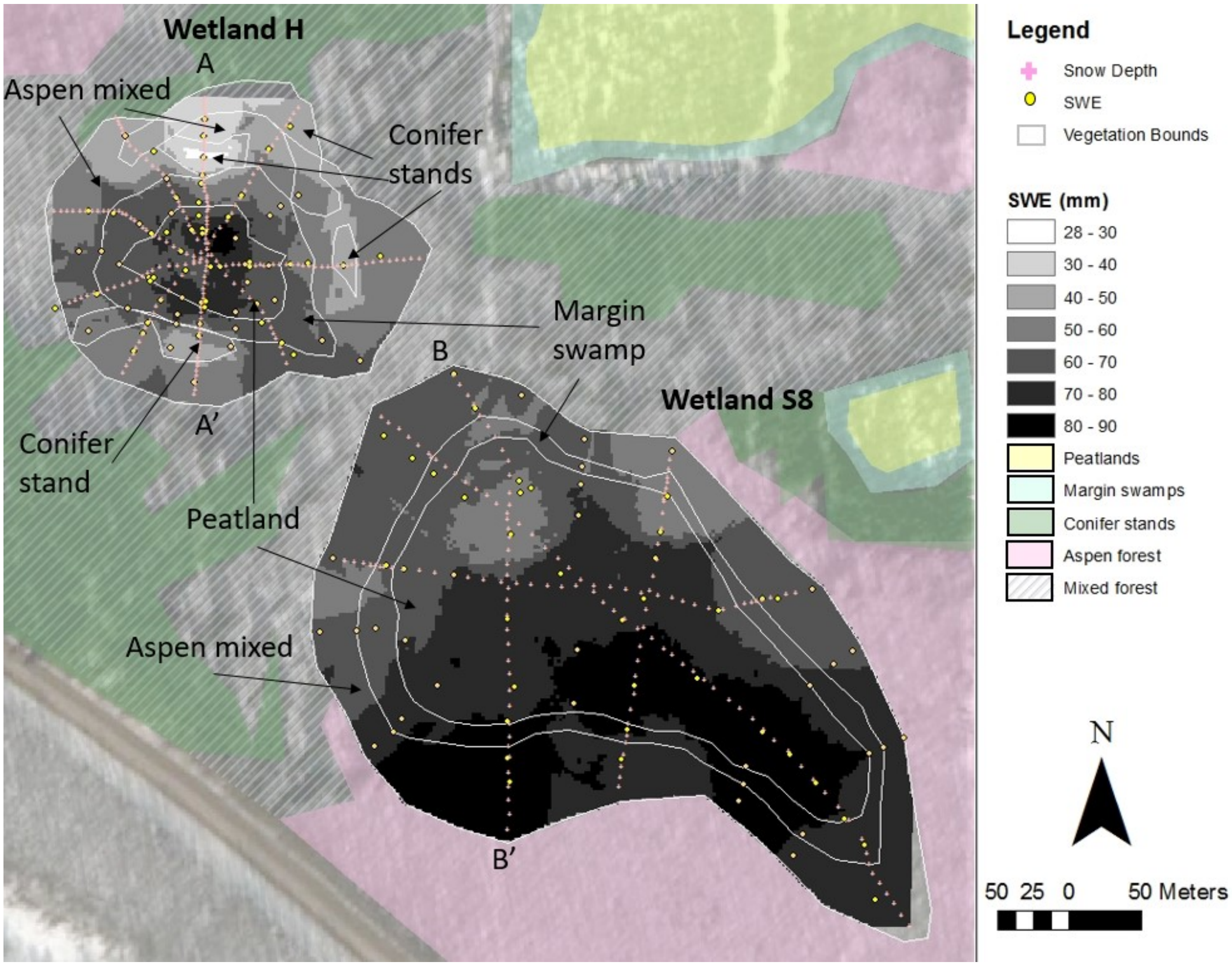


Figure 3.3: Kriged snow water equivalence (SWE) using ArcMap V.10.4 for peak winter snow accumulation at perched wetlands H and S8 5 March 2016. Vegetation zones are outlined in grey. Measured snow depths are pink crosses; snow water equivalence measurements are yellow circles. Vegetation zones of surrounding landscape are delineated using a satellite photo (Google Earth) as follows: peatland, margin swamp, conifer stands, aspen and mixed forest.

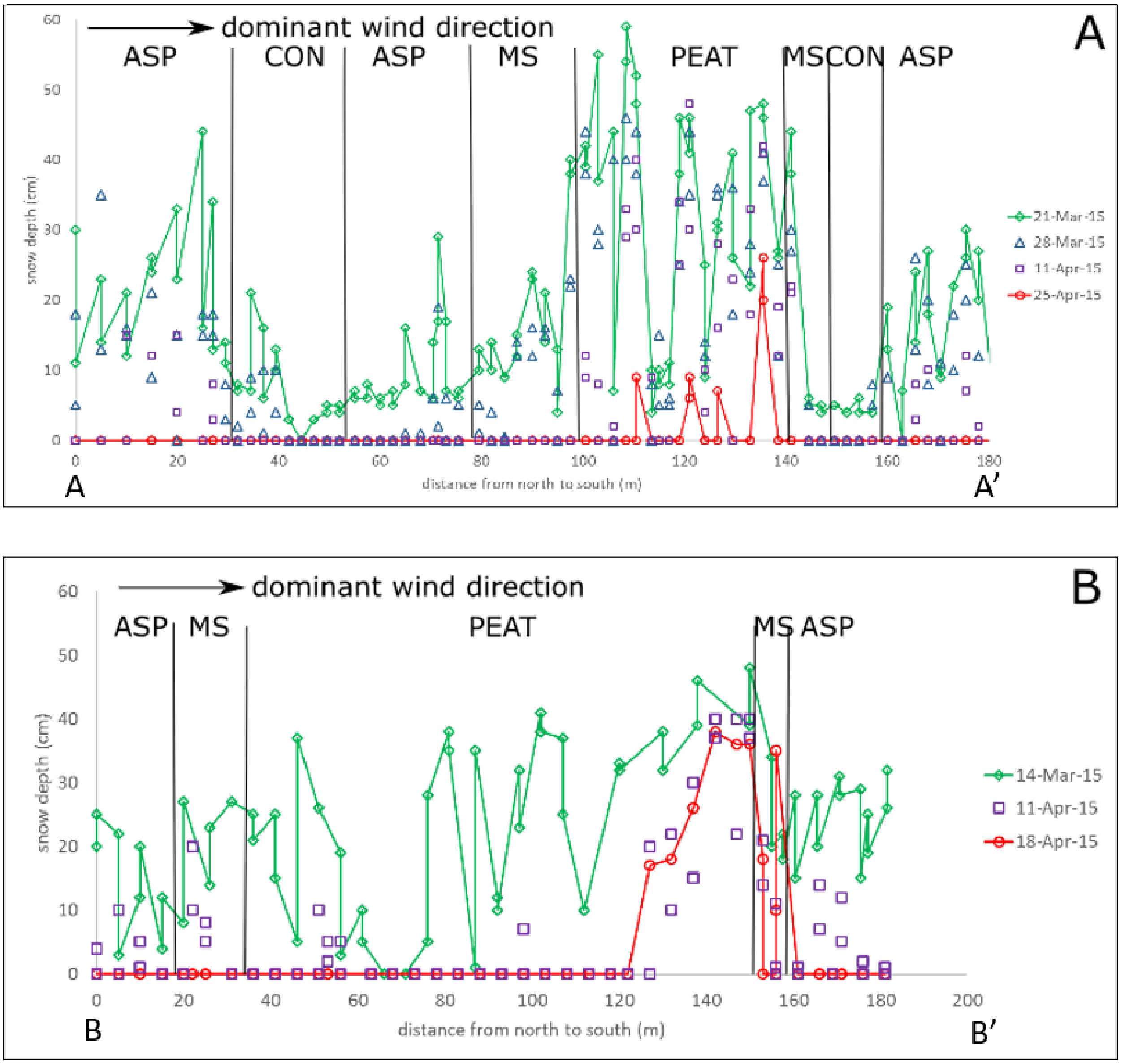


Figure 3.4: Snow depth across north-south transects for 2015 at wetlands H (a) and S8 (b) during spring melt. Prevailing wind direction is from the north. Earliest and latest transects are shown with a line to better view changes in snow depth. Transects are shown on Figure 3.3.

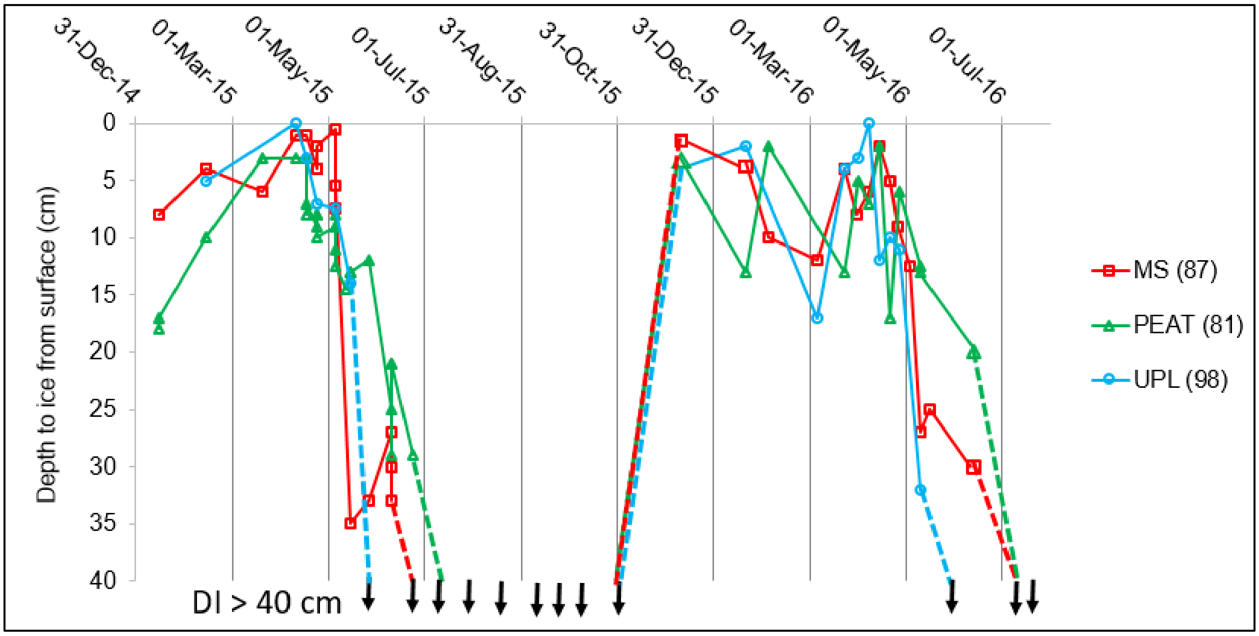


Figure 3.5: Depth to ice from surface for 2015 and 2016 at representative locations at perched wetland H. MS is margin swamp, PEAT is the peatland, and UPL is the adjacent upland. Numbers beside the labels indicate well site (Figure 3.1). When depth to ice was greater than 40 cm, recorded as > 40 cm, noted on the figure by a black arrow. Dashed line indicates extrapolation to > 40 cm.

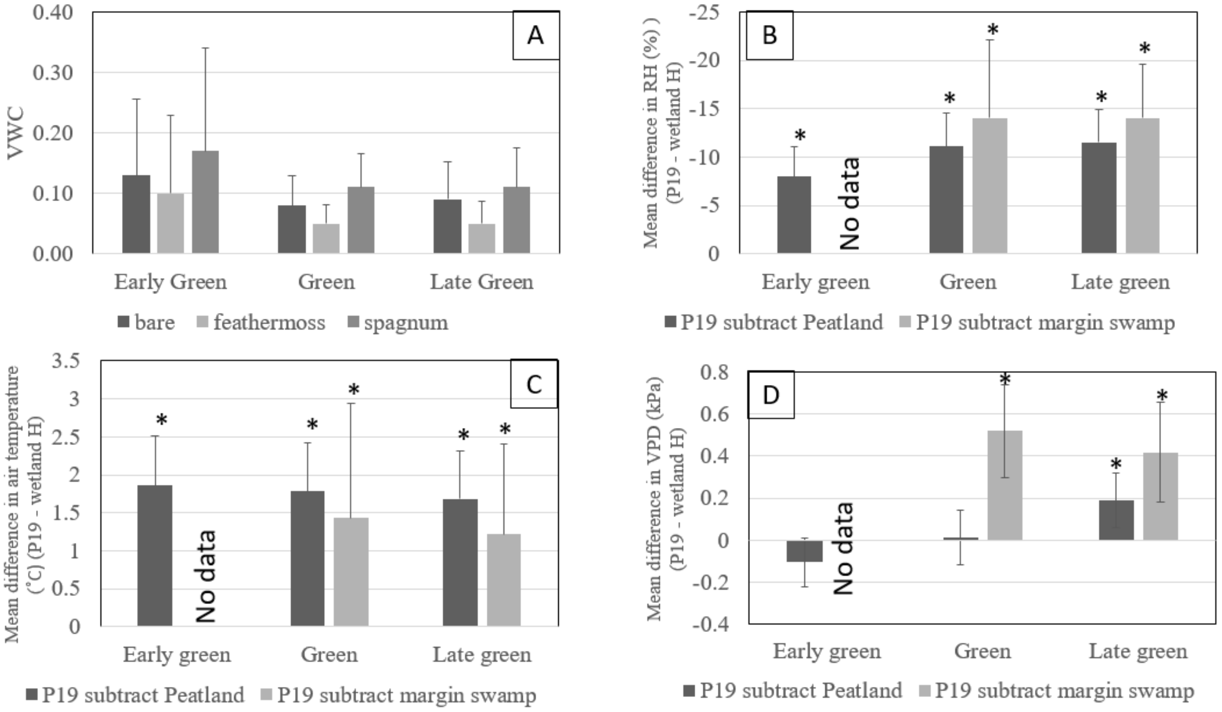


Figure 3.6: a) Average soil moisture (volumetric water content, VWC) in dominant surface covers on the peatland at perched wetland H taken at 6 cm depth measured May - September 2015. No statistical comparisons were made between surface covers. Panels b-d: Mean difference between Pond 19 (P19) and components of wetland H (Peatland and margin swamp) for b) relative humidity (RH), c) air temperature, and d) vapour pressure deficit. (+) values signify higher mean at Pond 19, (-) signifies higher mean at wetland H. Data were collected from RH-air temperature probes located 20 cm above the surface adjacent MET towers at Pond 19, wetland H and in the margin swamp. (*) signifies a significant difference between P19 minus wetland H compared to null hypothesis of zero (no difference) at 5% probability using a t-test. Data are divided into early green, green, and late green periods. Variability (error bars) are represented by ± 1 standard deviation.

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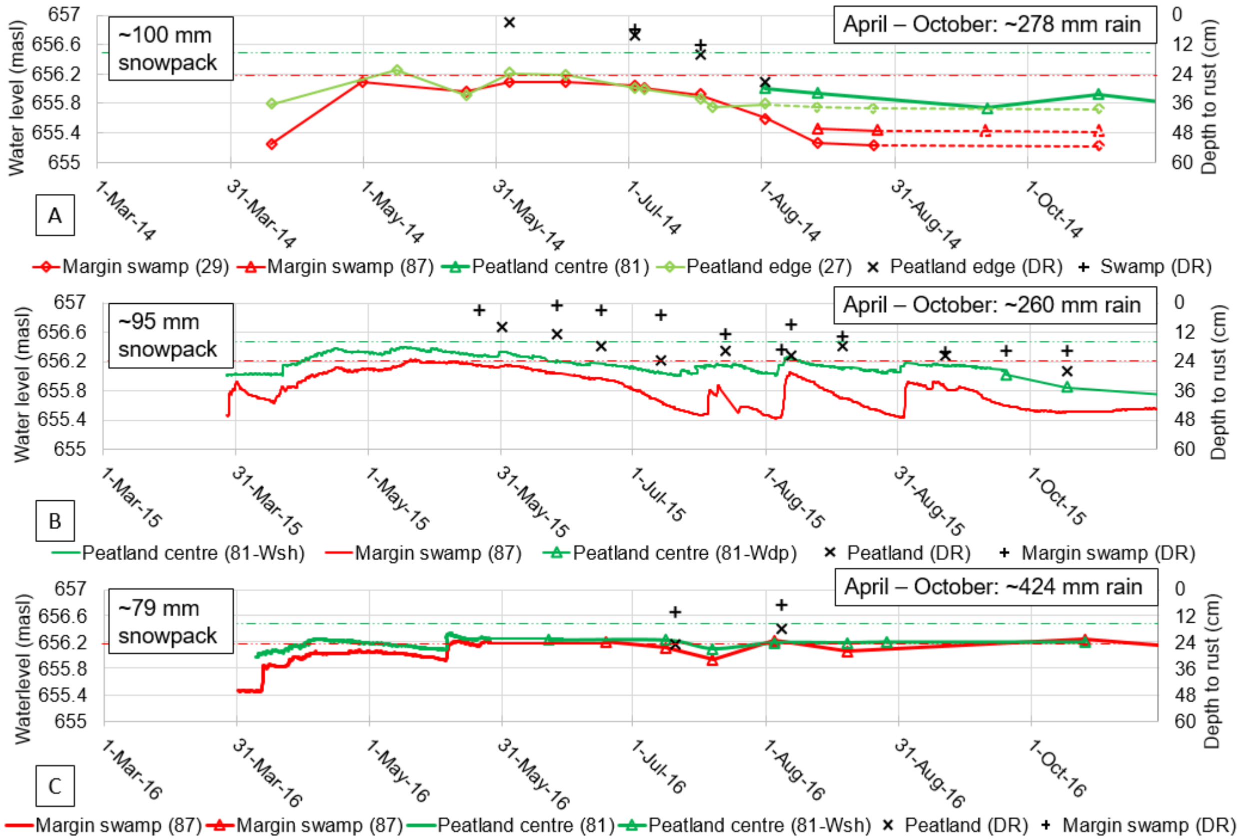

Figure 3.7: Water level in the peatland and margin swamp for a) 2014, b) 2015 and c) 2016. Dashed lines represent a dry well. Wells were frozen from November until beginning of April (shown by flat line in continuous water levels). Elevation of peatland hollow (site 81) is 656.5 masl. Elevation of swamp hollow (site 87) is 656.2 masl. Depth to rust from surface (DR) is shown for peatland and margin swamp. Depth to rust is a proxy for depth of the oxic layer in a soil column. Precipitation between April and October (mainly rainfall) and March snowpack shown for each year.

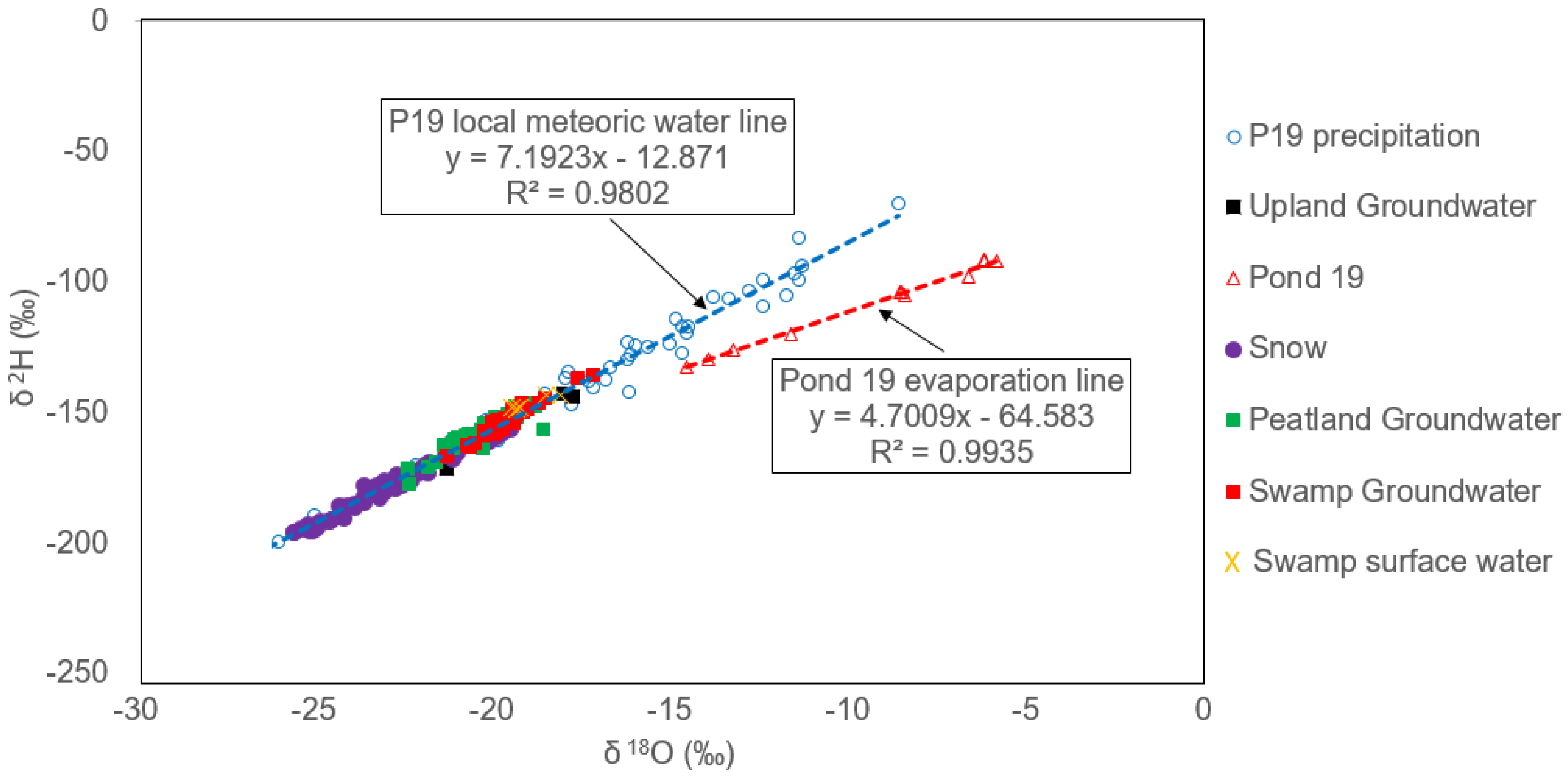

Figure 3.8: Local meteoric waterline (LMWL) for Pond Catchment 19 (P19 precipitation) and Pond 19 evaporation line (Pond 19). Ground (squares), surface (crosses) and snow (closed circles) water samples are plotted for Perched Wetland H. The global meteoric waterline has a slope of 8 for reference to Pond Catchment 19 LMWL (USGS ,2004).

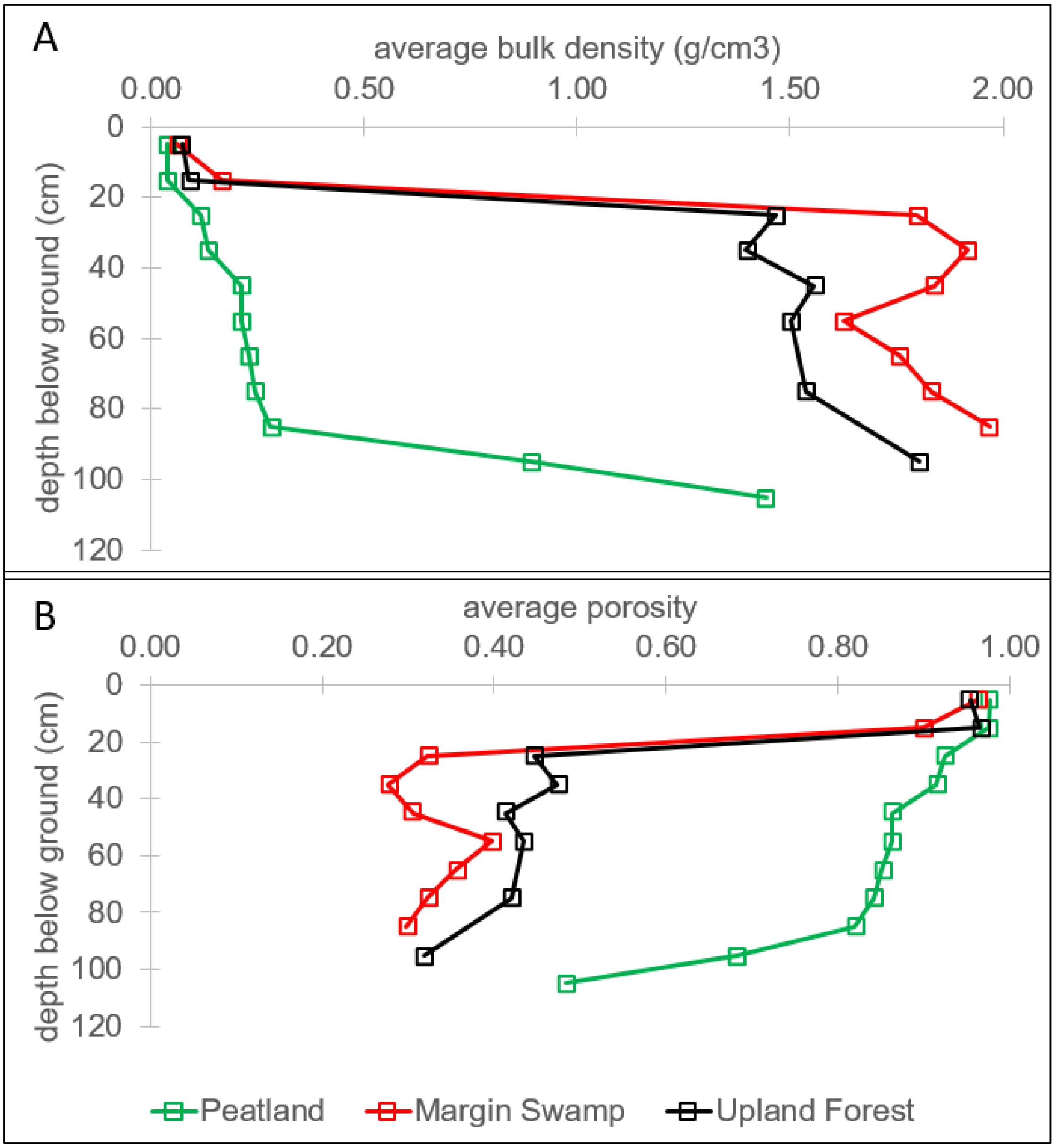

Figure 3.9: a) Average bulk density b) and porosity profiles for peatland, margin swamp, and upland forest at perched wetland H. Descriptive statistics (n, standard deviation) are presented in Appendix Table A.1 as the error bars are too small for figure.

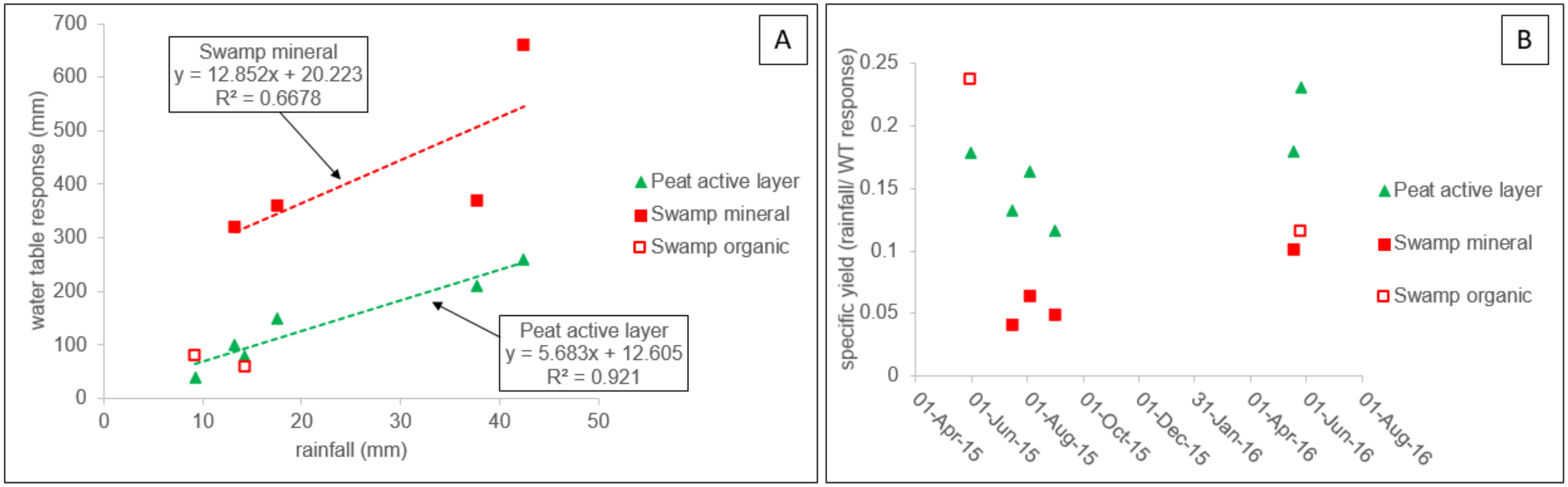

Figure 3.10: a) Water table response as a function of rainfall input for peat active layer, swamp mineral and organic soils. b) Specific yield for rain events of 2015 and early 2016 for peatland active layer, and margin swamp mineral and organic soils.

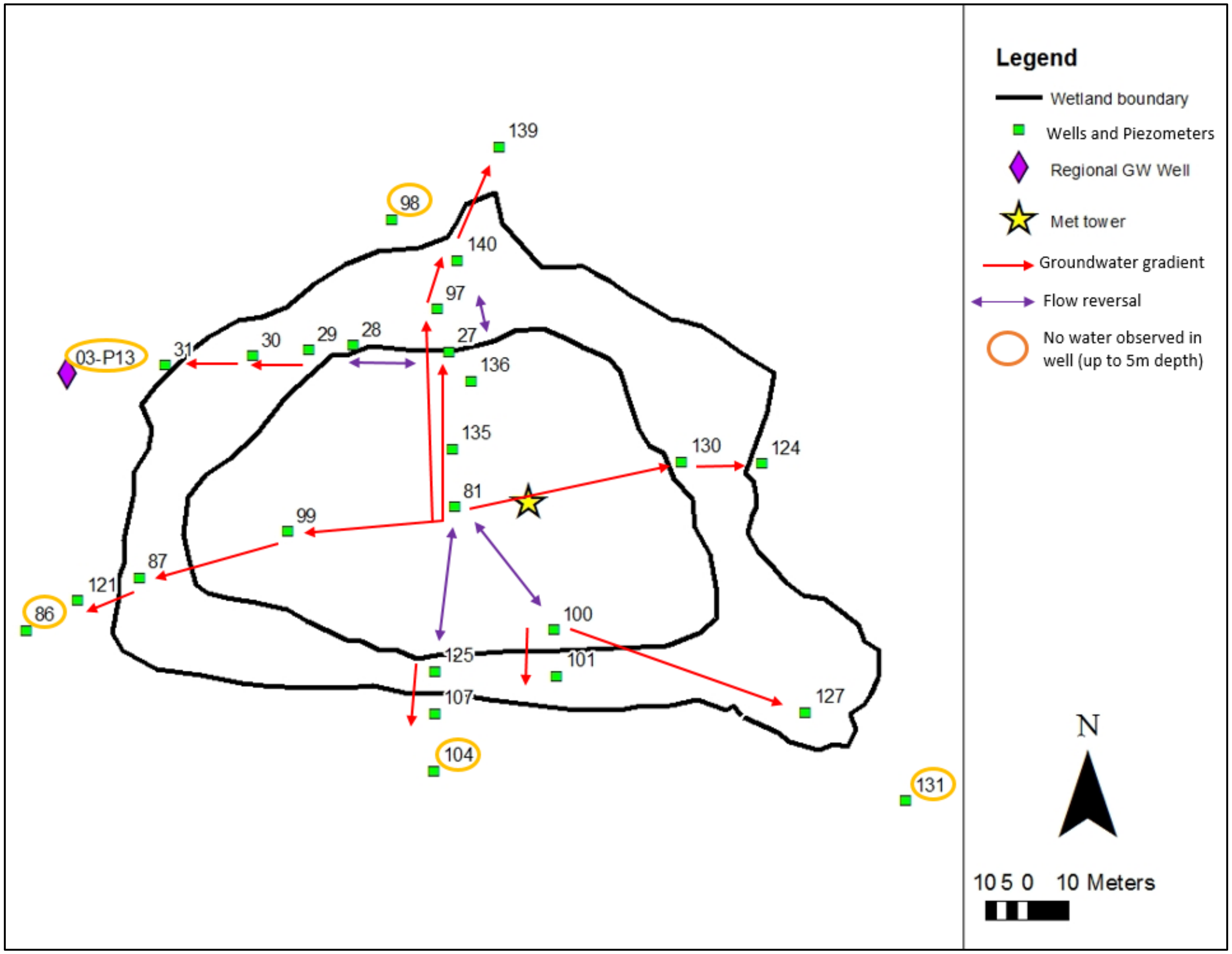

Figure 3.11: Plan view of groundwater flow paths around perched wetland 2014-2016. Includes site numbers, wetland bounds, groundwater flow paths and flow reversals, regional groundwater, and permanently dry wells. Wells and piezometers are < 5m depth. Regional GW (groundwater) well extends to 23 m depth.

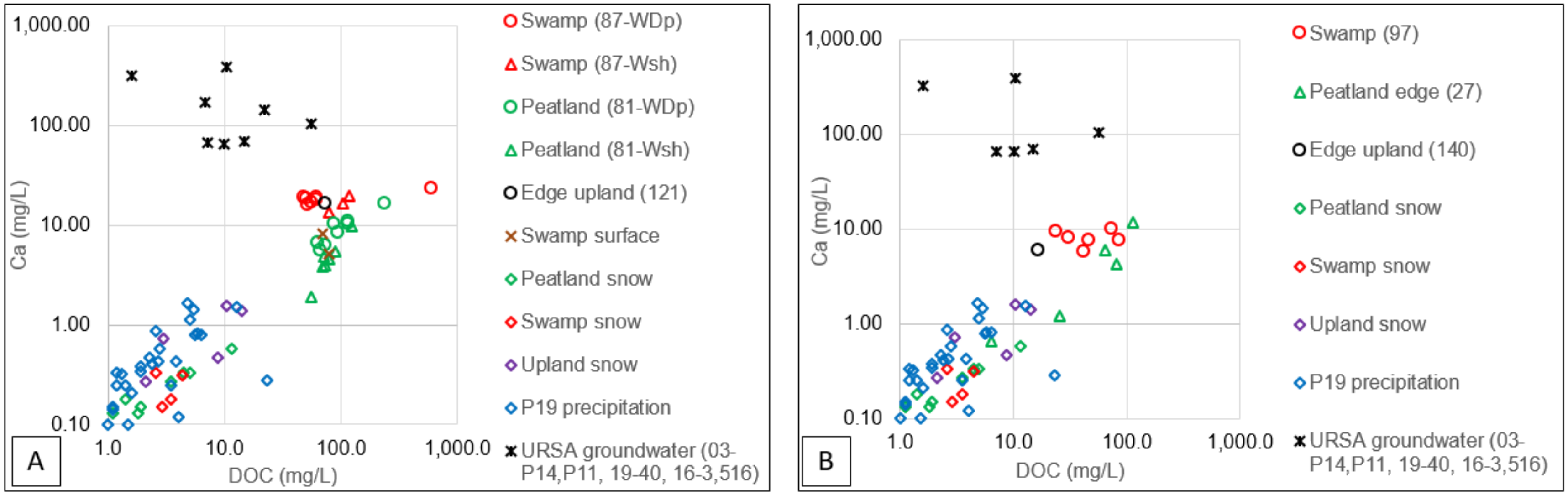

Figure 3.12: a) Bi-variate plot of calcium (Ca) and dissolved organic matter (DOC) along sites 81 – 87 – 121 transect at perched wetland H with snow, precipitation, and deep to local groundwater from URSA catchments (Pond Catchment 19 sites 03-P14, P11, 40, Pond Catchment 16 sites 3, 516), b) Same as a) but along the sites 27 – 97- 140 transect at perched wetland H. WDp is a deep well screened 50 – 100 cm below ground, and Wsh is a shallow well, screened 0 – 50 cm below ground. Axes are logarithmic.

Chapter 4: Isolated peatland formation in a sub-humid climate

1.0 Introduction

In Chapter Two, isolated perched peatlands in the Boreal Plains (BP) were examined using a water budget approach. Permanent wetland conditions are maintained through autogenic processes such as negative feedbacks which function to decrease evapotranspiration (ET) to the extent that net precipitation (P net) is greater than actual evapotranspiration (AET) (Chapter Three). The margin swamp surrounding the peatland may not exhibit P net > AET, and instead may have low storage which creates a high frequency of wetting, allowing for maintenance of hydric soils and fostering of wetland vegetation (Rodriguez-Iturbe, 2000; Rodriquez-Iturbe et al., 2007; Chapter Three). A flow chart conceptualizing perched wetland maintenance was presented in Chapter One (Figure 1.5). Research detailed in previous chapters has described how the study wetland maintains saturated conditions and generates excess water in a sub-humid climate (Figure 1.5 and hypotheses 1 - 3: Figures 1.2 – 1.4). A fourth hypothesis proposes that the peatland formed during a historically wetter period, and that the physical properties of decomposed peat may have facilitated decreased seepage, maintaining wetland conditions in subsequent drier climates. Central to this hypothesis is the question: Can an isolated peatland develop in a sub-humid climate, or is peat relic i.e., formed in a wetter climate from allogenic water?

Historically high water tables (WT) in adjacent hillslopes generating flow during a wetter climate could have contributed allogenic water to the site, facilitating the development of peat. Additionally, in this wetter climate local hillslope processes could have generated lateral flow to the wetland via transmissivity feedback or groundwater ridging (Redding and Devito, 2010; Buttle, 1994). However, given the shallow topography and small catchment surrounding the study wetland (wetland H, Chapter Two), hillslopes would have been unlikely to generate sufficient water to saturate the wetland. This is primarily due to large hillslope storage capacity and lack of functioning confining layer (CL) proximal (<1 m) to the surface (Redding and Devito, 2010). Instead, the wetland may rely on soil textural layering and low storage to produce saturated soil and excess water in order to facilitate peat development through paludification (Chapter Three).

Paludification is the conversion of upland forest to peatland; peat accumulation over a previously dry mineral soil (Joosten and Clarke 2002; Lavoie et al., 2005). Processes occurring during paludification include reduction in: soil temperature, microbial activity, decomposition of organic matter, aerated or oxic zone, and plant nutrient availability (Taylor et al., 1987; Payette 2001), resulting in decreased productivity and formation of peat soil.

There is limited understanding of 'edge' systems (typically <150 cm of peat) occurring along the transition zone between peatland and forest (Bauer et al., 2009). In the transition zone, wetland boundaries are difficult to distinguish due to dynamic hydrologic conditions (Locky et al., 2005). Several studies have observed wetland expansion into adjacent forests during wet periods (e.g., Warner and Rubec, 1997; Bauer et al., 2003) and that decreased water levels may result in shrinkage of wetland boundaries (Hartshorn et al., 2003). The entire perched peatland (wetland H) displays characteristics of transition zones, including accumulation of <150 cm of peat.

A study of the transition zone between upland forest and peatland in the BP of Saskatchewan reported that basal peat was oldest at the peatland edge (3800 calendar years before present (cal. years bp)), becoming younger toward the upland forest (800 cal. years bp; Bauer et al., 2009). Further, Bauer et al. (2009) concluded that at all points analyzed on the transition zone, peat initiation occurred via paludification ~4000 years ago. A peatland located in the central mixed wood sub region of Alberta was found to originate through paludification around 3400 cal. years bp in a climate similar to present (Schweger and Hickman, 1989; Kubiw et al., 1989). The authors speculate that landscape scale paludification took place in the boreal region following the mid-Holocene warm period which ended approximately 4000 years ago. In an analysis of basal peat from some 90 sites in Alberta, it was determined that the oldest peatlands in the URSA are between 7,000 and 8,000 years old (Halsey et al., 1998). Modern climatic conditions originated 3000 - 4000 years ago (Vance et al., 1983). If basal peat in the study perched peatland is older than 4,000 years, this peatland may be relic, having formed under historic climatic conditions.

Groundwater fed peatlands like those observed in Bauer et al. (2009) develop rapidly in the groundwater discharge zone, resulting in similar ages between the peatland centre and edge. If the perched peatland is relic, the basal ages of the centre and peatland edge should be similarly old (e.g., groundwater fed peatland in Bauer et al., 2009), since expansion is no longer possible in the current climate due to lack of allogenic water (Chapter Two). Another peatland in Bauer et al. (2009) was shown to develop over clay, resulting in slow expansion, and differing ages between the peatland centre and edge. If the study perched wetland is expanding under current conditions, basal peat in the centre should be oldest, becoming younger toward the peatland margin (e.g., peatland formed over clay in Bauer et al., 2009). Two explanations present:

a) Did the peatland form and expand in the current climate (<4000 years old) by the process of paludification? i.e., are the ages of the basal peat edges different than the centre? Or,
b) Did the entire peatland form during a historically different climate? For example, did favourable conditions in continental Canada following deglaciation, around 8,000 years ago, combine to create the subject peatland?

No research to date has documented perched peatland formational age in the BP. Age of formation will offer insight into the maximum time scale required to develop these unique systems, and whether they could form in the current sub-humid climate. Furthermore, is there intrinsic resilience in isolated perched peatlands or are these systems likely to undergo a regime shift to forestland? Does the margin swamp function as a buffer to peatland loss? Examination of peatland origin and development outlined in this paper will provide a framework for response to these questions.

2.0 Site description

Core samples for this research were collected in a perched peatland located at Pond Catchment 19 in the Utikuma Region Study Area (URSA 56°6'N, 116°32'W) in north central Alberta. The climate is sub-humid, with average annual precipitation (486 mm) < potential evapotranspiration (518 mm; Environment Canada, 2003; Winter and Woo, 1993; Marshal et al., 1999). Daily average temperature ranges from -14.6 ℃ in January to 15.6 ℃ in July (Environment Canada, 2003). The region is classified as central mixed wood in the Boreal Forest of Alberta (Natural Regions Committee, 2006). Pond Catchment 19 is located on the transition zone between a stagnant ice moraine to the east (fine-textured; Ferone and Devito, 2004) and a glaciofluvial outwash deposit to the west (coarse textured; Smerdon et al., 2005). Previous work has determined regional groundwater to be approximately 20 m below ground in a sand aquifer, separated from shallow perched groundwater by meters of unsaturated soil (Riddell, 2008; Chapter Two). Perched wetlands occur in this landscape where a clay CL is proximal (< 1 m) to the surface (Chapter Two).

Research was carried out on perched wetland H at Pond Catchment 19, which occupies a topographic high. Topography adjacent the wetland is shallow, with a maximum slope of 0.03.

Wetland H has a closed irregular shaped catchment (0.8 ha) and no channelized flow outlet. Elevation differences between upland hillslopes and perched wetland H are up to 2.4 m (Chapter Two). Perched wetland H consists of a 0.24 ha peatland encircled by a 0.25 ha margin swamp. The peatland is classified as coniferous treed basin bog (Canadian Wetland Classification System, National Wetlands Working Group, 1997), and as wooded bog by the Alberta Wetland Classification System (ESRD, 2015). The margin swamp is classified as a hardwood treed peat margin swamp (National Wetlands Working Group), and a deciduous wooded swamp (ESRD, 2015). Peat depths range from ~1 m in the centre to 40 cm at the edge (Figure 4.1). Depth of margin swamp organics is ~20 cm (Figure 1). A clay CL underlies the peatland; the CL occurs between 0.6 and 1 m below the margin swamp, overlain by thin layers of silt and fine sand (Chapter Two). The clay CL depth increases to 1.5 m or greater below the surrounding upland forest.

The forest canopy encircling the wetland complex consists of aspen (*Populous tremuloides*) and stands of white spruce (*Picea glauca*) in the north, east, and south portions of the wetland. Dominant wetland vegetation comprises paper birch (*Betula papyrifera)*, alder (*Alnus*), and willow (*Salix*) in the margin swamp, and stunted black spruce (*Picea mariana*) with bog birch (*Betula pumila*) in the peatland. Peatland understory vegetation is predominantly Labrador tea (*Rhododendron groenlandicum*), leatherleaf (*Chamaedaphne calyculata*), cloud berry (*Rubus chamaemorus*) and bog cranberry (*Vaccinium oxycocco*). Hummocks and hollows in the peatland are dominated by sphagnum (*magellanicum, fuscum, angustifolium*) and feathermosses. Microtopography variations across the peatland are on the order of 30 cm between hummocks and hollows.

3.0 Methods

Ages of organic material within the peatland and swamp were measured to address the formational hypothesis of relic peatlands. To obtain a spatial distribution of peat initiation, the centre, north and south edges were dated (Figure 4.1). Margin swamp organics were also dated for comparison with the peatland system. Bulk density – porosity profiles (n = 6 in peatland, n = 2 swamp) determined the spatial distribution of active peat (H1 - 4), and lower decomposed peat (H6-10) within the perched wetland (Chapter Three). Carbon accumulation in each core was estimated using % organic matter (OM) and bulk density. Long term (apparent) accumulation rates were calculated using basal peat ages and amount OM in each core, similar to Bauer et al. (2009). In the peatland centre (site 81, Figure 3.1), edges (sites 27,100. Figure 3.1) and margin swamp (sites 87, 97 Figure 3.3) 5 g subsamples were taken within the fibric, mesic, humic, and basal peat layers to estimate % OM. Samples were air dried, ground into fine powder, weighed, and combusted at 375˚ C for 16 hr in a muffle furnace (Carter, 1993). Ash content was weighed post combustion to estimate loss on ignition (LOI). A 34% organic matter content was used to distinguish basal peat from underlying mineral soil, in accordance with the Canadian System of Soil Classification (Soil Classification Working Group 1998). Basal peat samples were taken 1 cm above the organic – mineral interface at sites 81, 27, 100, 97, and 87, following the method outlined in Bauer et al. (2009). In the peatland centre (site 81) and southern edge (site 100), samples 1 cm in length were taken at the top of the mesic and humic peat layers. In the north peatland edge the top of the mesic layer was sampled. The margin swamp was also dated in the north and west at the top of the mesic organics. Twelve samples from five different core sites around the wetland were radiocarbon (C-14) dated (Figure 4.1). Macrofossils (wood, bark, and *sphagnum*) were removed from organic samples selected for C-14 dating from the peatland centre, edge and margin swamp. Macrofossils were pre-treated employing the acid-base-acid (ABA) method (Olsson, 1986), freeze dried, and submitted to the Accelerator Mass Spectrometry Laboratory at the University of Ottawa. Radiocarbon dates were calibrated using Intcal 13 (Reimer et al., 2013) from OxCal Version 4.2 (Ramsay, 2009). To characterize the hydrology of each core site, the median WT below ground was calculated for snow-free season (April to October) of 2015.

4.0 Results

Organic matter depth and loss-on-ignition profiles

Spatial distribution of OM depth around the peatland was relatively uniform, 90-100 cm in the peatland centre, decreasing to 50 – 65 cm in the peatland edge. Margin swamp and upland organics depths were 20 cm or less. The peatland centre (site 81) comprised > 90 % OM to 97 cm depth as determined by LOI. 97 – 102 cm averaged 72% OM (Table 4.1). At 103 cm, a sharp decrease in % organics to 37% marked the transition between peatland and mineral soil. OM below 105 cm (in clay) was less than 10%. The northern peatland edge (site 27) exhibited 46 cm of > 90 % OM (Table 4.1). A further sharp transition to mineral soil occurred at 47 cm, 38 % OM; only 9% OM at 48 cm was recorded. The southern peatland edge (site 100) showed OM > 88 % to 59 cm. From 59 – 66 cm, % OM varied between 45 and 74 %, with transition to mineral soil at 68 cm depth, signaled by 34 % organics at 68 cm depth and 6 % OM at 70 cm (Table 4.1). The west (site 87) and north (site 97) margin swamp contained OM > 80 % to 15 and 17 cm respectively. At the boundary of peat and mineral soil, a 2 cm layer of ‘muck’ was noted containing 20 – 30 % OM (Mitsch and Gosselink, 2007).

Peat macrofossils

Macrofossil sampling for C-14 dating of OM within the wetland identified paper birch seeds, paper birch bark, spruce needles, woody debris, decomposed sedges and charcoal. Material dated for each sample location and depth is summarized in Table 4.3. For consistency, paper birch remains were chosen for dating macrofossils. No shells (indicators of aquatic environments) were observed in the samples.

Radiocarbon dates

The basal peat date in the peatland centre (site 81) was 4425 cal. years bp. In the southern peatland edge (site 100), the basal date is similar at 3780 cal. years bp (Table 4.3). A younger basal peat age of 2070 cal. years bp was measured in the northern peatland edge (site 27). Basal ages in the north (site 97) and west (site 87) margin swamp organics were similar at 200 and 180 cal. years bp respectively (Table 4.3). The top of the humic peat layer exhibited variable ages ranging from 115 cal. years bp in the northern peatland edge, 1185 cal. years bp in the southern peatland edge, and 530 cal. years bp in the peatland centre. The top of the mesic peat ranged from 590 cal. years bp to modern (>1950) for peatland centre and southern edge respectively (Table 4.3). Top of mesic organics in the swamp (8 – 10 cm depth) were of modern origin i.e., >1950's bomb carbon. Depth to age profiles are presented in Figure 4.2.

Organic matter accumulation and long-term rates

Total OM accumulation was 191 kg m^2 in the peatland centre (site 81, 102 cm OM; Table 4.2). OM totalled 85 and 55 kg m^2 in the southern (site 100, 66 cm OM) and northern (site 27, 47 cm OM) peatland edges respectively (Table 4.2). There was proportionally less OM in the margin swamp, totaling 12 and 17 kg m^2 in the west and north swamps respectively. Addressing long term (apparent) accumulation rates, the margin swamp accumulated OM faster than the peatland, showing rates of 69 – 75 g m^{-2} year^{-1}. In the peatland, rates ranged from 43 g m^{-2} year^{-1} in the centre to only 23 and 27 g m^{-2} year^{-1} in the southern and northern edges (Table 4.2).

Median water table depth

Median WT depth was shallowest in the southern peatland edge (23 cm), increasing in depth 33 and 38 cm in the peatland centre and northern edges respectively (Table 4.2). Median WT depth was 45cm below ground in the north and west margin swamps in 2015 snow-free season.

5.0 Discussion

5.1 Carbon accumulation

The centre of perched wetland H (100 cm organics) accumulated ~ 50 kg m^2 more OM than a core of similar depth (114 cm organics) in the transition zone of another BP peatland (Bauer et al., 2009). Discrepancies in peatland centre cores between peatland H and Bauer et al. (2009) may be due to differences in bulk density, controlled largely by WT fluctuations. The peatland core (114 cm) in Bauer et al. (2009) had a median WT of 14.5 cm compared to peatland H (site 81, 100 cm) median of 33 cm below ground. Higher bulk densities in the centre of peatland H resulted in more carbon storage compared to the peat core in Bauer et al. (2009). The reason for the differences in soil characteristics are likely due to water source: groundwater fed peatlands in Bauer et al. (2009) led to a stable, high WT (e.g., Peatland 208 at the URSA; Hokanson et al., 2016) whereas isolated peatlands (peatland H) are subject to with greater WT fluctuations, which enhance decomposition rates (Waddington et al., 2015).

Peatland edges (45 - 65 cm organics) at wetland H (55 - 85 kg m^2) and in Bauer et al. (2009) (48 - 75 kg m^2) accumulated similar amounts of OM. Bulk density of peatland edges in the BP was found to be greater than the centre for all hydrogeologic settings (Hokanson et al., 2016), supporting findings of similar OM accumulation at wetland H and in Bauer et al. (2009) on peatland edges. Results suggest small isolated peatlands may store large amounts of organic matter and carbon due to higher bulk densities in peatland centres.

Previous landscape scale wetland analysis has neglected small systems (< 100 m diameter), as the scale of studies, e.g., 30x30m pixels, are too coarse to distinguish them from surrounding uplands (Ducks Unlimited Canada (DUC) Boreal Enhanced Wetland Classification System (EWC), 2015). Future work should undertake an inventory of small isolated peatlands across the boreal landscape in order to accurately assess the amount of carbon stored in these systems, as initial results suggest small peatlands contain higher carbon than was anticipated.

5.2 Peatland development

Similar basal ages were observed in the centre and southern edge of the peatland, ~2000 years older than those in the north. These results indicate that a large portion of peat initiation occurred in the centre and southern portions of the peatland 3000 – 4000 years ago. After the initial formation of peat in the wetland, data show that the peatland expanded northward for over 2000 years. Though detailed macrofossil analysis of basal peat communities was not undertaken, material used to date the basal peat suggests that peat deposition was initiated by paludification, as the macrofossils present were not reflective of an aquatic (lake infilling) setting (Kubiw et al., 1989). Results obtained at perched wetland H indicate that the oldest basal samples originated around 4000 years ago. These results align with findings in the literature and may be further evidence that peat developed via paludification. Large tracts in the boreal forest region were paludified 3000 – 4000 cal. years bp, corresponding to a change in the regional climate from warmer and drier (mid Holocene warm period) to wetter and cooler (Kubiw et al., 1989; Halsey et al., 1998; Bauer et al., 2003). Assuming that peat formed in a climate similar to the present, it appears that allogenic processes did not play a dominant role in the formation of the wetland, and that instead soil textural layering promoted the establishment of permanent wetland conditions.

A clay layer underlies the peatland, increasing in depth at the wetland edges (Figure 2.4, Chapter Two). The flat morphology of the clay layer implies that water would saturate in the wetland centre, and then shed toward the adjacent upland, rather than accumulating in a depression. Studies have shown that local topography controls lateral peat expansion (e.g., Bauer et al., 2003). Low storage and frequency of wetting, similar to the processes occurring presently in the margin swamp (Chapter Three), may have initiated peat formation in the wetland centre, as low storage caused by proximity of the clay CL to the surface promoted permanent saturated conditions. It may be inferred that once peat soil was established at perched wetland H, paludification initiated and drove expansion northward over the next 2000 years. Depth to CL layer may also control the extent of peat expansion. As the depth to CL increases, so does soil water storage (Devito et al., 2005b), requiring more water inputs to saturate the soil. It may be postulated that when the CL attained > 0.5 m depth, expansion of peat arrested, and instead a swamp was formed. This premise is substantiated by the age discrepancy between basal dates in the peatland and adjacent swamp: swamp organics formed 200 cal. years bp compared to >2000 cal. years bp in the peatland. It is also possible the peatland could have historically expanded beyond its current extent, but subsequently retrenched due to fire.

The presence of charcoal was ubiquitous in peatland and swamp organics, occurring consistently at depths between 30 – 40 cm in the peatland, and at the base of margin swamp organics (Table 4.1). Studies have associated fire with paludification, given the rise in WT observed post-fire (Korhola, 1995). Fire may also have prevented the expansion of peat, as smoldering effects in peatland margins have been shown to burn > 40 cm (Hokanson et al., 2016; Lukenbach et al., 2016). The frequent burn return interval characteristic of the BP (~120 years, Turetsky et al., 2011) suggests estimates of long-term peat accumulation rates over the past 3000 years in peatland H may be difficult to accurately assess (Bauer et al., 2009). In research conducted on the margin of a BP peatland with similar peat depths to perched wetland H, presence of charcoal was reported (Bauer et al., 2009). This research indicated that fire played a dominant and complex role on plant communities and carbon accumulation along peatland margins. Though my research has indicated that the peatland developed and expanded in a climate similar to present, underlying historical processes controlling paludification or peatland loss such as fire and WT rise are difficult to observe and quantify. However, Bauer et al. (2009) noted that margin plant communities responded dynamically to changes in climate and hydrology, inferring that these systems exhibit resilience to environmental fluctuations through changes in wetland vegetation assemblage. The margin swamp may function as a buffer to regime shifts between peatland and upland forest following disturbance. Future paleoecological research should focus on detailed macrofossil analysis to determine the formational environment of perched wetland H; more specifically, research should consider the question: Was the basal vegetative community in the peatland similar to vegetation presently found in the margin swamp? Such an analysis will help determine if the peatland developed over a previously existing swamp wetland environment.

6.0 Conclusions

Peatland H accumulated 191 kg m^{-2} of organic matter in the centre, and 55 – 85 kg m^{-2} of organic matter in the edges. Results suggest small wetlands may store larger amounts of carbon due to higher bulk density of organic soils. Landscape scale inventories of small peatland systems should be undertaken to determine if these peatlands should be accounted as significant carbon stores.

The earliest basal peat in perched wetland H originated 4400 cal. years bp. Peat formed initially in the centre and southern portions, and expanded northward 30 m over 2000 years. Discrepancy in basal ages between the peatland edge and margin swamp suggest fire may have impacted the dynamics of this system. Peatland development corresponded with the end of the mid-Holocene warm period, and the onset of current climatic conditions in the boreal. This period aligns with the onset of paludification documented in peatlands across the western boreal region. Since the peatland developed in a climate similar to present, allogenic sources of water may not have been required, as soil textural layering, i.e., a clay CL near the surface, promoted saturated conditions. The hypothesis of a relic peatland formed in a climate different than the present is therefore unlikely. Instead, the peatland appears to have originated through the process of paludification in a climate similar to the present. Future work should focus on macrofossil community assemblage in an effort to define the formational environment of the peatland and its subsequent evolution.

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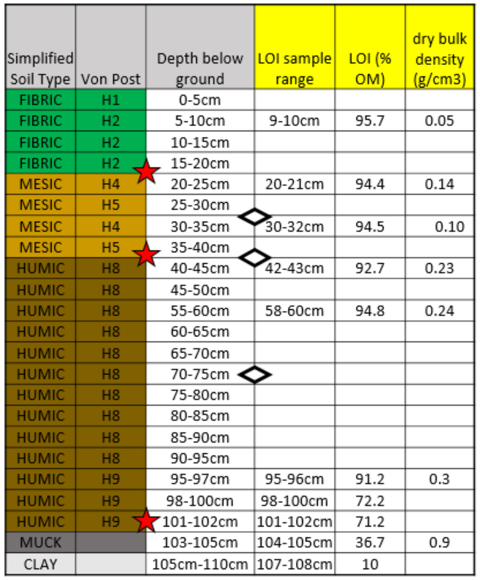
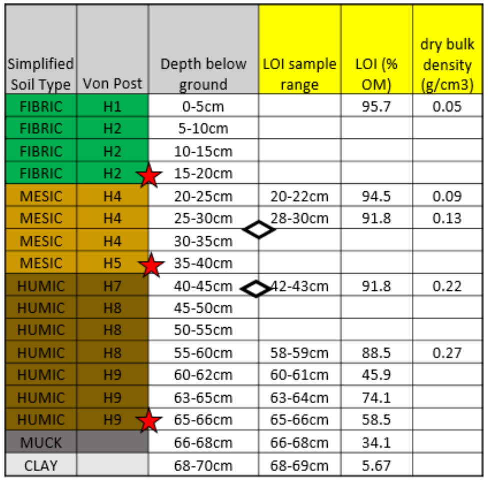
Table 4.1: Soil profiles with carbon dating locations (red star), loss-on-ignition (LOI) in organic matter % (OM), and dry bulk density. Charcoal layers are noted by black diamonds. (a) peatland centre (site 81) (b) southern peatland (site 100) (c) northern peatland edge (site 27) (d) west margin swamp (site 87) and (e) north margin swamp (site 97).

A



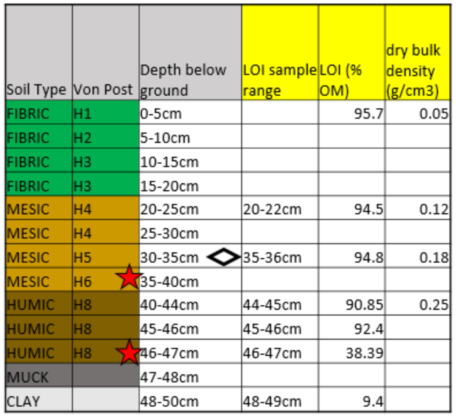
Simplified Soil Type	Von Post	Depth below ground	LOI sample range	LOI (% OM)	dry bulk density (g/cm3)
FIBRIC	H1	0-5cm			
FIBRIC	H2	5-10cm	9-10cm	95.7	0.05
FIBRIC	H2	10-15cm			
FIBRIC	H2 ★	15-20cm			
MESIC	H4	20-25cm	20-21cm	94.4	0.14
MESIC	H5	25-30cm			
MESIC	H4	30-35cm ◇	30-32cm	94.5	0.10
MESIC	H5 ★	35-40cm			
HUMIC	H8	40-45cm ◇	42-43cm	92.7	0.23
HUMIC	H8	45-50cm			
HUMIC	H8	55-60cm	58-60cm	94.8	0.24
HUMIC	H8	60-65cm			
HUMIC	H8	65-70cm			
HUMIC	H8	70-75cm ◇			
HUMIC	H8	75-80cm			
HUMIC	H8	80-85cm			
HUMIC	H8	85-90cm			
HUMIC	H8	90-95cm			
HUMIC	H9	95-97cm	95-96cm	91.2	0.3
HUMIC	H9	98-100cm	98-100cm	72.2	
HUMIC	H9 ★	101-102cm	101-102cm	71.2	
MUCK		103-105cm	104-105cm	36.7	0.9
CLAY		105cm-110cm	107-108cm	10	

B



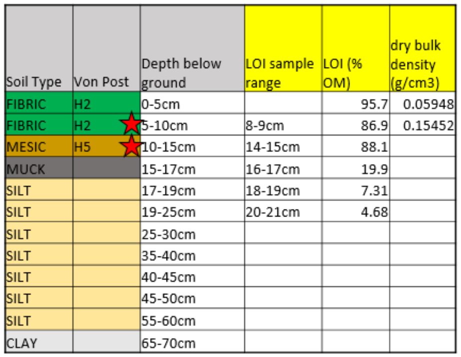
Simplified Soil Type	Von Post	Depth below ground	LOI sample range	LOI (% OM)	dry bulk density (g/cm3)
FIBRIC	H1	0-5cm		95.7	0.05
FIBRIC	H2	5-10cm			
FIBRIC	H2	10-15cm			
FIBRIC	H2 ★	15-20cm			
MESIC	H4	20-25cm	20-22cm	94.5	0.09
MESIC	H4	25-30cm	28-30cm	91.8	0.13
MESIC	H4	30-35cm ◇			
MESIC	H5 ★	35-40cm			
HUMIC	H7	40-45cm ◇	42-43cm	91.8	0.22
HUMIC	H8	45-50cm			
HUMIC	H8	50-55cm			
HUMIC	H8	55-60cm	58-59cm	88.5	0.27
HUMIC	H9	60-62cm	60-61cm	45.9	
HUMIC	H9	63-65cm	63-64cm	74.1	
HUMIC	H9 ★	65-66cm	65-66cm	58.5	
MUCK		66-68cm	66-68cm	34.1	
CLAY		68-70cm	68-69cm	5.67	

C



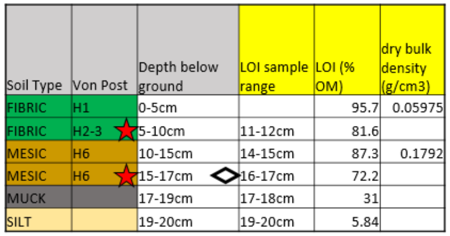
Soil Type	Von Post	Depth below ground	LOI sample range	LOI (% OM)	dry bulk density (g/cm3)
FIBRIC	H1	0-5cm		95.7	0.05
FIBRIC	H2	5-10cm			
FIBRIC	H3	10-15cm			
FIBRIC	H3	15-20cm			
MESIC	H4	20-25cm	20-22cm	94.5	0.12
MESIC	H4	25-30cm			
MESIC	H5	30-35cm ◇	35-36cm	94.8	0.18
MESIC	H6 ★	35-40cm			
HUMIC	H8	40-44cm	44-45cm	90.85	0.25
HUMIC	H8	45-46cm	45-46cm	92.4	
HUMIC	H8 ★	46-47cm	46-47cm	38.39	
MUCK		47-48cm			
CLAY		48-50cm	48-49cm	9.4	

D



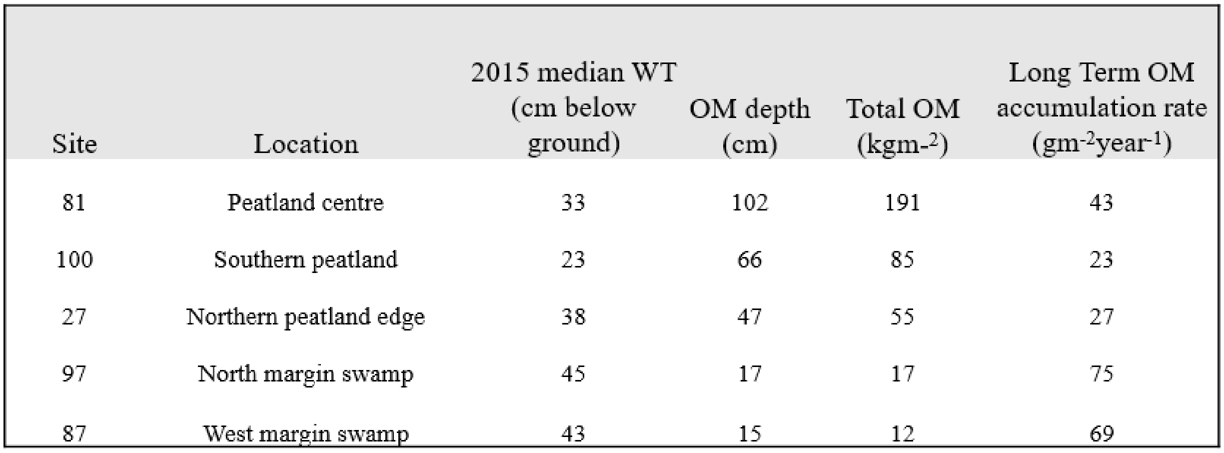
Soil Type	Von Post	Depth below ground	LOI sample range	LOI (% OM)	dry bulk density (g/cm3)
FIBRIC	H2	0-5cm		95.7	0.05948
FIBRIC	H2 ★	5-10cm	8-9cm	86.9	0.15452
MESIC	H5 ★	10-15cm	14-15cm	88.1	
MUCK		15-17cm	16-17cm	19.9	
SILT		17-19cm	18-19cm	7.31	
SILT		19-25cm	20-21cm	4.68	
SILT		25-30cm			
SILT		35-40cm			
SILT		40-45cm			
SILT		45-50cm			
SILT		55-60cm			
CLAY		65-70cm			

E



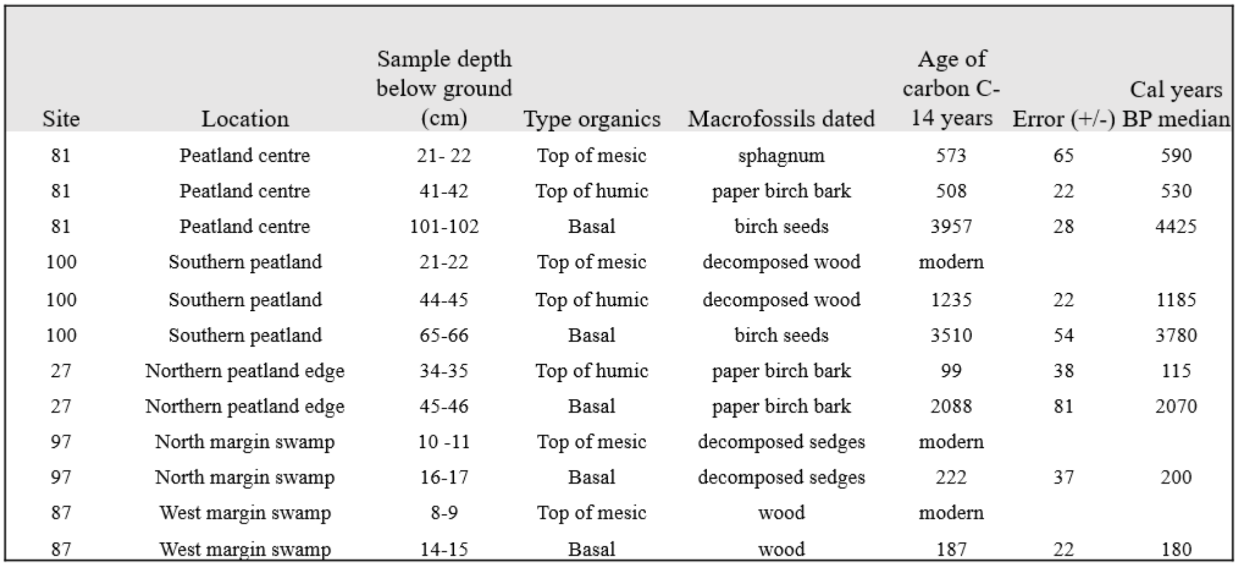
Soil Type	Von Post	Depth below ground	LOI sample range	LOI (% OM)	dry bulk density (g/cm3)
FIBRIC	H1	0-5cm		95.7	0.05975
FIBRIC	H2-3 ★	5-10cm	11-12cm	81.6	
MESIC	H6	10-15cm	14-15cm	87.3	0.1792
MESIC	H6 ★	15-17cm ◇	16-17cm	72.2	
MUCK		17-19cm	17-18cm	31	
SILT		19-20cm	19-20cm	5.84	

Table 4.2: Site characteristics (location, median water table depth) and organic matter (OM) accumulation



Site	Location	2015 median WT (cm below ground)	OM depth (cm)	Total OM (kgm-^{2})	Long Term OM accumulation rate (gm^{-2}year^{-1})
81	Peatland centre	33	102	191	43
100	Southern peatland	23	66	85	23
27	Northern peatland edge	38	47	55	27
97	North margin swamp	45	17	17	75
87	West margin swamp	43	15	12	69

Table 4.3: Sample depth, location, type of organic, macrofossils dated, radiocarbon age and calendar years before present. Modern denotes sample is younger than 1950s bomb carbon.



Site	Location	Sample depth below ground (cm)	Type organics	Macrofossils dated	Age of carbon C-14 years	Error (+/-)	Cal years BP median
81	Peatland centre	21- 22	Top of mesic	sphagnum	573	65	590
81	Peatland centre	41-42	Top of humic	paper birch bark	508	22	530
81	Peatland centre	101-102	Basal	birch seeds	3957	28	4425
100	Southern peatland	21-22	Top of mesic	decomposed wood	modern		
100	Southern peatland	44-45	Top of humic	decomposed wood	1235	22	1185
100	Southern peatland	65-66	Basal	birch seeds	3510	54	3780
27	Northern peatland edge	34-35	Top of humic	paper birch bark	99	38	115
27	Northern peatland edge	45-46	Basal	paper birch bark	2088	81	2070
97	North margin swamp	10 -11	Top of mesic	decomposed sedges	modern		
97	North margin swamp	16-17	Basal	decomposed sedges	222	37	200
87	West margin swamp	8-9	Top of mesic	wood	modern		
87	West margin swamp	14-15	Basal	wood	187	22	180

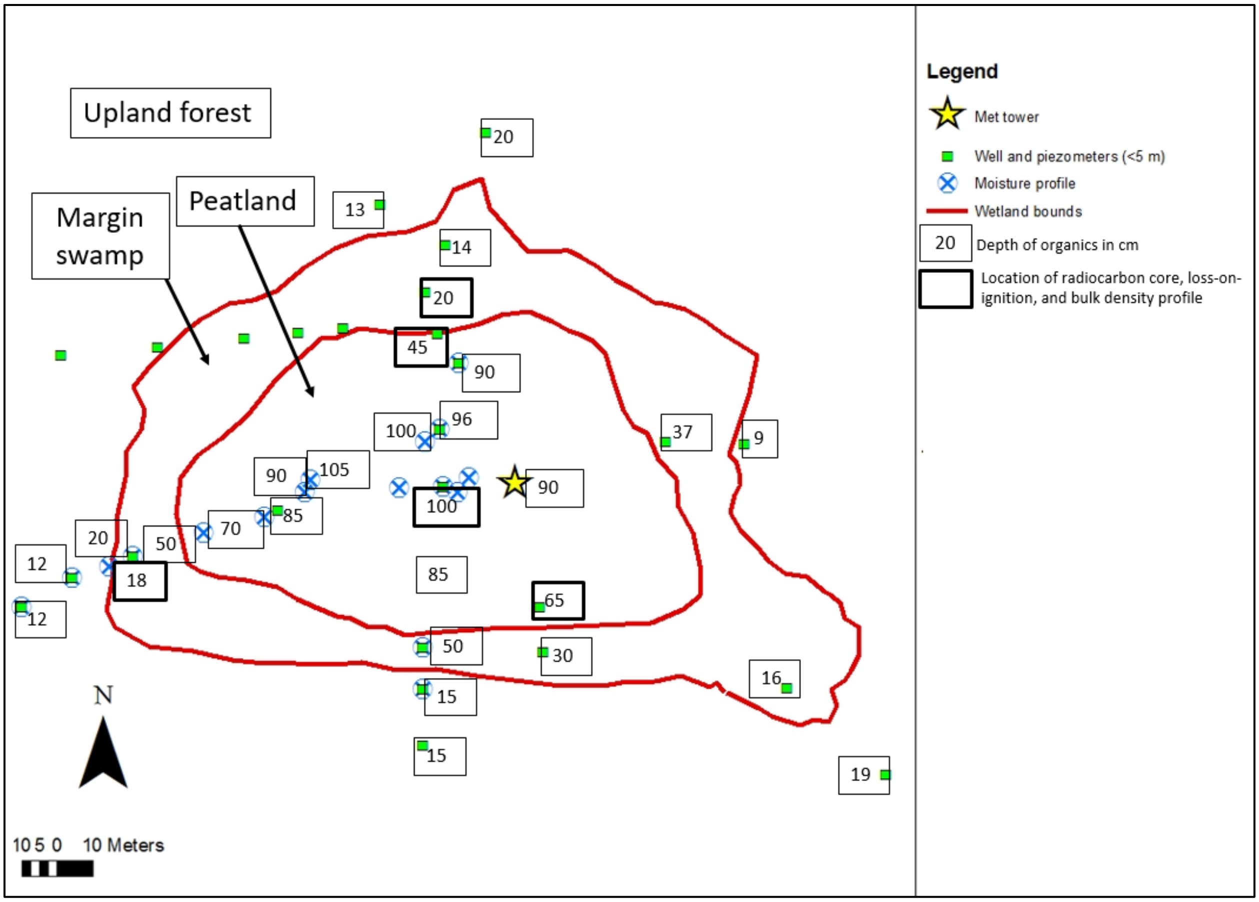


Figure 4.1: Study wetland with spatial distribution of organic soil depth and location of radiocarbon, loss-on-ignition, and bulk density profiles. See Figures 2.1 and 2.2 for study location of perched wetland H.

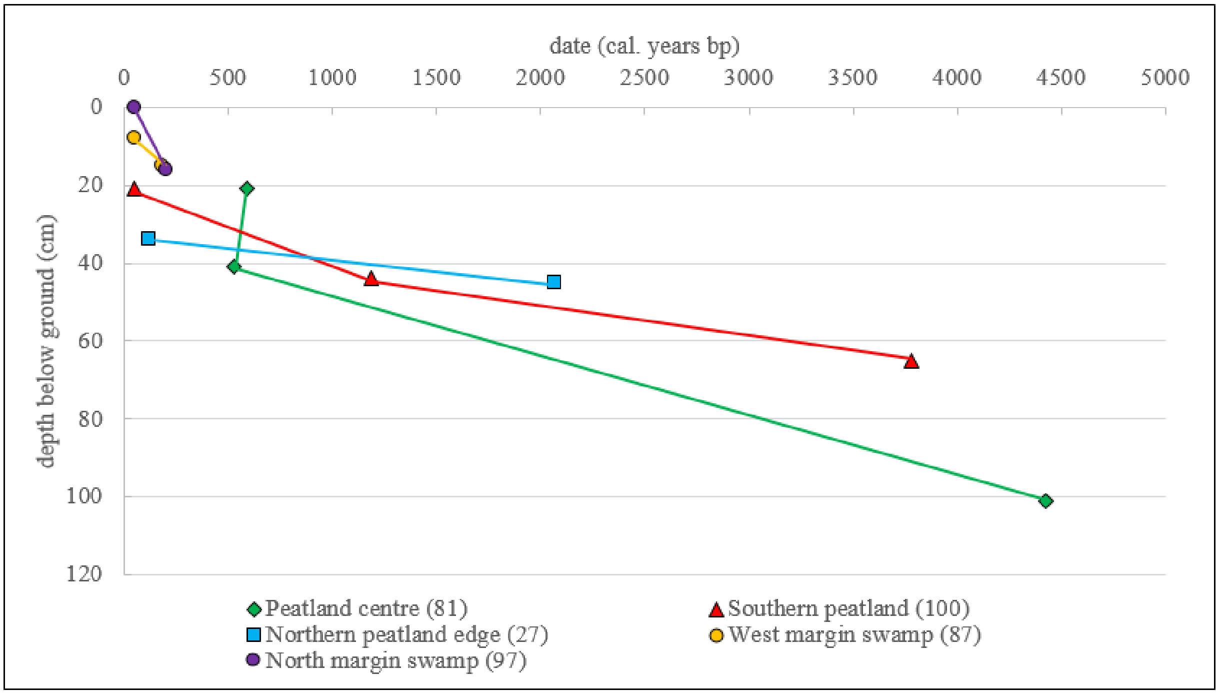


Figure 4.2: Depth vs. age plot for radiocarbon dating profiles around wetland H.

Chapter 5: Isolated perched wetland complexes: summary of hydrologic function and implications of research

1.0 Introduction

Peatlands occupy up to 50% of the landscape in the BP (Vitt et al., 2000), forming in diverse geologic settings and landscape positions with varying degrees of ground and surface water contribution (Ferone and Devito, 2004; Smerdon et al., 2005; Riddell, 2008; Hokanson et al., 2016). Precipitation (P) and evapotranspiration (ET) are the dominant fluxes in the peatland water budget (Ferone and Devito, 2004; Thompson et al., 2015; Riddell et al., 2008). The climate is in moisture deficit, as regional P is less than ET (Winter and Woo, 1993; Marshall et al.,1999). Allogenic water sources are often assumed for peatland maintenance (Price et al., 2010), but perched peatlands isolated from regional groundwater have been identified in the BP (Riddell, 2008). Initial research on perched peatlands in the Utikuma Region Study Area (URSA) indicate that they may not rely on local ground and surface waters (Riddell, 2008), giving rise to the research question for this thesis: How does an apparently isolated permanent perched wetland maintain saturated conditions in a sub-humid climate? To conceptualize the maintenance of the BP wetland, four alternative hypotheses were presented (Chapter One Figures 1.2 – 1.4).

Current thinking suggests that permanent perched systems cannot exist without an allogenic water source in moisture deficit climates (e.g., Cable-Rains et al., 2006; Peters et al., 2006; van der Kamp and Hayashi, 2009; Price et al., 2010). Results laid out in thesis demonstrate that perched peatlands do not require groundwater and may function as autogenic systems, capable of generating water. Perched systems may prove useful in wetland reconstruction in the Athabasca oil sands, as they may be constructed in any landscape position and provide water to surrounding vegetation (Riddell, 2008). This chapter will summarize the principal findings of my research by evaluating the above hypotheses and presenting an updated conceptual model for permanent perched wetland maintenance. Implications and future research questions related to wetland reconstruction and vulnerability of these systems to disturbance such as climate change, wildfire and anthropogenic activities are explored.

2.0 Alternative hypotheses for wetland maintenance and formation

2.1 Allogenic wetland maintenance

To my knowledge, the findings reported herein are among the first to document isolated peatlands in a sub-humid climate (Riddell, 2008). To maintain permanent wetland conditions in a water deficit climate, perched peatlands require either allogenic sources (local ground or surface water) and or autogenic processes to increase wetland P relative to ET. Hillslopes in the BP do not generate sufficient subsurface lateral flow or surface runoff (Devito et al., 2005b; Redding and Devito, 2010), unlike other documented perched wetlands (e.g., prairie potholes, vernal pools). This is attributed to high storage capacity of the heterogeneous glacial till characteristic of the BP. The study wetland H is isolated from allogenic water sources, as groundwater flow is directed away from the wetland, and regional groundwater has remained 23 m below the surface through 12 years of monitoring (Chapter Two). The absence of a functioning confining layer (CL) proximal to the surface in adjacent hillslopes increases soil water storage, limiting near surface runoff potential from upland to wetland. In the BP, uplands are hydrologically disconnected from wetlands, except during periods of water surplus, occurring on average once every 20 years (Devito et al., 2005b, Mwale et al., 2009). Further, water tables (WT) from wetland to upland were found to be an inverse of topography, as uplands are dominated by ET losses, infiltration and high storage capacity (Devito et al., 2005a).

Near surface runoff over frozen soil and groundwater ridging were additional mechanisms predicted to produce allogenic water to the wetland. Concrete frost, a barrier to infiltration, was not observed in the surrounding upland during spring melt. Absence of concrete frost resulted in snow melt water infiltrating, rather than flowing laterally towards the wetland (Redding and Devito, 2011). Silts in the hillslope base were conducive to groundwater ridging (Gilham, 1984; Buttle, 1994), similar to conditions described at an adjacent perched wetland (wetland S8; Riddell, 2008). However, continuous and spot water level monitoring over both wet and dry cycles revealed that groundwater flow was always directed from the margin swamp to the hillslope base at wetland H, an indication that groundwater ridging is unlikely to provide water to the wetland.

A local CL consisting of saturated clay over unsaturated sand beneath the wetland maintains the perched WT, rendering perched wetland H hydrologically isolated from adjacent hillslopes and regional groundwater table. The uplands adjacent wetland H are consistently unsaturated. The water budget confirms low ground and surface water losses in a dry year, and wetland P > AET. These data refute the hypothesis of an allogenic wetland, and support the hypothesis of an autogenic system functioning to conserve water in a moisture deficit climate (Figure 5.1).

2.2 Autogenic wetland maintenance

Chapter Three examined the autogenic processes operating to increase P relative to ET and the interaction between soil water storage and P to generate water within the wetland. Precipitation data showed that decreased interception over the wetland resulted in a ~70 mm increase in P net relative to adjacent forest in 2015, suggesting that low interception over the wetland is an important control on the water budget.

Sheltering and shading of the wetland by the adjacent forest and increased snow in the peatland were found to prolong snowmelt by 2 - 3 weeks compared to the upland, decreasing the duration of ET. Protection afforded by surrounding forest decreased energy available at the surface for evaporation, as evidenced through air temperature and relative humidity data. Compared to open Pond 19, perched wetland H was 2 ℃ colder and relative humidity 8 – 11 % greater during the snow-free period. Insulating properties of snow and peat (Kershaw and Gill, 1979; Laberge and Payette, 1995) facilitated persistence of ice in the rooting zone well into the growing season, lowering transpiration rates. Deep peatland WT coupled with low surface soil moisture was further evidence of decreased wetland ET, inferring a capillary break between WT and peat surface during a summer with below average precipitation (Hayward and Clymo, 1982; Price, 1991; Kettridge and Waddington, 2014). Ground and surface water isotope samples from the peatland and margin swamp exhibited a distinct precipitation rather than evaporation isotopic signature, signalling low wetland evaporation.

Low soil water storage in the swamp and lower peat controlled the frequency of wetting. In the peatland, the catotelm remained saturated, conserving water during dry periods (Boelter, 1969; Ingram, 1978). During wet periods, the WT rises into the active layer, to be shed radially towards the peatland edge and margin swamp. Low storage capacity in the swamp is a result of high bulk density and low porosity of mineral soil above the CL layer. Low specific yield within the swamp promotes rapid WT rise with limited P inputs, maintaining anoxic or wetland conditions. It is therefore probable that the margin swamp can maintain wetland conditions even if P < AET, provided that low storage and frequency of wetting creates variable soil moisture, preventing incursion of upland plant species. This research highlights the importance of autogenic processes and soil textural layering in maintaining a permanent, isolated wetland in a regional moisture deficit (Figure 5.1).

2.3 Isolated peatland formation: relic peatland hypothesis

Radiocarbon dating shows that basal peat in the centre and southern peatland edge at perched wetland H formed ~4000 years ago. A much younger basal age in the northern peatland implies that the peat expanded northward for 30 m over 2000 years. Peat initiation corresponded with the end of the mid Holocene warm period, and the onset of climatic conditions similar to present day (Halsey et al., 1998). This change in climate resulted in landscape scale paludification (conversion of upland forest to peatland; Lavoie et al., 2005) across the western boreal region (Halsey et al., 1998). It appears that the subject peatland initiated in a climate similar to the present, inferring that allogenic water sources were not required for peat development (Chapter Four). Instead, soil textural layering resulting in a CL near the surface that promoted permanent saturated conditions, facilitating the development of peat soil and expansion via the process of paludification. Considering the results of radiocarbon dating undertaken, and the probable formational age of the peatlands, the hypothesis of a relic peatland is unlikely (Figure 5.1).

3.0 Implications

3.1 Perched wetland reconstruction

Landscape scale reconstruction of open pit mines in Alberta’s oil sands is currently underway to restore the land to equivalent capability (Devito et al., 2012; Pollard et al., 2012). Since wetlands occupy up to 50% of the landscape (Vitt et al., 2000), there is a predictable emphasis in the literature on the best means to reconstruct sustainable wetlands (e.g., Pollard et al., 2012; Nwaishi et al., 2015; Borkenhagen and Cooper, 2015; Ketcheson et al., 2016). The current paradigm features wetlands reliant upon local ground and surface water (e.g., Nikanotee, Price et al., 2010; Ketcheson et al., 2016) or intermediate to regional groundwater (e.g., Sandhill, Pollard et al., 2012; Ketcheson et al., 2016). Given the prevailing view that fen peatlands are dependent on allogenic groundwater, wetlands to date have been constructed in low-lying regions (Ketcheson et al., 2016). In the Athabasca oil sands, contamination of groundwater from salt and hydrocarbons associated with mining materials used in watershed reconstruction hinders successful wetland reclamation (Quagraine et al., 2005; CEMA, 2014). For example, harmful sodium salts can migrate upwards through mining material (Purdy et al., 2005), impeding growth and establishment of wetland flora and fauna (Trites and Bayley, 2005).

Perched wetlands present an alternative option in wetland reconstruction. Research for this thesis examined an entire wetland complex isolated from runoff (surface and sub surface flow), local and deeper groundwater (Chapter Two). Beyond this, the perched wetland was found to generate water to the surrounding upland forest during periods of water surplus such as spring melt and following summer storms. Incorporating perched wetlands into watershed reconstruction could provide an important fresh water source for adjacent forest vegetation during drought periods (Riddell, 2008), and runoff generating areas (depending on their connectivity) during wetter periods in the climate cycle (Devito et al., 2012; Devito et al., *In press*). The autogenic function of perched wetlands suggests that they may be constructed in any hydrologic response area or landscape position, as long as certain requisites are met.

Chapter Three details how soil textural layering controls WT response in perched wetlands. Low storage in the swamp and lower peat determines frequency of wetting and anoxic conditions. A clay rich CL < 1 m (ideally <0.5 m) from the surface impedes vertical movement. In wetland reconstruction, similar soil texture layering could be employed to establish wetland conditions: silt, fine sand or decomposed peat above a shallow (< 1 m) flat CL. Such a shallow soil configuration could be constructed on any flat surface in the landscape, creating poor drainage, thereby enhancing wetland formation. Given the high frequency of wetting associated with low storage, upland vegetation is unlikely to establish itself in such an environment (Rodriguez-Iturbe, 2000).

As a constructed perched wetland develops, a mire system or early peatland may form (Chapter Four). Negative feedbacks accompanying mire formation include decreased productivity and decreased organic matter decomposition (Payette, 2001), promoting formation of peat soil. A further negative feedback associated with succession may include shading and protection by adjacent forest canopy, which would function to lower available energy at the surface, decreasing wetland ET, and promoting excess water (Petrone et al., 2007, Chapter Three). Prolonged snowmelt, and persistence of ice are additional negative feedbacks associated with water conservation in perched systems that may enhance the development of peat soils (Chapter Three).

Though perched wetlands have not been built *per se* on reclaimed land in the Athabasca oil sands, opportunistic wetlands (OW) with similar characteristics to natural perched systems have been observed (Kevin Devito and Mika Little-Devito, 2016 personal communication). Early inventories of OW indicate that a number (>30) are developing on diverse landforms at Syncrude's Mildred Lake lease (Kevin Devito and Mika Little-Devito, 2016 personal communication). These landforms vary geologically from coarse-textured tailing sand to fine-textured overburden dump (Kevin Devito and Mika Little-Devito, personal communication). OW on fine textured landforms display rapid WT response to P events, similar to the margin swamp at perched wetland H. Initial soil cores in these OW reveal a CL < 1 m from the surface, often < 0.5 m. Preliminary data on OW suggest perched wetland reconstruction is achievable at relatively low cost. Initial surveys across the URSA, a natural analogue to the oil sands, confirm that small isolated wetlands are a frequent feature in the natural landscape (Kevin Devito personal communication, 2016; Riddell, 2008) and may play an important role in forest biodiversity in the BP.

3.2 Susceptibility to disturbance

Climate change

Previous work has indicated that perched wetlands may be particularly susceptible to climate change, given their relative isolation and dependence on P and ET (Riddell, 2008). However, research conducted for this thesis has shown that a number of negative feedbacks exist to counter the regional climate deficit, resulting in wetland P > ET (Chapter Three). Systems like perched wetland H may in fact have greater resilience to changes such as increased temperature and drought (e.g., Kettridge and Waddington, 2014; Waddington et al., 2015) than those partially dependent on allogenic sources as local ground and surface water contributions are likely to be impacted by climate change (Winter, 2000).

Results reported in this thesis demonstrate that low soil water storage due to soil textural layering preserve wetland conditions through dry summers. It can be hypothesized that wetland H will remain a wetland even if all the peat is removed, as the proximity of the CL allows saturated conditions to develop with limited P inputs. It is therefore improbable that this system will undergo a regime shift to forest with the advent of predicted climate change. Instead, the most drastic result of climate change within the peat system may be a reversion to swamp wetland conditions.

Wildfire

A recent paper on burn severity in BP peatlands has concluded that peatlands with ephemeral groundwater connections are the most susceptible to deep burning (Hokanson et al., 2016). Systems connected to ephemeral groundwater had higher bulk densities near the surface and thus greater smoldering and burn depth (Hokanson et al., 2016). The study also found that peat margins burned deeper than peatland centres, and that burn severity was related to hydrogeologic setting (Hokanson et al., 2016; Lukenbach et al., 2015). This work infers that an isolated peatland will not be as susceptible to deeper burning as an ephemerally connected peatland. On the other hand, given the large proportion of margin to total wetland area of wetland H, this smaller system may be susceptible to deeper burning. Research on the recovery of peatlands following wildfire demonstrates that a number of autogenic processes relating to species composition and burn severity function to increase WT following fire (Kettridge et al., 2014; Lukenbach et al., 2016). Though fire return intervals are expected to decrease with climate change (Bond-Lamberty et al., 2007), isolated peatlands may have sufficient autogenic processes in place to counter significant peatland loss. The numerous charcoal layers observed in core samples from wetland H are evidence of such resilience.

Anthropogenic activity

Industrial activities in the BP have increased exponentially in the last 50 years due to forestry and petroleum exploration (AEP, 1998). Many wetlands have been impacted by road and seismic line construction across the Western Boreal Forest (AEP, 1998). Land use managers must consider the relative influence of allogenic water sources vs. autogenic processes maintaining wetland systems. In respect of perched wetlands, disturbance to adjacent hillslopes and surrounding forest is not likely to create an impact. Removal of upland aspen or spruce trees directly adjacent the wetland could impact the wetland water budget through an increase of ET.

However, an increase in ET may be countered by a reduction in tree root suction of water from the wetland periphery, as tree root demand has been removed (Lubczynski, 2009). Results from this thesis demonstrate that direct disturbance of mineral soil textural layering is likely to have a significant impact on perched wetland hydrologic function. The anthropogenic threat to small isolated wetlands requires inventory mapping as these systems are largely ignored in landscape scale wetland inventories e.g., DUC enhanced wetland classification (EWC, 2015). Such under representation could result in loss of small wetland systems if their extent and importance are not considered from a land management perspective.

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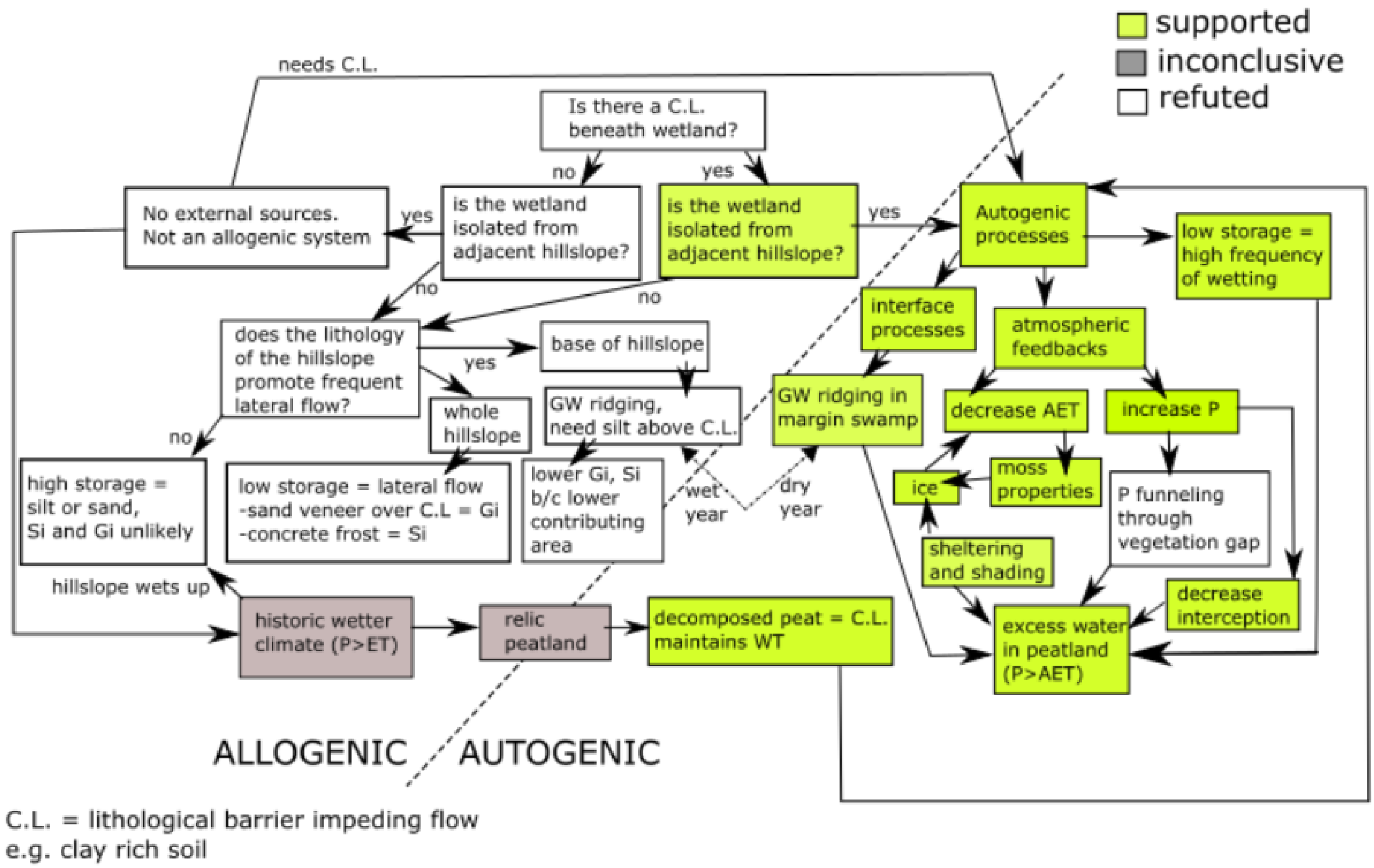

Figure 5.1: Updated flow chart for conceptualization of permanent perched wetland maintenance and formation in a sub-humid climate. Boxes are divided into 'supported', 'inconclusive', and 'refuted' based on data presented in Chapters Two, Three and Four.

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Appendix A

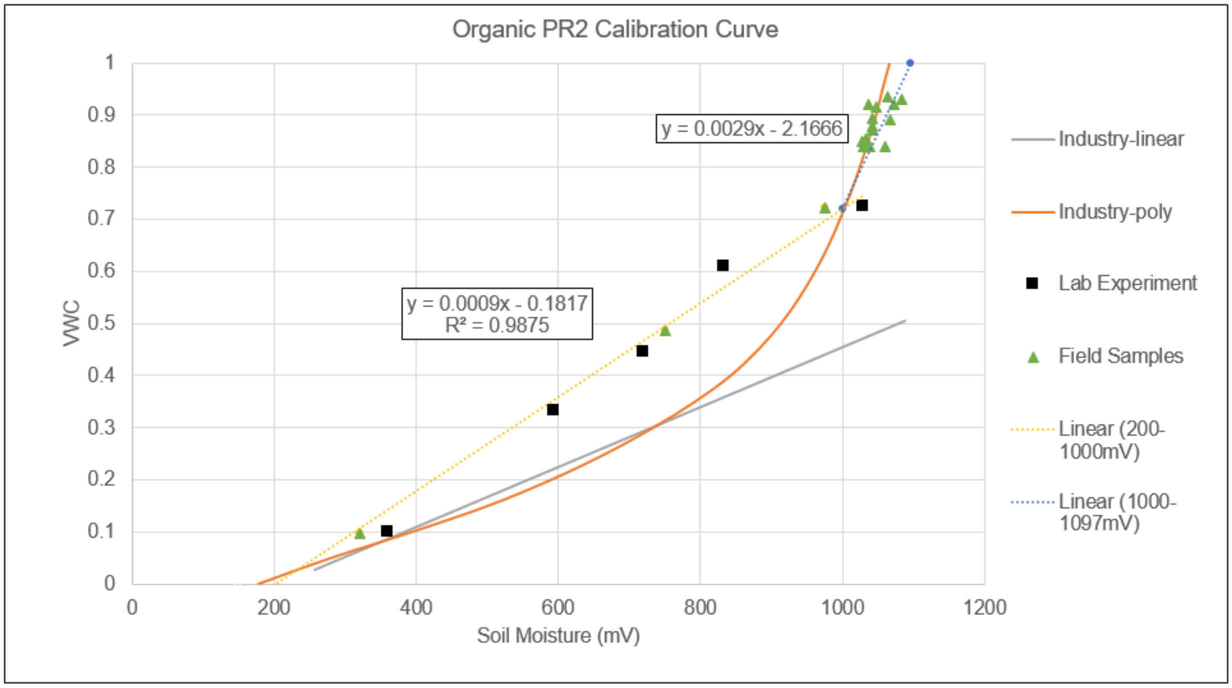


Figure A.1: Organic calibration curve for PR2 soil moisture data. Field and lab samples plotted against soil moisture revealed a two-part calibration: 0-1000 mV, and >1000 mV.

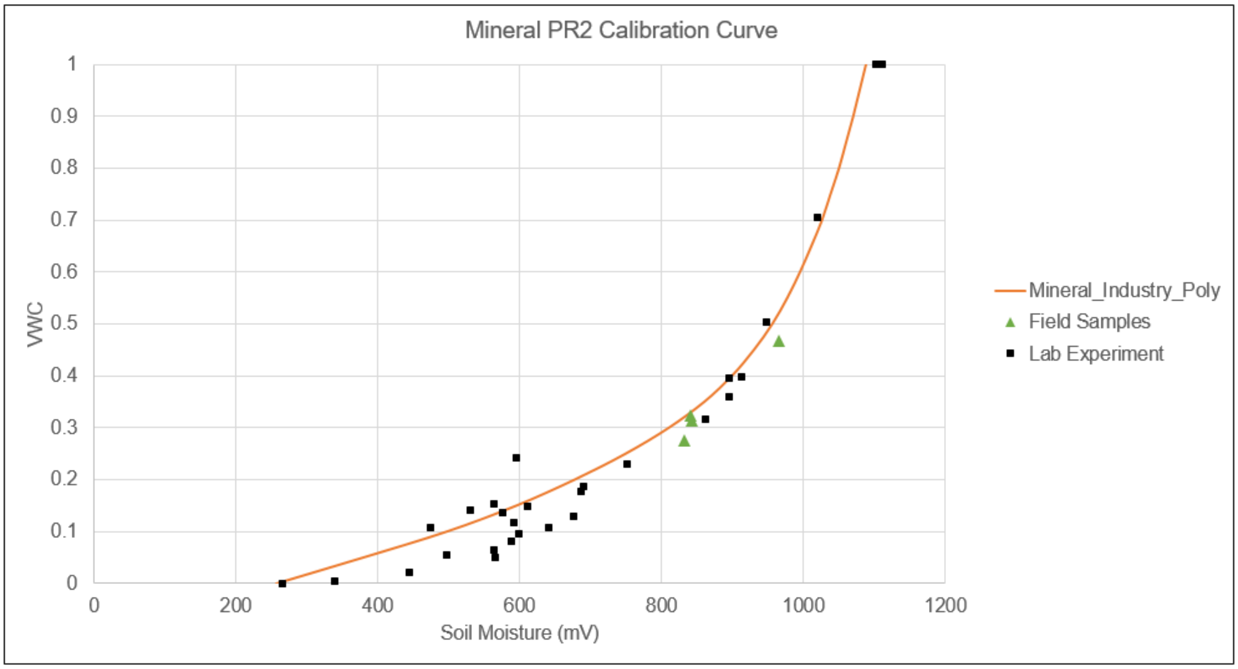
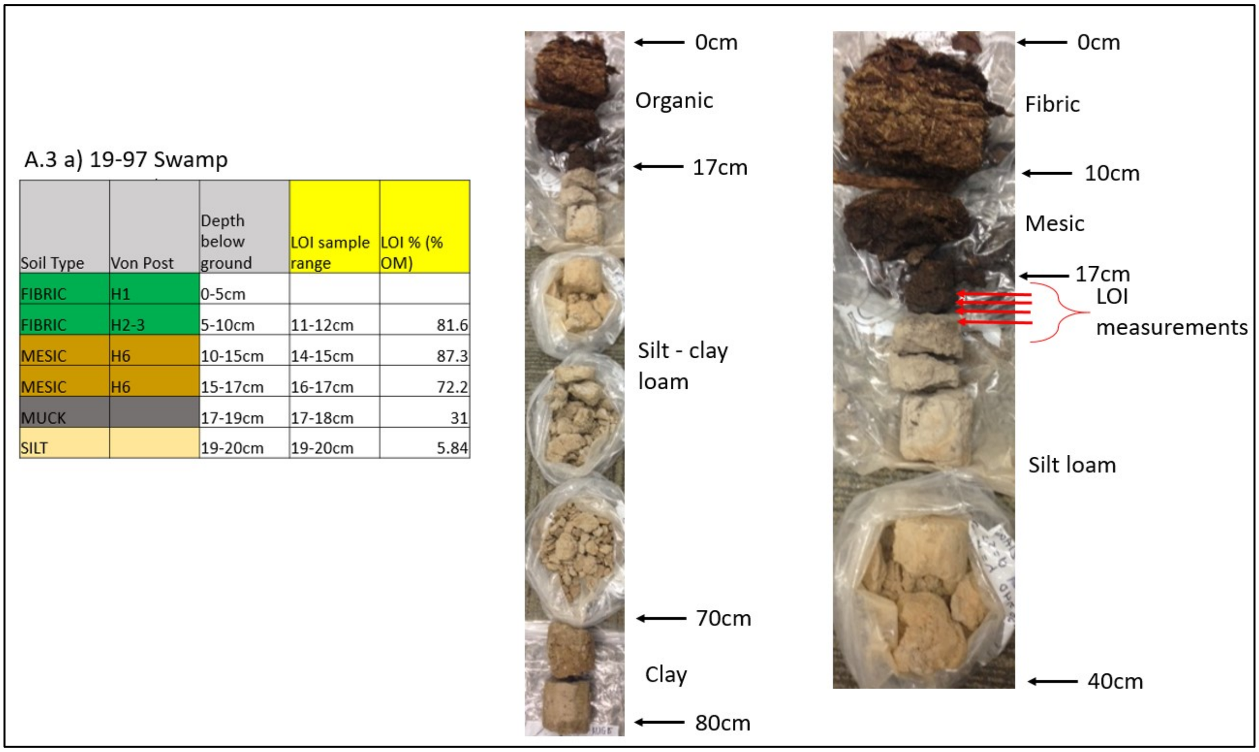


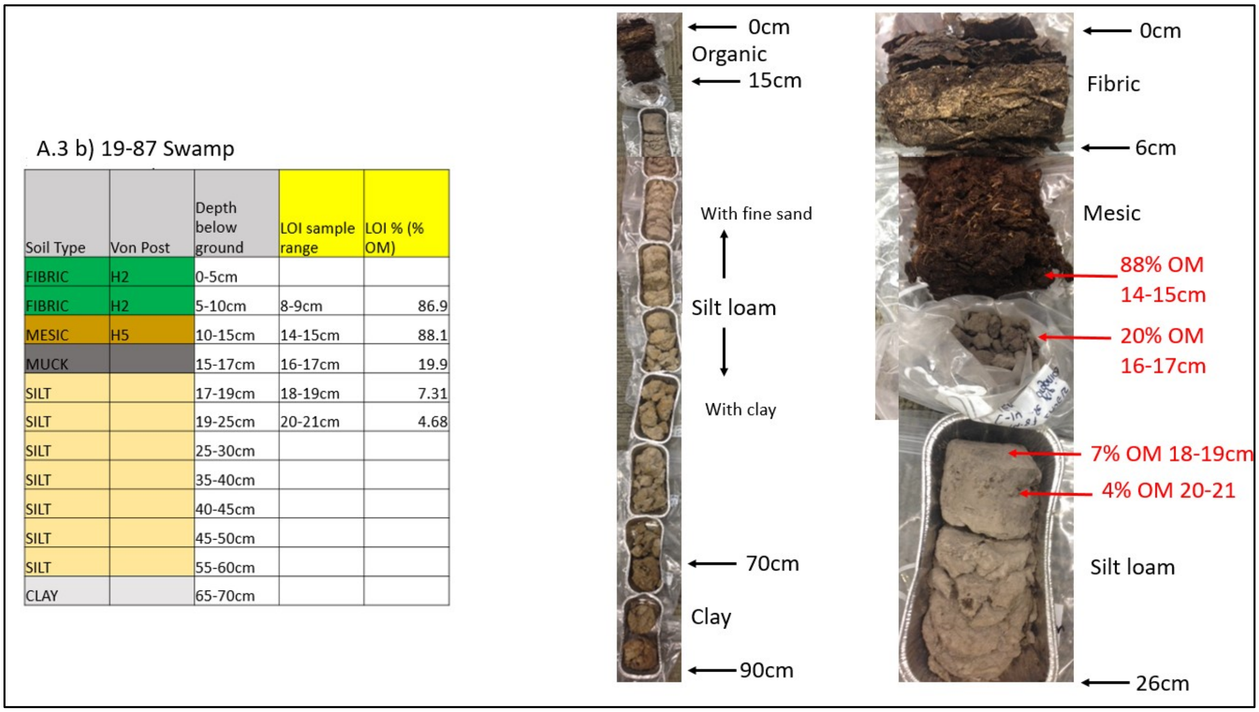
Figure A.2: Mineral calibration curve for PR2 soil moisture data. Field and lab samples match the factory mineral polynomial calibration curve supplied by Delta-T devices.



A.3 a) 19-97 Swamp

Soil Type	Von Post	Depth below ground	LOI sample range	LOI % (% OM)
FIBRIC	H1	0-5cm		
FIBRIC	H2-3	5-10cm	11-12cm	81.6
MESIC	H6	10-15cm	14-15cm	87.3
MESIC	H6	15-17cm	16-17cm	72.2
MUCK		17-19cm	17-18cm	31
SILT		19-20cm	19-20cm	5.84

Figure A.3: Soil profiles for a) margin swamp site 97 at perched wetland H



A.3 b) 19-87 Swamp

Soil Type	Von Post	Depth below ground	LOI sample range	LOI % (% OM)
FIBRIC	H2	0-5cm		
FIBRIC	H2	5-10cm	8-9cm	86.9
MESIC	H5	10-15cm	14-15cm	88.1
MUCK		15-17cm	16-17cm	19.9
SILT		17-19cm	18-19cm	7.31
SILT		19-25cm	20-21cm	4.68
SILT		25-30cm		
SILT		35-40cm		
SILT		40-45cm		
SILT		45-50cm		
SILT		55-60cm		
CLAY		65-70cm		

Figure A.3: Soil profiles for b) margin swamp sites 87 at perched wetland H.

A.3 c) 19-100 Peatland

Simplified Soil Type	Von Post	Depth below ground	LOI sample range	LOI % (% OM)
FIBRIC	H1	0-5cm		
FIBRIC	H2	5-10cm		
FIBRIC	H2	10-15cm		
FIBRIC	H2	15-20cm		
MESIC	H4	20-25cm	20-22cm	94.5
MESIC	H4	25-30cm	28-30cm	91.8
MESIC	H4	30-35cm		
MESIC	H5	35-40cm		
HUMIC	H7	40-45cm	42-43cm	91.8
HUMIC	H8	45-50cm		
HUMIC	H8	50-55cm		
HUMIC	H8	55-60cm	58-59cm	88.5
HUMIC	H9	60-62cm	60-61cm	45.9
HUMIC	H9	63-65cm	63-64cm	74.1
HUMIC	H9	65-66cm	65-66cm	58.5
MUCK		66-68cm	66-68cm	34.1
CLAY		68-70cm	68-69cm	5.67

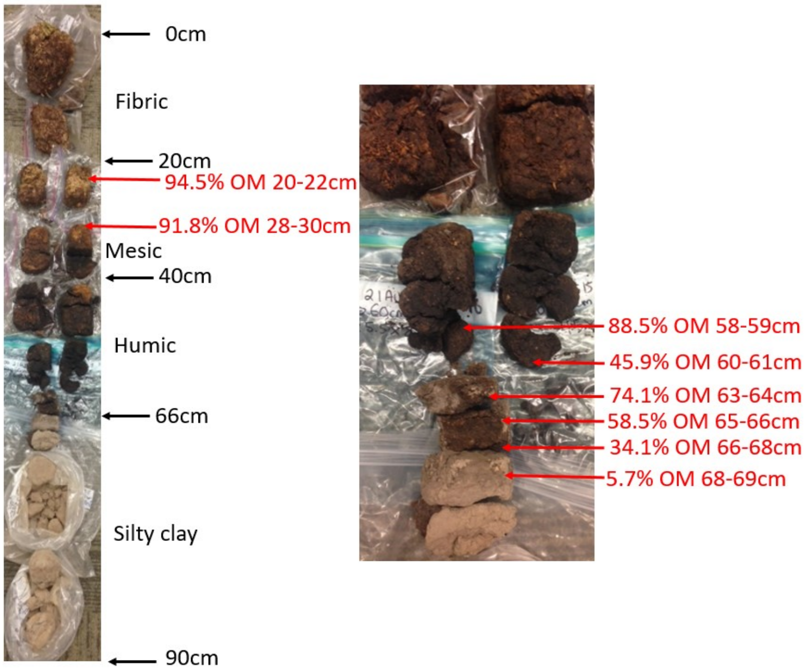


Figure A.3: Soil profiles for c) peatland edge site 100 at perched wetland H.

A.3 d) 19-81 Peatland

Simplified Soil Type	Von Post	Depth below ground	LOI sample range	LOI % (% OM)
FIBRIC	H1	0-5cm		
FIBRIC	H2	5-10cm	9-10cm	95.7
FIBRIC	H2	10-15cm		
FIBRIC	H2	15-20cm		
MESIC	H4	20-25cm	20-21cm	94.4
MESIC	H5	25-30cm		
MESIC	H4	30-35cm	30-32cm	94.5
MESIC	H5	35-40cm		
HUMIC	H8	40-45cm	42-43cm	92.7
HUMIC	H8	45-50cm		
HUMIC	H8	55-60cm	58-60cm	94.8
HUMIC	H8	60-65cm		
HUMIC	H8	65-70cm		
HUMIC	H8	70-75cm		
HUMIC	H8	75-80cm		
HUMIC	H8	80-85cm		
HUMIC	H8	85-90cm		
HUMIC	H8	90-95cm		
HUMIC	H9	95-97cm	95-96cm	91.2
HUMIC	H9	98-100cm	98-100cm	72.2
HUMIC	H9	101-102cm	101-102cm	71.2
MUCK		103-105cm	104-105cm	36.7
CLAY		105cm-110cm	107-108cm	10

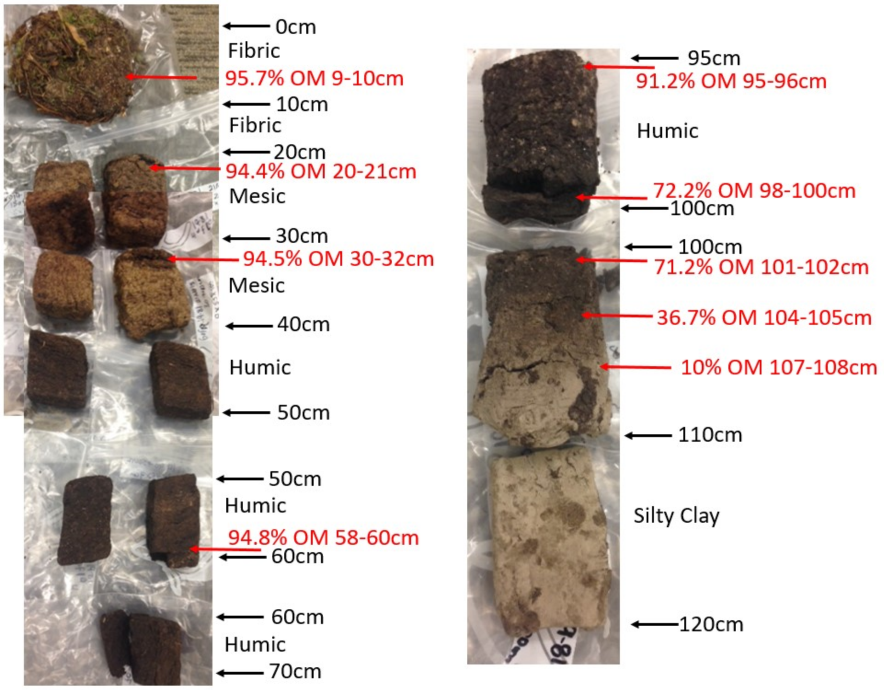


Figure A.3: Soil profiles for d) peatland centre site 81 at perched wetland H.

A.3 e) 19-27 Peatland

Soil Type	Von Post	Depth below ground	LOI sample range	LOI % (% OM)
FIBRIC	H1	0-5cm		
FIBRIC	H2	5-10cm		
FIBRIC	H3	10-15cm		
FIBRIC	H3	15-20cm		
MESIC	H4	20-25cm	20-22cm	94.5
MESIC	H4	25-30cm		
MESIC	H5	30-35cm	35-36cm	94.8
MESIC	H6	35-40cm		
HUMIC	H8	40-44cm	44-45cm	90.85
HUMIC	H8	45-46cm	45-46cm	92.4
HUMIC	H8	46-47cm	46-47cm	38.39
MUCK		47-48cm		
CLAY		48-50cm	48-49cm	9.4

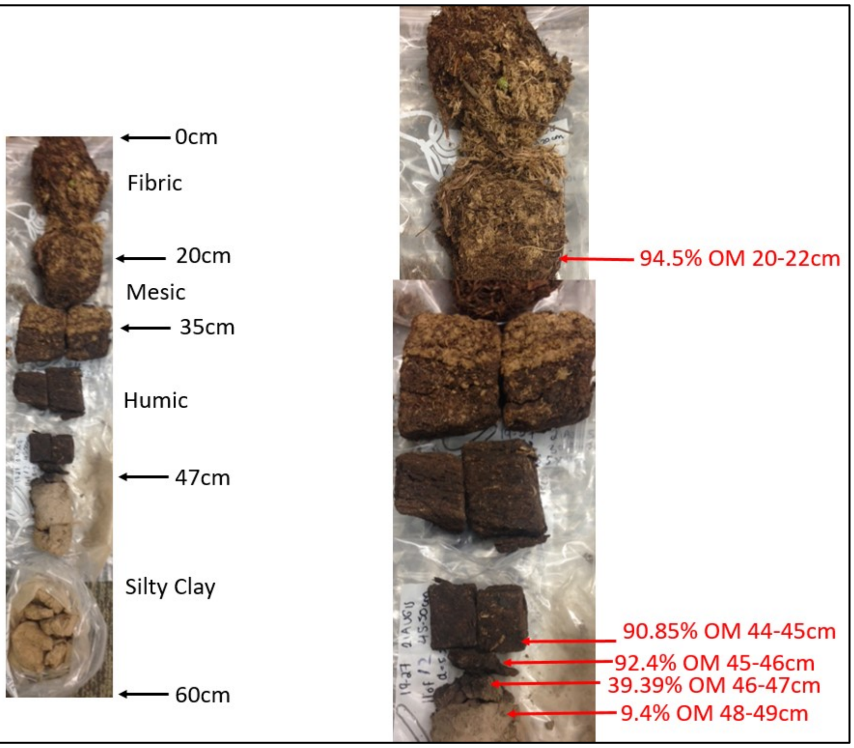


Figure A.3: Soil profiles for d) peatland edge site 27 at perched wetland H.

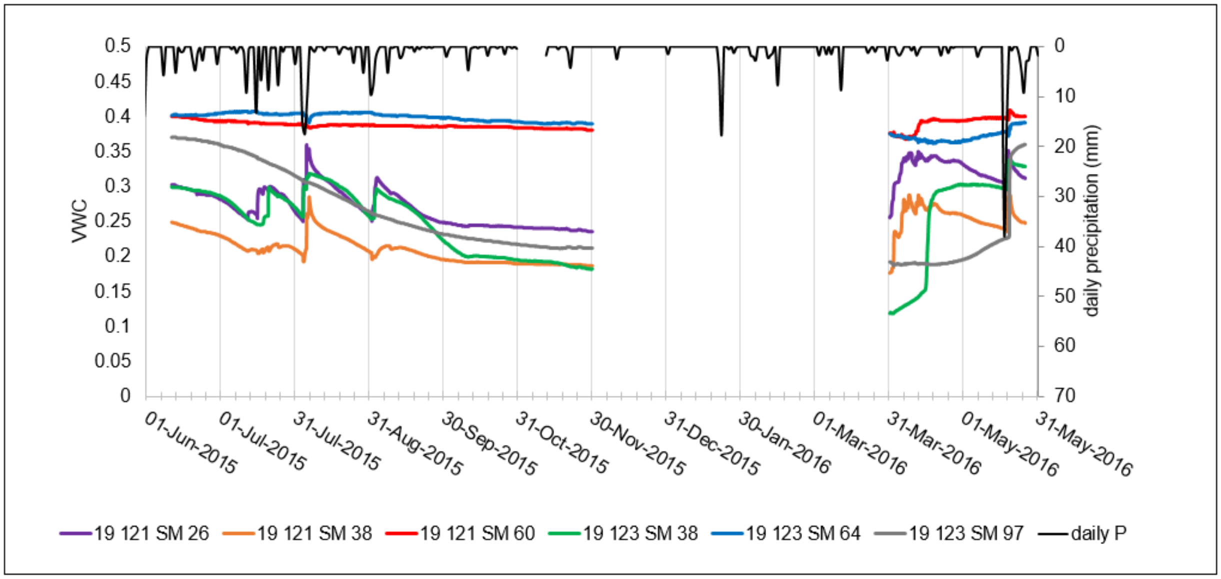


Figure A.4: Volumetric water content (VWC) measured at soil moisture sensors installed in soil pits along the wetland-upland transition zone June 2015 - May 2016. Daily precipitation is shown in black.

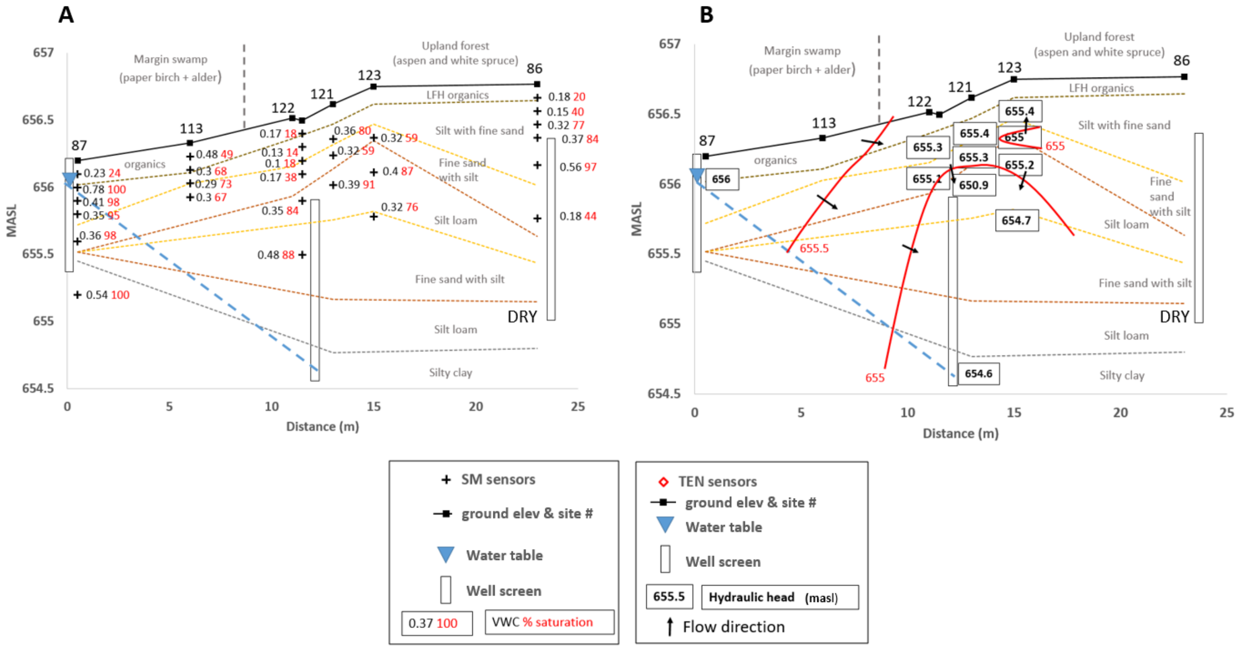


Figure A.5: a) Soil moisture (volumetric water content, VWC and percent saturation) distribution across the wetland – upland interface during wet conditions 7 August 2015. b) Unsaturated hydraulic head (in masl) with hydraulic head distribution across the wetland – upland interface 7 August 2015. Horizontal axis is distance from site 87 (Figure 3.3); vertical axis is elevation in masl. Soil stratigraphy, water table, well screens, and location of sensors are presented.

CONIFERS ASPEN

MARGIN SWAMP PEATLAND

Figure A.6 a) Differences in snow variability 28 March 2015 in conifer stands, aspen forest, margin swamp (riparian) and peatland at wetland H.

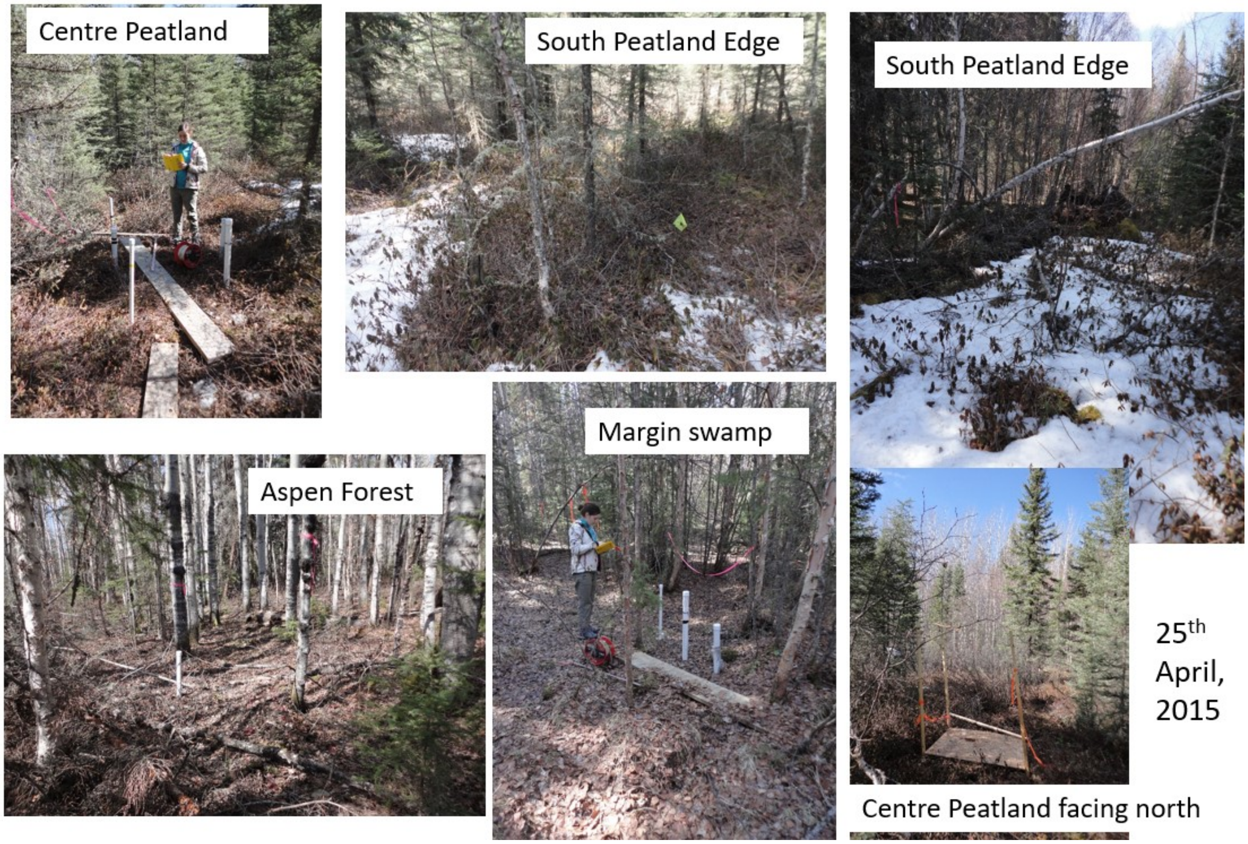


Figure A.6b: Differences in snow accumulation on 25 April 2015 around wetland H. Riparian is margin swamp.

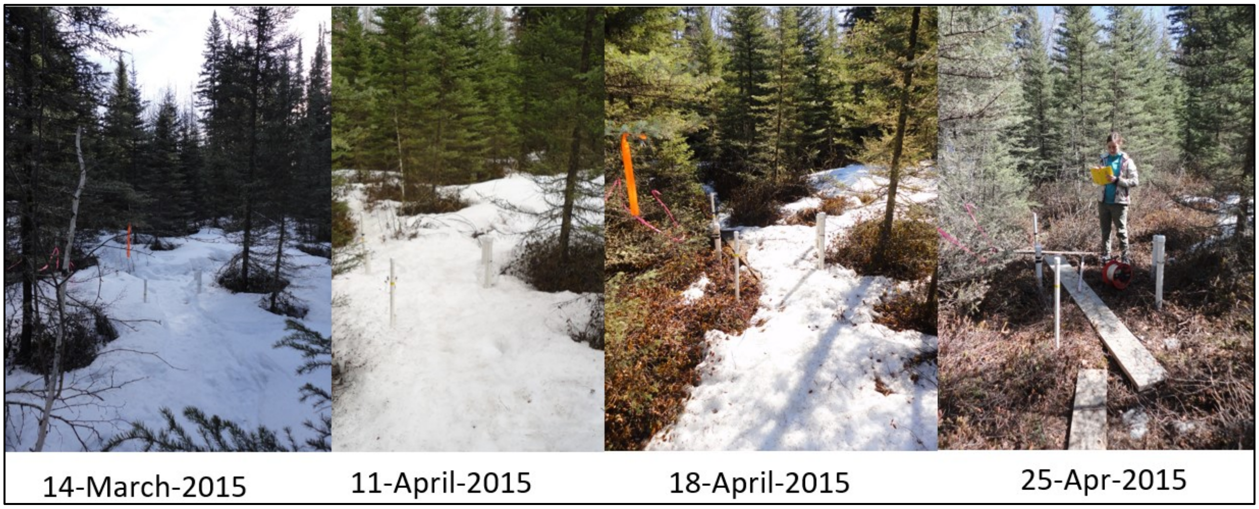
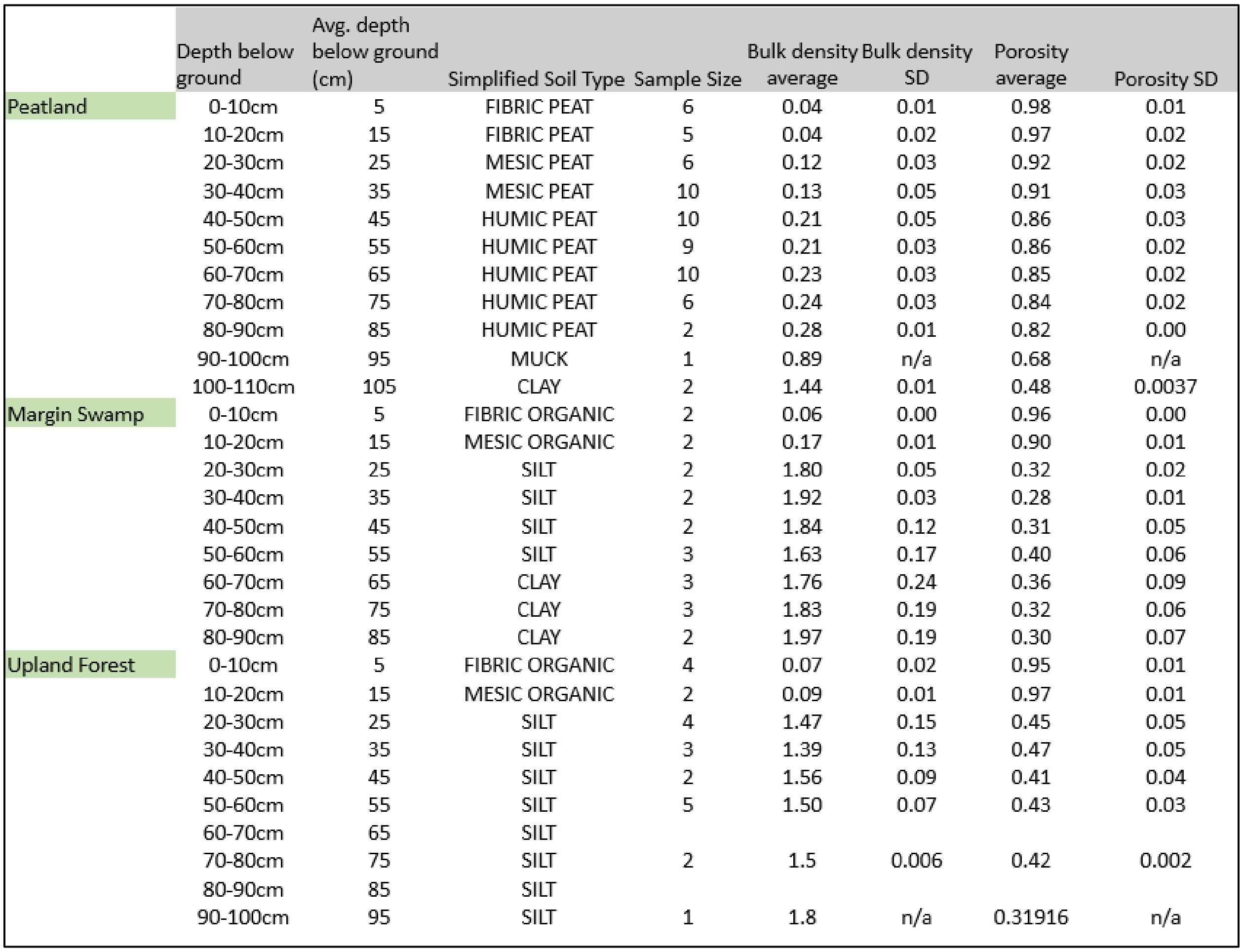


Figure A.6c: Ablation in the peatland centre (site 81) at wetland H 2015

Figure A.6 d: Differences in snow cover between the north and south peatland edges 25 April 2015. Note the lack of snow on the northern edge (left panel), compared to southern edge (right panel), due to aspect and shading from adjacent forest.

Table A.1: Soil physical properties at perched wetland H in peatland, margin swamp and upland forest.



	Depth below ground	Avg. depth below ground (cm)	Simplified Soil Type	Sample Size	Bulk density average	Bulk density SD	Porosity average	Porosity SD
Peatland	0-10cm	5	FIBRIC PEAT	6	0.04	0.01	0.98	0.01
	10-20cm	15	FIBRIC PEAT	5	0.04	0.02	0.97	0.02
	20-30cm	25	MESIC PEAT	6	0.12	0.03	0.92	0.02
	30-40cm	35	MESIC PEAT	10	0.13	0.05	0.91	0.03
	40-50cm	45	HUMIC PEAT	10	0.21	0.05	0.86	0.03
	50-60cm	55	HUMIC PEAT	9	0.21	0.03	0.86	0.02
	60-70cm	65	HUMIC PEAT	10	0.23	0.03	0.85	0.02
	70-80cm	75	HUMIC PEAT	6	0.24	0.03	0.84	0.02
	80-90cm	85	HUMIC PEAT	2	0.28	0.01	0.82	0.00
	90-100cm	95	MUCK	1	0.89	n/a	0.68	n/a
	100-110cm	105	CLAY	2	1.44	0.01	0.48	0.0037
Margin Swamp	0-10cm	5	FIBRIC ORGANIC	2	0.06	0.00	0.96	0.00
	10-20cm	15	MESIC ORGANIC	2	0.17	0.01	0.90	0.01
	20-30cm	25	SILT	2	1.80	0.05	0.32	0.02
	30-40cm	35	SILT	2	1.92	0.03	0.28	0.01
	40-50cm	45	SILT	2	1.84	0.12	0.31	0.05
	50-60cm	55	SILT	3	1.63	0.17	0.40	0.06
	60-70cm	65	CLAY	3	1.76	0.24	0.36	0.09
	70-80cm	75	CLAY	3	1.83	0.19	0.32	0.06
	80-90cm	85	CLAY	2	1.97	0.19	0.30	0.07
Upland Forest	0-10cm	5	FIBRIC ORGANIC	4	0.07	0.02	0.95	0.01
	10-20cm	15	MESIC ORGANIC	2	0.09	0.01	0.97	0.01
	20-30cm	25	SILT	4	1.47	0.15	0.45	0.05
	30-40cm	35	SILT	3	1.39	0.13	0.47	0.05
	40-50cm	45	SILT	2	1.56	0.09	0.41	0.04
	50-60cm	55	SILT	5	1.50	0.07	0.43	0.03
	60-70cm	65	SILT					
	70-80cm	75	SILT	2	1.5	0.006	0.42	0.002
	80-90cm	85	SILT					
	90-100cm	95	SILT	1	1.8	n/a	0.31916	n/a