The Hydrology of Passive and Active Restoration in Abandoned Vacuum Extracted Peatlands, Southeast Manitoba

By

Melanie Hawes

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The undersigned certify that they have read, and recommended to the Senate for acceptance, a **MASTER'S THESIS** entitled:

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Supervisor: Dr. P. Whittington

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Committee Member: Dr. V. Chen

Date: Aug-31-2018
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Committee Member: Dr. M. Strack

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Abstract

Natural, self-regulating bogs have high water tables during wet periods of the year and can retain their moisture content within the acrotelm to sustain the physiological functions of the *Sphagnum* during dry periods. Peat extraction disrupts the hydrology and natural regeneration of most cut-over bogs. Although regeneration occurs more readily on block-cut sites, vacuum harvesting has become the main method of extraction and therefore requires more rigorous restoration efforts afterwards. Two methods of restoration are observed in this paper, passive restoration at Moss Spur and active restoration at Elma North. To establish and regenerate, *Sphagnum* moss requires a water table within 0.4 m of the peat surface and soil-water pressure (ψ) not exceeding -100 cm. These parameters were established for bog restoration; however, bogs develop from fens, thus the active restoration is aimed towards a fen system. The hydrogeomorphic setting in Manitoba allowed for Moss Spur to regenerate passively, while Elma presented an opportunity to explore a combination of active restoration techniques used in eastern Canada and Europe. Moss Spur was expected to be barren, much like a comparable site in Quebec, however groundwater discharge was found to occur throughout Moss Spur over three study seasons which likely resulted in its spontaneous regeneration since abandonment. It is still unknown if the active restoration treatments conducted at Elma will shorten fen regeneration time to decades rather than centuries, but in one season the water table levels were increased >100 cm and soil tension improved to bring it well within the acceptable threshold for *Sphagnum* establishment.

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1 Introduction

1.1 Thesis Structure

This thesis comprises two manuscripts focused on assessing the hydrology of restoration efforts in two Manitoba peatlands from 2014 to 2017. Each manuscript represents a different approach to the restoration of peatlands in Canada; one of which (Chapter 2) highlights understanding the importance of the hydrogeomorphic setting in which restoration occurs, and the other (Chapter 3) represents the current trajectory of an exciting new research direction in the country. Before we can understand these two manuscripts we must understand were we have come from, and thus a brief review of peatland restoration in Canada is needed. The end of this chapter will place the two studies into their proper context and how they both contribute to a better understanding of peatland restoration in Canada.

1.2 A Brief History of (the hydrology of) Peatland Restoration in Canada

Wetlands provide important ecosystems services such as habitat creation, nutrient and sediment filtration, carbon sequestration, and flood intensity regulation (Environment Canada, 2015) and cover 14% of Canada's landmass, but are declining due to anthropogenic activities (Environment Canada, 2015). Bogs and fens are classified as organic wetlands, often called peatlands (National Wetlands Working Group, 1997), which cover approximately 113 million hectares in Canada's boreal region (Swystun et al., 2013) and represent over 90% of all Canadian wetlands. Canada's abundance of peatlands has led it to be one of the world's leaders in harvested peat production (CSPMA, 2014); peat is extracted mainly for horticultural purposes (growing medium) in Canada (Hendrie, 1995) but can be used a fuel which is more common in Europe.

Bog peatlands are the most commercially viable peatland type because of the abundance of *Sphagnum* peat, as *Sphagnum* mosses are the dominant peat forming species and are more prevalent in bogs than fens (where true mosses dominate). Peatlands exhibit the common characteristics shared among all wetlands, which are being saturated with water, having hydrophytic vegetation, and biological activity adapted to wet environments (National Wetlands Working Group, 1997). It is the way in which peatlands, specifically bogs, receive water that sets them apart. Bogs are ombrogenous, meaning they only receive water via precipitation, whereas fens generally have standing water within them and can be connected with groundwater discharge and surface waters (e.g., streams). Only the upper few cm of *Sphagnum* moss is alive, which grow on top of decaying moss and naturally divide the peat into an upper layer (acrotelm) and lower layer (catotelm) (Ingram, 1978). The acrotelm is typified by loose, living plant material, large pore spaces and is seasonally unsaturated, while the catotelm is decomposed compacted peat with slow water movements through tiny pore spaces (Quinty & Rochefort, 2003). These two layers work together to keep the water table at a more stable level: the acrotelm sheds excess water through its large pores, whereas the catotelm, with its small pores and low specific yield, which prevents water tables from falling too low. It is the catotelm moss that is harvested due to the moss's extreme water retention capacity and decay resistance (Read et al., 2004).

Once a bog has been chosen as an extraction site, the proper permitting protocol must be adhered to before extraction may commence. Manitoba is the only Canadian province with stand-alone legislation regarding peatland stewardship (Legislative Assembly of Manitoba, 2014), which states that a harvested peatland must be restored, rehabilitated, or reclaimed once extraction ends. Permits and licenses must be applied for before ground is broken, and an environmental impact assessment must be completed before licenses are granted, including a post-harvest restoration plan (Legislative Assembly of Manitoba, 2014). Once licensed, preparing a bog for peat extraction requires the installation of drainage ditches to lower the water table and dry out the bog so that the acrotelm can be removed to access the decayed catotelm (peat). Ditches are dug, typically in 30 m spacing, throughout a site to sufficiently drain it in preparation for harvest. Various techniques have been used to harvest a peatland; however, vacuum harvesting is the most common extraction method (Price & Heathwaite, 2003). Once the bog is drained and the acrotelm removed, the surface is tilled to dry the peat and a tractor, with a vacuum, sucks up only the uppermost dried catotelm (~1 mm per pass). A single site can be vacuum harvested for up to 30 years, taking 5-7.5 cm of peat per year from a bog 4.5-6 meters deep (Radjevic, 2008).

Undisturbed peatlands have the ability to self-regulate; the peat matrix is able to shrink and swell in response to seasonal wetness (Ingram, 1983) or drainage (Whittington & Price, 2006) via its ability to shed water during periods of high water table, and prevent extreme water table fluctuations during dry periods (Price & Ketcheson, 2009). Harvesting peat disrupts the hydraulic connectivity below, affecting the ability of vegetation to regenerate on abandoned harvest sites. Money (1995) found the hydrological conditions (water table, pore-water pressure, and soil moisture) left from the block-cut method of peat extraction to be more conducive to natural regeneration than vacuum extraction, however, vacuum harvesting is preferred as it is more economically viable for the peat companies. Vacuum extracted sites experience less extreme but generally worse average conditions (Price et al., 2003). The high soil water tension caused from the harvest allows for vascular plants to more readily regenerate on these abandoned areas than peat moss. Moss, being non-vascular, exerts more energy for water uptake with the increased soil water tension than vascular plants, making hydrology a key factor in a site's ability to sustain regenerative growth. The once intact acrotelm maintained stable water levels from which the *Sphagnum* was able to access water; thus, without the acrotelm, the remaining peat will degrade instead of regenerate (Price et al., 2003). Soil-water pressure (ψ) is essentially how hard the plant has to "suck" water up through the soil and into its tissue via capillary action. Ψ between -200 and -600 cm will drain the hyaline cells (Clymo & Hayward, 1982), located within the *Sphagnum* leaves, leaving the moss without structural support and unable to photosynthesize (Gerdol et al., 1996). Price & Whitehead (2004) observed that even when the water table fell below -50 cm from the surface, the capillary fringe maintained a zone of saturation within -30 cm of the surface. Ketcheson & Price (2014) noted that only a small amount of water (i.e., morning dew) was able to revive dehydrated moss cushions.

Restoration research on peat-mined bogs began in eastern Canada in the 1990s (Rochefort, 2000; Daigle & Gautreau-Daigle, 2001) with the goal to return the areas to functional, carbon sequestering ecosystems (Rochefort, 2000). A comprehensive review of Canadian efforts follows in the next section. It is important to note that the goal is not to return to the site to harvest in the near future, as bogs develop over thousands of years, making peat a non-renewable resource on human timescales. Restoration in these sites is difficult because *Sphagnum* moss does not grow in a soil, it *is* the soil. Once the living part of the plant (acrotelm) has been removed to access the peat for extraction, nothing remains to regenerate once extraction is complete. Note that natural bogs develop from fens or forested swamps over thousands of years (Sjors, 1963; Glooschenko and Martini, 1983), thus restoration should be aimed towards a fen ecosystem.

There also exists a distinct difference in the hydrogeomorphic settings between Europe and Canada, and even eastern Canada and western Canada, thus resulting in various results and conclusions from each study site. The hydrogeomorphic setting encompasses the hydrogeology (hydrology, climatology, geology), and the geomorphology of an area, meaning that a restoration technique that works well in one area may not work in another with a different hydrogeomorphic setting. For example, Quebec and Manitoba are within different Ecozones, which are underlain by different types of bedrock, and experience different climate regimes. Therefore, restoration efforts performed in Quebec, which represent the majority of Canada's restoration efforts, may not work, or even be necessary, in Manitoba. Similarly, the techniques used in Europe, i.e., ditch blocking, were not solely effective to promote restoration in Quebec, hence the need for Canadian specific studies, detailed below.

1.3 Quebec

The Lac-St-Jean (LSJ) bog is part of the Ste-Marguerite-Marie peatland in Quebec, a block-cut peatland located in a humid continental climate (LaRose et al., 1997) above a well -developed iron pan of mineral sediments (Price, 1996) disjointing the bog from the aquifer below (LaRose et al., 1997).

Price (1996) found that the water table threshold for successful peat growth is 0.4 m below the bog surface; a water table deeper than 0.4 m is unable to reach the acrotelm and sustain moss growth. With a water table hovering near the 0.4 m threshold at LSJ, and matric tension being greater in areas of low water table and low soil moisture (LaRose et al., 1997), the landscape was not conducive to *Sphagnum* establishment. Graf et al. (2008) found that fen vegetation returned to abandoned sites more readily than bog vegetation, i.e. sedge peat would establish faster than *Sphagnum*, with appropriate hydrological conditions. It was also noted that fast recovery rates relied heavily on a high water table and a thin layer of residual peat (Graf et al. 2008, Poulin et al. 2005).

The anthropogenic component of restoration generally ends with drainage ditch infilling to rewet the extracted peatland. Most of the distorted hydrology will be restored simply by blocking the ditches; however, the soil structure of the peat remains permanently altered and thus the way water is stored within the peat matrix (Price, 1996). Although water retention is improved, it is still not sufficient enough to support a *Sphagnum* community (Price, 1998), the collapsed peat matrix reduces the specific yield from 0.5 to 0.05 (Price et al., 2003), consequently creating greater water table fluctuations. "Specific yield is the ratio of the volume of water yielded by gravity drainage to the volume of the block of soil" (Price et al., 2003). Acrotelm peat has a high specific yield whereby the water is able to readily drain from the larger pores, resulting in minimal water table fluctuations throughout the season (Price et al., 2003). Catotelm peat has higher water retention capacity (Price et al., 2003) because of its smaller pore size and reluctance to allow easy water drainage due to gravity, hence the lower specific yield of catotelm peat and greater resulting water table fluctuations.

LaRose et al. (1997) discovered that leaving open water reservoirs also aided in the rewetting process. Since water stored in the unsaturated portion of the cutover peat supplies water for surface evaporation (Price, 1997), a steady water table indicates the evaporative demand is met, according to soil water tension profiles at LSJ (Price, 1997). During wet periods, the water table recovered with blocked ditches, but Price (1997) noticed a quicker recession in drier periods when compared to a natural site. Adding a layer of mulch consisting of donor *Sphagnum*, in addition to open water reservoirs, will regulate the water table and make it comparable to a natural system (Price, 1997). The mulch layer was also found to increase soil moisture levels by 10-15% (Price, 1997) since it has a higher albedo than bare peat (Price et al., 1998).

Not far from LSJ, Bugnon et al. (1997) had a cutover peatland in St-Modeste, near Riviere-du-Loop, re-contoured into V-shaped profiles and hung clear plastic sheets above some of the sections, as well as spreading hand-picked *Sphagnum* onto the experimental plots covered by straw mulch. The re-profiling seemed to compensate for the shortcomings of just blocking the ditches in restoration efforts, as *Sphagnum* began to establish in greater abundance along the center of the V contour in plots also aided by the plastic sheets when compared to the control site (Bugnon et al., 1997). Since vacuum extraction leaves behind a relatively level peat field, there exists little to no microtopography suitable for *Sphagnum* establishment (Price et al., 2003), Campeau et al. (2004) experimented with enhancing the microtopography across a site before spreading *Sphagnum* diaspores across the area. The positive relief of the re-contoured landscape proved to be unsuccessful for moss colonization, since *Sphagnum* more readily regenerates in shallow basins (Campeau et al., 2004), as seen with moss establishment along the center of Bugnon's V contour. Excess moisture in depressions may seem counterintuitive for successful moss growth, but Rochefort et al. (2002) explains that many species of *Sphagnum* are able to thrive in areas with temporary shallow flooding; continuous flooding will damage established mosses, however. Therefore, maximum water level does not correlate with maximum plant regeneration, but instead variable wetness balances the negative impacts of flooding (Campeau et al., 2004).

Cacouna is another experimental treatment bog within Quebec, with conclusions reached by Price & Whitehead (2004) regarding *Sphagnum* establishment on a cut-over peatland such that non-vascular species (i.e., moss) cannot establish on top of a mulch layer. However, in lower areas with near-saturated conditions, moss establishment will prevail and continue to spread laterally as the moisture levels stabilize in the peat (Price & Whitehead, 2004). Although the spread of moss allows the moisture regime within the peat to stabilize, generally, vascular plants establish first on a fresh surface from the seed bank left after extraction (Girard et al., 2002). The roots of these plants are able to pull water up from deeper below the surface than moss have access to, thus increasing evapotranspiration rates and causing the water table to recede further below the surface (Ingram, 1987; van Seters & Price, 2001). Evapotranspiration is the main source of yearly water loss in most bogs (Ketcheson & Price, 2011). The lower water table effectively creates a lower specific yield, meaning greater fluctuations throughout the season, and lower hydraulic conductivity (van Seters & Price, 2002). Saturated hydraulic conductivity within the acrotelm can decrease up to five orders of magnitude within -50 cm of the peat surface (Hoag & Price, 1995). Site restoration should aim for uniform moisture regimes rather than pockets of *Sphagnum*-conducive conditions (Ketcheson & Price, 2014).

With the results of the Lac St. Jean and other sites established, the first ecosystem scale (rather than plot scale) restoration project took place the Bois-des-Bel (BdB) peatland in Eastern Quebec. BdB has been experimentally treated and monitored for nearly two decades. BdB is a vacuum harvested peatland also located near Riviere-du-Loop, Quebec, atop the iron pan sediments, described by Price (1996), below. Restoration of this site began in 1999 after 19 years of abandonment and minimal natural revegetation (Shantz & Price, 2006a). The first measures taken were to till the cutover surface, and spread 3000 kg ha^{-1} of straw mulch across the site, and block the drainage ditches (Rochefort, 2000). Studies have shown that the mulch spread over an area will mostly decompose after three years, by which time the moss cover should be stable enough to prevent erosion (Petrone et al., 2004). A second application of mulch may be required in areas left with bare peat (Shantz & Price, 2006b). Petrone et al. (2004) found that by adding straw mulch, evaporation decreased between 8% and 13% when compared to a nearby control site.

The ditch blocking, bund construction, and mulch application on the site has proven successful in this region of Quebec; since restoration efforts began at BdB in 1999, a moss carpet approximately 20 cm thick has colonized the site (McCarter & Price, 2015). Collectively, the experimental design used at BdB and promoted elsewhere is the moss layer transfer technique, or MLTT. The issue surrounding restoration 10 years later has now shifted from creating and maintaining hydrological stability for *Sphagnum* establishment to establishing fluid connectivity between cutover catotelm and newly grown acrotelm (Ketcheson & Price, 2014). In order for the new acrotelm to retain moisture levels similar to those of a natural system, the *Sphagnum* must be able to use capillary force to bring water up from depth to the surface; if the regenerated system is unable to perform this function, it is not fully restored (McCarter & Price, 2013). By using drought tolerant species of moss, such as *Sphagnum fuscum*, in the mulch and diaspore mixture, the regenerated acrotelm may be better suited to transport water from the catotelm for sustained growth (McCarter & Price, 2015). McCarter & Price (2015) expect BdB to self-regulate and become a net carbon sequestering system over time.

Radcliffe and Rasmussen (2002) found that compressing mineral soils increased unsaturated hydraulic conductivity (K_{unsat}) and water was able to reach the surface; Kennedy and Price (2004) and McCarter and Price (2014) speculated that decreasing pore size in *Sphagnum* decreased and increased the saturated and unsaturated hydraulic conductivity, respectively, allowing water held in the catotelm to better reach the acrotelm. A section of regenerated acrotelm in BdB was compressed during the winter using a tractor to decrease pore size and increase hydraulic conductivity to remedy the disconnect between remnant peat and new acrotelm (McCarter and Price, 2015), coinciding with results from Golubev and Whittington (2018) that an increase in peat bulk density, due to a reduction in peat volume will increase K_{unsat}.

1.4 Southeast Manitoba

The Elma experimental treatment site was abandoned in 2007 and resembled Bois des Bel in Quebec prior to restoration efforts, with minimal vegetation and mostly bare peat. The Elma site is located near the main Sun Gro processing plant approximately 10 km south of the town of Elma, not too far from the other research site, Moss Spur. Moss Spur has "spontaneously" regenerated and is located approximately 20 km west of the town of Whitemouth, MB. The two study sites are located within the Boreal Plains ecozone, characterized by moderately warm summers and cold winters (Smith et al., 1998), and are located adjacent to fields experiencing active extraction.

Peat extraction began at Moss Spur in 1940 by Sun Gro Horticulture Inc. (Swystun et al., 2013), and was the first extraction operation in Manitoba; later abandoned in 1993. The majority (~95%) of Moss Spur is currently experiencing an accelerated rate of vascular plant and *Sphagnum* regeneration, which raised the question "why?". Most peatland restoration projects have occurred in Quebec, but Manitoba offers different geography, hydrology, and geomorphology, or hydrogeomorphology. Chapter 2 describes the search for answers from Moss Spur as to why passive restoration has worked at this site while other sites, in Quebec and Europe, require an active approach to achieve *Sphagnum* regeneration.

Restoration efforts for the Elma site began in the fall of 2015. Baseline hydrological measurements, as well as greenhouse gas emission measurements, were conducted that summer for comparison. Restoration began at Elma with field re-contouring into a checkerboard pattern (Figure 3-1) and perimeter ditch in-filling. The purpose of re-contouring was to ensure even water distribution from re-wetting and snow-melt. The south portion not re-contoured was left to re-wet itself in hope of creating a transition area into the surrounding natural bog. The hydrology of the site was monitored during the summers of 2016 and 2017 via wells and piezometers. The novelty of Elma is that it will be restored as a fen instead of a bog; not a lot of research has been conducted on active fen restoration in Manitoba.

The objective of this thesis is to examine the hydrology of two vacuum-extracted peat bogs in Manitoba and compare them to what is known about bog hydrology for restoration based on efforts in Quebec, and hydrological requirements for fen restoration.

2 The hydrology of the spontaneous regeneration of a cutover bog in southeast Manitoba, Canada

2.1 Introduction

Wetlands provide many critical ecosystem services such as carbon sequestration, flood protection, and habitat for an abundance of species (Bunting and Whitehouse, 2008). Bogs and fens, organic wetlands also known as peatlands, are the most dominant type of Canadian wetlands (Stewart & Kantrud, 1971), covering approximately 13% of Canada's surface area (Tarnocai et al., 2011). The abundance of peatlands in Canada has, in part, led the country to be one of the world's leaders in peat extraction for horticultural purposes (Hendrie, 1995).

Peat harvesting most often occurs in bogs. Bogs are characterized by a surface topography of hummocks and hollows of peat mosses and are ombrogenous (receiving water via precipitation only). *Sphagnum* mosses are the dominant peat forming vegetation, which grow on top of decaying moss and naturally divide the peat into an upper layer (acrotelm) and lower layer (catotelm) (Ingram, 1978). The acrotelm is comprised of living moss with large pore spaces, generally unsaturated. The catotelm is continuously saturated and has slower water movement between smaller pores of the compacted peat (Quinty & Rochefort, 2003). The air-water interface at the lowest annual water level is where the divide between acrotelm and catotelm is defined (Ingram, 1978).

Manitoba has the most peatland by percentage of area of any province in Canada (38% (Swystun et al., 2013)), and contributes ~ 13% to Canada's peat extraction total production (Natural Resources Canada, 2012) with Quebec dominating the Canadian industry. When a peatland is cutover for extraction, drainage ditches are dug throughout the area to lower the water table, so machinery can access the site to remove the surficial vegetation and top ~50 cm of moss (acrotelm). A vacuum harvester then sucks up the dried (catotelm) peat. According to the Canadian Sphagnum Peat Moss Association (CSPMA), a single site can be harvested for up to 30 years, taking 5-7.5 cm of peat per year from a bog 4.5-6 meters deep (Radjevic, 2008). Once extraction is complete the bog needs to be restored, however, abandoned vacuum-harvested sites usually do not revegetate quickly (Lavoie and Rochefort, 1996; Ferland and Rochefort, 1997). The disturbed bog is a source of atmospheric CO_2 (Price and Waddington, 2000; Waddington et al., 2001).

Most of what is known about peatland restoration in Canada comes from experimental sites in Quebec (Rochefort et al., 2003). Peat extraction disrupts the hydraulic connectivity between the catotelm and acrotelm, affecting the ability of vegetation to regenerate on cutover sites (McCarter & Price, 2013). Extraction causes high soil water tension, allowing for vascular plants to more readily regenerate on abandoned sites than *Sphagnum* moss (peat). Peat moss, being non-vascular, requires more energy for water uptake with the increased soil water tension than vascular plants, making hydrology a key factor in a site's ability to sustain regenerative growth (Price & Whitehead, 2001). The previously intact acrotelm maintained stable water levels from which the *Sphagnum* was able to access water; thus, without the acrotelm, the remaining peat will degrade instead of regenerate (Price et al., 2003).

From what is known in Quebec, it will take years for the hydrology to stabilize enough to promote *Sphagnum* permanence even if the drainage ditches are dammed immediately after abandonment, which is normally not the case. When potential nutrient loading from peat mining in Manitoba's Interlake region became a concern in Manitoba (Swystun et al., 2015), the Manitoba government placed a two-year moratorium (June 2011; and still in place at time of writing) on peat extraction in the Interlake region until long term effects could be realized (Swystun et al., 2015). Bill 61, the only stand-alone regulation regarding peatland restoration in Canada, was then implemented (June 2015), stating that harvested peatlands must be restored, rehabilitated, or reclaimed (Manitoba Government, 2014). Bill 61 came into effect based on the data compilation and research conducted by the International Institute for Sustainable Development (IISD). Due to the lack of harvesting and peatland restoration studies in Manitoba's Interlake region, the IISD, necessarily, used literature from different areas, notably Quebec and Europe, to project the risk to the peatlands in the Interlake region and harvesting's impact on Lake Winnipeg. It is therefore important to stress that the provinces (Manitoba and Quebec) are located within different hydrogeomorphic settings and ecozones, which means that the underlying bedrock characteristics and climate are completely different. Manitoba, located within the drier (annual precipitation 400-600mm) Boreal Plains Ecozone, is underlain by limestone sediments. The pores in fractured limestone are relatively large, allowing for greater water flow through them. Quebec is located within the wetter (1000+ mm) Boreal Shield Ecozone, underlain by shield bedrock (Precambrian rock) with small, closely packed pores which restrict water movement through them (Waller, 1982). The Boreal Shield Ecozone of Quebec also has a lower rate of evaporation than the Boreal Plains Ecozone of Manitoba. The literature review conducted by the IISD gave some insight to peatland hydrology, however, due to the great differences in hydrogeomorphic setting between Quebec and Manitoba, not all of the projected outcomes may manifest within the Interlake region.

There is a growing body of literature developing for the western boreal plain peatlands. Ferone & Devito (2004) observed that during times of drought, peatlands draw up water from below to sustain the vegetation within them and replenish that water source with excess water during wet periods. In Ferone & Devito's study (2004), the reservoir was an adjacent pond, however, peatlands in the western boreal plain access the groundwater, and replenish it, as required based on climatic pattern (Thompson et al., 2015).

The Moss Spur peatland is located in south eastern Manitoba, left unharvested for approximately 23 years with minimal restorative work conducted on the site. The majority (~95%) of Moss Spur is currently experiencing an accelerated rate of vascular vegetation, with some *Sphagnum*, regeneration. A comparable time-since-extraction site in Quebec (Bois des Bel) showed no such regenerative vigor before reclamation, however, after restoration efforts, including rewetting, diaspore dispersal, and fertilization (Campeau & Rochefort, 1996) regeneration began to take hold at Bois del Bel. The Moss Spur bog in Manitoba has begun to "spontaneously" regenerate itself after only 20 years with no major active reclamation work. Why? The objective of this research was to determine the water budget within the Moss Spur bog, and how it relates to the regeneration.

2.2 Study Site

Moss Spur is located approximately 12 kilometers northwest of Whitemouth, and 28 kilometers southeast of Beausejour, Manitoba (49°59' N, 96°8' W), approximately 100 kilometers east of Winnipeg. When harvesting stopped in 1995 (Swystun et al., 2013), Moss Spur had been mined for horticultural peat for 59 years via block cutting and vacuum harvesting. Once left, the study area was left to regenerate naturally as the majority of the secondary drainage ditches collapsed, as well as beaver activity via dams, raised the water level (Holtslag, 1998).

Moss Spur is located in the Boreal Plains ecozone, which is characterized by moderately warm summers and cold winters (Smith et al., 1998). Beausejour is the closest station with 1981-2010 climate data (Table 2-1), with a mean annual temperature of 2.8ºC. January and July temperatures are -16.9ºC and 19.3ºC, respectively. Precipitation totals 570.3 mm, with 20% falling as snow (Environment Canada, 2016).

The 700 ha peatland was nominally divided into 24 sections (not delineated in Figure 2-1) by existing drainage ditches easily identifiable in satellite images and was labeled alphabetically beginning from the northwest corner with A and ending in the south with X (Figure 2-1). The drainage ditches correspond to, but are not limited to, the borders of the zones (i.e., there are ditches within zones). In June, 2014, a rudimentary site survey at Moss Spur identified 5-6 distinct vegetation assemblages across the site. We chose to instrument hydrological equipment in these assemblages at locations that were also accessible as high water tables, hidden/collapsed drainage ditches and deep, wide primary drainage ditches made much of the site very difficult to navigate safely.

The vegetation present throughout Moss Spur included *Sphagnum* hummocks, Labrador tea (*Ledum groenlandicum*), willow species (*Salix spp*), and black spruce (*Picea mariana*), narrow-leaved cattail (*Typha angustifolia*), rush species (*Juncus spp*), and cottongrass (*Eriophorum spp*) at the time of data collection. A more detailed vegetation description per site can be found in section 1.4.1, as well as Gagnon (2017).

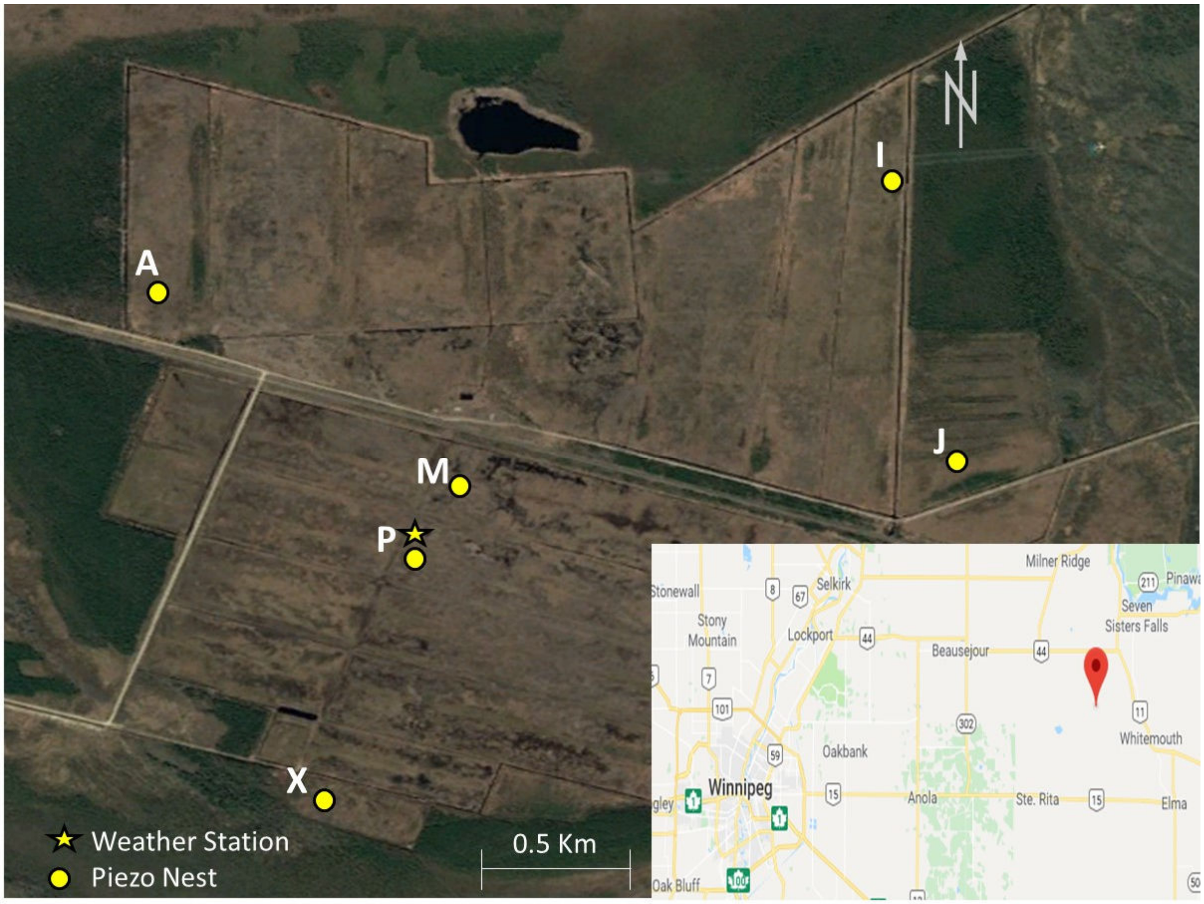


Figure 2-1. Moss Spur study site.

2.3 Methods

2.3.1 Well and piezometer construction and installation

Wells and piezometers were installed in nests at six locations across the site (J, I, P, X, A, and M) (Figure 2-1). Each nest had three or four piezometers with 20 cm slotted intakes and one well with slotted intakes up the length of it, constructed from 2.54 cm diameter PVC pipes. The pipes were placed into pre-augured holes, with the piezometers at 0.5 m, 1.0 m and 1.5 m (and deeper where the peat permitted) below the ground surface. Water level measurements were taken every few weeks from June to Sept 2014, every ~third day from May 12 to August 11, 2015, every

~tenth day from May 9 to August 9, 2016, and every ~three weeks in 2017 using a blow stick. Barodivers (Schlumberger) were installed in each well in 2015 and recorded water levels every hour.

Pipe top elevations within a nest were surveyed relative to each other using a tape measure and 60 cm long bubble level, measuring each pipe against a reference pipe (typically the most central pipe). For example, if the well was used as the reference pipe, the other pipes were measured as +/- the height of the well to compensate for uneven ground without adjusting the water level measurement within the pipes which assumes level ground. We estimate the precision of this method to be within a few millimeters. In 2015, a Trimble DGPS base station was set up on a cement pad at a known location while the rover (precision +/- 15mm, PDOP count of >200 with >10 minutes of carrier phase) was used to determine the height of the chosen reference pipe within the nest. The elevation obtained from the DGPS of the central/reference pipe was then used to correct the reference height of the central/reference pipe in each nest to meters above mean sea level (msl) for the best possible accuracy within a nest and for reasonable accuracy between nests, given the large (100s m) lateral distances.

Surface elevation around the well was also measured using a similar method. The well in each nest was used as a reference point by measuring the surface out to 150 cm from the well, in 30 cm increments, in each cardinal direction (N, E, S, W). A narrow wooden board with a bubble level was extended from the well so an accurate measurement from the ground to the board could be recorded. These measurements allowed for an estimate of the water table depth up to 150 cm beyond the well in the nest and a measurement of the surface variability.

2.3.2 Hydraulic Conductivity and Groundwater Flow

Hydraulic conductivity (K) tests were performed on each pipe within the nests monthly in 2015. Each piezometer was developed at the beginning of the field season; bail K tests were completed and measured until the return was at least 80% of the initial water level within the piezometer during the test. Darcy's law was used to calculate specific discharge of groundwater at each nest by taking the gradient between the deepest and shallowest piezometers and the lowest K value of all piezometers in the nest.

During the 2016 field season (May 9 – August 9), three additional (roving) nests were installed at each site within approximately 50 m, in a fan shape, from the original nest in order to compare the results from the 2015 K tests and increase confidence in the spatial homogeneity (or heterogeneity) of the gradient/K within a site. Basically, the roving nests were installed in a repeating week-long process. Day one, the three additional nests were installed. Day three, they were measured, and measured again on day 4 to see if they were equilibrated. If yes, they were then developed (water agitated within the pipe and fully evacuated) and allowed to recover for two more days before the K test was preformed (day 7). Once recovered, they were removed and moved to the next site. This was repeated for 5 nests (J, M, P, A, X) over a total of ~8 weeks (June 13 to Aug 10) (note: Day 7 of one nest would also be day 1 of the next).

2.3.3 Meteorological

A weather station was located at Site P which collected data from June 20 to August 27, 2014 and May 13 to September 27, 2015. The weather station consisted of a rain gauge (Texas Instruments 525), temperature/relative humidity sensor (HCS3), and a net radiometer (Kipp and Zonen NRLite) connected to a Campbell Scientific CR1000 data logger. The weather station and loggers were not installed at Moss Spur in 2016, so data were used from the weather station installed at the Elma bog located approximately 25 km southeast of Moss Spur.

2.3.4 Evapotranspiration

Lysimeters (25 l buckets, 30 cm diameter) were installed at Sites A, J, M, and P, in triplicate, and were weighed almost daily from June 16 to August 11, 2015 using a Brecknell electro Samson 25 kg scale (+/- 10 g). Sites X and I were excluded from this experiment due to similar vegetation composition and water levels with those of Sites A and J, respectively. The Priestly-Taylor (PT) (1972) method was used to calculate evapotranspiration for each site from the lysimeter data and estimate total evapotranspiration for Moss Spur such that

$$E_t = \propto \left(\frac{s}{s+\gamma}\right)\left(\frac{Q^* - Q_g}{L_v \rho}\right)$$

Equation 2-1

where E_t is the evapotranspiration rate (mm d^{-1}), L_v is the latent heat of vaporization (J kg^{-1}), s is the slope of the saturation vapour pressure-temperature curve (Pa $^{o}C^{-1}$), γ is the psychrometric constant (0.0662 KPa $^{o}C^{-1}$ at 20 ^{o}C), Q^* is the net radiation flux (J d^{-1}), and Q_g is the ground heat flux (J d^{-1}). Qg was assumed to be 10% of Q* for our calculations. Evaporation requires energy from the sun, atmospheric demand, and an ample water supply. Eq. 1 uses the parameters from the weather station to determine the energy (Q_g and Q^*) and the atmospheric demand (s) but does not account for the water supply of the area ($\propto$). Therefore, $\propto$ must be determined for each lysimeter in order to adjust the PT equation for actual evapotranspiration by determining the slope of the actual vs. potential evapotranspiration.

2.3.5 Soil water tension

Tensiometers were also installed in 2015 at Sites J, M, and P; Site A was excluded in this experiment due to flooded conditions, while Sites X and I were again excluded for the reasons stated above.

The tensiometers were installed at depths of 30 cm, 20 cm, 10 cm, and 5 cm below the ground surface at each site and measured every ~three days from June 13 to August 11, 2015 using a Soil Measurement Systems Tensimeter. A known volume of water was added to the top of the tensiometers when the water level within the instrument fell below the calibrated clear plastic top.

2.4 Results

2.4.1 Vegetation survey

A 2014 vegetation survey (Gagnon, 2017), not part of this thesis, ranked the Moss Spur sites in order of best to worst based on the abundance of bog vegetation present, which we valued as better. The sites are ordered as follows, with site J being the 'best', followed by sites I, P, X, A, and site M as the 'worst'. Bog vegetation was based on the presence of *Sphagnum* or true mosses as opposed to vascular wetland plants like cattails and rushes.

The vegetation present at site J included *Sphagnum* hummocks, Labrador tea (*Ledum groenlandicum*), willow species (*Salix spp*), and black spruce (*Picea mariana*). Site I exhibited similar vegetation, only with less abundant *Sphagnum* moss. Site P had some *Sphagnum* present but was dominated by willow species and narrow-leaved cattail (*Typha angustifolia*). Sites X and A were predominantly flooded and dominated by narrow-leaved cattail, rush species (*Juncus* *spp*) and willow species. Site M was predominantly bare ground with sparse patches of cottongrass (*Eriophorum spp*) at the time of data collection.

2.4.2 Meteorological

The average temperature recorded by the weather station set up at Site P in Moss Spur was similar (within a degree) between the 3 seasons of data collection and to the historical data from the Beausejour weather station for most months. Compared to the historic data, the 2015 and 2016 field seasons had above average precipitation (+199 and +143 mm) (Table 2-1). The weather station was not installed until mid-June in 2014 and had retained water from a plugged system upon dismantlement in September, which would possibly render the August precipitation data unreliable.

Table 2-1. 2014-2016 Moss Spur meteorological data compared to 30 years of historical data from the Beausejour weather station. The 2016 weather station data from the field was collected from the Elma bog, located approximately 25 kms SE of Moss Spur. Note that June 2014 only has 10 days of data, as the weather station was set up late in the season.

Precip (mm)	1981-2010	2014	(+/-) Historical (mm)	2015	(+/-) Historical (mm)	2016	(+/-) Historical (mm)
May	58.1			149.8	91.7	82.4	24.3
June	87.5	36.1	51.4	88	0.5	128.9	41.4
July	87.1	32.6	54.5	183	95.9	72.3	-14.8
Aug	76.3	0.7	75.6	123.3	47	105.8	29.5
Sept	65.1			29.4	-35.7	127.8	62.7
Total (mm)	374.1	69.4	-181.5	573.5	199.4	517.2	143.1

Avg Temp (°C)	1981-2010	2014	2015	2016
May	11.4		12.1	12.8
June	16.7	18.8	17.4	16.6
July	19.3	18	20.6	19.0
Aug	18.5	18.3	18.4	18.1
Sept	12.5		16.1	13.4

2.4.3 Evapotranspiration

Evapotranspiration data collected from the lysimeters had $\propto$ values ranging between 0.7 (site A) and 1.2 (also site A) (Table 2-2). The $\propto$ values were determined from the slope of best fit from each lysimeter (Figure 2-2) and then averaged for the total evaporative losses (Table 2-2). Each slope is colour coded to the respective symbol in the Figure, associated with an individual lysimeter in the field. The slopes for each lysimeter have the least variation at site M (0.80 to 0.86) and the most at A (noted above). Sites J and P each have one distinctly different slope compared to the other two at each site. The average daily ET at sites M, J, P, and A are 2.8, 2.9, 3.2, 3.4 mm/day, respectively, throughout the 2015 field season. The total ET per site per month ranged between 393 (M) and 468 (A) mm (Table 2-3).

Table 2-2. Alpha values per lysimeter per site.

Site	JL1	JL2	JL3	PL1	PL2	PL3	AL1	AL2	AL3	ML1	ML2	ML3
α	1.1	0.7	0.7	0.7	1.0	1.0	1.1	1.2	0.7	0.8	0.9	0.8

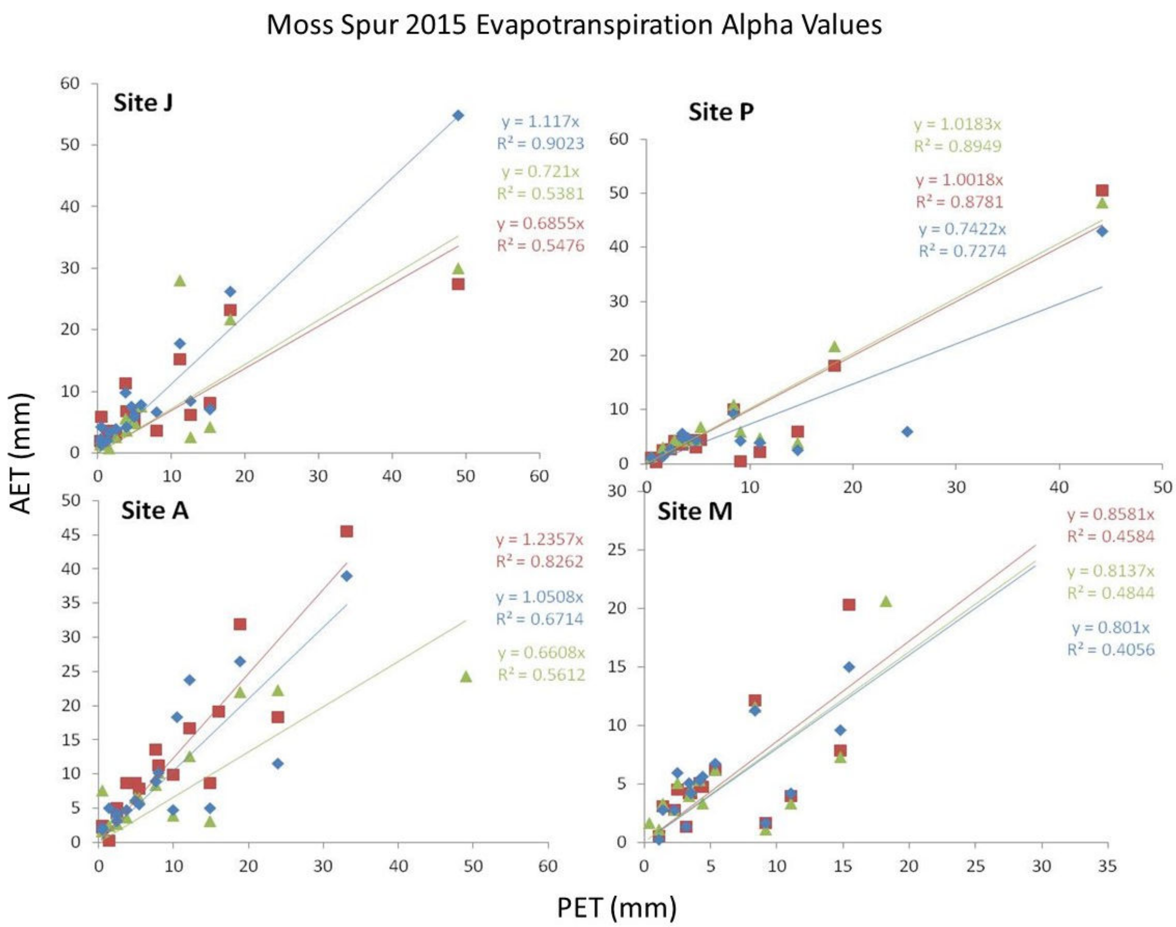


Figure 2-2. Alpha values determined per lysimeter per site. The alpha values are inserted into the P-T equation to determine the total ET per site.

Table 2-3. Average alpha values and ET per site. The values were averaged from Table 2-2 to determine total ET per site in Table 2-3.

2015	Site A	Site P	Site J	Site M
α	0.98	0.92	0.84	0.82
May	106	100	91	89
June	133	125	114	112
July	106	99	91	89
Aug	75	70	64	63
Sept	47	44	41	40
Total (mm)	468	438	401	393
Average (mm/d)	3.4	3.2	2.9	2.8

2.4.4 Water table

Water table measurements taken in 2014 were compared against site J (noted above as having the "best" bog like vegetation) in a percent frequency chart (Figure 2-3) which shows site J having water table levels at or above the surface for approximately 56% of the time, ranging from 15 cm above the surface to -15 cm below. Site I did not have standing surface water but ranged from just below the surface to -45cm. Site P was flooded 8% of the time, with a minimum water level of -30 cm; site X had the widest range of water table fluctuations, varying from 50cm of standing water (64% flood frequency) to -50cm below the surface. Site A had a 100% flood frequency level, while site M had an 18% flood frequency and levels down to -55cm.

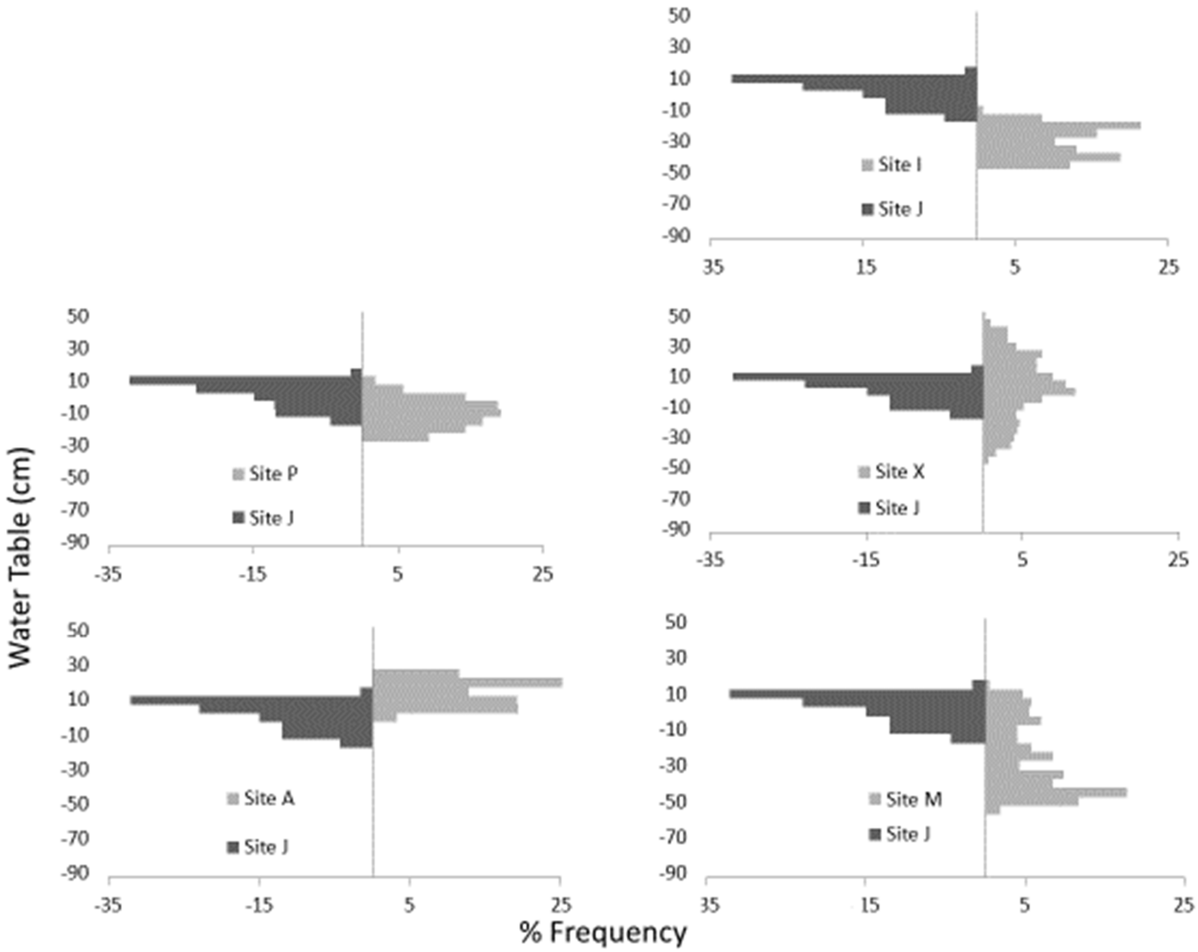


Figure 2-3. 2014 percent frequency of groundwater at the surface per site compared to Site J.

Site J has the most topographical variation between hummocks and hollows (SD=11.0 cm) compared to the other five sites (Figure 2-4; note different vertical scale in J). Sites I, A, P, X, and M are less variable with the surrounding area, with descending standard deviations of 3.3, 2.2, 2.1, 1.4, and 1.3 cm, respectively.

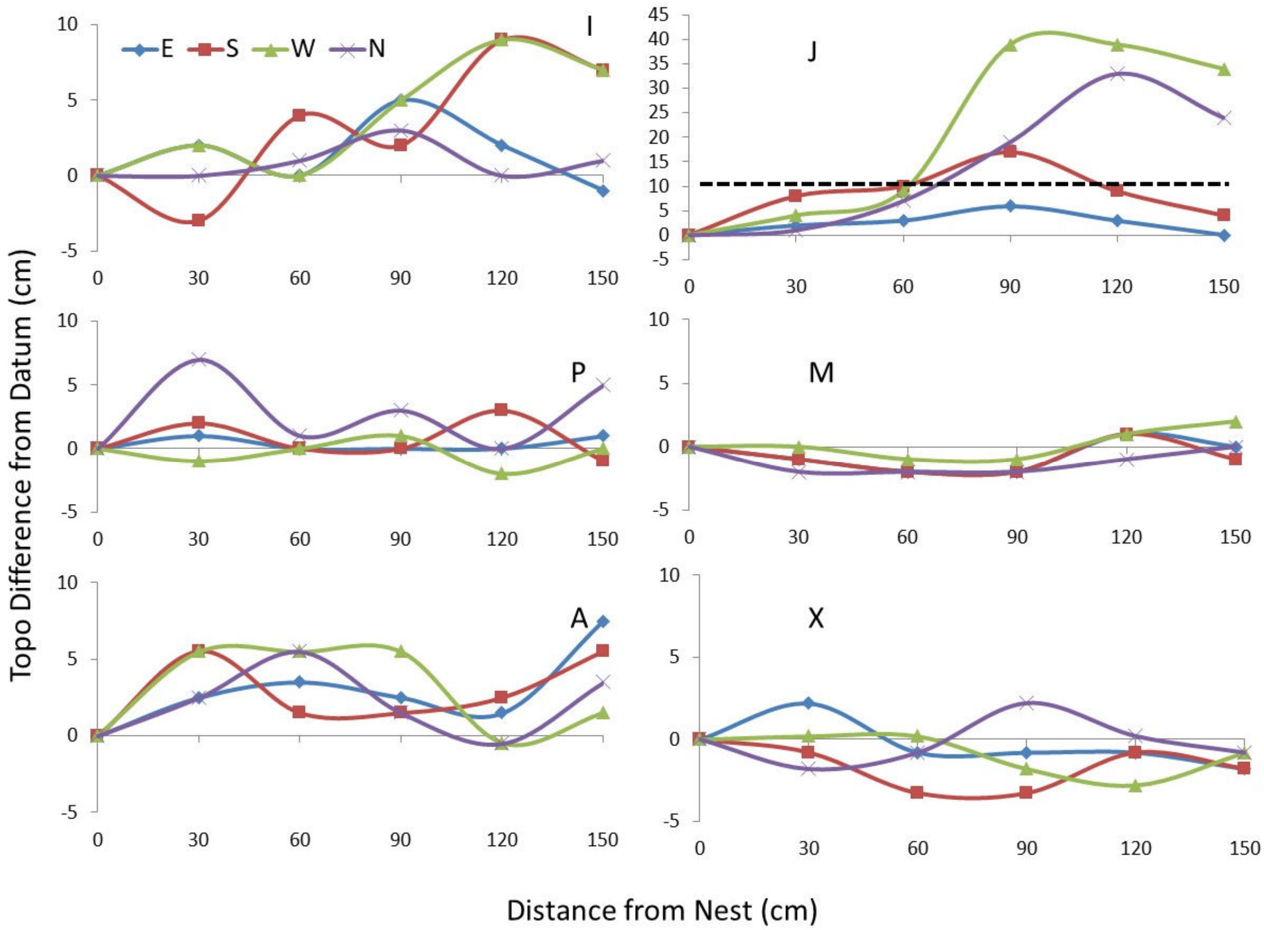


Figure 2-4. Topographical variability up to 150 cm from the nest in four directions.

2.4.5 Soil water tension

Sites J and P had average soil tensions of 15.9 and 1.6 cm, respectively (Figure 2-5a) at the 5 cm level. Sites J, P, and M had average soil tension of 6.2, 14.6, and -7.5 cm, respectively at the 10 cm depth (Figure 2-5b). The soil tension at these sites did not drop below zero, with the exception of site M and a few P, indicating flooded conditions on average. Site J appeared to have a higher (less negative) soil water tension within the top 5 cm of peat than at the 10 cm depth, but site P shows the reverse, and appears to be drier on top and wetter at the 10 cm depth, which is expected.

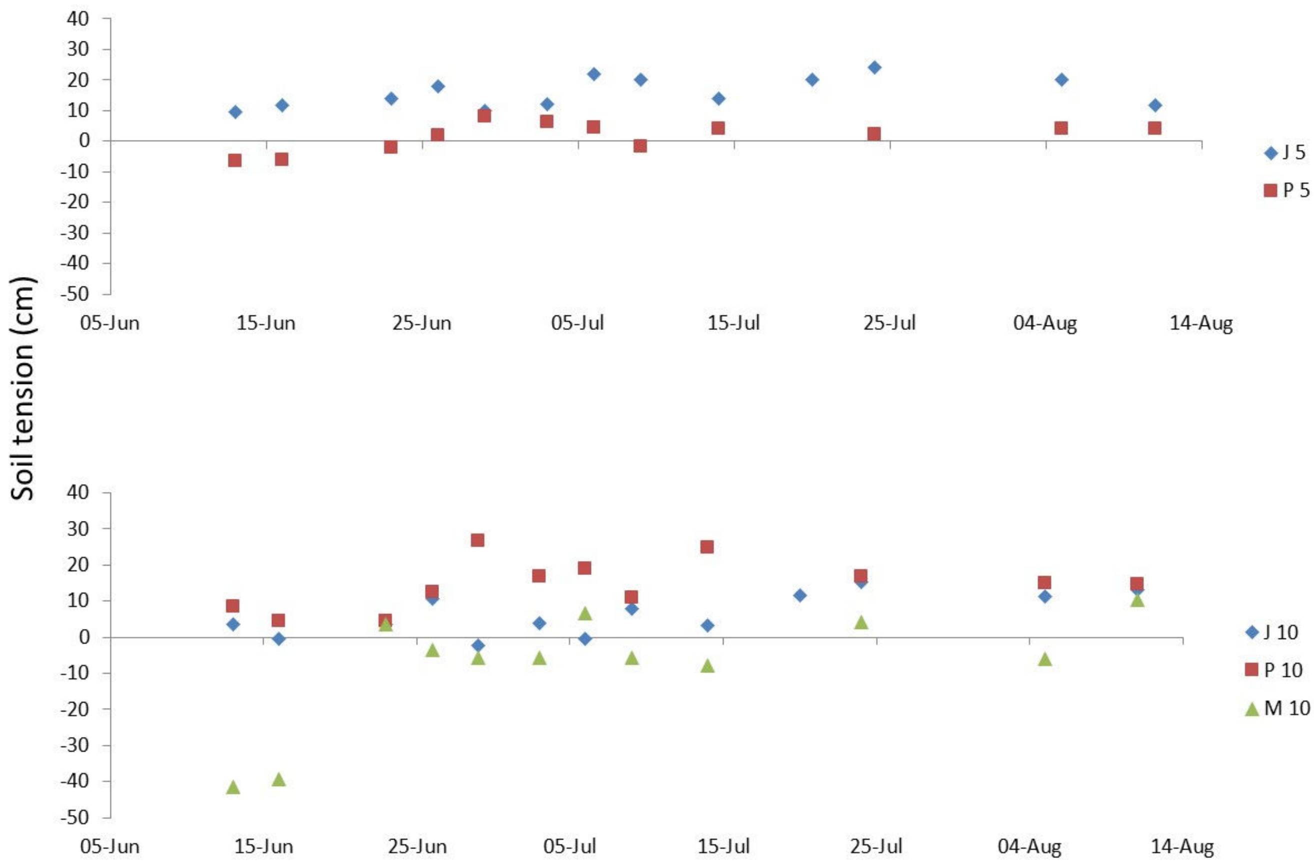


Figure 2-5 a, b. Soil tension within the top 10 cm of peat, 2015. The soil tensions show positive values, indicating standing water at these sites. The optimal soil tension for Sphagnum growth is > -100 cm.

2.4.6 Hydraulic conductivity and groundwater flow

The geomean from monthly K tests (n=4) was used to compare the hydraulic conductivity between piezometers within each permanent nest in 2015 and 2016. Hydraulic conductivity had the quickest recovery time at 50 cm for sites I, P, X, and A, whereas Site M had the quickest return rate at 100 cm and J at 150 cm (Figure 2-6). The 2016 geomean comparison for the nests (Figure 2-6) excludes site I due to lack of access. K generally declined with depth.

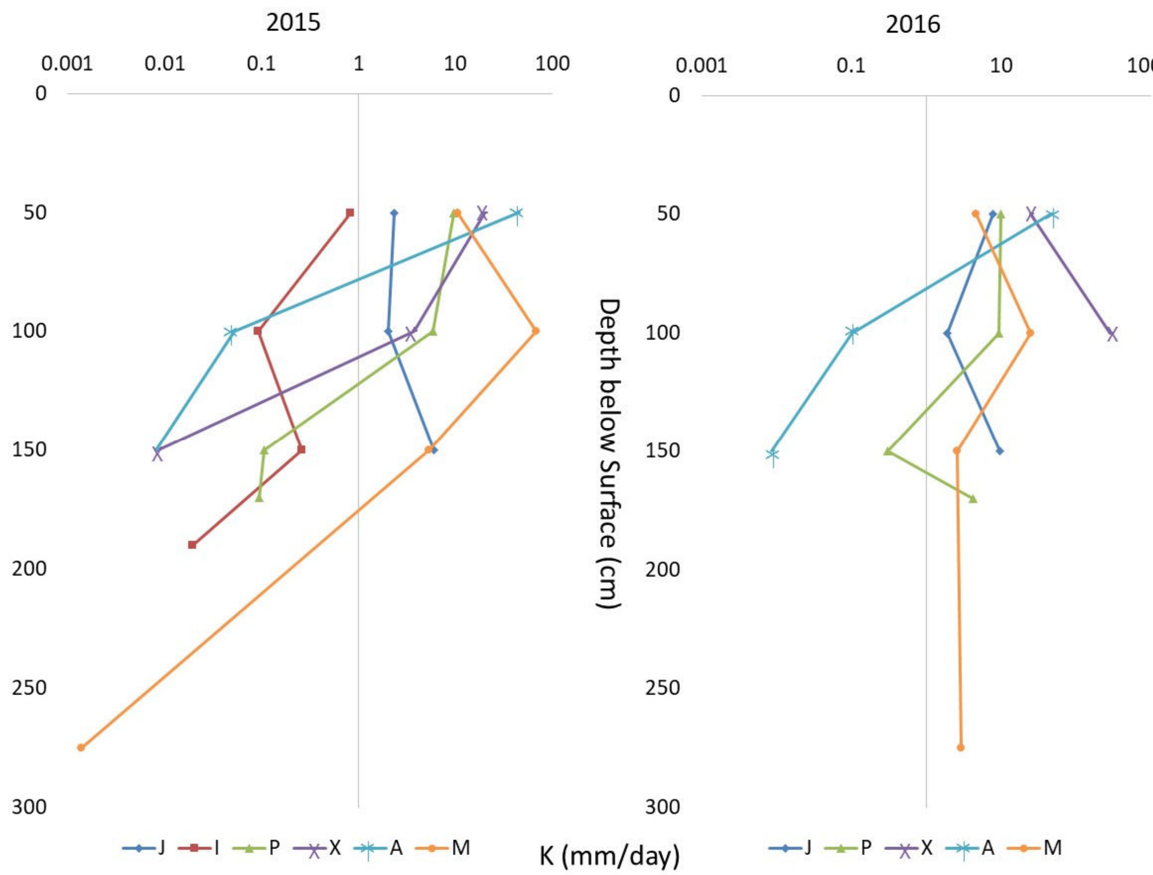


Figure 2-6. 2015 and 2016 K Geomeans per piezometer within each nest.

K tests conducted for the three roving nests were compared to the main nest (Figure 2-7). Site X at 100 cm was determined to have a significantly higher recovery rate than any other piezometer (285 mm/day); peat cores taken for a supplementary project (Patterson and Whittington, submitted) showed site X to be a floating mat with a ~100 cm depth, likely explaining the quick recovery time. Site X also only had one 150 cm roving piezometer because that was the only nest with peat deep enough to conduct a K test; the other roving nests at site X had shallow peat and we hit sediment beyond 115 cm. The roving K values range the most within the top 100 cm at site J, while the other five sites (with respective roving nests) have the widest ranges at 100 cm and 150 cm depth (Figure 2-7). Site P ranges from 0.03 to 5.60 mm/day K with the main nest recovering at 0.30 mm/day at the 150 cm piezometers. As discussed previously, site X was a floating mat at 100 cm depth which explains the wide K range and accelerated recovery rate. The roving piezometer at 150 cm may have been inhibited by sediment, explaining the slow rate of recovery. Site A has the largest range at 100 cm (0.02 to 0.49 mm/day) from the main nest recovering at 0.10 mm/day. The 100 cm has a 66 mm/day average recovery rate at site M, while the 150 has a 36 mm/day average recovery rate. Sites M and P have the largest 150 cm K ranges of the sites measured at Moss Spur, and they happen to be within the closest proximity to one another. The extraction activities in the M/P area may have influenced the K rate at depth.

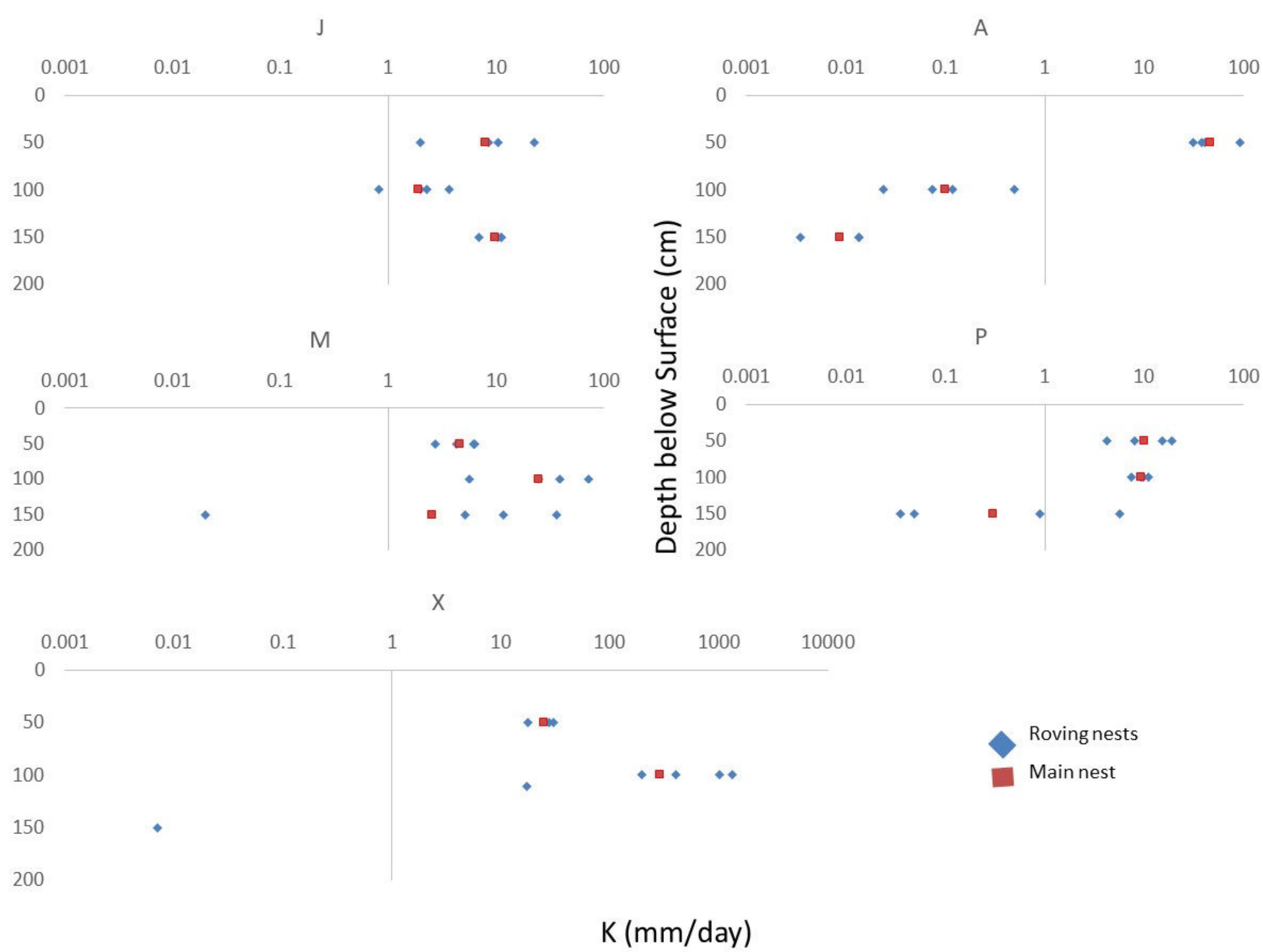
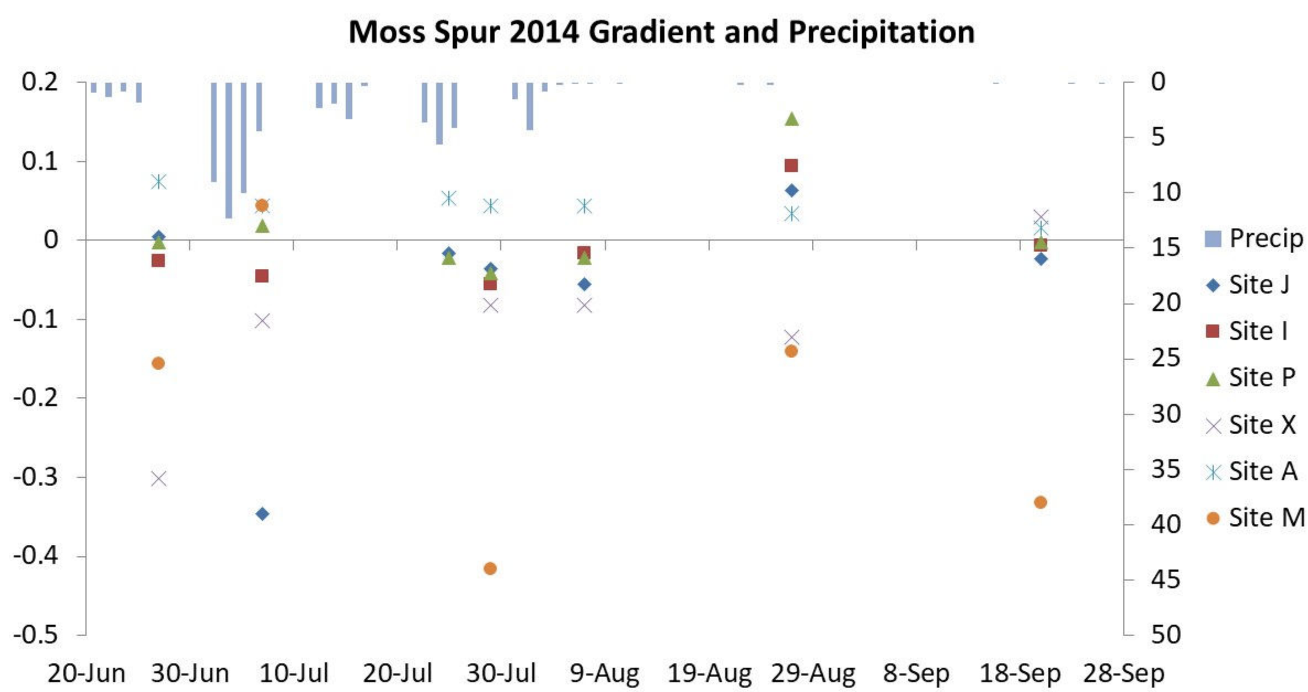


Figure 2-7. K of each main nest compared with three roving nests at each site.

The gradients through time at each nest in 2014 (Figure 2-8a) exhibit groundwater discharge at sites J, I, X, P, and M, with water flowing from depth to the shallower piezometers (shown as negative values). Site A has groundwater recharge (positive values), with water flowing from the shallow piezometers to depth. The opposite is true in 2015, where most sites exhibit groundwater recharge conditions, with the exception of sites I and P (Figure 2-8b). Site J hovers near the surface throughout most of the field season, but still experiences recharge conditions. Conditions are similar in 2016 as they were in 2015 (Figure 2-8c), with sites J and X hovering near the surface but exhibiting groundwater discharge conditions, P and M experiencing discharge conditions, and sites A and I having groundwater recharge conditions. The average gradient values per year are summarized in Table 2-4.



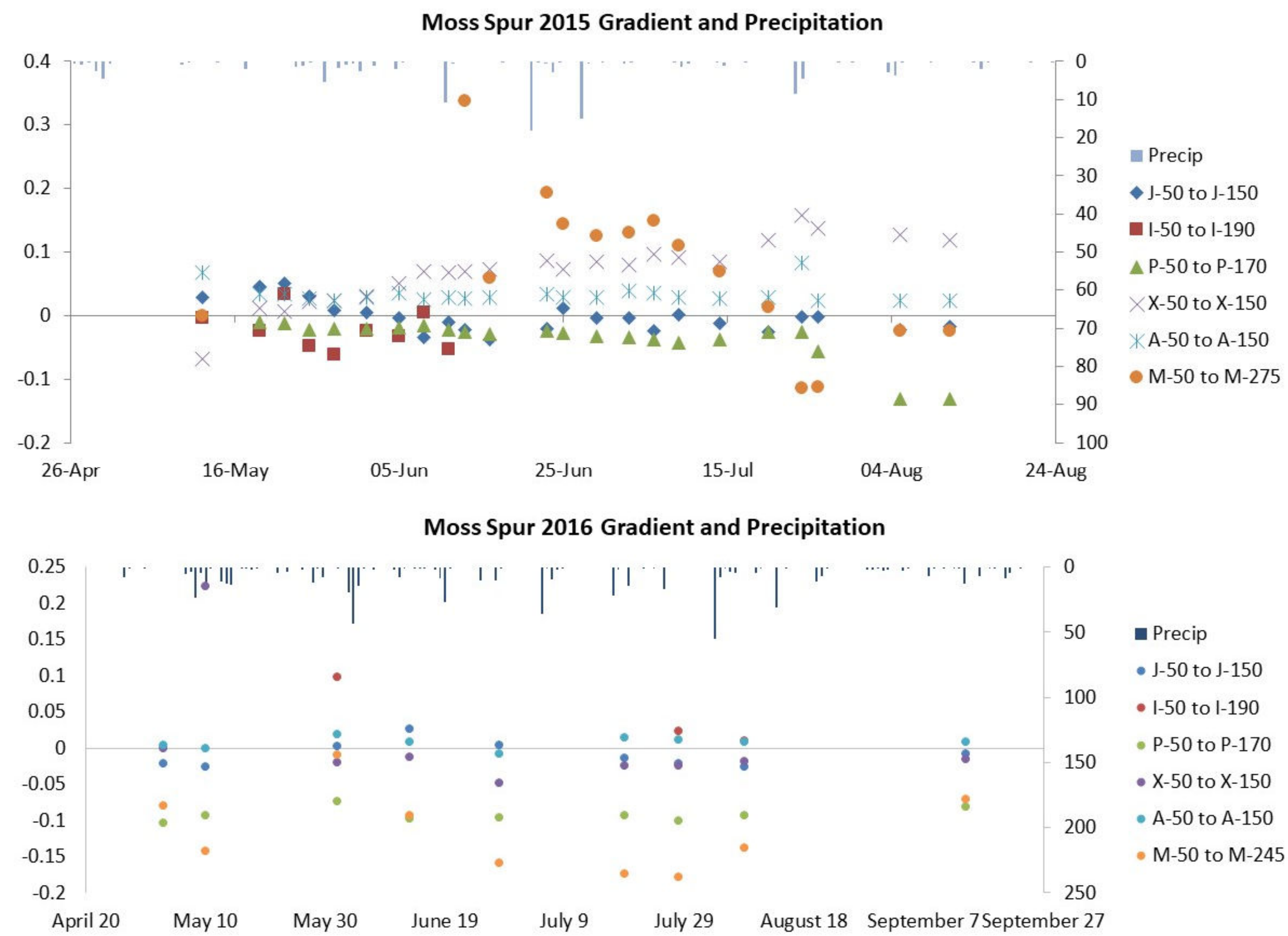


Figure 2-8 a, b, c. Gradients through time per nest.

Table 2-4. Average gradient comparison. A negative value indicates groundwater discharge while a positive value indicates groundwater recharge.

	Average Gradient (mm/day)					
Year	Site J	Site I	Site P	Site X	Site A	Site M
2014	-0.06	-0.01	0.01	-0.11	0.04	-0.2
2015	0.00	-0.02	-0.04	0.07	0.03	0.08
2016	-0.01	0.04	-0.09	0.01	0.01	-0.12

Site J had the highest specific discharge (-1.3 mm/day) in 2015, coupled with sites P and I (-0.8 and -0.1 mm/day, respectively) indicating groundwater discharge; sites X, A, and M indicate groundwater recharge, with specific discharges of 0.1, 0.06, and 0.02 mm/day, respectively (Figure 2-9). The 2016 values represent a clearer indication of discharge and recharge conditions (Figure 2-9). Sites P, M, X, and J exhibit groundwater discharge conditions, with specific discharge values of -0.37, -0.14, -0.07, and -0.01 mm/day, respectively. Groundwater recharge conditions was evident at site A (0.02 mm/day). Site I was not measured for flux in 2016 due to lack of access. The average flux values per year are summarized in Table 2-5.

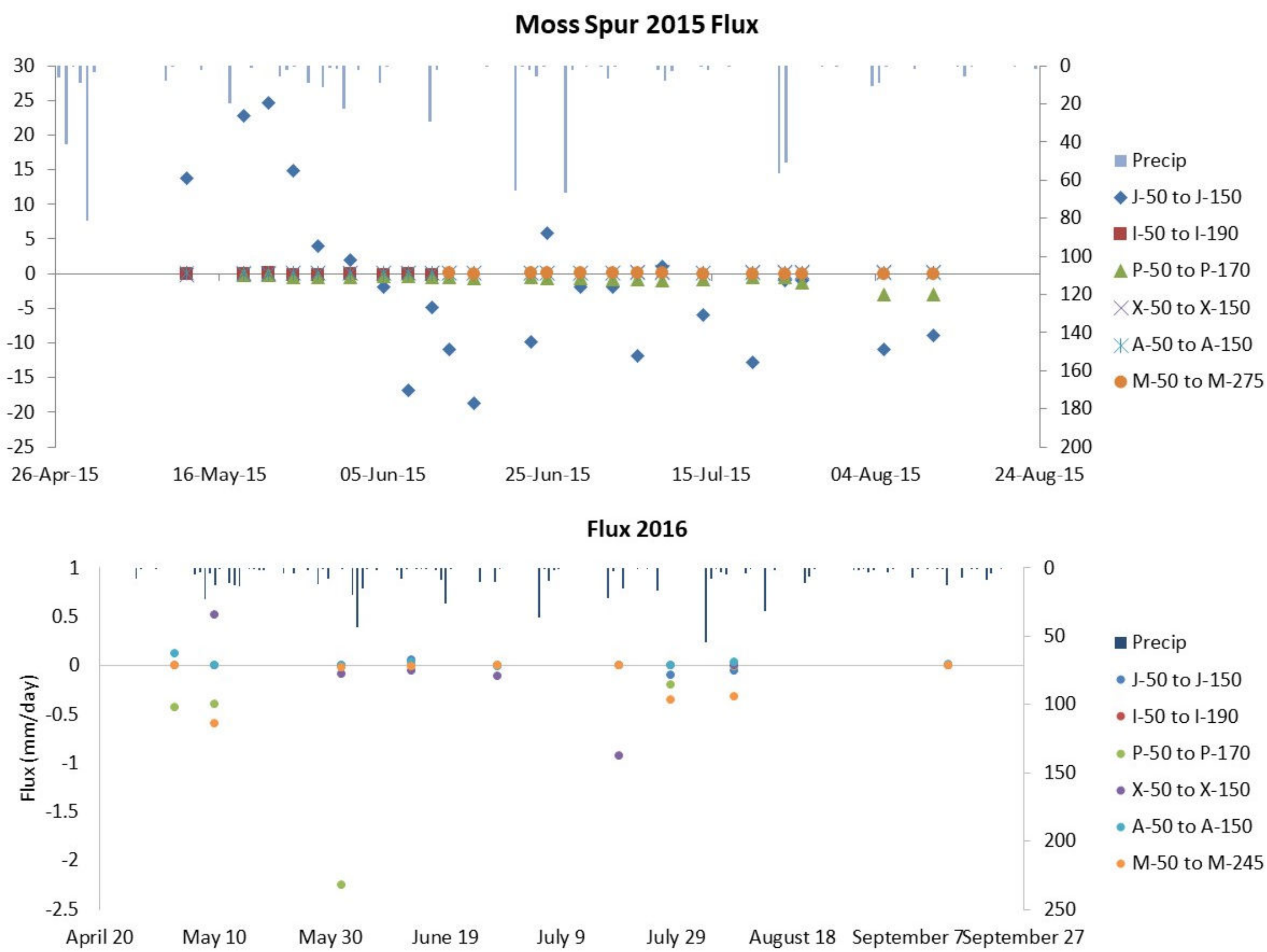


Figure 2-9. Groundwater flux comparisons between field seasons.

Table 2-5. Average flux comparison. A negative value indicates groundwater discharge while a positive value indicates groundwater recharge.

	Average Flux (mm/day)					
Year	Site J	Site I	Site P	Site X	Site A	Site M
2015	-1.3	-0.1	-0.8	0.1	0.1	0.0
2016	-0.01	--	-0.37	-0.07	0.02	-0.14

2.5 Discussion

Sphagnum requires water levels to be within 40 cm of the surface, and soil pressure to be >-100 cm to not be stressed (Price and Whitehead, 2001; Sagot and Rochefort, 1996). The vegetation pattern throughout Moss Spur ranges from most bog-like to least bog-like as follows: J, I, P, X, A, M, according to a vegetation survey conducted in 2014 (Gagnon, 2017). Site M had minimal vegetation and was what we expected the majority of Moss Spur to look like, such as previous work conducted in Quebec would have led us to believe (McCarter and Price, 2014). However, the bare ground and sparse sedges of Site M only composed ~5% of Moss Spur, with the other ~95% comprising various wetland vegetation such as willows, and even large *Sphagnum* hummocks, as seen at Site J (Figure 2-4).

The meteorological data (Table 2-1) compares the 30-year historical norm from the Beausejour weather station with the 2014-2016 field season at Moss Spur. The average monthly temperatures were all within one degree of each other, except for September, 2015 which was ~3°C warmer than normal; the one-month average temperature spike at the end of the growing season would likely not have affected the growing period compared with the historical normals.

The 30-year norm shows 374 mm of precipitation for May to September, compared with 140 and 200 mm surpluses in 2015 and 2016, respectively. The 2014 field season was 180 mm drier than normal, adjusting the total historical precipitation to the months that were measured in 2014. The total surplus in 2015 flooded sites J, X, A, and even M at stages throughout the field season, which was generally the driest site. Since the abandonment of Moss Spur, vascular plants have been abundant at sites X and A, creating more of an open water wetland than a bog environment. If moisture deficit years like 2014 were prominent, sites X and A would be drier (sub surface water table) which would possibly allow for *Sphagnum* establishment.

Although sites J and M are ranked as "best" and "worst" for bog vegetation, the evapotranspiration (ET) rates are surprisingly similar (Table 2-3). Site M (α=0.82) exhibits an average ET rate of 2.8 mm/day with bare ground, while site J (α=0.84) is at 2.9 mm/day with *Sphagnum* hummocks at the site; the seasonal totals are 393 and 401 mm, respectively. These sites have the lowest rate of ET of the four sites measured, meaning that there is a lack of water available to evaporate at site M, and the available water at site J is not all being evaporated. Site P (α=0.92) had the next highest ET rate (3.2 mm/day, and 438 mm total), second to site A (α=0.98) with an average of 3.4 mm/day and 468 mm total ET. Vascular plants transpire water almost constantly during the day, which may explain the higher daily and seasonal totals for site P and A. Site A was also flooded, allowing for uninhibited evaporation from the open water. All four sites had alpha values below 1, indicating not all of the water available for evaporation actually gets evaporated. The ET variability within each site is likely due to individual lysimeter placement, although they were placed as evenly as possible within the sites with dominant vegetation/surface cover to allow for representative ET measurements. Site A lysimeters were placed using the same methods, but the site was flooded for the entirety of the field season and on occasion the lysimeters had floated up and tipped over, causing that day's data to be disregarded.

The water table levels across Moss Spur give some insight as to the scale of "good" to "bad" bog vegetation within each site. Sites I and M had water levels which remained below the surface for a majority (95%) of all three years, sites J, P, and X hovered near the surface, and site A was flooded during all three years. The precipitation surplus in 2015 and 2016 created flooded conditions for all six sites at some point throughout the years, lasting for varying amounts of time, proving how excessive the total amount of precipitation accumulated actually was during those years. The *Sphagnum* already present at sites J and I was able to handle the water table fluctuations; however, it was simply too wet at sites where moss had yet to establish, i.e., sites P, X, and A. Granted it takes more than one field season to regenerate moss, the excessively wet years were not conducive to passive restoration. Site M is the exception, with a water table level hovering near -40 cm below the surface for the majority of the three years. Site M is nearly void of vegetation, with the exception of sporadic cotton grass plants, suggesting that the available water at site M is deeper than the other sites; the vascular vegetation will have access to the deeper water supply via its roots that *Sphagnum* does not possess. Topography plays a role in the water table position also. Site J seems to be the Goldilocks zone for *Sphagnum* growth, but it has the greatest topographical variation with hummocks and hollows compared to the relatively level terrain of the other sites (Figure 2-4). The topographical variation creates a regeneration niche (Grubb, 1977) where there is greater chance for *Sphagnum* to continue to colonize site J than there would be at, say, site P with a phenological niche, or pattern of seasonal development (Grubb, 1977).

Sphagnum requires the soil tension to be greater (less negative) than -100 cm to have adequate water for survival. Moss Spur was well within the -100 cm limit for soil tension during our study, thereby not rendering it a limiting factor for regeneration. It should be noted that because site A was flooded, soil tension was not measured since it is the same as measuring the water table.

The gradient at sites J, I, and A were consistent for all three years of data collection; sites J, I, and P were consistently negative (experiencing groundwater discharge), and site A was consistently positive (experiencing groundwater recharge). Site X was negative in 2014, switching to a positive gradient in 2015 and 2016. Site M only experienced a positive gradient in 2015. 2015 had 56.3 mm more precipitation than 2016, but both years were well above the historical average for precipitation, possibly explaining why 2014 was the only year that site M experienced groundwater discharge. 2014 and 2016 were also drier compared to 2015, which may have created more opportunity for groundwater discharge conditions; 2014 and 2016 had lower water tables from less rain than 2015, which then created less pressure to suppress groundwater upwelling. Note that 2016 was wetter than the 30-year norm, but still drier than 2015, whereas 2014 was drier than normal.

2.5.1 The importance of groundwater

We believe that the drainage (artificial drought) and extraction (i.e., lowering the peat surface) of Moss Spur created surrogate conditions of extreme drought, causing the water table within the remaining catotelm peat to be much lower than it normally would be, and thus exert less pore water pressure on the regional aquifer. With less pressure being exerted from the previously water-logged bog surface, regional groundwater pressures were no longer supressed by the elevated bog water tables above, and were able to flow up through the limestone and lake sediments to supplement the internal water table within the remnant bog (Figure 2-10), though we argue this effect was heterogeneous across the bog due to differences in the hydraulic properties of the lake sediments beneath the peat (Patterson and Whittington, submitted).

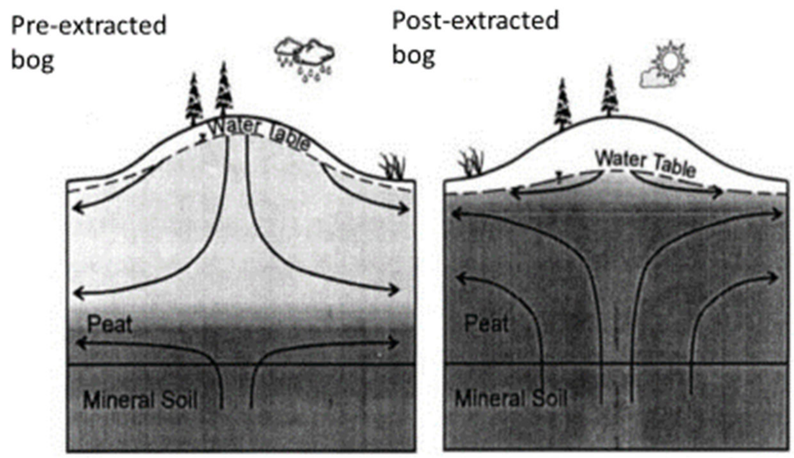


Figure 2-10. Pre- and post-peat extraction water table levels. Pre-extraction, the water level is high, the catotelm is saturated, and there is a lot of pressure from above which prevents the groundwater from upwelling into the bog. Post-extraction, water levels are lowered, the catotelm has dried out and become light, and the pressure has eased off the groundwater which allows it to upwell into the system (adapted from Siegel et al., 1995).

This phenomenon, known as a groundwater flow reversal, made water available for establishing vegetation throughout Moss Spur. The opposite occurred at sites with groundwater recharge (positive gradients); when there was excess precipitation during the season, the peat became water-logged once more and exerted enough pressure on the groundwater to prevent upwelling. Site A was continually flooded, thereby exerting enough force from the surface to keep the upwelling from occurring. Note that sites J, I, and P were located adjacent to drainage ditches which would aid in expelling excess water and allowing for groundwater discharge to occur. Site A is not near a ditch, and also located at a lower elevation being at the edge of the peatland, which may explain why it remained flooded throughout the study seasons. The flips between discharge and recharge between seasons at site X make some sense since 2015 and 2016 were wet years was the wettest year (and the only year experiencing groundwater recharge at that site); however, the flip to groundwater recharge in 2016 at site P is counterintuitive to the literature. The 2015 water balance table (Table 2-6) lists sites from “best” to “worst” with respect to *Sphagnum* regeneration, but the best sites should have a more positive water balance. Surprisingly, site M has a higher water balance than site A; one would think with the lack of vegetation at site M it would have the lowest water balance of the sites measured. Although sites J and M are opposite extremes relative to established vegetation, they are the most similar in ET loss, both total and per day (Table 2-3). This suggests that with proper restorative mitigation (i.e. diaspore spreading and mulch cover), site M has a good chance to recover to the state of site J. Since ET was not measured in 2016, a water balance could not be calculated for Moss Spur during that field season.

Table 2-6. 2015 water balance for Moss Spur sites with ET data. Water balance was calculated by subtracting the ET from the total precipitation then +/- the flux per site. Flux per site was mm/day (Table 2-5) * number of days measured, May through September (n=153).

2015 Water Balance

Site	J	P	A	M
P (mm)	573.5	573.5	573.5	573.5
E (mm)	-401	-438	-468	-393
GW (mm)	198.9	122.4	-9.2	-3.1
Total (mm)	371.4	257.9	96.3	177.4

In 2015 the sites with groundwater discharge conditions (J, P, and I) are comprised of regenerated bog vegetation such as *Sphagnum* mosses, as opposed to primarily vascular vegetation like sites A, X, and M. Groundwater upwelling supplies excess water to the catotelm peat above the regional aquifer making the water available to the moss. In areas of groundwater recharge, precipitation infiltrates through the catotelm to the aquifer below. When water is not readily available, vascular plants develop a larger root mass to meet their requirements. *Sphagnum* moss is non-vascular and therefore lacks the ability to grow roots to seek out water, thereby requiring a water table within 40 cm of the surface.

Spontaneous moss regeneration does not only occur in Manitoba. Just south of Shippagan, New Brunswick, the block-cut method of extraction was used in a bog until 1970, leaving the landscape in an alternating pattern of berms and trenches like that of Cacouna (Taylor & Price, 2015). No restoration measures had been taken at the time; however, *Sphagnum* naturally regenerated in the trench areas across the site (Taylor & Price, 2015). It was also noted that vacuum harvested fens regenerate faster than vacuum harvested bogs (Graf et al, 2008); the surrogate drought conditions leading to groundwater flow reversal within Moss Spur effectively made the site a fen, as bogs are defined as being ombrogenous. Thin residual peat was found to accelerate the rate of revegetation also (Graf et al. 2008, Poulin et al, 2005), and with the moratorium on new peat harvest leases within Manitoba (Swystun et al., 2015), existing sites were extracted as deep as allowed by legislation before being left for restoration. Therefore, although Bois-des-Bel in Quebec was used as a comparison site to Moss Spur, it is not entirely accurate to state that the hydrogeomorphology was the only difference between the sites, leading to spontaneous regeneration in Manitoba but not in Quebec.

2.6 Conclusions

The results suggest that the upwelling of groundwater into the remaining catotelmic peat was enough to stimulate vegetation regeneration at Moss Spur. Groundwater recharge conditions still occurred at sites X and A regardless of the flooded condition in the sites in 2015; however, in 2016 these sites experienced groundwater discharge. We speculate that these sites are simply too wet to support *Sphagnum* establishment, however there is an abundance of established vascular wetland vegetation. Sites J (both years) and I (2015) experienced groundwater discharge throughout the growing season, which is speculated to be the cause of the established *Sphagnum* hummocks at those sites, while site P switched from an area of groundwater recharge to discharge between 2015 and 2016. Groundwater discharge was able to occur at sites throughout Moss Spur because of Manitoba's hydrogeomorphic setting; groundwater upwelling does not occur to this extent in Quebec. Sites M and P had lower average rates of evapotranspiration compared to sites A and J, which may be attributed to the type of dominant vegetation within each site. Although topography differed between sites, the water table levels followed the hummocks and hollows within each area, mimicking the natural functions of an intact peatland.

3 Elma North: Re-contouring a cutover peatland to improve hydrology and promote *Sphagnum* regeneration in southeast Manitoba, Canada

3.1 Introduction

Canada is one of the world's largest producer of horticultural peat (CSPMA, 2014), generating millions of dollars of revenue from this resource; Manitoba's contribution is ~13% of Canada's total production. Peat extraction is intensive and requires drainage of the peatland (typically bogs) and the removal of the surficial vegetation. The ombrogenous nature of bogs is what separates them from fens; bogs receive water strictly from precipitation. Bogs develop over thousands of years due to a combination of ecohydrological processes making conditions unsuitable for vegetation not adapted to a low pH and ombrotrophic nutrient level (Quinty & Rochefort, 2003). Ironically, this also makes the reestablishment of bog species difficult, post extraction. Abandoned harvested sites usually do not revegetate quickly (Lavoie and Rochefort, 1996; Ferland and Rochefort, 1997) and reasons will be explained in more detail below. Consequently, the peatland shifts to a predominant and persistent net source of atmospheric CO_2 (Price and Waddington, 2000; Waddington et al., 2002) instead of a sink, therefore bringing restoration efforts to the forefront of research.

Peat extraction requires dewatering the peatland to lower the surface water table; ditches are dug throughout the targeted field in order to lower the water table so agricultural-type equipment can remove the surface vegetation and acrotelm. The acrotelm is the top ~50 cm of the living peatland, having loosely packed *Sphagnum* moss with large pore spaces, a high hydraulic conductivity, and is left unsaturated by the seasonal water table fluctuations (Ingram, 1978). Once the acrotelm is removed, the catotelm is exposed and targeted for peat removal. The catotelm is the saturated under layer of the peatland composed of decayed, tightly packed *Sphagnum* moss with small pores and a lower hydraulic conductivity than the acrotelm (Ingram, 1978). Once peat extraction is completed on a field, restoration is the next step. However, the exposed catotelm at the surface is not conducive to *Sphagnum* regeneration. *Sphagnum* grows on its dead self, and the newly exposed catotelm does not promote appropriate conditions for new moss establishment.

Sphagnum establishment depends on water table stability and hydraulic connectivity with the existing peat (Price, 1997), so proper water management is required for moss establishment on cutover peatlands. Re-contouring the cutover surface can help to retain water which increases the volumetric soil moisture (ɵ) content, and effectively reduces soil water tension, in the upper layers of the remnant catotelm (Bugnon et al. 1997). *Sphagnum* reestablishment has been shown to require water tables within 40 cm of the surface and soil water tensions of >-100 cm (Price and Whitehead, 2001; Sagot and Rochefort, 1996). To achieve these conditions, various techniques have been trialed. Surface re-contouring at St-Modeste bog near Riviere-du-Loop (Bugnon et al., 1997) used a V-shape to create a microclimate for *Sphagnum* establishment, which proved to be more helpful than ditch blocking alone (Bugnon et al., 1997). The creation of surface microclimates via re-contouring was found to increase water storage in cutover peatlands where the acrotelm has been removed (Heathwaite et al., 1993). A study conducted at Bic-Saint-Fabien bog in Quebec also concluded that surface leveling and bund forming aided in water retention after snow melt to keep the moisture within the cutover field and not run off into the remaining perimeter ditch (Malloy, 2013). The bog peatland restoration techniques developed over the past 25 years in Canada have been effective, particularly when diaspore reintroduction and mulch cover are used after the ditches have been blocked and the cutover section has been re-contoured into shallow basins or low bunds (Price et al., 2003).

The successful restoration projects noted above, as well as many others, have mainly taken place in a maritime climate (Quebec and New Brunswick) typified by major surplus of precipitation (300+ mm per year) and have attempted to restore to a bog ecosystem. Restoration to a fen ecosystem is a relatively new endeavour in Canada and fen restoration in a continental (drought-prone) climate, such as the Canadian Prairies, is also novel. The geography between the maritime climate and continental climate is vast and comes with separate hydrogeomorphic settings. The wetter, cooler maritime climate limits the evapotranspiration from bogs nestled within the area, and the Precambrian rock underlying the peatland prevents groundwater from upwelling into the system. The hot and dry continental climate of the prairies promotes a greater evapotranspiration rate, and the underlying limestone allows for groundwater upwelling should the dry conditions promote such an event. With the ability for groundwater flow reversal to occur within prairie bogs (Fraser et al., 2001), restoration to a fen system would occur with minimal effort and not require an overland water source into the peatland. Given the different climate and hydrology required for a fen vs bog for the end peatland goal, a different surface re-contouring technique was used to retain water in Manitoba than has been used in the maritime study sites. Therefore, the objectives are to determine if a new surface re-contouring pattern would promote an elevated water table level and soil tension to promote the establishment of new *Sphagnum* moss on the cutover field.

3.2 Study Site

The Elma peatland and processing plant is located ~10 kilometers south of Elma, Manitoba, approximately 100 km east of Winnipeg, Manitoba (-49º50' N, 95º54' W), located within the Boreal Plains ecozone of Canada. The closest weather station with 1981-2010 climate data is located in Beausejour, ~30 km northwest of Elma (Table 3-1). The mean annual temperature for the area is 2.8ºC, with January and July of -16.9ºC and19.2ºC respectively. Total precipitation is 570.3 mm, with snow accounting for 20% of the total (Environment Canada, 2016). Annual evapotranspiration is estimated at ~500 mm/year for the southeastern part of Manitoba (Natural Resources Canada, 2016).

Elma North is a 7.5 ha extracted site, left for restoration in 2014 after 12 years of active peat vacuum harvesting. The site had been regularly tilled for weed control, and the secondary ditches had filled in from slumping and wind erosion (Figure 3-1a). Willow (*Salix spp*) and cattail (*Typha spp*) were the dominant vegetation growing on site, mainly in the secondary ditches. Elma North was re-profiled in September 2015 to flatten the typical dome shape of the cutover surface and thoroughly infill secondary ditches. Due to the drought-prone nature of the climate, surface re-contouring that would retain as much water as possible was implemented. Bulldozers created a checkerboard grid with 418 cells approximately 9 m x 9 m with bunds 30-40 cm tall (Figure 3-1b). The primary perimeter ditch was also backfilled, and re-profiled into a slight slope to restore the connectivity between the natural area (to the west (Nat1) and north (Nat2)) and the cutover site. Crescent shaped bunds 30 cm tall, 1 to 2 m wide and 10-15 m long, were created along half of each sloped section on the south, west, and north sides of the cutover area to retain water on site.

The naming convention used for the site is in reference to the grid cell the relevant instrument is installed in. The upper left cell is A1 (with columns being letter and rows numbered) to the lower right cell as V19.

Table 3-1. Historical weather station data compared with the 2015 and 2016 field seasons.

Precip (mm)	Historical 1981-2010	2015	+/-	2016	+/-
May	58.1	149.8	+ 91.7	82.4	+ 24.3
June	87.5	88	+ 0.5	128.9	+ 41.4
July	87.1	183	+ 95.9	72.3	-14.8
Aug	76.3	123.3	+ 47	105.8	+ 29.5
Sept	65.1	29.4	-35.7	127.8	+ 62.7
Total	374.1	573.5	+ 199.4	517.2	+ 143.1

Avg Temp (°C)	Historical 1981-2010	2015	+/-	2016	+/-
May	11.4	12.1	+ 0.7	14.7	+ 3.3
June	16.7	17.4	+ 0.7	16.6	- 0.1
July	19.3	20.6	+ 1.3	19	- 0.3
Aug	18.5	18.4	- 0.1	18.1	- 0.4
Sept	12.5	16.1	+ 3.6	13.4	+ 0.9
Avg field season temp (°C)	15.7	16.9	+ 1.2	16.4	+ 0.7

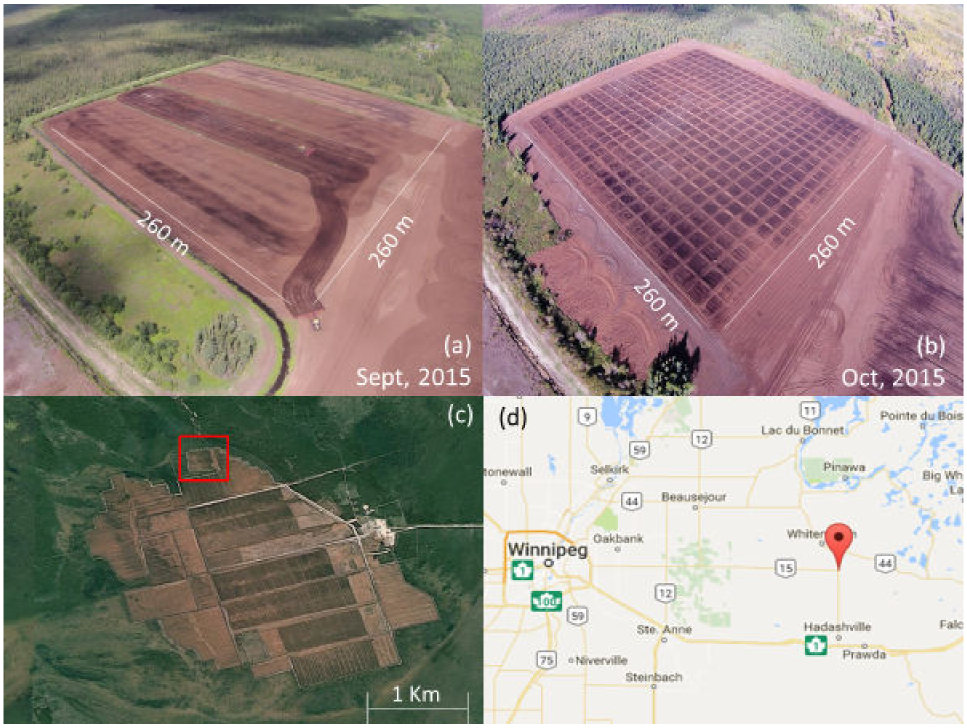


Figure 3-1 a, b. Pre- and post-surface re-contouring of Elma North. The waffle-like grid pattern is designed to retain snow melt and precipitation evenly over the site.

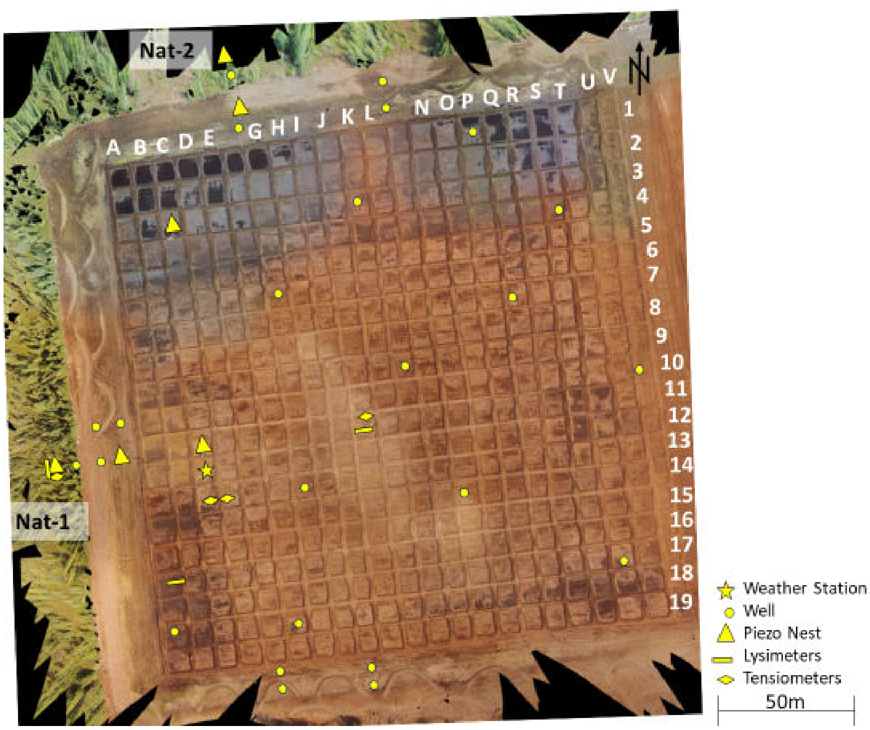


Figure 3-2. Study site of Elma with the locations of wells, piezometer nests, lysimeters, and tensiometers.

3.3 Methods

3.3.1 Well and piezometer construction and installation

Piezometer nests were installed in four locations in the site in 2015, two located in the cutover area (approximately where C11 and C3 are located now; note that the grid did not exist for the "pre" monitoring that occurred in summer 2015), and two in the surrounding natural area along the north and west edges of the site sufficiently back from the edge to not be impacted by the cutover field. Wells were installed in transects between nests C11 and Nat1, and C3 and Nat2. Piezometers were constructed from 2.54 cm diameter PVC pipes, with 20 cm slotted intakes, and installed into pre-augured holes; wells were constructed from 2.54 cm diameter PVC pipes with slotted intakes up the length of the pipe. The nests had piezometers placed at 0.5 m, 1.0 m, and 1.5 m below the ground surface, and deeper when possible, to a maximum depth of 2.45 m below the surface in Nat2. Water table measurements were taken manually three times during the season using a blow stick after installation and development of the nests. Development consisted of bailing out the well and piezometers and allowing the water to return before taking a measurement with the blow stick.

Immediately prior to the re-contouring, the wells and piezometers were removed and after Elma North was re-profiled (October 2015) into a checkerboard pattern the nests were reinstalled at C11 and C3, approximately in the same location as they were pre-re-profiling; nests in the natural sites Nat1 and Nat2 remained intact. Additional wells were installed throughout the grid for a total of 24 wells to capture any variability across the site. Two additional piezometer nests were installed at the site, one along the west side of the cutover area in the transition zone, and one on the north side in the transition zone, using the aforementioned methods. Elma North had a total of 44 wells and piezometers installed in 2016, and water table measurements were taken every ~ three days using a blow stick. Barodivers (Solinst) were installed in each well within the four original nests (C3, C11, Nat1, and Nat2), along with the well at L9, and recorded water levels hourly. Manual measurements were taken every ~3-4 weeks in 2017

The surface elevation profile was measured around the wells in each nest (i.e., solo wells were omitted) in 30 cm increments up to 150 cm from the well in each cardinal direction (N, E, S, W) for a total of 20 points. A "2x4" (lumber) with a 60 cm long level attached was positioned on the well top and the distance from the level to the ground was recorded. This estimated the water depth below the surface beyond the well itself. This was particularly important in the natural sites where the difference in elevation of the surface between hummock/hollow was very large and thus well installation location could heavily influence the depth to water table reading.

3.3.2 Meteorological

A weather station was installed in C12 and collected data from May 4 to November 7, 2016. The weather station consisted of a rain gauge (Texas Instruments 525), temperature/relative humidity sensor (HCS3), and a net radiometer (Kipp and Zonen NRLite) connected to a Campbell Scientific CR1000 data logger.

3.3.3 Evapotranspiration

Lysimeters were installed in the Natural site 1 (Nat1) and grid cells A16 and J11, in triplicate. Each lysimeter contained a monolith (18.9 L bucket, 30 cm diameter) of intact peat and was placed into the hole created, as flush as possible to the surrounding surface. Each lysimeter was weighed every ~three days from May 10 to August 10, 2016 using a Brecknell electro Samson 25 kg scale (+/- 10 g). Water was added or drained as needed to each lysimeter to match the saturation level of the surrounding peat. Actual evapotranspiration for each lysimeter was calculated and compared to the potential evaporation using the Priestley-Taylor equation (1972). The PT equation uses radiation and temperature data collected from the weather station on site, but as it is a simplification of the more complicated Penman Monteith (Penman, 1963; Monteith, 1965) equation. The PT model ignores surface roughness, stomatal resistance and other vegetation specific parameters and are replaced by direct measurements of evaporation using the lysimeters. The regression between actual and potential yields the alpha ($\propto$) coefficient which takes into account the amount of water available for evaporation and corrects the PT model.

3.3.4 Tensiometers

Tensiometers were installed in Nat1, C13, D13, and J11 at depths of 5, 10, 20, and 30 cm below the surface at each site. Measurements were taken every ~three days throughout the 2016 field season using a Soil Measurement Systems tensimeter (m H_2O). If the water in the tensiometer fell below the line of site (i.e., below the clear plastic tube at the top), water was added and recorded to estimate the water level in the tenisometer at the time of the reading. Measurements were not taken when sites were flooded since those data are effectively the water level which is measured manually from the wells in adjacent piezometer nests.

3.4 Results

3.4.1 Meteorological

The average temperature at Elma North from May through October 2016 was 14.4ºC, with 568.4 mm of precipitation falling over the same time period. A monthly breakdown of average temperature and precipitation is shown in Table 3-1. Temperatures between the two field seasons were similar to the 30-year mean with most months being within 1ºC of the mean. May 2016 and Sept 2015, however, where >3ºC warmer. The 2015 field season had ~200 mm more rain than the historical average, while 2016 had ~140 mm more rain than the historical average, from May to September.

3.4.2 Evapotranspiration

The alpha (α) value is the slope of the regression line (Figure 3-3) between actual and potential evaporation for the same time period determined by the lysimeter and Priestly-Taylor (PT) model (1972), respectively. The average ∝ values of the triplicates within each site range from 0.38 (Nat1) to 0.83 (A16). After adjusting the PT equation with these α values, it was determined that the seasonal totals for the 2016 study period (May to August) evaporation from Nat1, A16, and J11 were 227.6, 230.5, and 364.2 mm, respectively. A monthly breakdown of evaporation per site is displayed in Table 3-2. Data were discarded after rain events since accurate evaporation could not be determined with the (unknown) addition of water to the bucket. It should be noted that periodically throughout the field season, the lysimeters in Nat1 were pulled up and dumped over by wildlife, and the lysimeters in A16 were consistently flooded for the months of July and August, potentially skewing the actual ∝ and ET data. The lysimeters at A16 were not re-located in the hopes that the cell would dry enough for measurements to continue, as other cells had done, therefore the "unquantified" amounts for July and August were open water evaporation.

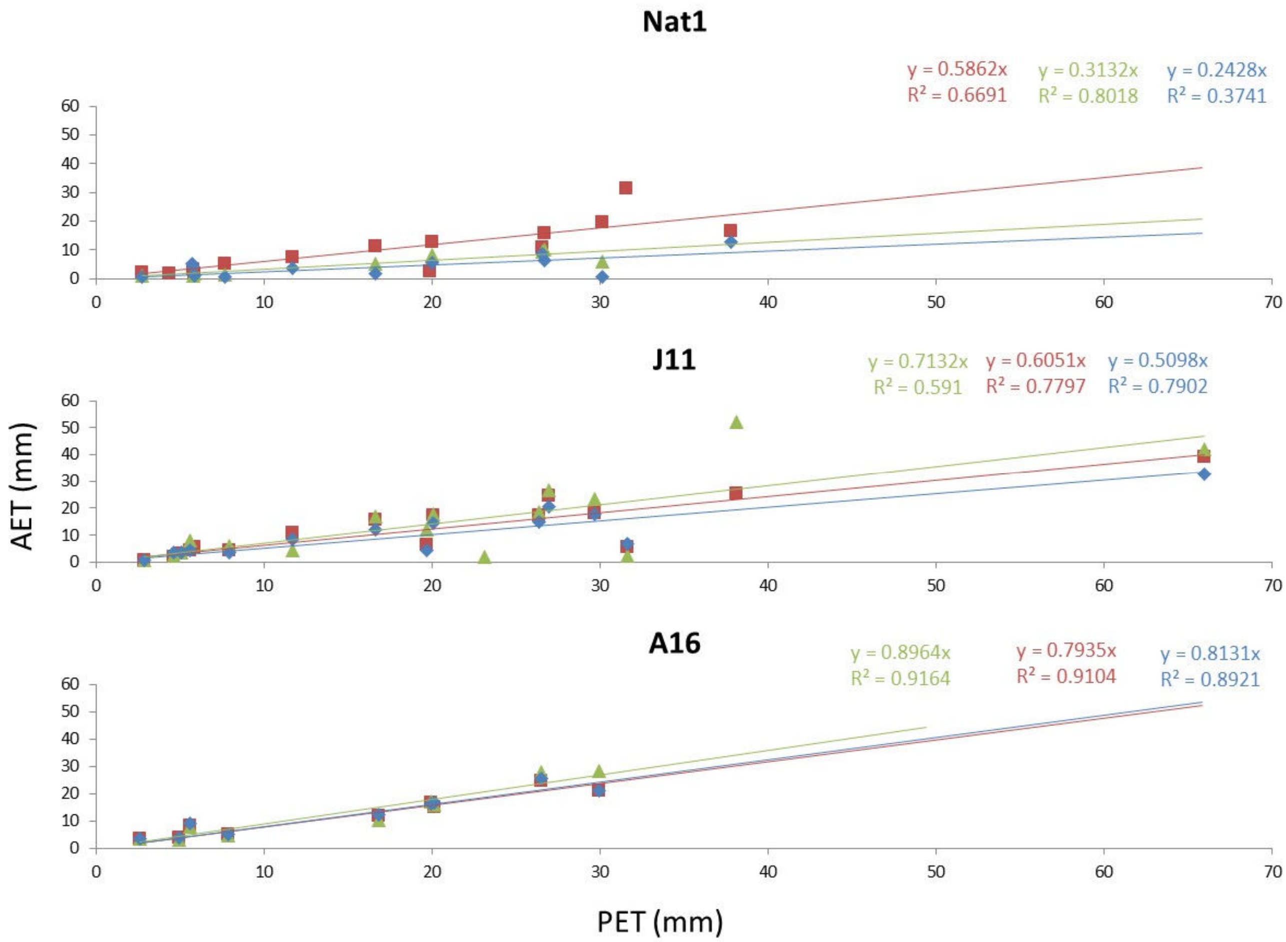


Figure 3-3. ET alpha values determined per lysimeter.

Table 3-2. Alpha and ET values for Elma, 2016 field season. * Note that A16 was adjusted for mm/day ET to correct for the number of actual measurement days (n=61) rather than for the full 123 days of Nat1 and J11.

	Nat1	A16*	J11
Avg α	0.38	0.83	0.61
May	46.3	101.5	74.1
June	58.9	129.0	94.3
July	66.0	unquantified	105.7
August	56.4	unquantified	90.2
Total (mm)	227.6	230.5	364.2
mm/day	1.9	3.8	3.0

3.4.3 Water table

The water table was measured three times in 2015 as baseline, pre-surface re-contouring data (Figure 3-4). The average 2015 water table was >100 cm below the surface in the cutover area (wells were ~1m deep and were dry), while the natural area averaged -46 cm water table (standard deviation, s = 25 cm). In 2016 the water levels rose to an average -14 cm in the cutover section (s = 29 cm) post- surface re-contouring, an increase of >86 cm from the previous year. The water table in the natural area also rose in 2016, averaging -18 cm, making both the cutover and natural levels indiscernible on a graph through time (Figure 3-5). A comparison between the limited instrumentation that existed in both 2015 and 2016 water table levels is displayed in Figure 3-4. Water table measurements, also displayed in Figure 3-5, show the average water table of the cutover section was 25 cm above the surface while the average water table in the natural area was -14 cm below the surface (Figure 3-4). The cells were flooded, hence the above-surface water level measurements in 2016. They remained flooded throughout 2017, thereby limiting data collection in that year. The simple balance of the main fluxes (P, E, GW) for Elma (Table 3-3) indicates A16 has a larger surplus than J11, which may not be accurate. A16 was only measured for 61 days due to lysimeter flooding, whereas J11 was measured for the full 123 days. There were also no piezometer nests located at A16 or J11, so the fluxes from C3 and C11 were used for the GW calculation, respectively. C3 had a flux of 0.09 mm/day over 61 ET days for A16, and C11 had a flux of 0.09 mm/day over 123 ET days for J11. Nat1 had a flux of 0.51 mm/day, however averaged with the flux of Nat2 (0.04 mm/day; average of 0.23 mm/day), the simple balance for the natural areas would be 317.9 mm.

The topography surrounding the wells within each nest varies between the cutover, transition, and natural sites Figure 3-6. The ground was mostly level, by design, within the grid cells of the cutover area (C3 and C11) and therefore likely representative of the other wells in the restored area. The transition zones were somewhat uneven (W3 and W5), with +/- 8 cm of variation, and the natural areas (Nat1 and Nat2) had hummocks and hollows as expected, with up to 69 cm of variation for the well. Grid cell C3 was not measured because it was flooded at the time and the soft bottom gave inaccurate topographical measurements, however the ground was relatively level and similar to cell C11.

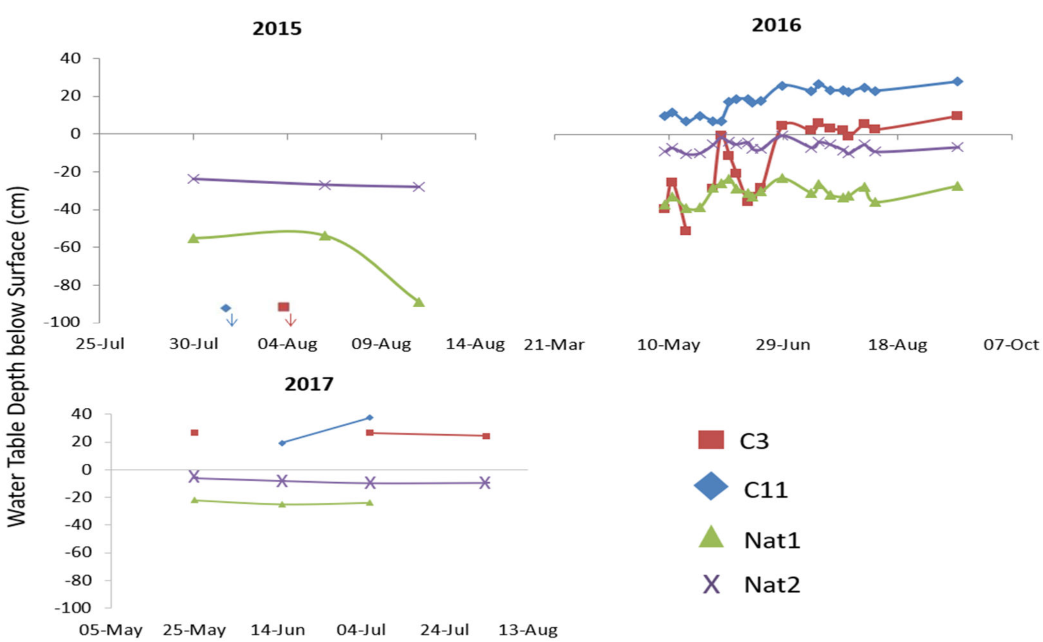


Figure 3-4. Water table comparisons between measurement years.

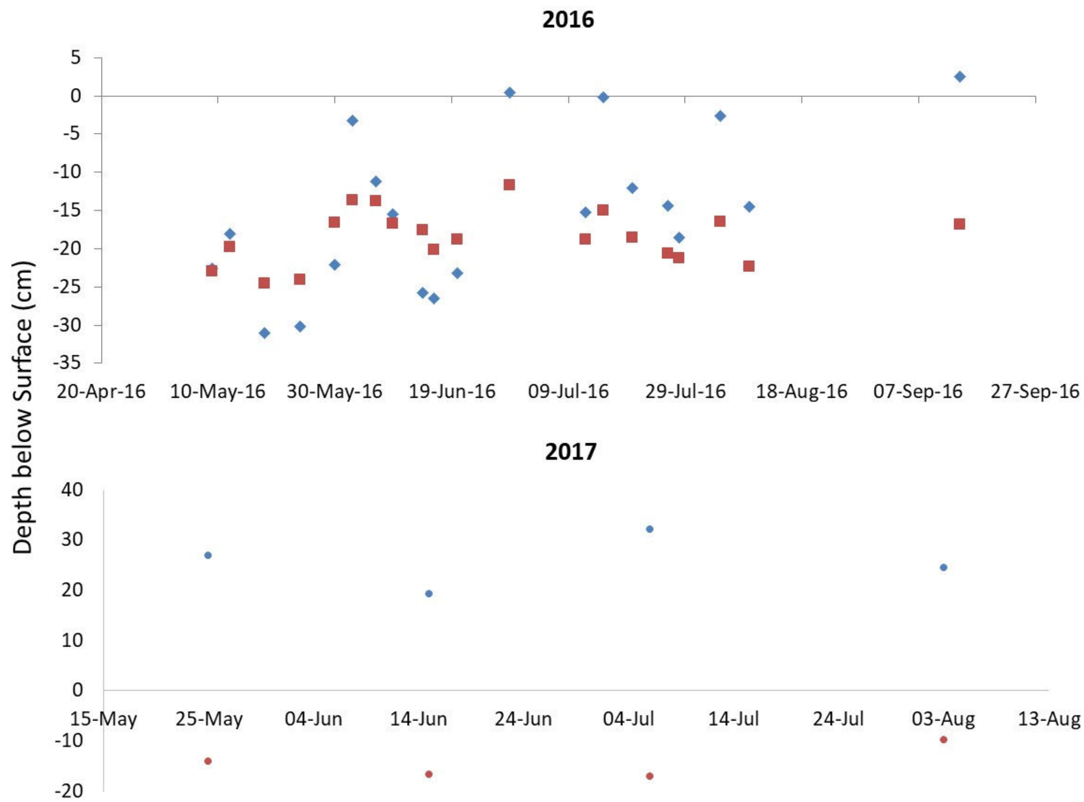


Figure 3-5. Natural vs cutover water table levels in 2016 and 2017. The 2016 average water table level for the cutover section was -15 cm, the natural average was -18 cm. In 2017, the average cutover water table level was 25 cm above the surface, while the natural was -14 cm.

Table 3-3. 2016 Simple balance for Elma. Note that ET from Nat1 was used in the average of bot natural sites. * A16 only had 61 days of ET measurements while Nat1 and J11 had 123 days. A16 also used C3 GW flux data. **J11 used C11 GW flux data.

2016 Simple Balance

Site	Nat1	Avg Nat1 and Nat2	A16 *	J11 **
P (mm)	517.2	517.2	517.2	517.2
E (mm)	-227.6	-227.6	-230.5	-364.2
GW (mm)	62.7	28.3	4.9	9.8
Total (mm)	352.3	317.9	291.6	162.8

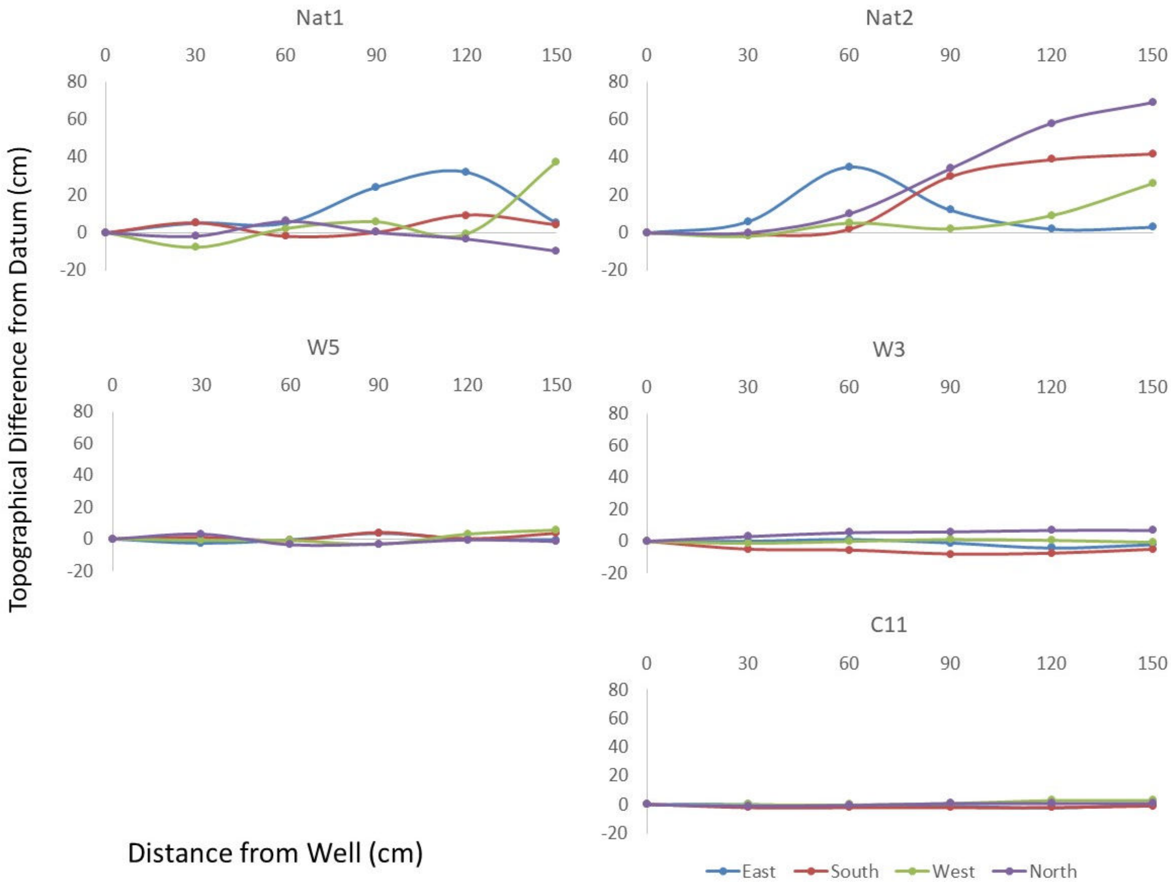


Figure 3-6. Topographical variability up to 150 cm from the nest in four directions. The x-axis represents the top of the well in the nest, used as the datum to measure the topographical variability in each direction.

3.4.4 Soil water tension

Tensiometers were not installed at Elma North in 2015, but visual observations during site visits in 2015 by the authors would confirm that the soil moisture in the exposed catotelm peat could drop below 50% by volume (Price, 1996) and create high soil tension non-conducive to *Sphagnum* growth. In 2016, the soil water tension averaged -14.5 cm for the top 5 cm of peat profile throughout the Elma site (Figure 3-7). Throughout the season, the cutover section at cells C13, D13, and J11 had average soil tensions of 6.2, 1.6, and -51.4 cm, respectively, within the top 5 cm of the surface. Nat1 had an average surface tension of -16.0 cm within the top 5 cm of the surface. Note that flooded conditions beginning at the end of June/early July decreased soil tensions considerably.

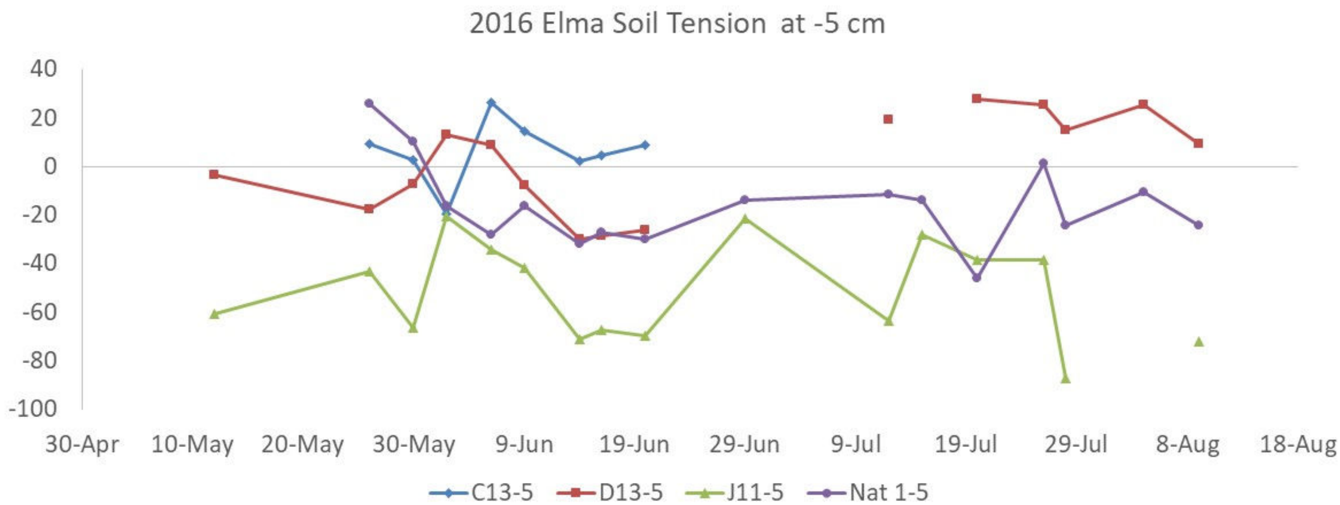


Figure 3-7. Average soil tension within the top 5 cm of peat.

3.5 Discussion

The waffle like grid pattern was effective in retaining water on the site. The experimental grid pattern was chosen to help retain snow melt and spring runoff in the hope of comparing success to an alternate research site in southeast Manitoba (South Julius; data not shown). Using the two most common measures of hydrological conditions conducive to bog restoration success: water tables above -40 cm and soil water pressures greater than -100 cm, we would declare the re-contouring efforts a success. Water tables rose nearly a metre from pre-restored conditions, and, as such, soil water tensions did not approach the -100 cm threshold. However, these conditions were established for bog restoration efforts, not fens. It is likely, however, that as fens (the goal of the restoration efforts in this paper) are supposed to be wetter than bogs (Kuhry et al., 1993) with water tables closer to the surface, that these metrics are still a good indicator of potential future success. A surplus of water would indicate success in restoration also. The simple balance for Elma (Table 3-3) compares Nat1 with an average of both natural sites, which has a range of 318 to 352 mm (average of both to Nat1, respectively). Although Nat2 had taller *Sphagnum* hummocks within 150 cm of the piezometer nest, the topography of both natural sites was similar (Figure 2-6), however Nat1 has a larger surplus than Nat2. Note that ET from Nat1 was used to calculate the water balance for Nat2, so this may not be an accurate statement. A16, albeit flooded through July and August, and J11 were similarly level by design. The flooded condition of A16 is not conducive for moss establishment, however considering the amount of moisture received along the outer edge of the grid compared with the dry conditions of the center, it could be hypothesized that A16, with subsequent drier years, would establish vegetation before J11.Vegetation establishment would also be an indicator of success. *Sphagnum* establishment is the goal for restoration, however before the moss can establish, pioneer species are required (Graf et al. 2008). Pre-surface re-contouring, cattail and willow species were established within the intermittent ditches of Elma; once vascular species establish post re-contouring, the successional moss species should develop over time. Fen restoration projects in Europe had to reintroduce *Carex* species, which are generally dominant in fens (Graf et al. 2008). Similarly, the moss layer transfer technique (MLTT) was used to disperse *Sphagnum* diaspores across South Julius, which was unfortunately flooded out and thereby unsuccessful. Although vegetation establishment would indicate hydrological success, it is beyond the scope of this thesis.

Evapotranspiration is the dominant water loss in peatlands, and also the prairies. Runoff in rivers in the prairies can easily be >80% of precipitation as snowmelt (Gray and Landine, 1988), but is infrequent and spatially constrained due to the arid climate and relatively flat topography of the prairies (Gray 1970). Therefore, ET still dominates the water balance. As such, understanding ET losses in restored peatlands, especially in the prairies, is important.

Unfortunately, due to flooded and difficult walking conditions, getting accurate measurements of evapotranspiration from parts of the restoration site (e.g., A16) was not achieved and likely underestimated. The lysimeters at J11, however, may indicate how drier conditions at the site may be in future years. J11 has an alpha value of 0.61, ranging from 0.5 to 0.7, with a total evaporative loss of 364 mm (Table 3-2). In a normal year (Table 3-1) precipitation totals 374.1 mm, or roughly the same as J11 lost as ET. It is important to note that the idea of a “normal” year in the prairies is comedic, as the natural cycles of wet and dry periods rarely results in a “normal” year in any given year. 2015 and 2016 were wet years and part of a decade long wet cycle. Gonzalaz and Rochefort (2014) note that the weather following the year of restoration was a major factor in predicting a site’s restoration success. It would therefore be interesting to see if 2015 and 2016 were “normal” years and estimate the water tables and soil water tensions at the site and whether the restoration would have been successful.

Recall that the 2015 and 2016 study seasons received 200 mm and 140 mm, respectively, of excess rain than the historical average of the previous 30 years (1981-2010), but what if only the normal precipitation had fallen? We used the pressure transducer installed at L9 to calculate the specific yield of the peat by measuring the rapid water table rise following a distinct precipitation input. Specific yield is the volume of water lost (gained) from the soil, per unit surface area, per unit decline (rise) in head (Freeze and Cherry, 1979), and thus is a dimensionless ratio of water table rise (or fall) to water input (or loss). Knowing the rise of the water table from the pressure transducer and the rain recorded at the weather station, we identified 13 rain/water table rise events and determined the specific yield for each. We then plotted these against the final water table depth below the surface (Figure 3-8) so that we could estimate, at a given water table position, what the change in water table would be given an output loss of 200 mm (the surplus from 2015).

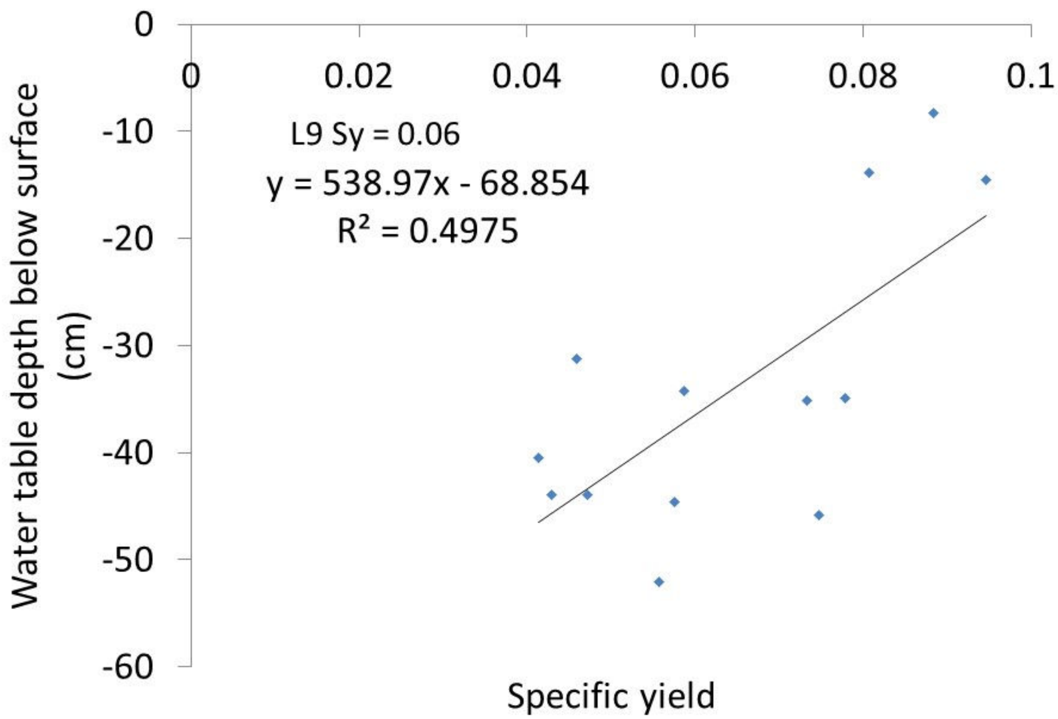


Figure 3-8. Specific yield determined from specific rain events and corresponding water table rise in the L9 grid cell.

The water table for each grid well in 2016 was "corrected" with a loss of 20 cm (200 mm) of water by assuming a specific yield of 1 for flooded conditions, and 0.06 for non-flooded conditions. The specific yield of 0.06 was the average of the 13 events. The resulting new average water table depth for the grid would be -348 cm. With specific yields of 0.05 and 0.08, the average grid water table would be -415 and -265 cm, respectively. Note that for ~half of the sites with flooded conditions (Sy = 1), the water level would remain at or near the surface. With a specific yield of 0.06 resulting from a 200 mm precipitation decrease, the water level would be nearly 3.5 m below the surface for the other half of the sites, which is impossible given that the residual peat depth was often <1 m. In addition, the extreme drying of the surface peat would effectively reduce the unsaturated hydraulic conductivity to zero, limiting further water loss, acting as a self preservation mechanism to prevent further water loss well before the water level dropped to -350 cm. It is quite likely that under such dry conditions, soil tension would drop below -100 cm at the surface, making the conditions unsuitable for reestablishment.

Recall that these criteria were established for bog restoration projects in Quebec. It is very likely that fens would require higher water tables and even less soil water tension for success, even in a wetter maritime climate like Quebec. Unfortunately, there are just not enough fen restoration projects to come up with new hydrological threshold criteria. On the other side of the spectrum, being too wet, as in 2017, has led to flooded conditions also not suitable to fen restoration. It is therefore critical to get the hydrology right, with contingencies in place for the weather of the year, especially in the early years of the restoration. Lessons learned here are being applied to future projects in the province whereby water table control structures are being considered so that the water table can be lowered or raised in a more stepwise, incremental fashion.

3.6 Conclusions

The Elma site had a water table level and soil tension rise within the cutover peat area to within the -40 cm and -100 cm threshold, respectively. The waffle pattern re-contouring method helped with water retention, however the study years were uncharacteristically wet compared to the 30-year normals, which may have contributed to the water table rise more so than the simple act of re-contouring the landscape. The flooded conditions of 2017 have left the area too wet for immediate *Sphagnum* establishment, but as a fen restoration project, the water levels should be higher than those within a bog.

Evapotranspiration dominates the water balance, and the center of the cutover area (the driest area) had a total ET of roughly the same amount of precipitation input from a “normal” year. The idea of “normal” is subjective and thus the amount of precipitation should be taken into consideration if using these ET data as a standard for comparison to other studies. The specific yield, however, was calculated to a “normal” precipitation year as well as a wet year and conclude that the water table rise in a “normal” year would be beyond the -40 cm, and close to the -100 cm, threshold and therefore inadequate for *Sphagnum* establishment.

The lesson learned from this fen restoration project is that Goldilocks hydrology is ideal; the re-contouring method needs to raise water table and soil tension level to a “just right” level for moss establishment to be successful.

4 Conclusion

Peatland extraction began long ago in Europe, using the extracted peat as a fuel source, before moving on to clear room for agriculture, and finally being utilized as a horticultural medium. Canada is now at the forefront of global peat extraction for horticultural use. Peatlands provide a plethora of ecological services, including water filtration, wildlife habitat, and flood control, and the heavy peat extraction practices around the world have since lead to protection laws and conservation movements for these diverse ecosystems. It is one thing to preserve in tact peatlands, however, the previously extracted ones had been left to the environment.

Peatland restoration has been incorporated into some legislation, and, in Manitoba, a post-harvest restoration plan must be included in the permit application before the commencement of harvesting. Different restorative techniques have been utilized throughout Europe and Canada, but the literature has proved that each plan needs to be site specific. The initial step in any restorative measure is to re-wet the peatland (generally by blocking the ditches) to restore a water table level conducive to *Sphagnum* moss growth. *Sphagnum* moss is the primary peat forming agent and requires specific environmental conditions in order to establish and thrive in an area. Since *Sphagnum* does not grow in soil, but *is* the soil, the disruption from peat harvesting leaves an unfavourable environment for *Sphagnum* regeneration. The moss requires a water table level of ~40 cm from the surface, and a soil tension of > -100 cm for this non-vascular plant to access the necessary amount of water.

In some instances, achieving the water level rise and appropriate soil tension is enough to promote *Sphagnum* establishment, like in some European bogs or in Moss Spur, Manitoba. However, some places require more extensive measures to be taken for regeneration to begin.

Bois des Bel (BdB), Quebec is a site in Canada which remained mostly bare after only re-wetting via ditch blocking occurred. Alternative measures were taken to promote *Sphagnum* establishment, such as spreading moss diaspores from an adjacent donor site across the cutover field before covering the area in a layer of mulch. The diaspore spreading and mulch layer proved effective in creating a hospitable environment for the newly established *Sphagnum* moss. Approximately 2,000 kms away at Moss Spur, Manitoba, no such restorative efforts had been made except for inadvertent ditch blocking by beaver dams in the 20 years since extraction ceased at the site. From restoration experiments performed at BdB, Moss Spur was expected to be bare cutover peat in need of active restoration to promote moss growth and regeneration, but that was not the case. Moss Spur had seemingly spontaneously regenerated with little more than beaver dam induced re-wetting.

One of the key findings at Moss Spur was groundwater flow reversal, a phenomenon known to occur under severe drought conditions. But the upwelling of groundwater into a bog contradicts the very definition of a bog, in which bogs are ombrogenous, only receiving water from precipitation. Upon further investigation, the groundwater flow reversals were able to occur because of the hydrogeomorphic setting in which Moss Spur was located. Compared to BdB in Quebec, Moss Spur is located within the Boreal Plains Ecozone underlain by limestone bedrock and has a drier climate with more evaporation than BdB. The Boreal Shield Ecozone where BdB is located, is comprised of Precambrian bedrock in a wetter climate with less evaporation than Manitoba. Combined with the dry climate, the peat extraction at Moss Spur created surrogate drought conditions within the bog, and the larger pores in the underlying limestone allowed for the previously suppressed groundwater to well up into the bog and replenish its water supply. Extensive restorative efforts were simply not required at Moss Spur like they were in BdB.

Groundwater flow reversals have also occurred in New Brunswick, in a block-cut bog which created microclimates within the remaining trenches where *Sphagnum* was able to establish.

Elma North, located approximately 25 kms southeast of Moss Spur, was extracted for 12 years and left untouched until 2014, except for weed tilling. Elma North is a small area, only 250 m x 250 m, and its secondary ditches had filled in from wind erosion and no longer drained the interior of water. A perimeter ditch surrounding the site remained, as active extraction was occurring in fields adjacent to Elma North. The goal was to level the cutover field, properly infill the secondary ditches and the perimeter ditch, and re-contour the interior into 418- 9 m x 9 m grid cells to aid in re-wetting. The perimeter of the site was sloped into a transition area leading down from the surrounding natural areas on the west and north sides to the cutover grid section. The study season was wet, and the grid cells retained the precipitation to a point of near flood conditions. The re-contouring (and excessively wet study season) proved to raise the water table > 100 cm from the year before, and improved soil tension to well within the acceptable requirements for *Sphagnum* moss growth. It is yet unknown if Elma North requires active measures to promote regeneration, since weed tilling prevented even wetland vegetation from establishing on the site, but it only required one season to create acceptable hydrological conditions for *Sphagnum* establishment. This new knowledge may prove to accelerate the rate of peatland restoration within the boreal plains hydrogeomorphic setting, and *Sphagnum* establishment may be possible over mere decades rather than centuries.

4.1 Sources of Error

Field hydrology, like any field work, consists of several on-the-spot measurements collected for future analysis. Data was never purposely skewed, however human error may have affected the accuracy and subsequent calculations for water table levels, ET, K, soil tension, or meteorological readings.

The weather station was installed and checked intermittently to ensure the solar panel was keeping the battery charged, and the rain gauge remained free of debris. At one point the rain gauge became clogged and did not record accurate precipitation rates over a weekend.

Water table levels and hydraulic conductivity were measured using a blow stick, where measurements can vary (1-2 mm) depending on the person taking them. To ensure consistency, the same technician used the same blow stick to perform measurements throughout the field season.

If water levels dropped below the clear tube at the top of a soil tensiometer, it was filled by hand in the field, so a reading could be recorded, and the calculation adjusted for the added volume. The volume added was measured as precisely as could be managed within a field setting.

Evapotranspiration was measured using 25 L buckets. The peat matrix within the bucket may have been altered from digging the hole and transferring it into a bucket. The vegetation on top of the bucket matrix had potential to dry out and wither (affecting ET rates), however the field crew were conscious of keeping the water levels within the bucket comparable to the surrounding area. There were also instances where wildlife dug up the lysimeters and dumped them out, causing that day’s data to be discarded. Flooding was an issue in Site A (Moss Spur) and A16 (Elma); the lysimeter would float up and tip over at Site A, and the whole A16 grid cell remained flooded through July and August 2016, resulting in discarded and unquantified data, respectively. Data was corrected during analysis to account for days of discarded data.

Adjustments were made in the field to correct sources of error when and where feasible.

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