Hydrology of natural and constructed ecotones surrounding peatlands in southeastern Manitoba

By

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Abstract

Ecotones are dynamic and biological communities between two ecosystems that ensure the exchange of energy, water, and nutrients and are typical between bogs and fens. Integrating this concept during the restoration of extracted peatlands and their natural surrounding is not common practise, in part to not being well understood. This thesis investigates the fundamental characteristics of the transition (ecotone) between natural bogs to fens and discusses various experimental management approaches that are used to restore transitions that have been compromised due to peat extraction. Data were collected from 5 transects from two (South Julius and Moss Spur 1) naturally undisturbed peatland sites and 8 identified transects from one (Moss Spur 2) disturbed peatland site in southeastern Manitoba. Each transect comprised 6 to 7 wells and 2 to 3 piezometer nests. These instrumentations allowed for the measurement of water table position, hydraulic conductivity and hydraulic gradients. Peat depths and surface elevation were determined for each transect at all sites while pH and electrical conductivity were measured at the undisturbed sites. At the disturbed site, water retention strategies were included to improve understanding of hydrological feedback across four experimental designs (5-Pond, 3-Pond, Berm and Control) at three sections (W-ECO, NW-ECO and S-ECO). Water tables were nearer to the ground surface in undisturbed areas compared to disturbed areas. The experimental management approach (after recontouring) applied at the disturbed site improved water table conditions especially on the 5-Pond treatment. Improved water table conditions coupled with improved flow rates may be vital for the transport of nutrient, water, and energy across the ecotone. Such improved conditions are important for the establishment of fen ecosystems.

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1 Introduction

1.1 Peatland overview

Peatlands are wetlands that store between 16-33% of the global soil carbon (Malloy and Price, 2014; Maltby and Immirzi, 1993; Xu et al., 2018; Yu, 2012), and, therefore contribute to the reduction of greenhouse gases (Evans and Warburton, 2010; Tarnocai et al., 2012) in the atmosphere. The ecohydrological integrity of peatlands is threatened when the carbon storage function is compromised through various activities such as drainage, agriculture, peat extraction and climate change. Perhaps the most important ecohydrological factor affected by drainage is the hydrology (particularly water table), of which nearly all biogeochemical processes depend on, or are strongly linked to, such as carbon sequestration. Human activities that alter the hydrology of natural peatlands, such as peat extraction, can leave these peatlands unable to revegetate and accumulate carbon. As a continual sink of atmospheric carbon dioxide that counterbalances the loss of methane, peatlands (located mainly within the northern hemisphere) have been successful in mitigating against the adverse effect of climate change globally. Thus, the long-term protection of the carbon sink function of the peatlands is important for achieving a net zero global carbon dioxide emissions. It is therefore important to protect peatland ecohydrological function to protect the carbon accumulation function, as well as learn prompt and active restoration techniques to get these disturbed ecosystems back to accumulating carbon as quickly as possible (Nugent et al., 2021). It is estimated that peatlands will help mitigate against the adverse effect of climate change by 2050 (Harris et al., 2021) making them very important climate drivers.

1.2 Hydrogeomorphic setting and succession (post-glacial landscape and factors controlling peatland succession)

Peatland development may occur through primary peatland formation via paludification or terrestrialisation (Anderson et al., 2003). Paludification is when peatlands form over previously forested land, grassland, or long-exposed bare lands; and terrestrialisation is when peatlands form through the in-filling of water bodies such as a lake (Anderson et al., 2003). During terrestrialisation, a succession of plant communities occur which gradually transform the aquatic environment into a terrestrial environment through a process known as hydroseral succession. Paludification appears to be more common in the boreal and subarctic regions of Canada (Borkenhagen and Cooper, 2016; Nicholson and Vitt, 1990; Turunen and Kuhry, 2006). The genesis and subsequent development of peatlands occur naturally with feedback from factors including hydrology, geology, and vegetation. Topography and climate are also strongly related to the development of peatlands with a higher abundance of peatlands usually found on flat lands and moist climates (Turunen and Kuhry, 2006). Understanding these allogenic and autogenic factors on peatlands can provide insight into the lateral expansion and succession of peatlands such as hydroseral succession. Hydroseral succession is the most frequent and typical form of autogenic development in peatlands (Charman, 2002). During the infilling process, there is a succession from fen to bog species due to the local accumulation of peat whose surface is gradually raised above the groundwater system. In the boreal regions of Canada, ponds surrounded by a marsh become gradually replaced by a rich fen which transitions into a poor fen and then finally into a bog. Sometimes, fens and adjacent bogs which eventually form can exist as small packets within the larger peatland complex.

1.3 Wetland Classification and research context (Bogs vs Fens)

According to the National Wetland Working Group (1997), a wetland is defined as "*a land that is saturated with water long enough to promote wetland or aquatic processes as indicated by poorly drained soils, hydrophytic vegetation and various kinds of biological activities which are adapted to a wet environment*". Wetlands are generally classified as mineral or organic. Peatlands are organic wetlands with more than 40 cm of accumulated peat (National Wetland Working Group, 1997) (though the 40 cm do vary globally with different local definitions); Canadian peatlands are comprised of bogs and fens (and some swamps). Hydrology is generally considered the key factor in distinguishing between fens and bogs: bogs are ombrogenous, meaning their water originates exclusively from atmospheric water (precipitation) in the form of snow or rain, fens, however, can have their water originate from the land or as groundwater discharge where there is contact with mineral soil (minerogenous). In the successional stages of peatland development, bogs are preceded by fens over a millennia (Warner and Asada, 2006). Bogs may exist as large (100s m diameter) island mounds surrounded by fens with the edge of the bog and the adjacent fen forming an ecological boundary known as an ecotone.

1.4 Hydrology of peatlands

Within the mid-latitudes, warming due to climate and the modification of precipitation regimes (Trenberth, 2011) are rapidly changing the hydrological conditions. The hydrological response is due to the delicate balance between evaporation and precipitation (Thompson et al., 2017). These hydrological conditions affect water supply within the peatland system and eventually affect certain physico-chemical and ecological conditions which further exacerbates climate change thus making hydrology an important factor to study (Bertrand et al., 2021). Water table depth (WTD) serves as a basis for developing an ecohydrological understanding of the linkage between hydrological, ecological, and biogeochemical feedbacks (Waddington et al., 2015). The overall result is that WTD can be used to predict ecohydrological variables such as carbon quality and sequestration rates and organic matter decomposition (Waddington et al., 2015), which are relevant in peatland restoration.

1.5 The margin as hotspots

The margin between two well-defined ecosystems (e.g., bog-to-fen) is an important biodiversity hotspot where novel and distinctive evolutionary forms may be generated and maintained (Kark and van Rensburg, 2006). The margin may also be one of the more sensitive areas (though there is lack of studies assessing this) of the peatland ecosystem where flow of materials between the two ecosystems occurs and where changes in the hydrology could have adverse results on the entire ecosystems.

1.6 Hydraulic conductivity and transmissivity feedback

One important hydrological feedback is the WTD-transmissivity feedback. Transmissivity (T) is the product of the saturated hydraulic conductivity (K_{sat}) and the thickness of the saturated aquifer (b). K_{sat} is a hydrophysical property which is a measure of how quickly water can flow through the soil and generally decreases with depth in peatlands due to increasing compaction and decomposition (Weber et al., 2017). Understanding the relationship between WTD, hydraulic conductivity and transmissivity can help to understand the flow of material from bog to fen via the ecotone between them. Fen and bog peat and the transition between them have a wide variation in hydraulic conductivity due to differences in peat total porosity as well as the pore spaces/sizes (Holden and Burt, 2003; Ramchunder et al., 2009; Weber et al., 2017). Such differences in hydraulic conductivity are what lead to differences in WTD characteristics which (in conjunction with the water chemistry) further influences the type of vegetation.

1.7 Natural ecotones and their function

Despite what appears to be their ecological importance, research which aims to define the transitional zones (ecotones) between fens and bogs is limited (Kark and van Rensburg, 2006). The health and integrity of peatland ecosystems are threatened when ecotones are altered because the ecotones ensure water, energy, and nutrient flow between the two ecosystems (Churkina and Svirezhev, 1995; Hartshorn et al., 2003). Ecotones also play a vital role in determining changes in peatland function and health within the context of climate change due to their wide distribution (Dimitrov et al., 2014) and anticipated sensitivity (Churkina and Svirezhev, 1995) to climate change drivers. Defining an ecotone is fundamentally significant to understanding the dynamics of peatland function mainly because ecotones support a great deal of biodiversity (Churkina and Svirezhev, 1995). Current research on peatland ecotones is focused on understanding gradients that exist across the ecotones such as the Bic-Saint Fabien fen peatland in Quebec (Lefebvre-Ruel et al., 2019).

1.8 Disturbance to peatland ecotones

Peat extraction is a profitable venture in Canada, often supplying jobs in rural areas, yet detrimental to the peatland ecosystem. During peat extraction, ditches are created with excavators to lower the water table of the bog peatland. Main ditches are created on the periphery of the extraction site while smaller parallel ditches orthogonal to the main ditches are created within the main extraction site. The upper living layer (acrotelm) of the peat bog is removed to expose the lower peat (catotelm) (Ingram, 1978). Peat is extracted over a period of time which in turn creates disturbance to ecohydrological factors that support *Sphagnum* regeneration. Peat companies may only extract peat to a portion of the bog depth based on regional legislation/regulations. After extraction, what sometimes remains is an extracted peatland surrounded by an undisturbed peatland, and in other cases, an extraction may end at the edge of the entire bog and thus surrounded by mineral land (such as a forested upland). An often-sharp transition exists where there is a drop in elevation (can be a few metres) between the surrounding landscape and the extracted site. The abrupt transition creates a disconnect between the extracted peatland and the surrounding landscape.

1.9 How to restore peatlands

Bog peat (*Sphagnum* peat) is sought after by peat industries because of the hydrophysical properties it possesses, and peat extraction is often stopped when minerotrophic sedge peat (fen peat in the depth profile) is reached. After peat extraction, extracted peatlands are required to be restored back to a functioning ecosystem. The Peatland Ecological Research Group (PERG) developed a bog peatland restoration technique known as the Moss Layer Transfer Technique (MLTT) and has been used all over Canada (Lefebvre-Ruel et al., 2019) and across the world, and has shown to be successful at re-creating moss carpets typical of natural bogs (González and Rochefort, 2014). The MLTT likely suffers drawbacks because bogs solely depend on atmospheric precipitation and thus the current MLTT method may suffer in extreme drought years and drier climates. This presents a challenge in applying such technique in more drought prone areas of Canada such as the prairies (Manitoba). The MLTT may also suffer drawbacks when the biochemistry of the residual peat is not taken into account. For residual peat whose biochemistry (pH, EC, minerals etc) matches typical fen peat (minerotrophic), restoration should be aimed at targeting a fen species rather than bog (Cobbaert et al., 2004; Zoltai and Vitt, 1995). Thus, novel restoration techniques for fens may be required. As noted earlier, there is typically a sharp transition between restored peatlands and surrounding ecosystems which is not typical of natural ecotone transitions. By restoring/creating the transition to enable an ecotone between the two ecosystems (natural and restored area), it could encourage the flow of water and nutrients to fens, better replicating the more complicated hydrology and biochemistry found in fens, as well as support the restoration in drier climates. Fens have been noted to have a wide range in nutrient conditions and vegetation community types (Zoltai and Vitt, 1995) which makes their restoration more complex but desirable to study.

1.10 Review of fen restoration

Different restoration and management techniques have been applied in fen restoration projects in Canada and across the world. Models used in fen restorations have been studied extensively in Europe (Beadle et al., 2015). Although natural fens form over millennia, restoration into a fen and subsequent ecotone creation is feasible if the topographic setting is configured to ensure a hydrogeological setting that can ensure the water supply requisite to sustain the function of a fen peatland (Devito et al., 2012). Due to the difference in climate and general hydrogeomorphic setting between Europe and North America (boreal and subarctic regions), it is important that new models are developed when restoring Northern peatlands. In Canada, various fen restoration project have been undertaken in places including Québec (Lefebvre-Ruel et al., 2019) and Alberta (Borkenhagen and Cooper, 2016) and have aimed at spontaneous revegetation.

Spontaneous revegetation is a natural way to allow peatland vegetation to re-establish automatically following recontouring the land surface and the blockage of drainage ditches.

1.11 Fen restoration projects in Manitoba

Peatland restoration design aims to return the landscape to a functioning ecosystem after peat extraction. In Manitoba, fen restoration and ecotone creation are new concepts, not attempted on many peatlands' restoration projects in the province. Fen restoration research began in May 2015 on two Sun Gro Horticultural industrial peat extraction sites (South Julius, Elma North) located in southeastern Manitoba, but a first mention of fen rewetting was in 2006 at South Julius. The first restoration attempt resulted in excessive flooding in one of the experimental sites (South Julius) in 2016. Attempts were also made in 2015 to restore the Elma North site to fen conditions and restore the ecohydrological connectivity between the restored fen and the surrounding landscape via gradual slopes (~35 m long with ~1 m drop) with crescent-shape bunds. The crescent shape bunds aimed to maximise water retention. For the fen restoration at Moss Spur, it was established that extracted fens were more likely to revegetate than extracted bogs. From a long-term restoration perspective, rewetted sites with longer years of rewetting showed relatively higher vegetation cover than shorter years.

1.12 Objective of the thesis

The overall objective of the thesis is to understand the ecohydrology of an artificial peatland ecotone (both unmanaged and managed) on the periphery of an extracted fen, as well as along natural peatland ecotones in the drought prone prairies (Manitoba) of Canada.

1.13 Thesis outline

This thesis comprises two manuscripts.

The first manuscript is entitled “Hydrological gradients along natural peatland (fen-to-bog) ecotones in the Julius bog complexes, Manitoba, Canada” and discusses the hydrological gradients that exist along natural undisturbed ecotones (reference ecotones). The second manuscript is entitled “Hydrology of a constructed ecotone at the periphery of a fen restoration, Manitoba, Canada” explores management approaches used to maintain the wetness of artificial ecotones at the periphery of an extracted fen with the surrounding landscape. Here, management techniques were applied to 3 out of 8 transects after which gradients were compared to the gradients of the remaining 5 (unmanaged) out of 8 transects. The results from the two manuscripts are compared to determine whether natural ecotones are “good” models for estimating peatland restoration success.

2 Hydrological gradients along natural peatland ecotones in the Julius bog complex, Manitoba, Canada

2.1 Introduction

Peatlands occupy between only 2-3% of the global land area yet store between 16-33% of the global soil carbon (Xu et al., 2018). Small, standalone peatlands are rare, with most being part of larger peatland complexes such as western Siberian boreal forest (Peregon et al., 2009) and the James Bay Lowland (Holmquist and Macdonald, 2014). Within these complexes are natural progressions from one peatland form to another, commonly bog to fen. Bogs are ombrogenous, meaning their water originates exclusively from atmospheric water (precipitation) in the form of snow or rain, fens, however, are minerogenous meaning they can have their water originate from the land or as groundwater where there is contact with mineral soil (National Wetland Working Group, 1997). The interface between bogs and fens, or an ecotone, have been found to be important because it helps ensure the flow of water, energy, and nutrients (Churkina and Svirezhev, 1995; Hartshorn et al., 2003). Understanding this interface (ecotone) of undisturbed/natural systems can provide insight when establishing restoration goals for extracted peatlands, and how these systems may respond to a changing climate.

The formation of peatlands (bogs and fens) and the transitional zone between them can occur through either terrestrialisation or paludification. Paludification is the most common process of peatland genesis (Borkenhagen and Cooper, 2016). Paludification begins on mineral soil on terrestrial ecosystems while terrestrialisation occurs through the infilling of a pre-existing water body (Nicholson and Vitt, 1990; Rydin and Jeglum, 2015). Peatland formation normally progresses from fens that are supplied by groundwater that has been in contact with mineral rich sediments (Borkenhagen and Cooper, 2016). The developed fen may exist adjacent to a pre-existing ombrotrophic (solely rain-fed) bog thus creating a transitional zone between the fen and the bog. The adjacent fen may gradually develop into an ombrotrophic bog, but this is a very slow process that can take thousands of years. The succession from fen to bog species is due to the local accumulation of peat whose surface is gradually raised above the local groundwater system. Sometimes, an ombrotrophic bog may exist adjacent to a mineral land (usually called an upland) instead of a fen, thus creating a type of transitional zone known as a lagg ecotone (Howie et al., 2012). The lagg zone is the ecotone between ombrotrophic bogs and adjacent mineral lands where runoff collects from the bog and the mineral soils (Howie and Meerveld, 2011).

Current studies in eastern Canada classify (lagg) transitions into four groups; i) an abrupt transition without an ecotonal community, ii) a narrow transition with a lagg-swamp ecotonal community (most common transition type), iii) a narrow transition with two ecotonal communities (lagg-fen and lagg-swamp) and iv) a broad transition with a large wetland adjacent to the bog (Paradis et al., 2015). Lagg studies often compare the lagg with open bogs (Pellerin et al., 2009) or compare the lagg with adjacent mineral land (Paradis et al., 2015). Such comparisons are done to analyse the similarities and differences of the lagg and either the bog or mineral land or both. The lagg has sometimes been loosely referred to as a type of fen (Conway, 1949) or “lagg-fen” (Rydin and Jeglum, 2006).

The focus of lagg studies is generally to delineate one peatland complex from mineral land (upland) and the impact they have on one another especially in a changing climate. Delineation has been based on factors including peat thickness, hydrology, vegetation, and biogeochemistry. For example, water table depth (WTD) is an important hydrological factor in delineating boreal transition zones (laggs) because of its effect on forest productivity (Dimitrov et al., 2014). Water table is also relevant for the survival of *Sphagnum*, an important peatland vegetation. It has been shown that changes in these factors can result from climate and that the lagg is pivotal in detecting these changes (Howie et al., 2016). Even though the factors have been shown as key detectors of climate change, not all the claims are evidence-supported and the interacting effect of these factors (in a changing climate) are poorly understood (Evans and Brown, 2017).

Like the lagg, the ecotones between bogs and adjacent fens may be of great importance due to the likelihood of being sensitive to climate change. From a historical standpoint, ecotone analyses have connected past climate change to changes in ecosystem boundaries (Wasson et al., 2013). It is possible that such ecotones could continue to serve as sensitive indicators for monitoring current and anticipated climate change. For ecotones to respond faster to environmental changes, they must have high resilience and stability with quick response rates such as the response to trace changes in climatic conditions (Wasson et al., 2013). Generally, it has been hypothesised that the margin (i.e. bog-to-fen transitions) found in wetlands (typically peatlands) may prove to be sensitive indicators of climate change due to the noticeable change in the gradients that exists on them (Noble, 1993). Such changes in the gradient may include, but are not limited to, changes in hydrology, pH, and electrical conductivity.

During wildfires, ecotones can act as smouldering hotspots where carbon loss from the margin can constitute about 50 to 90 % of the total peatland carbon loss. Aside the carbon loss, steady drops in both local and regional groundwater can occur (Mayner et al., 2018). Drops in groundwater may further increase the risk of wildfires (high smouldering effect) in peatlands leading to the significant loss in the peatland carbon as well as key peatland ecohydrological functions (Elshehawi et al., 2019). Studies have shown that the long term maintenance of permanent peatlands with up to 10 m thick of peat is determined by high and steady water table regimes (Grundling et al., 2013; Kelbe et al., 2016). Sensitivity of the ecotone implies they are more likely (higher risk) to be affected by wildfire and thus it is important to study the ecotone especially when the warming climate is likely to cause more wildfires in the future.

Understanding the gradients on the ecotone can also be beneficial to peatland restoration because the ecotone can act as a reference for artificially created ecotones. Choosing an “appropriate” reference ecotone to study can be challenging because there are no specific laid-out criteria and standard procedures for ecotone creation. The process of choosing a reference requires the selection of naturally undisturbed peatland sites that can potentially represent a stage in which the created ecotone is likely to go through at a particular time.

Literature on Manitoba peatland ecotones is limited. Some studies in Manitoba have focused on boreal-tundra or arctic-subarctic ecotones (Harper et al., 2011; Mamet and Kershaw, 2013; Shinneman et al., 2016). In one study, a survey was conducted to find the differences in lake response to recent climate change (Shinneman et al., 2016). Other studies have focused on ecotones as habitats for fauna while some have discussed tree spatial patterns along ecotones within the context of climate change. But specific studies that focus on the gradients created by abiotic factors across natural peatland ecotones have been less explored in Manitoba. Therefore, this study aims at exploring ecohydrological gradients that exist across natural peatland ecotones which may be relevant in studies on climate change.

Therefore, the objective of this paper is to assess the ecohydrological gradients of bog-fen transitions in southeastern Manitoba.

2.2 Study site

The study sites are in South-eastern Manitoba, located within the Julius Bog complex which is within the boreal forest of the Manitoba lowlands (49°58'59.0"N, 96°10'23.6"W) stretching across the Precambrian shield (Bannatyne, 1980) (Figure 2-1). The Precambrian shield is predominantly granitoids (mainly granite and granite gneisses) and mafic metavolcanics (Bannatyne, 1980).

The closest (~ 23 km away) Environment Canada weather station with 30-year normal is Beausejour, which has annual precipitation of 570.3 mm of which 117.8 cm falls as snow (Environment and Climate Change Canada, 2021) and average January and July temperatures of -16.9 ℃ and 19.3 ℃, respectively (Environment and Climate Change Canada, 2020).

In July 2019, a natural bog to fen transition (Moss Spur 1) was instrumented with 2 parallel transects (Table 2-1) comprising wells and piezometers. The transects were ~200 m long starting in the bog and ending in the fen.

The bogs at Moss Spur 1 are treed bogs dominated by a surface cover of *Sphagnum* with black spruce, tamarack, and Labrador tea, while the fens were dominated by sedges. Each transition zone had a mixture of vegetation from both the bogs and fen

In May 2020, four additional transects (South Julius; Table 2-1) were established. Transects were shorter (~100 m) starting in the fen and ending in the bog. Vegetation at South Julius was similar to vegetation at Moss Spur 1.

Transects at Moss Spur (MS) were labelled based on cardinal direction at the site (MS-W vs. MS-E), the same is true for South Julius (SJ), however, the addition of a N and S prefix to denote the area of the transects within the peatland. The cardinal directions were also used to label wells with additional numbers or letters. Each transect started at 0 m from the fen.

All transects are located more than 500 m from the closest part of the peat extraction sites (Figure 2-1), suggesting that they are undisturbed, yet close enough to be accessible for repeated measurements. Figure 2-2 shows a map on how wells were installed along transects at each location and the distance between the wells.

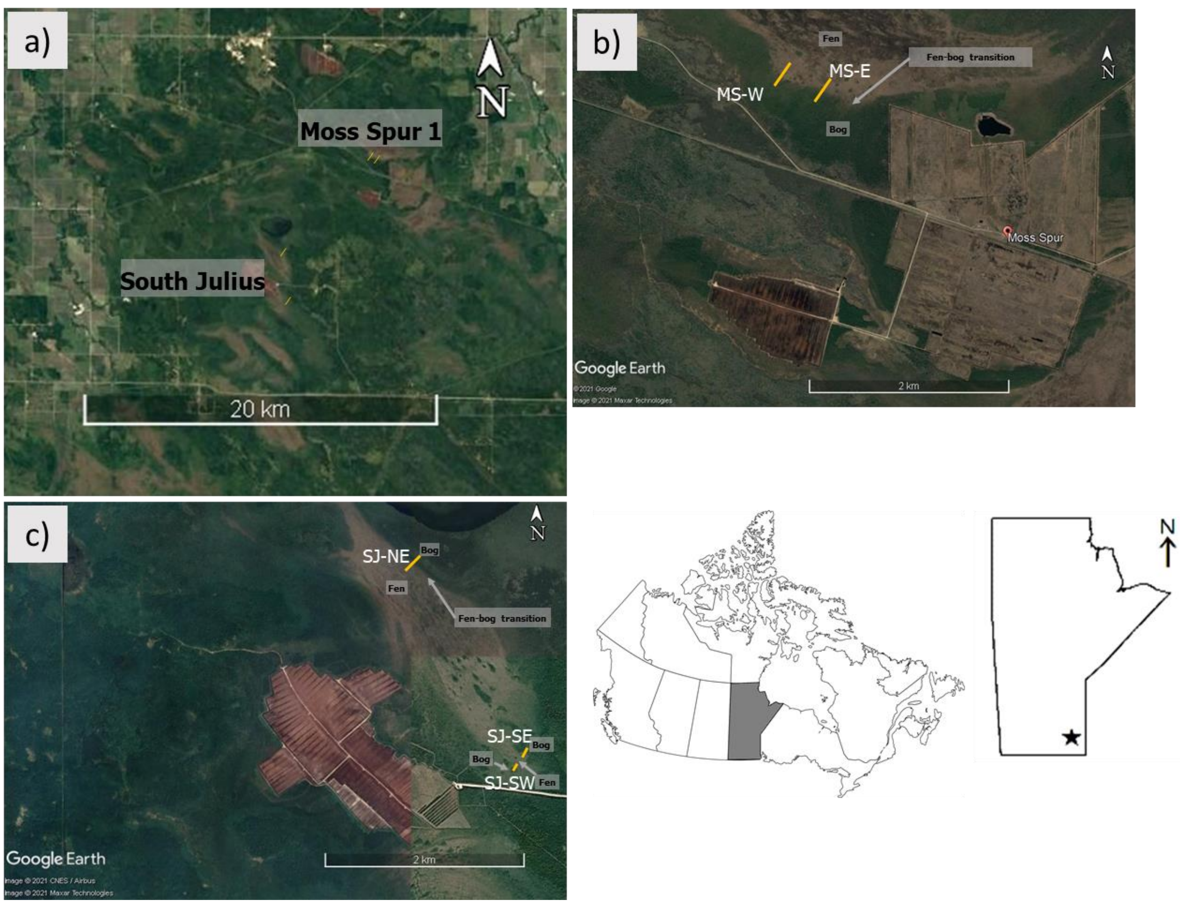

Figure 2-1: Study sites. Yellow lines indicate transects, a) Aerial view of both Moss Spur 1 and South Julius natural sites, b) Moss Spur 1 (MS) with transects, c) South Julius (SJ) with transects

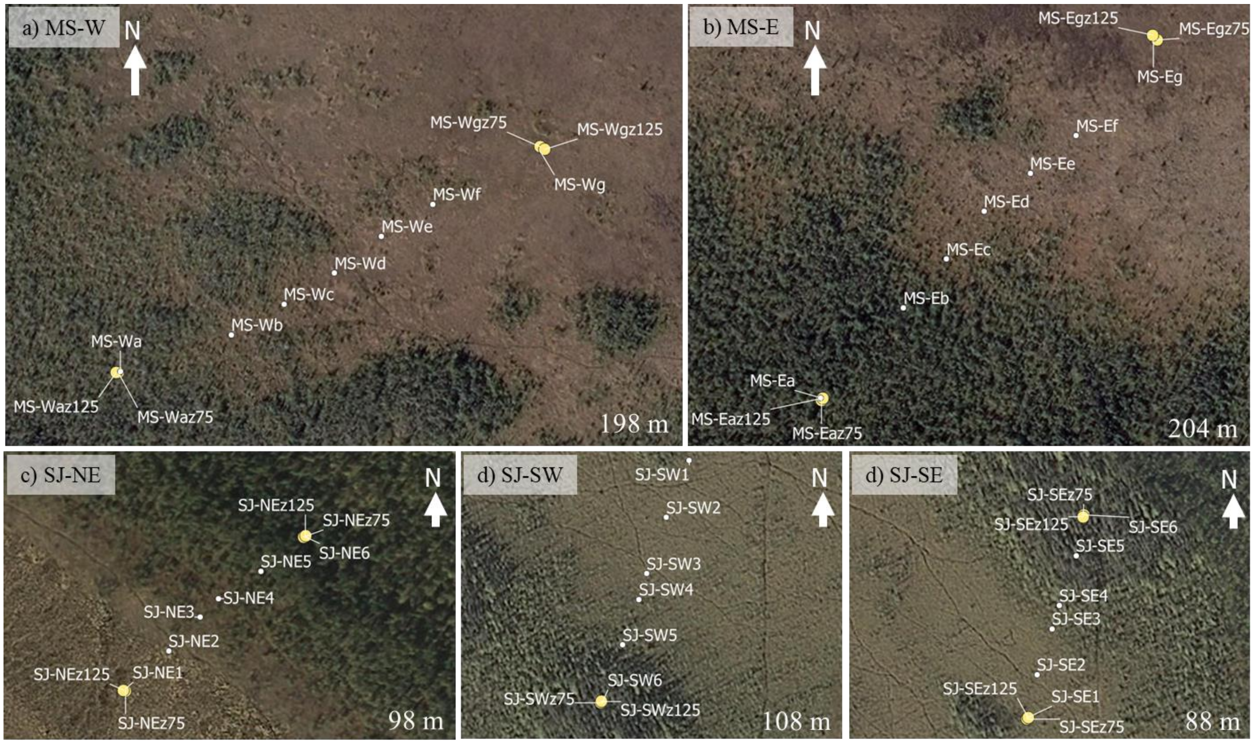

Figure 2-2: Location of wells (small white dots) and piezometers (large yellow dots) along transects

Table 2-1: Undisturbed natural peatland ecotone (MS and SJ)

Site	**Transect**	**Middle Coordinates**		**Low MASL**	**High MASL**	**Mean (MASL)**	**Approx. Transect length (m)**
		Northing	**Easting**				
Moss Spur 1 (MS)	MS-W	50° 0’ 5.40”	96° 9’ 48.96”	282.2	282.7	282.4	198
	MS-E	50° 0’ 0.00”	96° 9’ 29.52”	282.0	282.5	282.3	204
South Julius (SJ)	SJ-SE	49° 56’ 20.76”	96° 13’ 39.00”	278.0	278.5	278.2	88
	SJ-SW	49° 56’ 20.76”	96° 13’39.00”	278.0	278.5	278.2	108
	SJ-NE	49° 57’ 24.48”	96° 14’ 34.44”	277.5	278.1	277.8	98

2.3 Methods

2.3.1 Well and piezometer construction, installation, and measurement

Wells and piezometers were constructed from 2.54 cm diameter PVC pipes. Wells ranged from 1 m to 3 m long depending on the peat depth and water table. Piezometer (20 cm slotted intakes) lengths were 75 cm and 125cm and each of these piezometers were used to create nests at both ends of each transect (i.e., in bog and fen). Pipes were installed into pre-augured holes slightly smaller in diameter than the pipe. Pipes were measured manually (depth below ground surface) with blow sticks at least once a week from July to August 2019 and May to August 2020. Pipes were purged/developed and hydraulic conductivity *(K_{sat})* (Hvorslev, 1951) was measured 1 time in 2019 and 10 times in 2020. Piezometers installed at the start and end points of each transect were used to determine the hydraulic gradient which in turn was used to determine specific discharge of groundwater using Darcy's law.

2.3.2 Elevation measurements

Ground surface and well top elevation along each transect was determined using an RTK system using a locally established, but geocorrected, benchmark. The RTK system includes a Leica GS14 receiver, a CS 20 data logger known as a film controller, running the Leica Captivate application, and a GX1230 base station (with GFU radio). All subsequent elevation measurements were done with the RTK system. The slope of each transect was then determined based on rise and run. Clay elevations were also determined by subtracting peat depths at each well location from the corresponding surface elevation values.

2.3.3 Electrical conductivity and pH

Measurement of pH and EC were completed at both MS and SJ on 4 and 6 August 2020 respectively using pH/EC tester from Hanna instruments (pH accuracy: ± 0.05, EC accuracy: ± 2%). For pH, the tester was calibrated using 4.01 and 7.01 pH buffers. True average pH values were the calculated using an arithmetic average of the hydrogen ion concentration rather than measured pH values. EC and pH were measured from water samples taken from each single well along a transect. EC measurements were corrected using the relationship presented by Rydin and Jeglum (2006):

$$EC_{corrected} = EC_{measured} - EC_{+H} \qquad \text{Eq. 2-1}$$

where $EC_{+H} = 3.49 \times 10^5 \times 10^{-pH}$ and 3.49×10^5 is the conversion factor for field measurements standardised to 25°C)

2.4 Results

The seasonal (May 1 to Sept 30) totals for precipitation were 366 mm and 281 mm in 2019 and 2020, respectively, compared to the 30-year climate normals of 374 mm. The average monthly temperatures were within 1℃ of the normals for all months except for May and September in all years. The May monthly temperature for all years were ~5℃ colder than normal. September 2019 and 2020 were ~2℃ colder than normal. Two single large rain events (40 mm/24 hours in 2019 and 50 mm/24 hours in 2020) helped reduced to deficit indicating that all study years drier than normal.

In 2019 MS-E and MS-W had an average water table depth (WTD) of -35.1 ± 13.2 cm and -20.5 ± 20.1 cm respectively. Average water table in the bogs were -46.7 ± 7.1 cm and -34.7 ± 18.6 cm for MS-E and MS-W respectively. At the transitional zones, MS-E had an average of -38.7 ± 7.3 cm while MS-W was -23.1 ± 18.8 cm. For average water table in the fen, MS-E was -18.1 ± 6.0 cm while MS-W was -2.6 ± 3.5 cm. It was observed that WTD on each transect trended bog > transition > fen.

The 2020 average WTD for MS-E and MS-W were -26.6 ± 12.1 cm and -11.6 ± 19.4 cm respectively, representing an overall rise of ~8 cm of water on both transects from 2019 to 2020. For the additional transects at South Julius, SJ-NE had the highest overall WTD (-14.2 ± 15 cm) while SJ-SW had the least (-7.9 ± 9.0 cm). Similar to Moss Spur, the SJ-NE also trended bog>transition>fen but surprisingly SJ-SW and SJ-SE trended bog > fen > transition (Table 2-2). All of the transects except SJ-SE and SJ-SW had bog water tables ~30 cm lower than in the fens. Along the transects, there was only a slight change in water table elevation **(**Figure 2-3**)**. The difference between water table elevation in the bog and fen was less than 10 cm (over a distance of at least 80 m), ranging from 0.6 to 9.5 cm, for all transects, indicating a generally flat water table along transects. This difference represents a gradient less than 0.001 for all transects. Also, maximum, and minimum WTD (2020) were generally parallel to the ground surface elevation profile (Figure 2-3) across all transects. Surface elevation profiles in the fens are also flatter at SJ-SW, SJ-SE, and SJ-NE (Figure 2-3).

The boxplot showed that individual wells installed within the fens showed no differences in WTD on each transect at the South Julius site (Figure 2-4). Wells within the transition zone generally showed differences on each transect at all sites except on transect SJ-SW. Except for the SJ-SE site, WTD was also significantly different for wells within the bogs for each transect. The boxplot further showed that WTD generally trended bog > transition > fen which was expected.

There was an inverse relationship between relative surface elevation (i.e., relative to the mean elevation of the transect) and water table (Figure 2-5), such that higher elevations (the bogs) have lower water tables (depth below surface), and the lower elevation (fens) had higher water tables. Relationships were typically very good, with R^2 exceeding 0.92 with four transects having similar R^2 values and MS-E showing the most different R^2 value. Compared to all other transects, water table at MS-E was only ~20 cm lower in the lower elevation, but similar in the higher elevations (i.e., bogs were similar, but fens less so). SJ-SE and MS-E showed the highest (-1.34) and lowest (-0.80) regression slopes respectively. SJ-SE (-0.80) and SJ-SW (-0.85) had similar regression slopes.

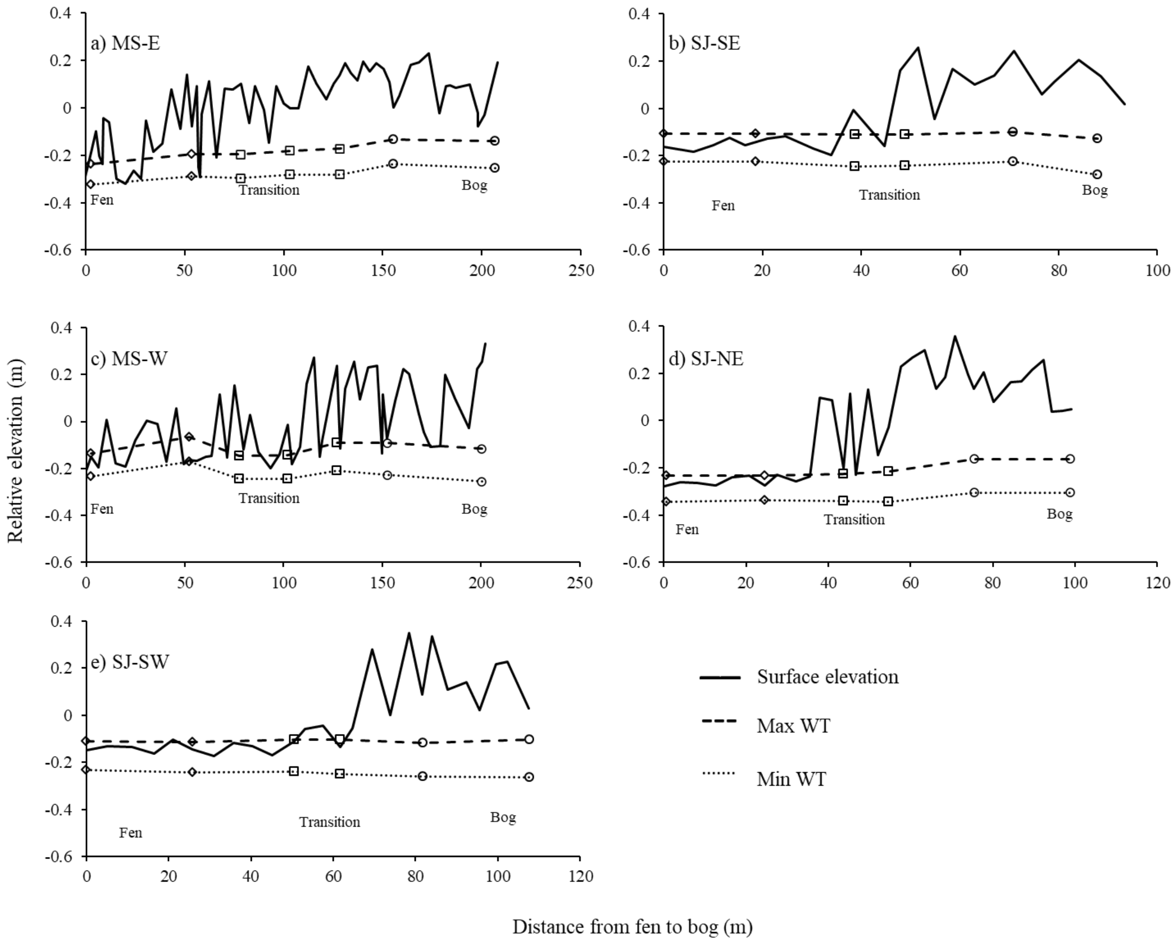

Figure 2-3: Relative surface elevation (relative to the mean elevation of the transect), minimum and maximum water table (WT) along each transect in 2020. Diamond points, square points and circular points represent fen, transitional zone, and bog respectively.

Table 2-2: Summary of average WTD for ecotone transects

	2019				2020			
	Bog	Transition	Fen	All	Bog	Transition	Fen	All
MS-E	-46.7 ± 7.1	-38.7 ± 7.3	-18.1 ± 6.0	-35.1 ± 13.2	-37.3 ± 7.6	-29.7 ± 6.5	-11.3 ± 5.4	-26.6 ± 12.1
MS-W	-34.7 ± 18.6	-23.1 ± 18.8	-2.6 ± 3.5	-20.5 ± 20.1	-24.9 ± 18.9	-14.2 ± 17.5	5.7 ± 4.6	-11.6 ± 19.4
MS	-40.7 ± 15.2	-30.9 ± 16.2	-10.3 ± 9.2	-27.8 ±1 8.4	-31.1 ± 15.6	-22.0 ± 15.3	-2.8 ± 9.9	-19.1 ± 17.8
SJ-NE					-32.1 ± 5.1	-12.6 ± 7.0	2.2 ± 2.3	-14.2 ± 15
SJ-SE			not installed		-24.8 ± 5.6	-8.4 ± 7.6	-10.0 ± 11.3	-11.9 ± 11.0
SJ-SW					-13.0 ± 5.7	-3.6 ± 4.3	-9.1 ± 11.2	-7.9 ± 9.0
SJ					-26.1 ± 9.3	-8.5 ± 7.4	-6.3 ± 10.9	-11.6 ± 12.4

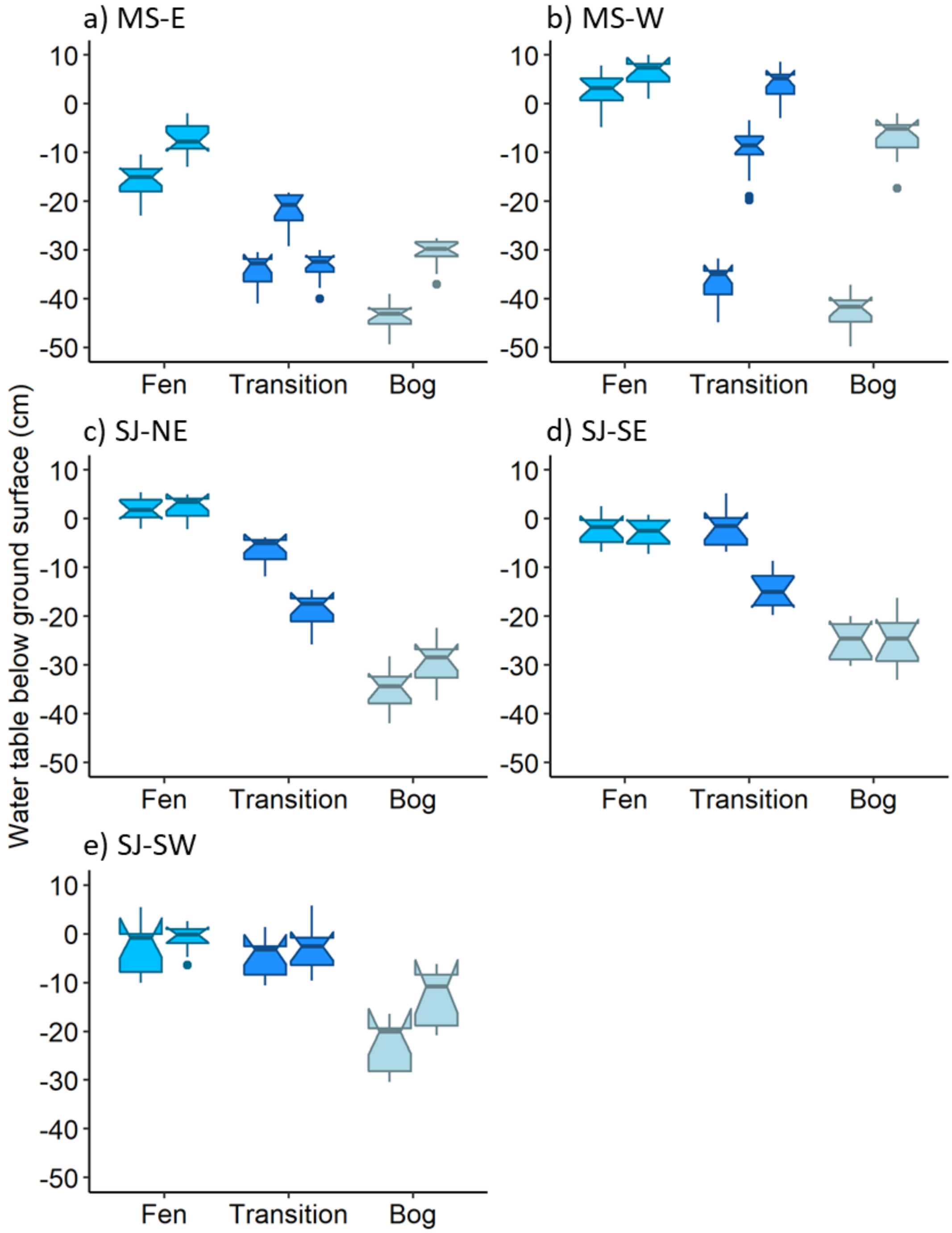

Figure 2-4: Boxplots showing the range of WTD for each well within each peatland unit from 22 May to 18 August 2020. Each boxplot represents a single well with >10 measurement points (though most are >15).

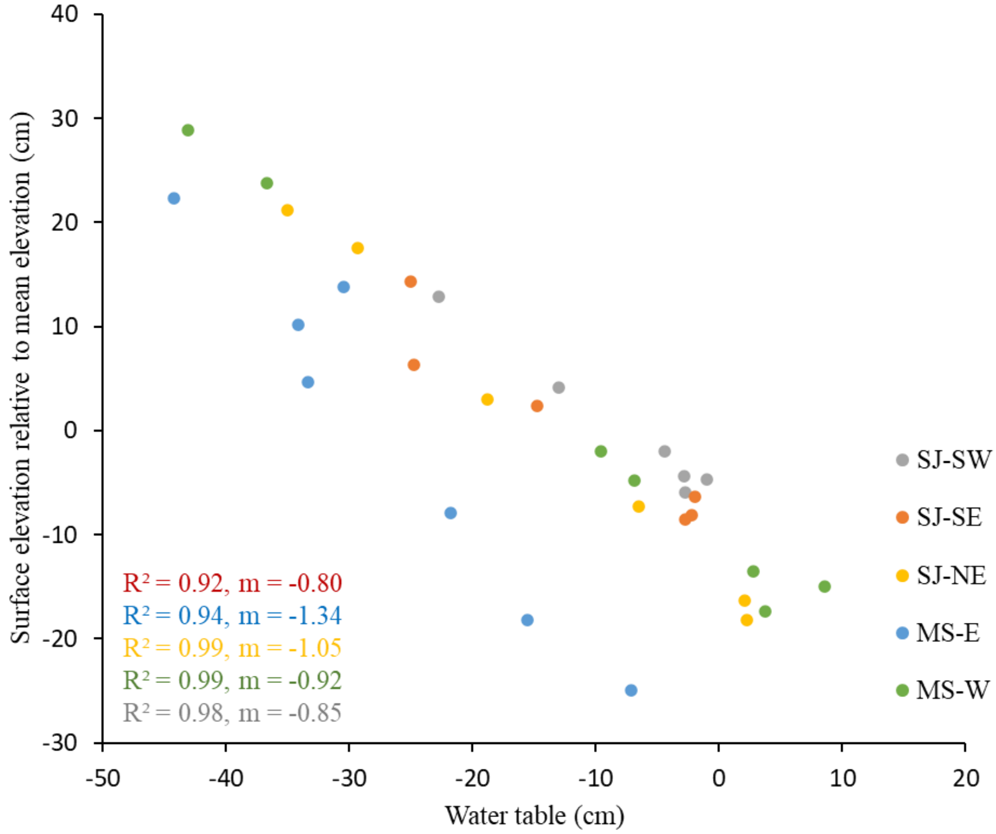

Figure 2-5: Relative surface elevation (relative to mean elevation for the transect) versus average water table for the 2020 season. Each point represents a single well along the transect

Hydraulic conductivity (K_{sat}) results from August 2019 at 75 cm and 125 cm depths within the bog declined with depth on one but slightly increased with depth on the other (MS-E) (Figure 2-6a). The 2019 results (recall – only 1 test was completed) were compared to the 2020 results (10 tests) and K_{sat} declined with depth (Figure 2-6b) at all locations. Additional K_{sat} data collected in 2020 also showed that K_{sat} generally increased near the fen-transition zone for all transects (Figure 2-6c). K_{sat} values were lower in the bogs on almost all transects compared to fens.

All hydraulic gradient values obtained over the season in bogs and fens that were compared showed both recharge (+) and discharge (-) conditions (Table 2-3). In the bogs, MS-W had the highest vertical gradient (0.071) while in the fen both SJ-SW and SJ-SE had the highest (0.049) (Table 2-3). Even though MS-E and MS-W were only 500 m apart, their gradients in the bog varied more (difference of 0.088). But in the fens for the two transects, gradients varied less (difference of 0.017). Geomean K_{sat} values from shallow piezometers (75 cm depth) were used to determine the specific discharge. Shallow piezometer was used due to the potential for flow to occur in the upper layer of the peat. For specific discharge values shown, only MS-E was discharging (upward flux) within the bog and the fen. SJ-SE appeared to be recharging (downward flux) more (0.111 m/day) within the bog while both SJ-NE recharged more in the fen through time (Figure 2-7b and Figure 2-7d).

Also, horizontal gradients and flow across each ecotone was determined (fen-to-bog) using wells installed at the "start" and "finish" locations of each transect (Figure 2-8). Gradients across ecotones were generally low and the flow along most transects (across the ecotones) were almost negligible (< 0.1 mm/day) (Figure 2-8b).

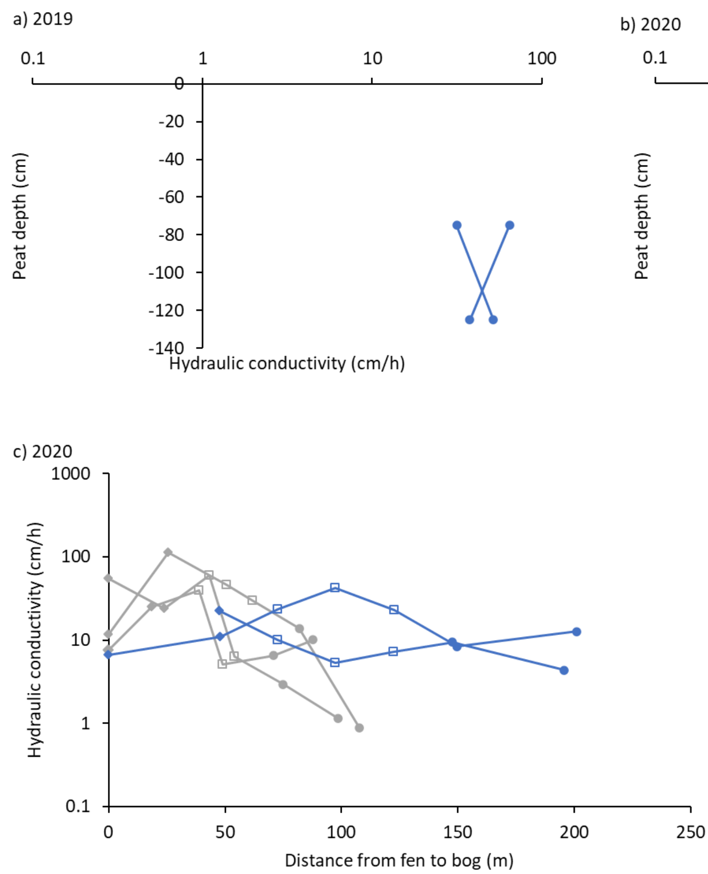

Figure 2-6: Changes in hydraulic conductivity with peat depth for piezometers within a bog or a fen for Moss Spur (blue) and South Julius (grey) in a) 2019 and b) 2020. c) Changes in hydraulic conductivity per well along each transect. Circular, square and diamond points represent bog, transition, and fen respectively.

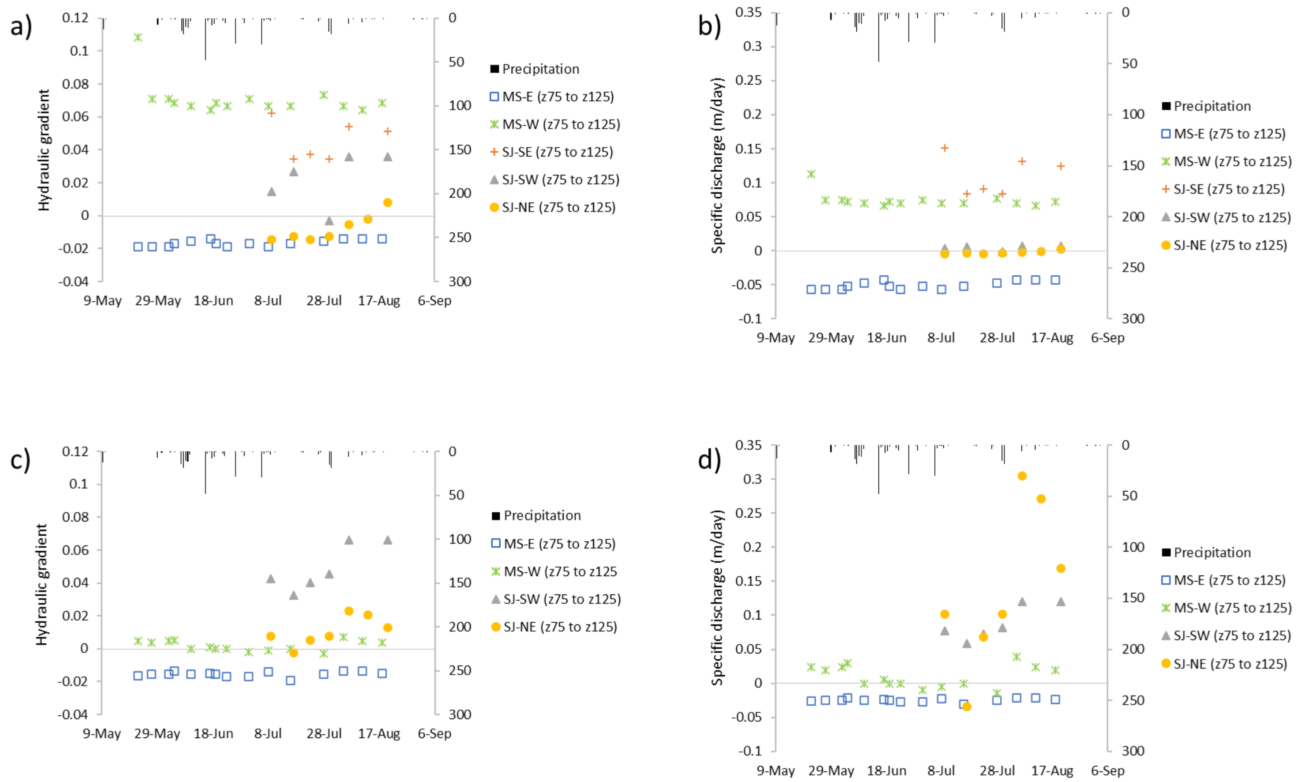

Figure 2-7: a) and c) are timestamps for vertical hydraulic gradients measured in bogs (top) and fens (bottom) respectively. b) and d) are timestamps for specific discharge in the bog (top) and fen (bottom) respectively. Note that a) and c) have the same vertical scale and b) and d) also have the same vertical scale. A positive value means groundwater recharge

Table 2-3: Gradient and specific discharge measured exclusively in fens and bogs. (-)ve values are discharge.

		Average gradient		Specific discharge (mm/day)	
		Fen	Bog	Fen	Bog
Moss Spur	MS-E (z75 to z125)	-0.015	-0.017	-24.0	-50.0
	MS-W (z75 to z125)	0.002	0.071	10.0	74.0
South Julius	SJ-SW (z75 to z125)	0.049	0.022	88.0	5.0
	SJ-SE (z75 to z125)	0.049	0.046	88.0	111.0
	SJ-NE (z75 to z125)	0.011	-0.007	140.0	-2.0

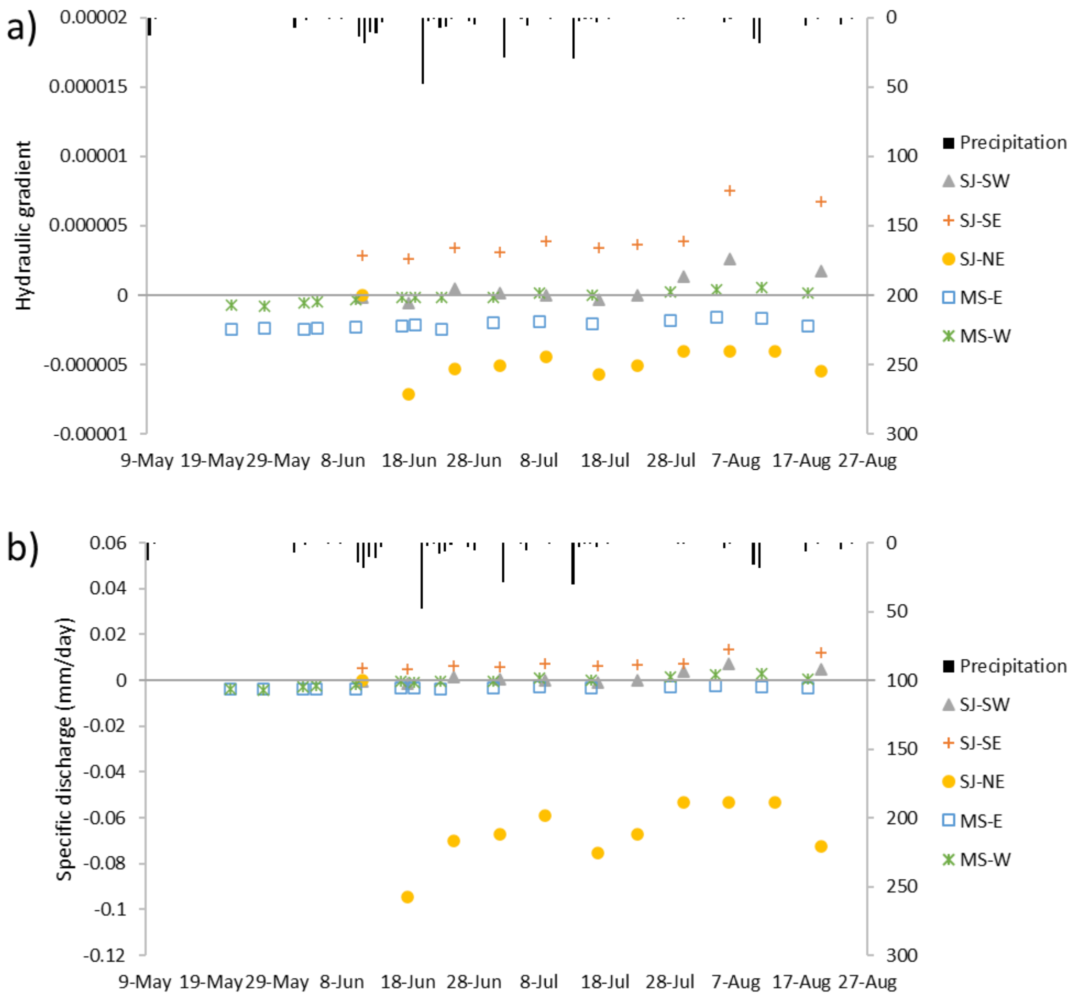

Figure 2-8: a) Horizontal hydraulic gradient. b) Specific discharge. +ve means from bog to fen

The means of the surface elevation of each of the Moss Spur transects were not very different (difference of 7 cm). These similarities were possibly the result of similarity in landscape positions. The slope for the two transects were also similar for MS-E (0.47 over 215 m) and MS-W (0.46 over 208 m). For the slopes along transects at South Julius, SJ-SW was 0.2 over 108 m, SJ-NE was 0.4 over 98 m and SJ-SE was 0.2 over 88 m making most of them similar (~0.002) except for SJ-NE (0.004).

Clay elevation increased from the fen to bog at Moss Spur (Figure 2-9a, c), however, was mostly flat at South Julius (Figure 2-9b, d, e). Average peat depth was higher at MS (3.04 ± 0.77 m) than SJ (1.97 ± 0.32 m) confirming that clay was generally flatter at SJ than MS. Overall average peat depth for all transects was 2.45 ± 0.71 m with averages per transect ranging from 1.7 m to 3.0 m.

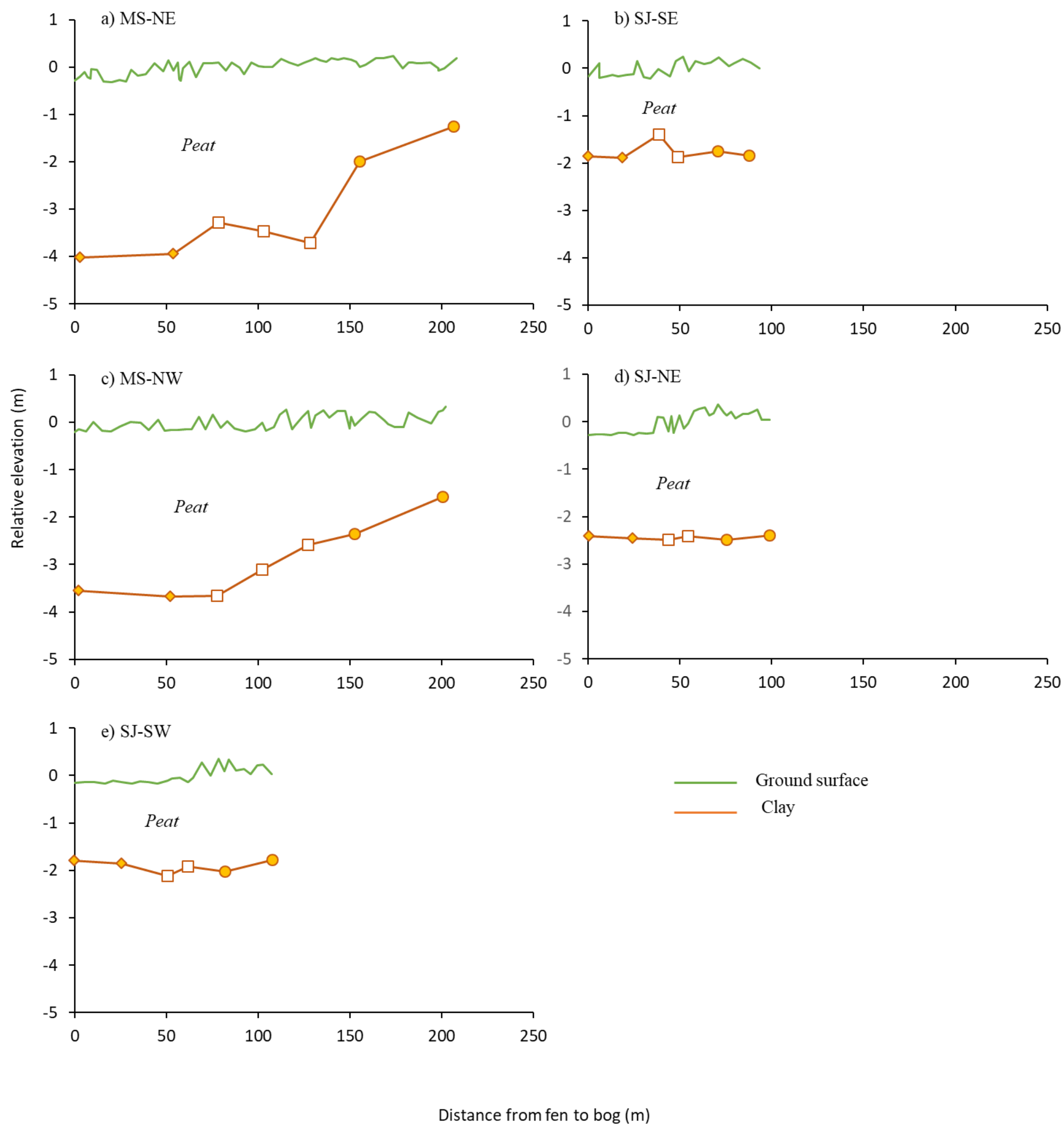

Figure 2-9: Clay elevations along transects at Moss Spur (a and c) and South Julius (b, d, and e). Circular, square and diamond points indicate bog, transition, and fen respectively.

Values for pH and EC generally decreased from fen to bog (Figure 2-10). On average, pH values at South Julius ($pH_{(Bog)}$ = 5.64, $pH_{(Transition)}$ = 5.90, $pH_{(Fen)}$ = 6.24) were generally higher than Moss Spur ($pH_{(Bog)}$ = 5.33, $pH_{(Transition)}$ = 5.65, $pH_{(Fen)}$ = 5.78) but the differences were not significant. On average, $EC_{corrected}$ values also decreased from fen to bog with higher values at the South Julius site ($EC_{(Bog)}$ = 282.35 ± 207.78, $EC_{(Transition)}$ = 245.35 ± 166.95, $EC_{(Fen)}$ = 411.75 ± 117.75) compared to Moss Spur ($EC_{(Bog)}$ = 98.59 ± 59.17, $EC_{(Transition)}$ = 157.70 ± 75.22, $EC_{(Fen)}$ = 158.41 ± 42.80). Values appeared to decrease sharply near the fen-transition zone at the South Julius site. One transect (SJ-SW) consistently recorded higher than the average values.

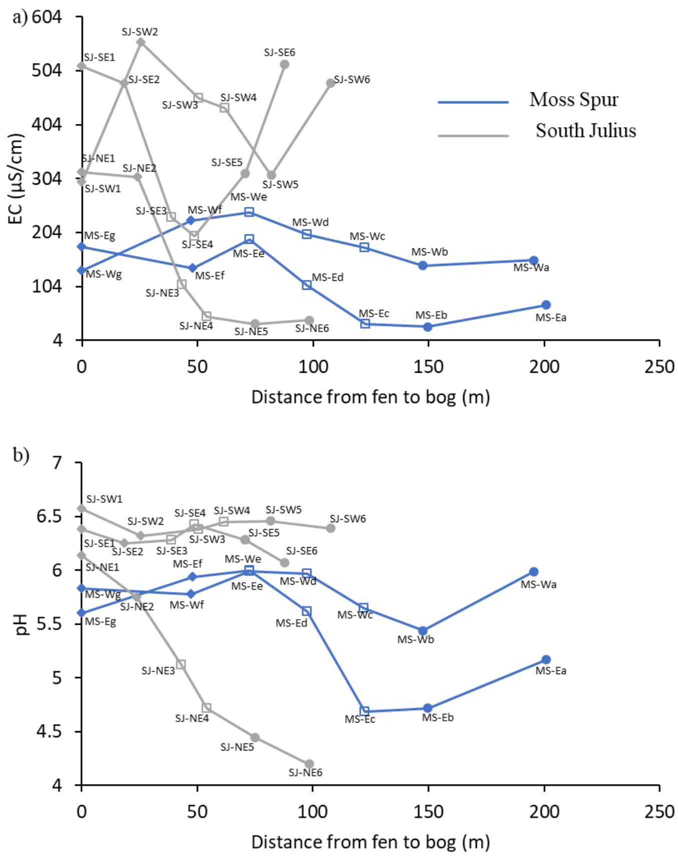

Figure 2-10: Changes in pH and EC along each transect (2020). Diamond dots are in the fen, square dots are in the transition zone, and circular dots are in the bog.

2.5 Discussion

There was a deficit in precipitation from May to September of 8 mm and 93 mm in 2019 and 2020 compared to the 30-year climate normal of 374 mm. The average monthly temperature was highest in July for all years with July 2020 having the overall highest average temperature. Even though 2019 had near normal precipitation, it was one large rain event that helped reduce the deficit. Larger singular rain events do not help with preventing *Sphagnum* desiccation or vegetation establishment.

Ecotone laggs are classified as either confined or unconfined (Langlois, 2014; Paradis et al., 2015). The topographical gradient of confined ecotone slope towards the lagg on both sides (with narrow thick peat layer) while unconfined slopes in one direction with gradual thin peat layer (Langlois, 2014; Paradis et al., 2015). The MS-W transect was the only observed confined ecotone lagg due to the local minimum elevation at the transition (Figure 2-3). The transition for all other transects were classified as unconfined. The differences in transition type have been noted to influence the input of fen/bog water to the transitional zone (Howie et al., 2008; Howie, 2013).

Naturally undisturbed peatlands are characterised by their high water tables (above or near -40 cm) even during the driest (summer season) periods of the year. Even though the total precipitation between 2019 and 2020 were different, the difference in average water table between 2019 and 2020 was only 8 cm at Moss Spur. Fens tend to have a nearer to surface water table than bogs which was what was observed in this study (~30 cm lower). This means that the fens became more flooded while water was locally trapped mostly within the hollows of the microtopography within the bogs. The hollows were formed between *Sphagnum* hummocks, some exceeding 50 cm in height. The surface elevation in the bogs were higher than in the fen (Figure 2-3). An inverse relationship between water table depth and surface elevation confirmed that lower water table (from ground surface) was towards the bogs (Figure 2-5). Water table at the transitional zones (ecotones) between the bogs and fens therefore tend to be intermediate (Figure 2-4). The fact that the maximum and minimum (measured in late summer) water table (Figure 2-3) have similar configuration indicate that water table at fen-to-bog (ecotone) margins is uniform. Like surface elevation, water table elevation was higher in the bogs than in the fens (Figure 2-3). Differences in total head (of water) elevation determines the direction of groundwater flow. This means that apart from transect SJ-SE and SJ-SW, the overall net flow of groundwater was from bog to fen for all transects (Figure 2-3).

Peat thickness along transects at Moss Spur 1 were generally higher in the fen and decreased towards the bog (Figure 2-9) as a result of the differences in clay elevation. These changes in peat thickness were not observed for South Julius due to the flatter clay elevation. This could suggest differences in the genesis and formation of the two peatland sites and their ecotones. Even though differences existed in peat depth, water table profiles and water table depths between the two study sites showed similarities, suggesting that autogenic and allogenic factors that control the peatland's evolution and development may be similar.

The decrease is K_{sat} with depth observed here is consistent with other peatland studies and it is often attributed to the differences in peat properties based on the degree of decomposition (Kurnianto et al., 2019), though these properties were not measured in this study. Trend in K_{sat}

measured from wells along the transects also showed higher values near the transitional zone (Figure 2-6c).

Gradients between the shallow (75cm) and deep (125 cm) piezometers showed recharge (downward flux) conditions within the bogs and fens for 4 of 5 of the transects except transect MS-E and within the bog of transect SJ-NE. Even though no piezometers were installed within the transitional zone, it could potentially be acting as a discharge zone with upward flux as was found by (Paradis et al., 2015). The highest average downward flux was measured in the fen. However, net groundwater flow across the ecotone between the fen and bogs were low. Daily flow was mostly from bog to fen with occasional switch in flow from fen to bog. These switches were not surprising as other studies have noted that groundwater flow is able to switch direction, a phenomenon known as groundwater flow reversal (Price, 2003).

The lagg/ecotone chemistry has been shown to be highly variable (Paradis et al., 2015), which is consistent with the results found in this study (Figure 2-10). The differences in pH between the transition zone and the bog and fen were similar even though the bog was more acidic than the fen. Comparing $EC_{corrected}$ for bog, transitional zone and fen, $EC_{(bog)}$ and $EC_{(transition)}$ were similar at South Julius. This could indicate that the adjacent bog had more influence on the transitional zone than the adjacent fen. At Moss Spur, $EC_{(transition)}$ and $EC_{(fen)}$ were similar, indicating the adjacent fen had more influence. These differences and similarities could provide insight into the delineation of the margin between the bog and the fen. EC and pH are part of the many chemical variables that determine the vegetation type and growth within peatlands (Paradis et al., 2015).

2.6 Conclusion

The hydrological characteristics of five ecotone transects at two sites were studied to detect similarities and differences. Comparisons in hydrology, topography, and water chemistry (pH and EC) were made. The objective of the thesis was to assess the hydrological gradients of bog-fen transitions in southeastern Manitoba. While there were similarities between the 5 transects, differences were also found, suggesting that, even with the same peatland complex, defining a 'characteristic' ecotone might be difficult. In the study, the hydrological and topographical gradients along natural ecotones are gradual. The ecotones were characterised as having high water levels and had pH and EC characteristics that were intermediate between the fens and bogs which bounded them. The surface topography of the ecotone appeared to influence the way groundwater flows on the ecotones with water level being closer the ground surface in the fen than in the bog. The ecotone was also determined to be potential groundwater discharge zones. Studying natural peatland ecotones within the hydrogeomorphic setting and weather conditions in Manitoba is important in modifying restoration goals in the province and helps to understand the overall integrity ecotones bring to the peatland ecosystem.

3 Hydrology of a constructed ecotone at the periphery of a fen restoration, Manitoba, Canada

3.1 Introduction

Ecotones, the dynamic zones where two biological communities meet and integrate (Hartshorn et al., 2003), are essential parts of the peatland ecosystem (Mayner et al., 2018) and often occur along ecological gradients typically between bogs and fens. These ecotones allow for the flow of energy, water, and nutrients between the ecosystems. Disturbances to one (or both) of the communities, such as peat extraction activities, typically results in an unnaturally abrupt change and the removal of the ecotone. Therefore, integrating the concept of constructed ecotones during the restoration of extracted peatlands with their natural surroundings should be completed; however, it is not currently common practice, in part due to not being well understood.

The flow of water (and thus energy and nutrients) through natural ecotones is largely controlled by the water table depth (WTD) – transmissivity feedback (Waddington et al., 2015), where transmissivity (T) is the product of the saturated thickness of the aquifer (b) and the saturated hydraulic conductivity (K_{sat}). Thus, deep peat with a high water table (large b) and a high K_{sat} will transfer the most water (Danielle et al., 2017; Morris et al., 2015; Waddington et al., 2015), the bulk of which will occur through the acrotelm. The acrotelm is the upper ~50 cm of a peatland that is variably saturated but has a high K_{sat}, specific yield, large pores, and low bulk density (Price et al., 2003; Price and Ketcheson, 2009; Ronkanen and Kløve, 2005). Below the acrotelm is the catotelm, which is permanently saturated, but due to the highly decomposed nature of the peat (Dixon et al., 2017), has much smaller pores and thus a much lower K_{sat}. Peat extraction removes the acrotelm, leaving behind the (now unsaturated) catotelm peat, reducing the transmissivity.

The moss layer transfer technique (MLTT) (Lefebvre-Ruel et al., 2019) is a well-established and well tested bog peatland restoration method, that, briefly, requires recontouring of the fields, construction of small ponds/berms (optional), spreading of straw mulch and donor material, fertilizer, and finally ditch blocking. Early trials identified the need to retain water on the sites, such that small basins (ponds) and terraces (berms) were tested. Studies (Campeau et al., 2004; Price et al., 2002) have shown that basins (ponds) are effective in maintaining positive hydrological conditions for *Sphagnum* re-establishment on cutover peatlands due to the microclimates they create than terraces (berms) whose microtopography do not have an overall benefit.

The application of the MLTT in Canada has normally focused on restoring extracted peatlands into bogs (González and Rochefort, 2014). A disadvantage of this method may be that bogs solely depend on atmospheric precipitation and thus bog establishment is not likely to succeed in extreme drought years or drier climates. Fens can depend on both atmospheric precipitation and groundwater as compared to bogs and present a more complicated hydrology. Also, fen peat may be reached during a peat extraction project which may allow for the creation of conditions (pH, electrical conductivity) favourable for the establishment of fen vegetation (e.g., sedges) rather than bog vegetation (e.g., *Sphagnum spp.*).

Therefore, one solution for fen restoration, to encourage more water/nutrient flow and to mimic the naturally more complicated hydrology of fens, is to connect the restoration area with the surrounding landscape by creating artificial ecotones between the neighbouring ecosystem (often natural bog) and the restoration area, rather than an abrupt transition.

By applying this concept of gradual slopes (in natural peatlands) to fen peatland restoration, we can attempt to establish a system that ensures the flow of groundwater into restored fen sites while retaining water on the slopes. This study hypothesises that creating ponds and berms within the slopes on the periphery of extracted peatlands improve hydrological conditions and facilitates the development of restored peatlands into a fen ecosystem. Therefore, understanding the ecohydrological gradients across constructed ecotones is important as suitable water storage and soil water pressure (> -100 cm) are critical for the re-establishment of peatland species, which in turn, encourages the accumulation of peat (Price, 2003; Price and Whitehead, 2001).

The main objective of this paper is to determine the best water retention techniques to encourage hydrological connectivity along artificial ecotones; thus, how the presence of ponds and berms control water table position and water flow in a fen restoration. The specific objectives were to 1) establish an ecohydrological connection between the surrounding landscape and the fen restoration through a constructed ecotone and 2) determine a suitable ecotone slope treatment and its influence on water storage and flow across restored artificial peatland ecotones.

3.2 Study Site

The study site (Figure 3-1) is in southeastern Manitoba (49°58'59.0"N, 96°10'23.6"W) within the Moss Spur peatland extraction site, which is part of the Julius Bog complex. The Julius Bog is located within the Precambrian boreal forests of the Manitoba lowlands, and it straddles the Precambrian shield which is predominantly granitoids (mainly granites and granite gneisses) and mafic metavolcanics (Bannatyne, 1980). Peat extraction at Moss Spur began in the early 1940s and ended in 1999 (Gagnon et al., 2018), and at Moss Spur 2 (located 1 km south west of the main Moss Spur site) extraction began in the late 1990s and continued until 2018.

Beausejour, the closest (~ 23 km away) Environment Canada weather station with 30-year normal has annual precipitation of 570.3 mm of which 117.8 cm falls as snow (Environment and Climate Change Canada, 2019). The average January and July temperatures are -16.9 ℃ and 19.3 ℃, respectively (Environment and Climate Change Canada, 2019).

The surface elevation difference across the Moss Spur 2 fields prior to restoration was approximately 1.5 m with remnant peat thickness ranging from approximately 0.1 to 2.40 m. Vegetation was mostly absent, except for some cotton grass (*Eriophorum spp.*) colonising the cutover area. The periphery of the extraction area consisted of a perimeter ditch which was approximately 1 m deep and 1 m wide which connected the internal (30 m spacing) ditches to the main drainage canal at the eastern section of the site.

Running parallel to the perimeter ditch to about 5-10 m away from the field was a 1 m high berm, constructed from the removed ditch material (mix of peat and clay). A large portion of the perimeter ditch running across transect NE to transect NM (Figure 3-1g) had been invaded by cattails (*Typha spp.*). Beyond the berms was either dominated by remnants of *Sphagnum spp.* (bog peatland) or invasive species plants (upland) including raspberry (*Rubus ideaus*) patches as well as debris of tamarack (*Larix laricina*) and spruces (*Picea mariana*). Beyond the 5-10 m range for the berms, the section capturing transects E and W (Figure 3-1a, e) consisted of peatland vegetation (treed bog). Vegetation types include a huge dense stand of tamarack (*Larix laricina*) and spruces (*Picea mariana*). The northern and southern treed section was noted as upland forest with a densely populated amount of paper birch (*Betula papyrifera*) with tamarack (*Larix laricina*) and spruces (*Picea mariana*) spread across.

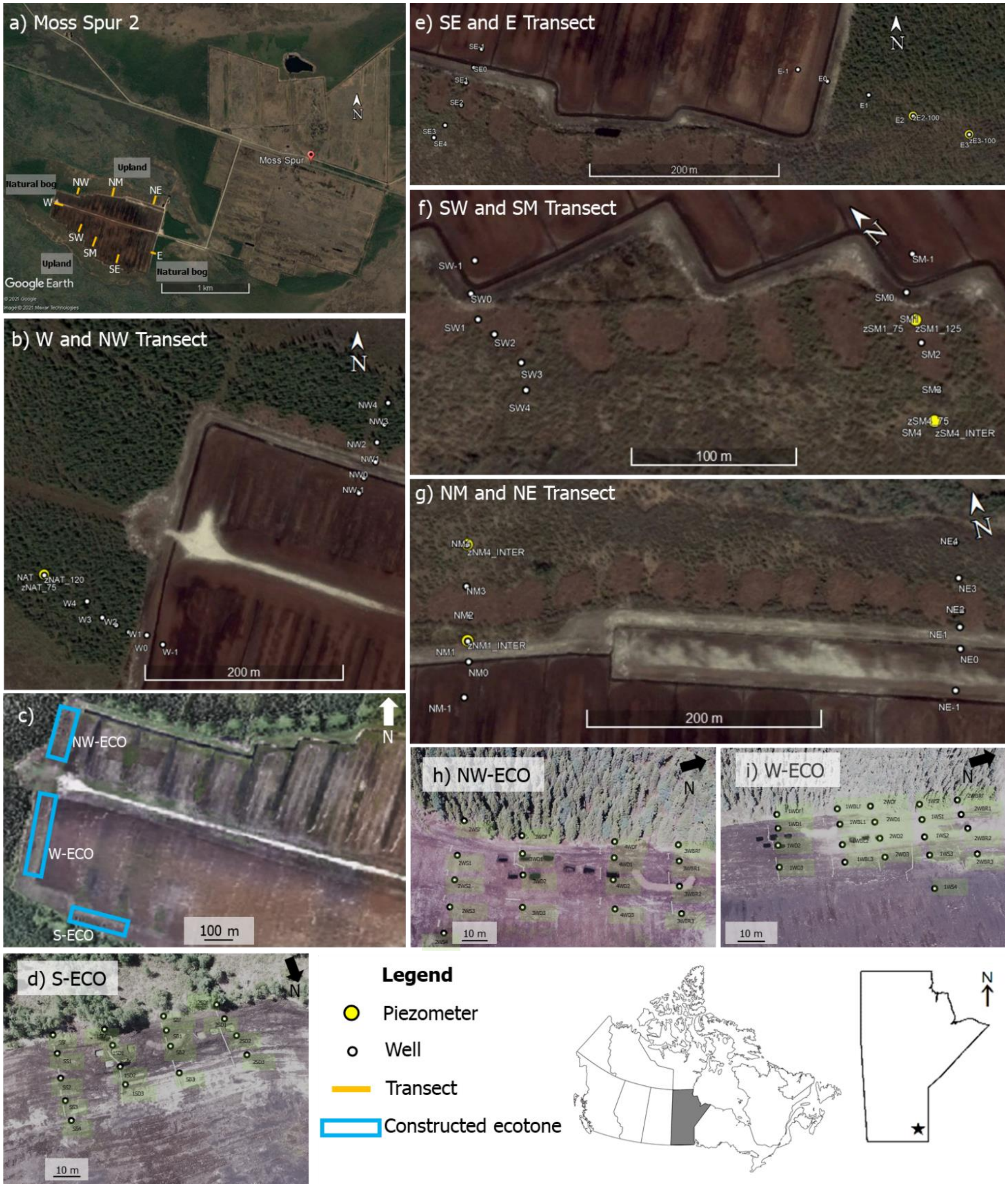

Figure 3-1: Study site with transects and ecotone sites

3.3 Methods

Pre-restoration monitoring took place between May and Sept 2019, and in Sept/Oct 2019 some restoration activities took place, with post-restoration monitoring occurring May to August 2020. Unfortunately, the restoration was halted in October 2019 due to heavy rain (107 mm over a few days), and, due to COVID-19 and equipment limitations, were not resumed in 2020. The original plan was to include the entire perimeter of the peatland (3.8 km) with replicates of the slope treatments (outlined below), but this did not occur. Therefore 2020 (May to Aug) was the main "post" restoration field season, but only for a small (mostly the western section) of the site was completed. (n.b. Restoration was completed in the fall of 2021, after the data collection period).

Restoration consisted of reprofiling the fields to remove the camber between the internal drainage ditches which helped infill any remaining internal ditches. Next, the berm material was used to infill the perimeter ditch starting at the middle of the western edge and working both clock- and counter-clockwise from that point; however, this was halted after only a few weeks due to the heavy rains. After the ditch was infilled, the surrounding ecosystem was "connected" to the restoration area with a slope (details below) forming the ecotone. The part of the perimeter that was able to be completed was divided into three sections called the NW-ECO (northwest ecotone), W-ECO and S-ECO (Figure 3-1d, h, i).

The three ecotone sections (NW-ECO, W-ECO, and S-ECO) (Figure 3-1, c, d, h, and i)) were approximately 100 m x 30 m and used to test 4 treatments to retain water on the slope. Treatments comprised: i) 5 pond configurations ("5-Pond"), ii) 3 pond configurations ("3-Pond"), iii) Berm ("1-Berm" and/or "2-Berm") and No treatment ("Control"). Treatments were replicated in all three sections of the experimental site. Treatments were applied in a pattern such that one alternated the other and each single treatment was separated by 5-10 m. Ponds were 3 m x 3 m with a depth of ~0.8 m. Berms were constructed from peat and were ~10 m long and 30 ± 20 cm high

3.3.1 Meteorological station

Meteorological stations located in the middle of the extraction/restoration area and the natural peatland on the west side at the study site were used to collect data from 14 June 2019 to 26 October 2019 and from 5 May 2020 to 19 August 2020. Both meteorological stations comprised a rain gauge (Texas Instruments 525), a net radiometer (Kipp and Zonen NR Lite), a temperature & humidity (HCS3) sensor all connected to a Campbell Scientific data logger (CR1000) running every minute and logging data at 15-minute intervals.

3.3.2 Well and piezometer construction, installation, and measurement

Wells and piezometers were constructed from 2.54 cm diameter PVC pipes. Wells ranged from 1 m to 3 m long depending on the peat depth and water table. Piezometer (20 cm slotted intakes) lengths were 50 cm, 75 cm, 120 cm, and an additional deeper piezometer where the length was the local depth to clay (between 120 and 220 cm). Pipes were installed into pre-augured holes slightly smaller in diameter than the pipe. Pipes were measured manually (depth below ground surface) with blow sticks tri-weekly from May to August 2019 and 2020, with a few “one off” measurements in Oct 2019 during the restoration. Wells and piezometers were developed prior to any testing, and after installation/start of a new field season.

Eight transects (named after their approximate cardinal locations, Figure 3-1a, with M being “middle”) were established along the perimeter of the restoration area and located ~400 m apart to capture the heterogeneity of the surrounding ecosystems. The transects began within 17 m of the ditch in the peat extraction area and ran perpendicular into the peatland/forest for a distance between 70 and 120 m from the ditch. The ditch is considered the 0 m point, where negative values are in the extracted site and positive values are away from the extracted site. On the constructed ecotone slopes (NW-ECO, W-ECO, S-ECO), mini transects consisting of 4 wells were installed (Oct 2019) through the treatments and measured tri-weekly in 2020.

Pipes were removed in late August 2019 in preparation for field recontouring while the restoration activities occurred and reinstalled in the same locations (±15 cm) afterwards (some fall 2019 and most in May 2020). Pipe top elevations were surveyed (2019 and 2020) with the RTK system (see description below).

In 2020, bail tests (n =41) were completed to determine the saturated hydraulic conductivity (K_{sat}) in wells at the W-ECO section. K tests were also completed on piezometers located on two older transects (NM and SM). The tests were done according to Hvorslev, 1951. Prior to the test, all pipes were developed (water agitated within the pipe and then removed by suction). Water was then allowed to fully recover. K_{sat} values were used to estimate transmissivities and specific discharge.

3.3.3 Soil water pressure

Tensiometers were installed in the W-ECO ecotone in 2020 (June 4 – August 10) to measure soil water pressure at 10 cm below ground surface. Tensiometers were installed close to a well located where the treatments were applied. Each tensiometer was 30 cm long and was made up of a 5.5 cm porous ceramic cup attached to a straight tube inserted into a pre-bored hole.

Pressure was measured tri-weekly with a tensimeter (accuracy of 1 mb). A known volume of water was added anytime the water level within the tensiometer fell below the clear plastic top.

3.3.4 Elevation measurements

Surface elevations were measured along each of the 8 transects in 2019 with an RTK system using a locally established, geocorrected, benchmark. The RTK system includes a Leica GS14 receiver, a CS 20 data logger running the Leica Captivate application, and a GX1230 base station (with GFU radio). All elevation measurements were taken with the RTK system. After recontouring in September 2019, surface elevation measurements were taken along impromptu transects (no permanent monitoring or installation) every 1-2 m that ran orthogonal to the filled perimeter ditch; transects were repeated every ~30 m along the perimeter (~500 m). Impromptu transects per treatment area totalled 7 for NW-ECO and W-ECO and 6 for S-ECO. Slope angle of each treatment area was then determined based on rise and run. Clay elevations were also found by subtracting peat depths (measured with an augur) at each well location from the corresponding surface elevation values.

3.4 Results

3.4.1 Weather conditions

An excessive rainfall event occurred on a single day within September 2019 but was not captured (Figure 3-2) as the weather station had been uninstalled to allow for surface reprofiling for restoration. However, another weather station installed 700 m away (data not shown) recorded 107 mm for that day and was likely an underestimate based on the presence of canopy cover. Precipitation in 2019 was not recorded until 14 June because weather station had not been installed and was not recorded from 13 May to 24 May 2020 (Figure 3-2) due to battery issues. Daily precipitation events occurred 36, 45, and 47 times for 2019, 2020, and 2021, respectively within this period. The total amount of precipitation for the period would have been greater if September rain event were captured.

Most months (except Sept and May) were within ~1 °C of the Climate Normals with Sept 2019 and May 2020 being much cooler (3.5 °C and 5.1 °C, respectively); overall 2019 and 2020 were ~ 1 °C cooler than average while 2021 was ~1°C warmer than average (Table 3-1). All seasons where notably drier (with all but four months being lower than normal) with 2019, 2020 and 2021 being 8, 93 and 190 mm less than normal, respectively; however, two very wet months (July 2019 and June 2020) reduced the net deficit, but these were largely due to a single large rain events (40 mm in 2019 and 50 mm in 2020). There was no large precipitation event for the 2021 season. Amongst all the three seasons compared to normal, the 2021 field season was the warmest and driest year.

Table 3-1: Comparing average temperatures along with monthly precipitation totals for 2019 and 2020 to 30 - year Climate Normals from Beausejour weather station (about 23 km from the study area) (Environment and Climate Change Canada 2020). Note that weather station was not installed until June and hence no data were recorded for May. * are data from Pinawa weather station (**Environment and Climate Change Canada 2019 and 2020) and *** combines data from study site and Pinawa weather station.

	Temperature (°C)				Precipitation (mm)			
	2019	2020	2021	T**	2019	2020	2021	P**
May	8.6*	6.3	9.2	11.4	31.5*	22.5	54.7	58.1
Jun	17.1	17.3	17.9	16.7	44.6	132.8	38.4	87.5
Jul	19.2	20.4	20.1	19.3	162.5	74.5	32.4	87.1
Aug	17.3	18.3	18.4	18.5	53.2	50.4	79.1	76.3
Sep	9	10.8	14.2	12.5	74.3	1	18.5	65.1
Sum/Ave	14.24***	14.6	16.5	15.7	366.1***	281.2	223.1	374.1

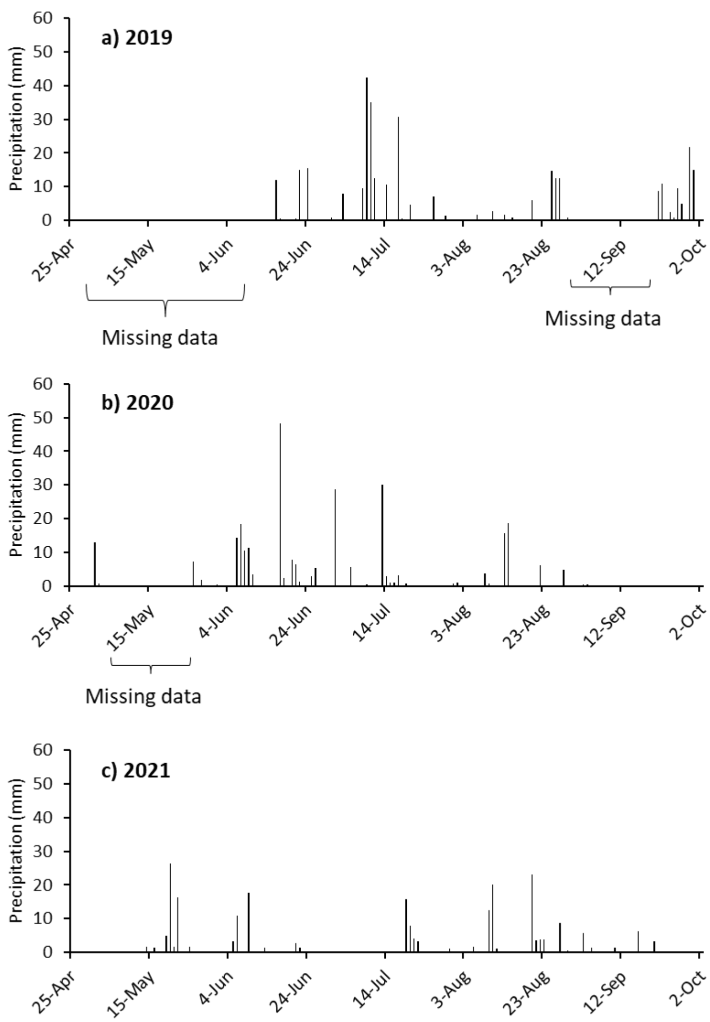

Figure 3-2: Daily precipitation for 2019, 2020 and 2021

3.4.2 Water table for 8 transects

Water tables were generally parallel to the clay surface and dropped sharply towards the perimeter ditch (within 20 m) showing the flow of groundwater towards the ditch for 2019 and the non-recontoured sites in 2020 and 2021 (Figure 3-3 d to h). However, for those sites recontoured in late 2019 (W, SW, and SM), water tables had gentler slopes (Figure 3-3 a to c). Water levels on non-recontoured (unmanaged) transects stayed below ground surface except for water in the peripheral ditch; however, for the recontoured transects (W, SW, SM), the maximum water table (Figure 3-3) in the peat extraction site (i.e., between -40 and 0 m) showed flooded conditions only in the spring.

The average depth to water table for all transects in 2019 was -69.9 ± 55.8 cm, ranging between -182.9 cm and +51.4 cm. Transect NE remained the driest (due to shallow peat depth) with an average WTD (relative to surface) of -21.1 ± 34.9 cm. Five of the six wells along Transect NE became dry from the middle of the summer season. Average WTD on transect SM was -102.8 ± 58.4 cm (deepest depth possible to measure). Transect SW had the widest range in WTD (+218.7 cm) while transect E had the narrowest range (+98.8 cm) between minimum and maximum values.

In 2020, at the recontoured sites, water tables increased (+29.9 cm) on average to -46.8 ± 35.8 cm, ranging between -134 cm and 3.6 cm. This average took ditch wells into account, even though the ditch itself no longer existed. For those transects not recontoured, and thus act as an interannual control, water tables (ditch wells taken into account) also increased (+35.1 cm) to -

28.8 ± 43.3, which is 5.2 cm higher than the recontoured transects (Table 3-2). In order not to completely remove water table values in the ditch, a weighted average approach was used by considering the location of each well relative to wells in ditches. (Most transects has 6 wells, and a simple average would assume each well represented 1/6th of the transect, or ~17%; in reality, the flooded conditions in the ditch well represented <1 % of the transect.) In doing so, results showed average water table increase (+30.9 cm) to -43.5 ± 35.8 for recontoured sites. For those transects not recontoured, water table increased (+18.4 cm) to -30.3 ± 43.3 cm, 12.5 cm lower than recontoured transects. WTD ranged between -134 to 3.6 cm for restored and -152 to 72.2 cm for unrestored sites.

Data for 2021, while measured, was not included in Figure 3-3 as the site was extremely dry throughout the season with most wells having no water in them for most of the season.

Clay elevations were lowest in the ditches, likely as a consequence of ditch excavation/construction. However, clay elevation increases away from the ditch (that is away from the peat extraction site) which could suggest the bog likely formed in a topographic depression in a post-glacial environment. Peat depth along transects averaged 118 cm and ranged between 15 cm and 242 cm (Table 3-3). The West transect (W) had the deepest peat on average (134 cm) and the Northeast transect (NE) had the shallowest (79 cm).

Table 3-2: Summary of water table for 2019 and 2020

		With ditch (2019)	With ditch (2020)	No ditch (2019)	No ditch (2020)	Weighted (2019)	Weighted (2020)	ΔWT
W, SW, SM	Max	47.6	3.6	-8	3.6	47.6	3.6	-44
(Managed ecotones)	Min	-182.9	-134	-182.9	-134	-182.9	-134	+48.9
	Ave ± SD	-76.71±59.1	-46.8 ± 35.8	-96.2 ± 42.7	-49.2 ± 36.5	-74.4 ± 50.8	-43.5 ± 43.4	+29.9
	Median					-81	-39.4	
SE, E, NE, NM, NW	Max	51.4	72.2	0	12.4	51.4	12.4	-39
(Unmanaged ecotones)	Min	-157	-152	-157	-152	-157	-152	+5
	Ave ± SD	-63.9 ± 51.2	-28.8 ± 43.3	-82.3 ± 38.8	-42.5 ± 34.2	-48.7 ± 54.7	-30.3 ± 51.1	+18.6
	Median					-60.4	-28	

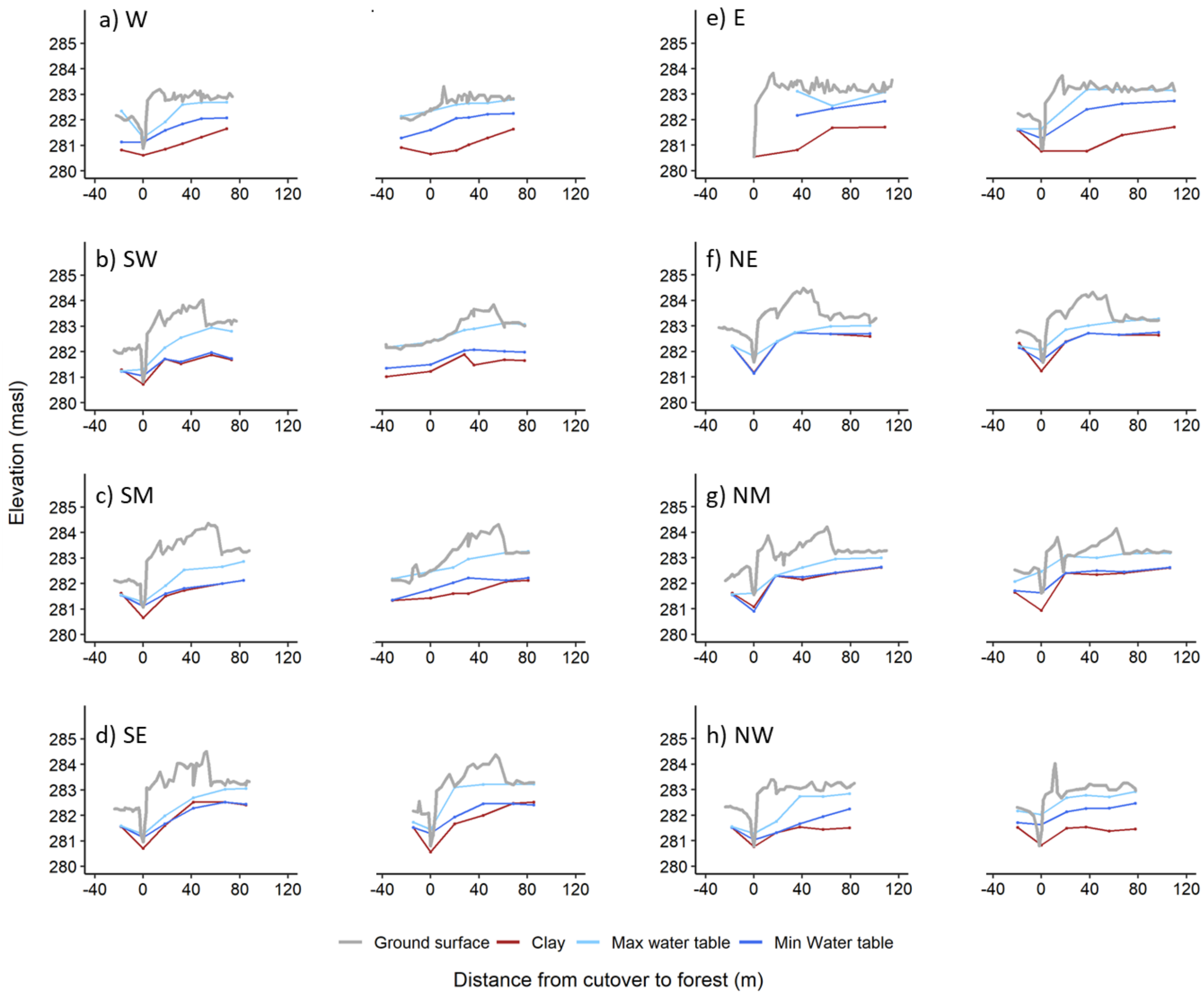

Figure 3-3: Surface and clay elevation, and maximum and minimum water table elevation for 2019 (left) and 2020 (right) for each transect. Note only a, b, and c were reprofiled.

Table 3-3: Average, Minimum and maximum peat depth for each transect established in 2019 and 2020.

	Ecotone site	Transect Name	Length (m)	Ave. Peat depth (m)	Min Peat depth (m)	Max Peat depth (m)
2019		NE	130	0.8	0.5	1.6
		NM	133	0.9	0.7	1.3
		NW	106	1.2	0.3	1.6
		W	96	1.5	0.5	1.9
		SW	101	1.4	1.2	2.0
		SM	111	1.3	0.9	1.9
		SE	111	1.0	0.4	1.9
		E	133	1.3	0.1	2.4
2020	S-EC	5-POND	21	1.0	0.7	1.3
		3-POND	22	1.2	0.7	1.5
		BERM	23	1.2	0.5	1.6
		CONTROL	32	1.0	0.6	1.4
	W-EC	5-POND	24	1.5	1.3	1.8
		3-POND	22	1.7	1.6	1.9
		BERM-1	21	1.8	1.7	1.9
		BERM-2	23	1.6	1.4	1.8
		CONTROL	35	1.7	1.3	1.9
	NW-EC	5-POND	24	1.4	1.1	1.7
		3-POND	23	1.2	0.9	1.5
		BERM	24	1.1	0.8	1.4
		CONTROL	35	1.2	0.8	1.6

3.4.3 Water table for experimental sites (ECO transects)

Depth to water table at each treatment site (and for each slope) were regressed against the control treatment of the same slope (Figure 3-4). Each set of regression points represents 2020 data from a single well closest to each treatment. Points that plotted above the 1:1 line denote wetter sites, and those below drier. The slopes (ranging between 0.8 and 1.55) as well as the y-intercept values (i.e., being above or below the 1:1 line) differed between treatments at all sites. All treatments being wetter at S-ECO, and all but the 3-Pond at NW-ECO. At W-ECO, however, some treatments fluctuated between being under or over the 1:1 line, suggesting a change in conditions over the season.

Average values for water tables for the similar treatments were generally close with 5-Pond having the overall highest average water table (-38.3 ± 24.1 cm) and the berms having the lowest average water table (-44.3 ± 22.8 cm) (Table 3-4).

Normalised frequency distribution of the deviation from the median water table (Figure 3-5) did not show important differences within treatments at the same site. The shape of distributions between the sites, however, were different, with S-ECO being more evenly distributed and NW-ECO and W -ECO being more peaked.

Table 3-4: Comparing averages of water table depth (cm) similar treatments from the three locations

	3-Pond	**5-Pond**	**Berm**	**Control**
W-ECO	-42.7 ± 15.7	-30.4 ± 21.7	-37.5 ± 18.9, -43 ± 17.6	-43.9 ± 20.4
S-ECO	-42.7 ± 23.1	-41.5 ± 30.3	-48.7 ± 29.6	-46.0 ± 24.4
NW-ECO	-42.1 ± 16.2	-44.2 ± 14.6	-35.2 ± 23.2	-43.2 ± 15.4
Overall average	-42.5 ± 18.4	-38.3 ± 24.1	-44.3 ± 22.8	-41.5 ± 21.7

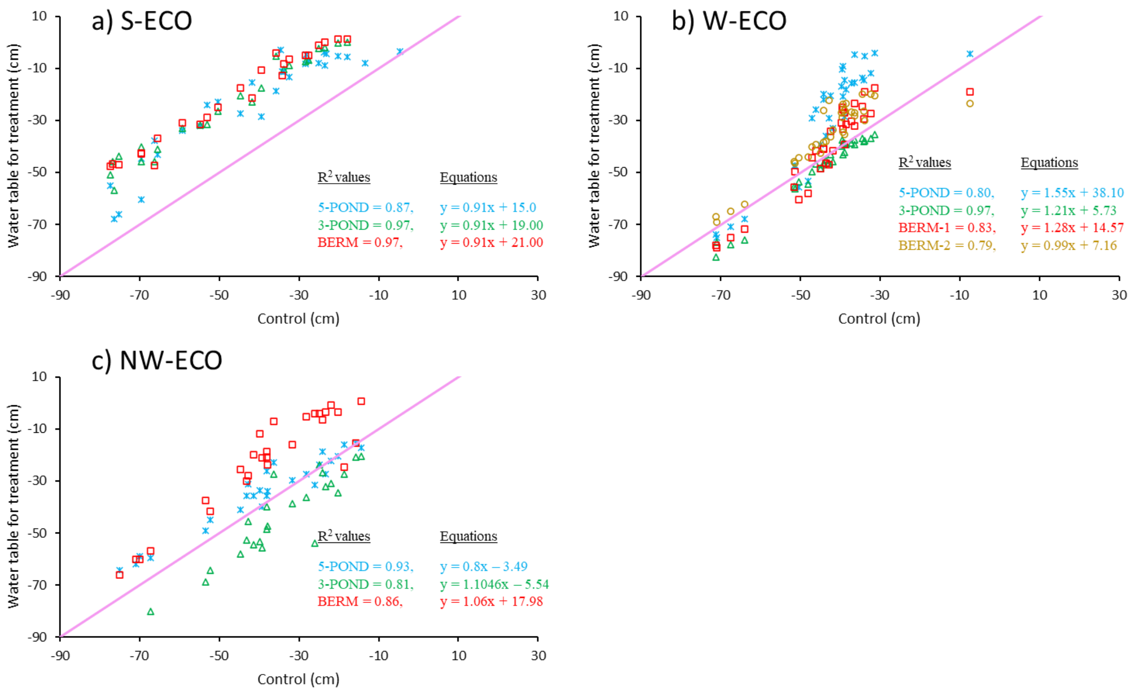

Figure 3-4: Water table responses at the treatment sites regressed against water table at control site

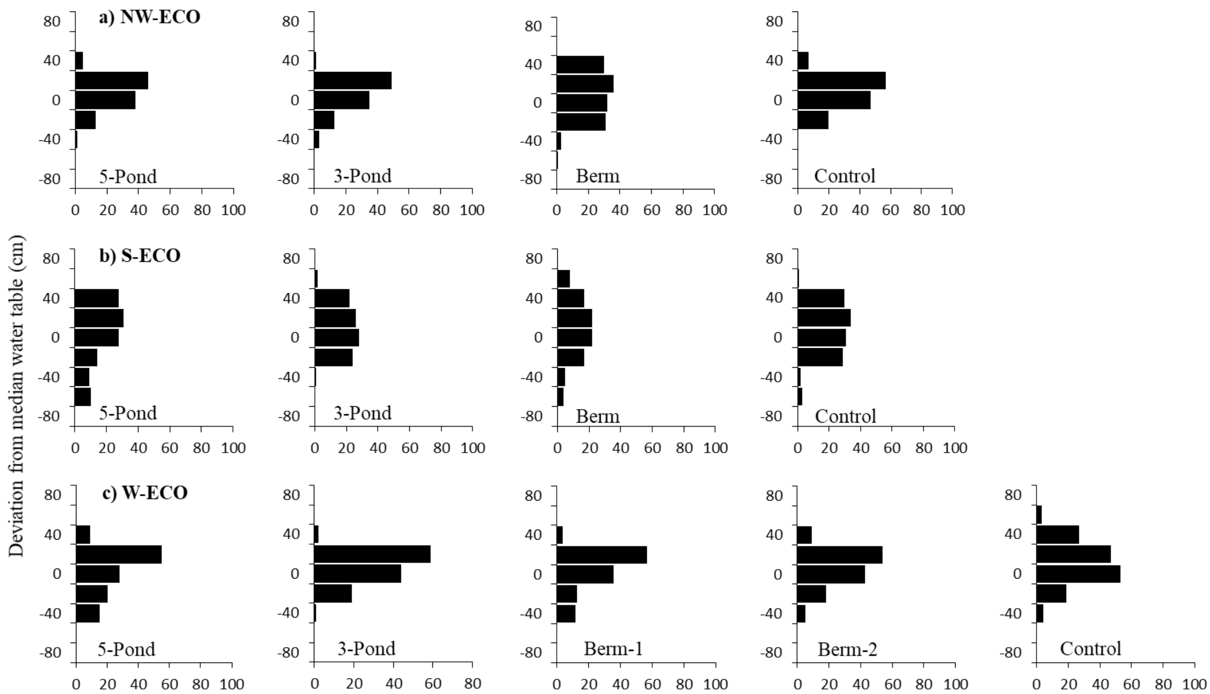

Figure 3-5: Normalised frequency of water table variation for treatments applied at all experimental sites from 5 May to 19 August 2020. The 0 on the vertical axis is the normalised median

3.4.4 Hydraulic conductivity and flow

The transmissivities of water into the perimeter ditch (from the surrounding landscape) along each transect (average transect length was 86 m) was used to estimate the daily total volume of water leaving the natural areas and into the restored site through the artificial ecotone in 2019. A K_{sat} value of 0.0187 m/day was used as this was the minimum K_{sat} value obtained from a piezometer installed at the site (50 m west of the Transect W). The computed transmissivity values ranged between 1.2 x 10^{-6} m^2/day (NE transect) to 1.47 x 10^{-4} m^2/day (NM transect). The daily total volume of water estimated to be moving into the peripheral ditch from the surrounding landscape was 0.189 m^3, or 0.0002 mm spread across the 80-hectare site. If we used the highest K_{sat} value recorded, these values are 6.294 m^3 and 0.008 mm.

Groundwater flow across the ecotone was denoted to be positive for flow from surrounding peatland into the cutover peatland. This means all positive values indicate discharge from the bog into the fen while negative values indicate a loss from the cutover. The gradients (2020) determined at each treatment showed both recharge to and discharge from the cutover. Berm-2, 5-Pond, and 3-Pond only showed positive gradients (discharge to cutover). Berm-1 showed discharge conditions while the Control treatment mostly showed recharge conditions (Figure 3-6). Berm-1 and 5-Pond generally showed higher gradients making it more likely for the highest flow to occur along them. Specific discharge was highest on average on the 5-Pond treatment (3.33 mm/day) while the lowest value (-0.1 mm/day) was on the 3-Pond treatment (Table 3-5). Based on the configuration of the treatments (Figure 3-1i), location of treatments could have played a role in the recharge/discharge of the groundwater. That is, 5-Pond and Berm-2 were closest and showed recharge conditions while the remaining treatments showed discharge conditions. Given the best-case scenario of specific discharge from the 5-Pond

(0.0033 m/day) and a total ecotone slope area of 6000 m^2, (peat depth: 1.5 m by site perimeter: 4000 m), the expected total volume of water via the ecotone to the restoration is 19.8 m^3/day and 0.025 mm (daily).

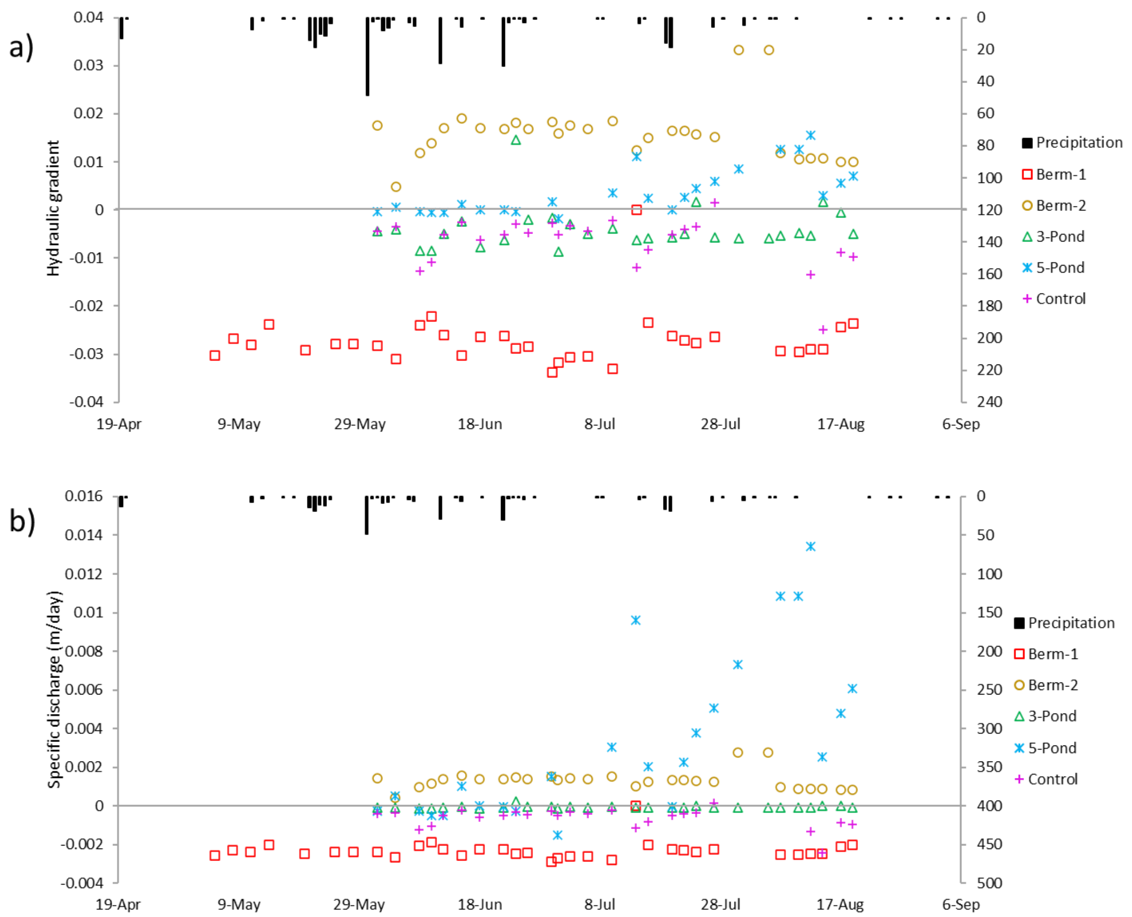

Figure 3-6: a) Hydraulic gradient timestamp per treatment at W-ECO. b) Specific discharge timestamp per treatment at W-ECO. Note that direction of flow is assumed to be from surrounding remnant peatland to cutover (+).

Table 3-5: Average specific discharge. Positive value means recharge to cutover while negative value indicates discharge from cutover

	Average	
Direction: Remnant to cutover	Gradient, dh/dl	Specific discharge (mm/day)
Berm-1	-0.027	-2.3
Berm-2	0.016	1.3
3-Pond	-0.004	-0.1
5-Pond	0.004	3.3
Control	-0.007	-0.6

3.4.5 Transmissivity of constructed ecotone

Transmissivity for the W-ECO site generally declined over the season by about three orders of magnitude (Figure 3-7) due to lower saturated thicknesses. Values ranged between 0.002 to 1.6 m^2/day. Values generally increased from the cutover wells towards the forest wells with Well 1 as the first (cutover well) and Well 4 as the last (forest well). On average, 5-Pond had the highest transmissivity (0.502 m^2/day) ranging between 0.0164 to 1.61m^2/day, Control had an average of 0.172m^2/day ranging between 0.00277 to 1.201m^2/day, Berm-1 averaged 0.148 m^2/day ranging between 0.0217 to 0.369 m^2/day, Berm-2 had an average of 0.080m^2/day and ranged between 0.0022 to 0.210 m^2/day and 3-Pond had the smallest average of 0.0447 m^2/day ranging between 0.00596 to 0.069 m^2/day.

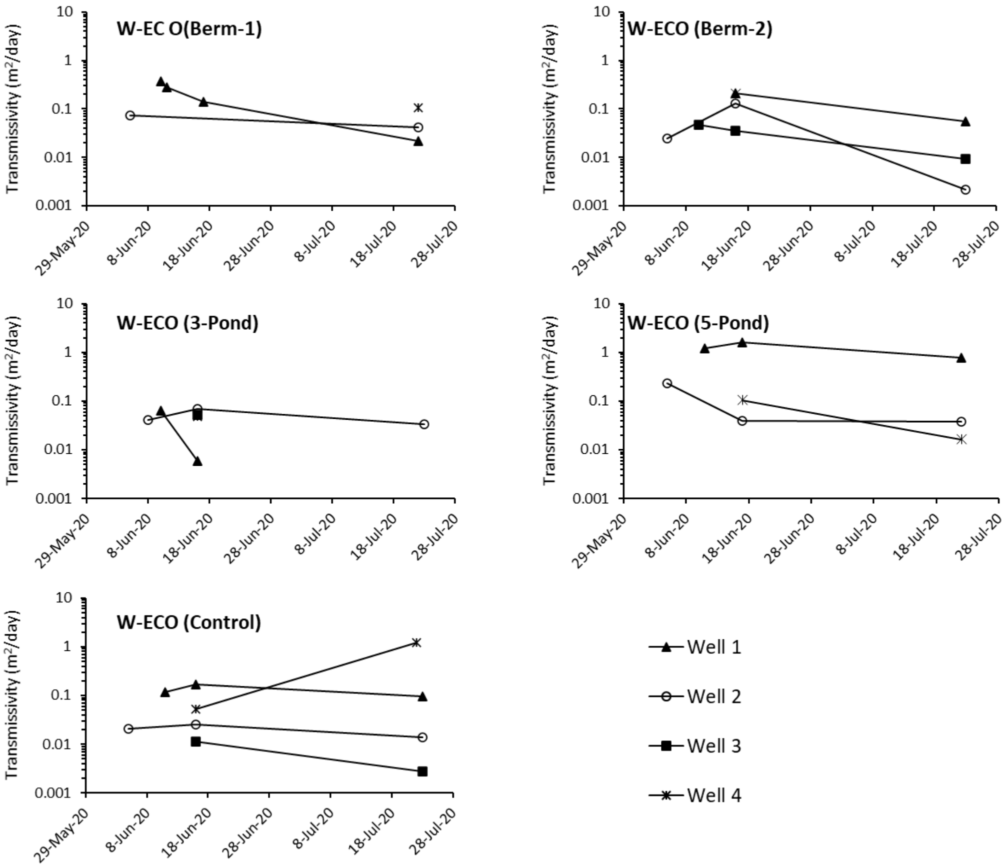

Figure 3-7: Transmissivity on the WEST ecotone slope. Each line represents a single well and each point on the line is K_{sat} on a specific day. Well 1 is the cutover well and Well 4 is in the forest.

3.4.6 Soil water tension for ECO transects

Soil water tension results (in 2020) from W-ECO site showed that 5-Pond, 3-Pond, Berm-1, Berm-2, and Control had averages of -18.2 cm, -36.0 cm, -37.6 cm, -30.3 cm, and -29.5 cm, respectively. Changes in soil water tension followed similar pattern as the changes in water table. At no point in any treatment did the measured soil water tension exceed -100 cm, and for most of the summer didn't exceed -50 cm, which could suggest no ecohydrological differences. Soil pressure for the 5-Pond treatment generally stayed higher than the remaining treatments, perhaps suggesting that if conditions did become stressed, the 5-Pond might have been best to mitigate these changes.

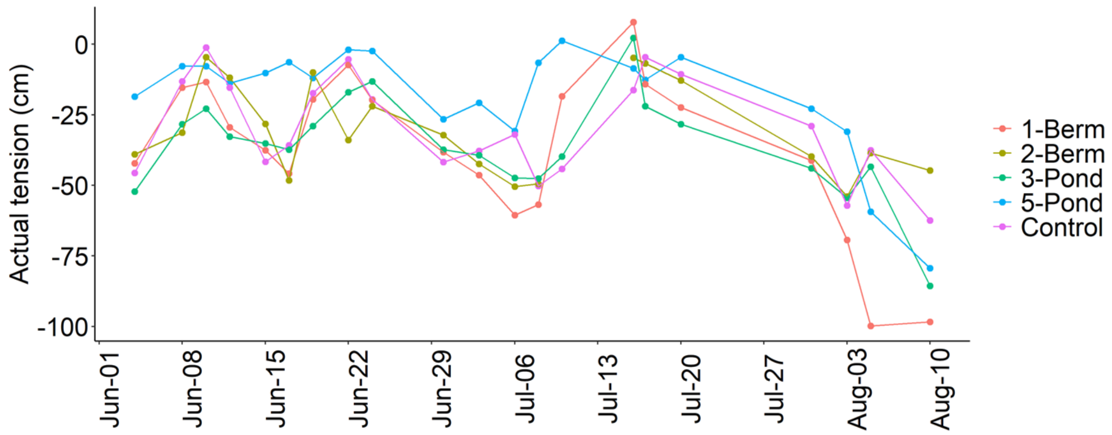

Figure 3-8: Soil tension within the top 10 cm of peat for treatments at W-ECO (2020). Note: Values above 0 cm indicate flooding conditions

3.5 Discussion

The weather condition for all the three seasons were drier than normal. The 2021 field season was warmer than normal while temperatures for 2019 and 2020 were below normal. These differences in precipitation and temperature can provide an interannual perspective on the response of the ecotones under different weather conditions, as, due to the heavy rain event that halted restoration plans in the fall of 2019, and the COVID-19 pandemic, more than half of the perimeter of the site was "unchanged" between the years.

Before recontouring, the mean water table along each of the transects across remnant ditches were different, showing that considering spatial heterogeneity is incredibly important in field-based studies. The differences in peat depth along each remnant ditch could have also contributed to water table differences. The fact that WTD remained different between all transects may also explain the differences in response to the impact of peat extraction on the peat matrix. Generally, water table continued to decline on all transects until some transects had some of their wells going completely dry. The water table decline was more noticeable near the remnant ditch. Surface topography did not change along transects that were not recontoured. These transects comprised a remnant ditch and a berm that remain unchanged. The peat depth along the non-recontoured transects also remained unchanged. But water table regimes changed.

During the 2020 season, there was a general rise in overall average water table of 43.2 cm from 2019. Water table rose more (+12.5 cm) on the recontoured transects than transects not recontoured signifying the impact of surface recontouring. In determining the mean water table of the sites, it was important to remove wells installed in the ditch to avoid bias in the data

The treatments (3-Pond, Berm, 5-Pond, and Control) were used to assess the real impact of recontouring and ecotone creation on the water retention. Each of the treatments appeared to have had a different impact on the water table and soil water tensions. Based on both water table and soil water tension, the 5-Pond treatment was notably wetter than the Control at all ecotone locations and could have only been slightly influenced by topography compared to the remaining treatments as shown by the regression line (Figure 3-4). The differences in the slopes of regression of water table for all treatments verses the control water table further explains how each of the treatment may be responding differently to water table decline throughout the study period. Generally, W-ECO was the wettest ecotone site and given that 5-Pond was made up of 5 basins, it may have appeared to be presumably more effective at retaining surface water (Figure 3-4). The W-ECO site was located at a relatively lower surface elevation zone with gentler slope. All these could have contributed to making the 5-Pond configuration the most effective retention treatment. These can provide insight into understanding the steps to take to establish effective water retention measures for artificial ecotones in peatland restoration.

Similar to the regression lines, the frequency distribution of the mean deviation of water table showed different responses of the experimental ecotone sites to water table changes (Figure 3-5). At the beginning of the field season, a substantial amount of water was retained in the 5-Pond and 3-Pond basins. The berms had smaller patches of water retained behind them. But the water appeared as surface run-off on the control treatments. The water in the ponds may have created a more stabilising effect on the water table than the control, but this was more evident at the W-ECO site (Figure 3-5). At the S-ECO, the berm appeared to be the least effective at stabilising the water table because of the larger spread in the deviation from the median water table.

Due to the absence of the acrotelm in extracted peatlands (and only the presence of catotelm peat), groundwater flow was extremely slow. It was not surprising that the transmissivity measurements along the transects prior to restoration were all low compared to natural peatlands. The gradients of 4 out of 5 of the transects of the experimental treatments maintained the same (either positive only or negative only) condition throughout the study except for 5-Pond. Specific discharge values showed that groundwater flowed either away or towards the cutover.

The transmissivity of the experimental treatments varied by orders of magnitudes with lower values recorded in the lower slope (near cutover area) compared to the upper slope (near forest). Compression of residual peat during peat extraction may have decreased the K_{sat} which in turn reduced transmissivity in the lower slope compared to the upper slope. For treatments in the lower slope, relatively high transmissivity values were mostly due to higher values of saturated thickness of the peat. Comparing all treatments at the W-ECO location, 5-Pond was more favourable at transmitting water.

Price and Whitehead (2001) determined that for *Sphagnum* reestablishment, soil water pressures higher than -100 cm were required. At no point in any treatment did the measured soil water tension exceed -100 cm, suggesting that any non-vascular vegetation would never have been stressed. This shows that the ecotone treatment areas (following recontouring) could be favourable for the regeneration of non-vascular vegetations. Soil water tension was generally lower (less negative) on the 5-Pond experimental treatment. Lower tension values indicate wetter conditions. The lower tension could have resulted in higher moisture content due to water seeping out of the pond through capillarity rise which compensates for the loss of surface moisture due to evapotranspiration. The 5-Pond's additional two basins compared to the 3-Pond made a difference in the water stored on the slopes. Thus, the 5-Pond maintained the lowest tension values as the higher basin count stored more water on the slope and for a longer period as well. All these soil water tension differences occurred at 10 cm below ground surface.

3.6 Conclusion

Applying some form of management technique may ensure the establishment and survival of peatland vegetation after peat extraction. This study used three treatments (5-Pond, 3-Pond, and Berm) and a control as a management technique. The results obtained from this study showed that ponds and berms on the periphery of extracted peatlands improved hydrological conditions. The average water table for all treatments was near -40 cm with 5-Pond staying above this value making it ideal for *Sphagnum* establishment. Knowledge of changes in water table and water tension with time can provide insight into the best time of the season to start peatland restoration activities. The 5-Pond configuration showed some promise in its effectiveness in improving water retention on the slopes. This is supported by other studies which have used basins on cutover peat surfaces to improve *Sphagnum* establishment (Campeau et al., 2004). Other studies have shown that ponds/basins are able to ensure wetter conditions for the diaspores of *Sphagnum* to develop (Price et al., 2002). It is important to note even though the 5-Pond seem to be more effective in retaining water, this may have been favoured by location as the 5-Pond treatments at different experimental locations were different. Other factors (beyond the scope of this research) may have favoured the effectiveness of the 5-Pond and need to be investigated in future studies. The results therefore show that restoration methods that have been developed in Canada may be equally effective when applied the prairies (Manitoba).

4 Conclusion of research

The research examined different management approaches in creating fen ecotones at the periphery of a fen restoration such that these ecotones can resemble the landscape position of natural fen to bog ecotones. From the study, differences were observed between the ecotones on the periphery of artificial ecotones and natural peatland ecotones. The artificial ecotones (unmanaged) were marked by steep slopes near a canal which drained water. This phenomenon of steepness was not observed on the natural ecotones in this study, rather gradual slope with near-ground surface water levels. Filling the peripheral ditches raised the water level while the experimental treatments improved water retention on the artificial ecotones even though water retention was not up to the extent of the natural ecotones. This implies that applying some management measures to the ecotone on the periphery of extracted peatland can be a steppingstone in the integration of the restoration into the ecosystem. The water level decline on the ecotones was rapid on both the managed (restored) and unmanaged artificial ecotones as compared to the natural ecotones on drier days following precipitation. But there was evidence in improvement in the water level on the managed ecotones than unmanaged. Water level is important because water influences the chemistry of the ecotone which in turn can have an influence on the type of peatland vegetation. A lower decline in the water table coupled with high water levels will ensure the establishment and survival of peatland vegetation. The landscape of the managed (restored) ecotone was made to “mimic” that of the naturally undisturbed peatland in terms of their gradual slopes. Comparing the restored ecotones with the natural ecotones, water tables were similar (nearness to ground surface) at the start of the study season. Water tables declined steadily on the natural ecotones but less steadily (and less sharply as well) on the restored ecotones. At both ecotones, the surface topography generally influenced the direction of groundwater flow (higher to lower surface elevation). Future study is required to investigate the long-term impact of the water retention treatment at the restored site on sedges and *sphagnum* establishment and survival.

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