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Research Article

Characterizing the Spatial Heterogeneity of Basic Physical Properties of Lake and Peat Soils as it Relates to the Moss Spur Peatland, Manitoba

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Abstract

Moss Spur (the study site) is a remnant vacuum-harvested peatland in south eastern Manitoba that has, with little intervention, revegetated on its own. As part of unraveling the mystery as to why, this study investigates the spatial heterogeneity of vegetation and underlying lake sediments at Moss Spur. Physical properties like hydraulic conductivity, bulk density and porosity relate to hydrology and the ability of water to flow, which are of importance in this study. This study looked at those properties and attempted to find a connection between the physical properties of the peat and underlying sediments and the heterogeneity of surface vegetation found at different study areas at Moss Spur. Peat cores as well as sediment cores were extracted from sub-locations within sites. Sample cores were tested via a variety of methods to establish their physical and hydraulic properties. Heterogeneity based on core samples was revealed between sites matching the general heterogeneity of surface vegetation at Moss Spur. This study presents some regionally key aspects to understanding groundwater relationships with respect to harvested bogs and Manitoba wetlands in general. The variability in lake sediment properties across even the relatively small site of Moss Spur suggests that lake sediment properties cannot be assumed to be the same at every location. Heterogeneity of the surface vegetation with respect to the spontaneous regeneration is found to be correlated with the underlying peat and lake sediments. It is expected that areas with lower bulk density and higher porosity and hydraulic conductivity K*, would be in the areas with the bog-like vegetation and as such with regrowth.*

Keywords: Peatland Restoration, Spatial Heterogeneity, Lake Sediments, Peat, Hydraulic Conductivity

1 INTRODUCTION

Peatlands cover over a third of Manitoba's land area[1], and globally, store twice as much carbon as all of the world's forests, despite covering only 3% of the Earth's surface[2]. It is generally well understood that peatland initiation and maintenance is governed by their hydrogeomorphic setting[3], that is, the combination of the area's hydrology (including climatology), hydrogeology, and geomorphology. There are two main types of peatlands in Canada: bogs and fens[4]. Bogs are ombrogenous, meaning that they receive water by precipitation only, isolating them from regional groundwater or surficial inputs of water. Bogs are the peatlands targeted for peat extraction to be used for fuel (more typically in Europe) or as a horticultural product,"peat moss", which is the main use in North America[5]. Manitoba contributes ~11% to Canada's peat production total, with the majority coming from Quebec and New Brunswick; Canada's is one of the world's largest producers of horticultural peat.

Harvesting a (bog) peatland requires digging drainage ditches to lower the water table so that machinery can be driven across the site to remove the upper ~50 cm of vegetation to get to the deeper, more decomposed peat. The surface is then tilled and allowed to dry so that only the upper ~1 mm of the peat surface is vacuumed up per pass of the harvester. Harvesting of a single site can last 30 years taking only 5–7.5 cm of peat per year and after harvesting is completed, restoration efforts begin. Despite being sold as a growing medium, the surfaces of the extracted peatlands are actually quite inhospitable to natural or spontaneous peatland vegetation regrowth. The inhospitality is due to the soil hydraulic properties of the peat that do not allow for the easy transmission of water, as well as the dark surface (low albedo) that promotes evaporation and thus desiccation of any vegetation that tries to establish. Therefore, active restoration of these peatland sites is required. The aim of restoration is to return the site back to a carbon accumulating ecosystem with vegetation similar to a natural bog (i.e., an abundance of Sphagnum moss). Much of the work done on peatland restoration in Canada has been completed in eastern Canada (Quebec and New Brunswick). However, the Moss Spur peatland in south eastern Manitoba has grown back wetland vegetatation without human intervention. Why? We suspect that the hydrogeomorphic setting is partly responsible.

The peatlands of the St. Lawrence Lowlands in eastern

Canada represent a different hydrogeomorphic setting than those peatlands in south eastern Manitoba. The Lowland's peatlands are located in the Boreal Shield ecozone and have Canadian Shield bedrock (an impermeable substrate) underlying them, which severely limits ground water flow[6]. This potential lack of water is made up for by the climate; Quebec has a much wetter climate (~1000 mm vs. ~570 mm precipitation totals at Moss Spur, annually)[7] and cooler growing seasons, which equate to less evaporation relative to Manitoba which possesses a hotter and drier climate[7].

Moss Spur is located within the Boreal Plain ecozone. Peatlands in the Western Boreal Plains (WBP) have been found to be more dependent on local and regional climate, bedrock and surficial geology because these regions experience decadal drought cycles[8, 9]. The combination of climatic and geologic characteristics of the Boreal Plains is unique in the Canadian boreal forest (Alberta, Saskatchewan, and Manitoba). The climate at each study site in the WBP region is characterized by average long-term annual precipitation that is equal to or lower than average annual open-water evaporation, yet peatlands still exist. Outwash, moraine and lacustrine deposits characterize the geology. The high density of wetlands, ponds, and shallow lakes in the Boreal Plains region reflects complex interactions with shallow-surface and groundwater flow systems[8], not typically found in Quebec. Study sites addressed by Devito et al.[8] include more than eight locations across the Boreal Plains in Alberta. It appears that when the local groundwater flow systems have higher hydraulic head than the bog (drought), water can actually discharge into the bogs until water levels are returned to normal and the head gradient driving recharge returns[10]. Groundwater flow reversals have been found to occur during periods of extreme drought. Water table drawdowns of 70 – 200 cm below normal conditions (drought-like condition) are enough to allow a flow reversal in the WBP peatlands[9]. Manitoba experiences decadal droughts[9] due to lower annual precipitation, and groundwater flow reversals have been known to supplement water to bogs in times of severe drought[11].

It has been hypothesized[12] that harvesting creates drought-like conditions due to the drainage ditches lowering the water table in the peatlands 1.5–3 metres. This lowered water table, like the droughts noted above, reduce the hydraulic head within the peatland and can reverse the direction of the gradient, allowing water from the mineral sediment below to come closer to the surface[11]. This is suspected to be what is happening at Moss Spur. Hawes & Whittington[12] found groundwater discharge zones in areas with better peatland vegetation establishment, and recharge zones in areas with poorer peatland vegetation re-establishment. However, they ignored the hydraulic properties of the underlying lake sediments in their study. The spontaneous revegetation at Moss Spur is not uniform, as some areas have better peatland vegetation regrowth, and other areas poorer regrowth (see Study Site for more details). Given that most post-glacial environments are far from homogenous, the different vegetation communities found at Moss Spur might be indicative of local differences in the physical properties of the peat and glacial lake sediments. Where soil bulk densities are lower and porosities are higher, one might expect groundwater upwelling to occur in greater amounts as lower bulk density and higher porosity could provide a less restricted flow channel. Less restriction enables higher hydraulic conductivity and thus more groundwater flow, thus assisting the vegetation to re-establish itself.

Therefore, the objective of this paper is to determine if the physical properties of the underlying peat and lake sediments is related to vegetation re-growth on the surface at the Moss Spur peatland. We expect that areas with lower bulk density and higher porosity and hydraulic conductivity K, would be in the areas with the bog-like vegetation. It is also expected to be the same outcome with vegetation regrowth; these parameters are outlined by Gagnon et al.[13]

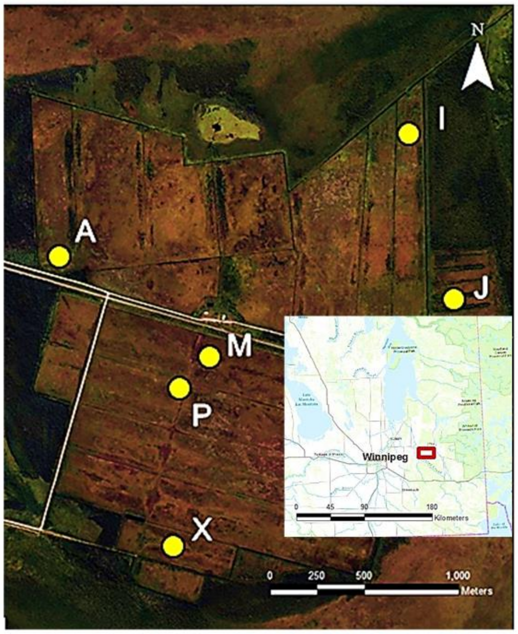

Figure 1: *This figure shows the study site area and where it exists in southeastern Manitoba. 1a: Sample locations within Moss Spur Manitoba harvest site. The yellow dots give an approximate location to core extraction sites and the letters refer to regeneration plots. b) A map of the geographic extent of Manitoba, Winnipeg has been emphasized for location reference and the red boxed area is expanded as Fig. 1a.*

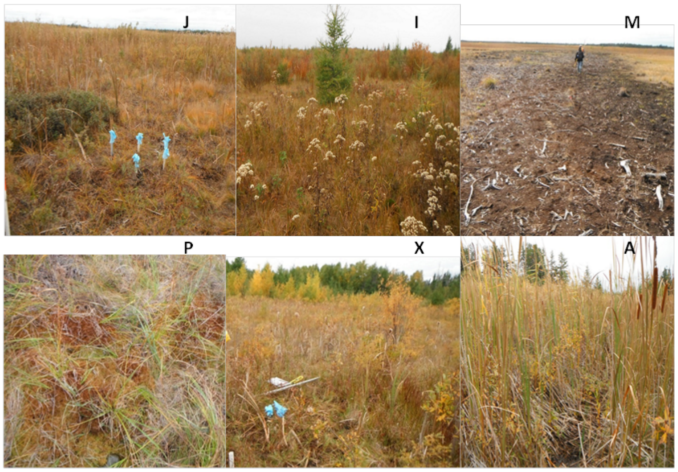

Figure 2: *Each of the labels in this figure corresponds to the location labeled in Fig. 1. This figure contains representative photos of each site (J, I, M, P, X, and A labelled accordingly).*

Bog--------J--------------I-----------M---P-X-------------------------- A--- *Fen*

Figure 3: *The arbitrary scale for sample sites at Moss Spur between bog and fen based on vegetation observed*[13, 14].

2 Study Site

Harvesting ceased in 1999 and since that time Moss Spur has had very little assistance in its natural vegetation regeneration[15]. Moss Spur is located in south east Manitoba (Fig. 1) between the towns of Whitemouth and Beausejour on the Canadian Pacific Railway (49.99°N, 96.13°W). The closest Environment Canada station is Beausejour (~28 kilometers northwest of the site) and the 1981–2010 annual mean temperature was 2.8°C with January and July temperatures of -16.9°C and 19.3°C, respectively[7]. Annual precipitation is 570 mm (20% falling as snow).

Moss Spur is located in a part of the former glacial Lake Agassiz basin in Manitoba. Glacial and glaciofluvial deposits cover much of Manitoba, especially in the south eastern and eastern regions[16]. The major Lake Agassiz sedimentary basin covers the Moss Spur area and has contributed to peatland development due to the characteristics of the bedrock and lake sediments beneath the peatland and the possibility of groundwater flows.

Moss Spur underwent 53 years of peat harvesting beginning in 1936[17]. Moss Spur had a total harvested area of approximately 440 hectares which has been divided into 24 sections, mostly separated by large remnant drainage ditches. These sections were labeled alphabetically starting at the northwest corner of the site (Fig. 1 a). Since abandonment, beavers have dammed many of the major drainage ditches effectively re-wetting much of the site[18].

At the time of data collection, the remnant bog had limited vegetation regeneration at site M, and good to very good regeneration[13, 14] at sites J, I, P, X and A (Fig. 2). Site M demonstrates what a typical post-harvest peatland would look like, with minimal vegetation regeneration. These sites were chosen to study because they embodied distinct assemblages of vegetation that seemed representative of the communities across the entirety of the site. The assemblages were obvious from imagery acquired by a drone showing distinct patterns across the site. Previous studies[12] instrumented 6 locations within these assemblages (J, I, M, P, X and A) with various hydrological instrumentation (wells and piezometers) thus the current study took advantage of these locations to characterise the peat and lake sediments.

The vegetation found at each location was placed on an arbitrary gradient (Fig. 3) between a natural bog to fen[13, 14], but based on dominant vegetation found in the various wetland classes present in Canada[4]. Site M was not able to be classified as it is just the old remnant peat surface (no plants present). Site J contained *Sphagnum* spp. mosses and was classified as the most bog-like of all the sites where data were collected. Site I, in the north sector, appeared to contain little or no *Sphagnum* spp. mosses but mostly *Polytrichum strictum* mosses. There was a good coverage of ruderal spp. as well as black spruce (*Picea mariana*), classified as more of a bog than a fen. Site P classified closer to a poor fen with presence of Labrador tea (*Rhododendron* spp.). Similarly to P, site X represented a poor fen as well, however with presence of cattails (*Typhaceae* spp.) and willows (*Salicaceae* spp.). Site A was a different site all together; with *Typhaceae* spp. and sedges (e.g., *Cyperaceae* spp.) in high standing water it would be considered some kind of marsh rather than a fen.

3 Methods

3.1 Field

Peat cores were taken with a Russian peat corer (Aquatic Research Instruments, Hope, Idaho, USA) which is a side-filling soil sampler and measures 5.08 cm in diameter with a 50 cm length and removes a maximum volume of 645 cm^3 of peat. Peat cores were taken starting at the surface in 50 cm increments up to 250 cm, or until the underlying mineral soil (lake sediments) were reached, usually between 100 and 150 cm, but in some cases less than 100 cm. Lake sediments were sampled with an Oakfield Model T soil auger (Oakfield Apparatus, Fond du Lac, Wisconsin, USA), with a sample removing end, and were retrieved at varying depths following peat core removal. The augers corer end has a length of 30 cm and a sample diameter of 1.905 cm.

At each main site (A, X, P, J, M) 3 sub-locations were sampled within each site, in a cluster sampling formation (section I had only 1 as the site was difficult to traverse). In an attempt to better characterise either the homogeneity or heterogeneity of each site's samples, soil auger cores were taken directly beneath the peat core samples via the Russian cores pre-established hole. All cores (peat/lake sediment) were wrapped in plastic wrap and then placed in sealable plastic bags to contain all of the material, and stored in a refrigerator (4°C) to slow decomposition of organic materials, until laboratory analysis.

Sediment cores were retrieved only from sections I, J, M, and X, at 3 sub-locations where the peat was cored. The reason for this was lack of equipment during site visitation during the season. Each sediment core sample was wrapped and stored in the same manner as the peat samples.

Hydraulic conductivity (speed of the bulk movement of water in the ground) was measured using three roving piezometer nests in roughly the same locations as the peat/lake sediment samples, which were all near the previously established nests of another larger study[12]. Each roving piezometer nest contained three piezometers (with 20 cm slotted intakes) at 50, 100 and 150 cm, and one well (approximately 100 cm long) using 2.54 cm inside diameter PVC pipe. Each site location (A, J, etc.) then, had four nests tested for hydraulic conductivity. The depths of the deeper piezometers varied with sample site location due to the peat depth at that location, but ranged 50 to 250cm. The Hvorslev[19] method [Eq. 1] was used to estimate the hydraulic conductivity and requires removing a volume of water from the pipe and measuring the rate of the return of the water, where K is hydraulic conductivity (m/s), r is the inside radius of the tube (m), L is the slotted length of the pipe (m), R is the outside radius of the pipe (m), T_0 is the basic lag time parameter.

When the recharge was too quick to measure manually, a Schlumberger level logger was used, which recorded measurements every 0.5 seconds.

3.2 Lab

Four parameters were determined for each lake sediment soil sample: hydraulic conductivity, particle density, porosity, and bulk density. Porosity (n) [Eq. 2, 3, 4] is also the empty volume (V_w) of the soil not occupied by solid particles (expressed as a proportion or percentage). Calculating porosity takes advantage of the known density of water as when the core is completely saturated (M_s), all of its empty pore space is occupied by water and the dry mass (M_d) is the mass of the core with no water present; the mass difference is the mass of the water, and as water has a density of 1 g/cm^3 the mass can be converted to a volume (V_w). Bulk density (ρ_b) [Eq. 5] is the mass of dry soil per total soil volume (V_t) including the air space (g/cm^3). Particle density (ρ_p) [Eq. 6] is the dry mass of soil (M_d) per unit volume of the soil particles (V_s)(g/cm^3). Particle mass was determined by grinding the sample with a mortar and pestle and weighing a subsample on a scale. Particle volume was determined by adding a known mass of soil (typically 10–15 grams) to an empty 200 ml volumetric flask. A second container of water with a known mass (and therefore volume) of water was poured into the volumetric flask until the water level in the flask reached the volume line in the narrow neck. The difference between the initial mass of water and the remaining mass would then be equal to the volume of the soil. Peat samples were only measured for bulk density.

$$K = \frac{\left(r^2 \times \ln\left(\frac{L}{R}\right)\right)}{2LT_0} \tag{1}$$

$$n = \frac{M_s - M_d}{V_s} \tag{2}$$

$$n = 1 - \frac{\rho_b}{\rho_p} \tag{3}$$

$$V_t = V_s + V_w + V_a \tag{4}$$

$$\rho_b = \frac{M_d}{V_t} \tag{5}$$

$$\rho_p = \frac{M_d}{V_s} \tag{6}$$

$$K = \frac{d_t^2 L}{d_c^2 t} \ln\left(\frac{H_0}{H}\right) \tag{7}$$

For hydraulic conductivity measurements each lake sediment core was sealed by wrapping the core in dry wall webbing to provide structural stability and then the core was repeatedly dipped in liquid paraffin wax[20] until a 4–5 mm thick wax "shell" was formed. The wax helps to ensure that preferential flow paths do not occur along the outside of the core[20].

A falling-head test was used to measure hydraulic conductivity (K). We assumed, *a priori*, that the cores would be low K cohesive sediments which requires smaller water volumes to run through the sample. Equation 7 (with falling-head hydraulic permeameter apparatus[21]) was used to calculate hydraulic conductivity (K), where time (t) is recorded

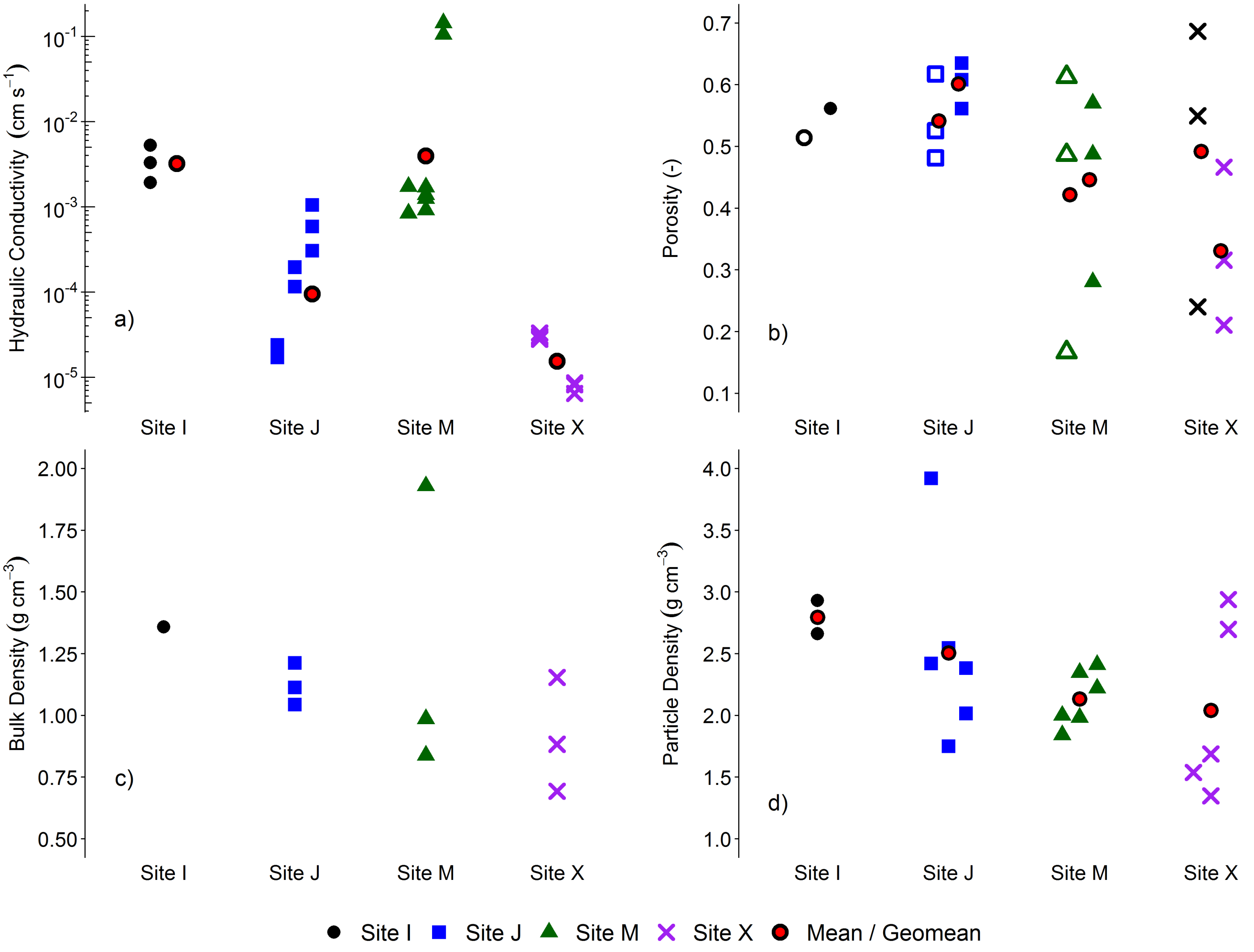

Figure 4: *a) Hydraulic conductivity of lake sediment samples, each tested a minimum of 2 times (excluding site M sample C). The points that are vertically stacked are repeated tests of the same sample core to increase the confidence of the test (e.g., J1 test 1, J1 test 2). Those points of the same symbol, but separated horizontally from the geomean are the different sub-sites (e.g., J1, J2, J3). The geomean is of all the tests (repeats and sub-sites). b) Porosity results from Eq. 2 and Eq. 3. Plotted points with a solid fill are results from the physical test of porosity [Eq. 2]. Points with a hollow fill are results from the mathematical check done to test accuracy in the study [Eq. 3]. c) Bulk density values for each sub-location at each site. d) Particle density values for each sub-location, each tested twice (excluding Site X sample B). Note y-axes do not start at 0 to preserve the scale require to display the data*

beginning at the point where the water drains from the initial height (H_0) until the water reaches a final height (H); the natural logarithm (ln). This parameter, then, is the change in head; it is affected by the diameter of the falling-head tube ($2r$) and the diameter ($2r_s$) and length (L) of the core.

The soil sample must be fully saturated before any measurement is taken, as under the principle of continuity, the volume of water entering the sample chamber must equal the volume draining from it[22]. If the sample is not saturated before the test starts, the results will be inaccurate. Each sub location sample was completed up to four times to assess repeatability.

4 RESULTS

4.1 Lake Sediments

Hydraulic conductivity values for each location are shown from the falling head permeameter tests (Fig. 4 a). Hydraulic conductivity of all lake sediment samples spanned 6 orders of magnitude between 6.4×10^{-6} and 1.7×10^{-1} cm/s. Site I had the smallest range (1.9×10^{-3} to 5.2×10^{-3} cm/s)

Table 1: *Sites ranked based on parameters and potential flow. Each parameter (e.g. porosity) is normalized and scaled equally (i.e. low, med, high), a qualitative rank for each site followed this process to generate the table*[13, 14].

Site	Porosity	Bulk Density	Particle Density	Hydraulic Conductivity	Potential Flow (sediments)	Peat Depth (cm)	Peat K	Peat Bulk Density	Classification (dominant flora)
A						80	Low	High	Marsh-like (sedges & standing water)
M	High	Low	Medium	High	Highest	250	High	Low	Unclassified (little - no plants)
P						160	Medium	Medium	Poor fen (Labrador tea)
X	Medium	Low	Low	Low	Low	100	Highest	High	Poor fen with cattails
I	High	High	High	High	High	135		Low	More bog than fen (little *Sphagnum* spp.)
J	High	Med-High	Med-High	Medium	Med-High	185	High	Low-Med	Most bog-like (*Sphagnum* spp.)

whereas site J had the largest (1.7×10^{-5} to 1.0×10^{-3} cm/s). Sub-locations are shown slightly offset and had a fairly tight grouping, showing the repeatability of the laboratory methods, but still showed heterogeneity within the site's location. Across the entire study area heterogeneity is quite apparent. The geometric mean of sites I and M were similar, and were both larger than J and X (Fig. 4 a). Geometric mean was used to show the central tendency of each site location.

Porosity of the lake sediments spanned from 0.16 to 0.68 across all sites. Sites I and J showed a small range relative to sites M and X. The range for site J is 0.48 to 0.64 whereas the range for site M is 0.17 to 0.61. Porosity values based on Eq. 2 and Eq. 3 are shown (Fig. 4 b). Each site contained 3 sub locations, as specified in the Methods excluding site I (only one sub location).

Bulk density (Fig. 4 c) of the lake sediments showed a small range across each site as well as within each site. Data ranged from 0.69 to 1.93 g/cm^3. Site J showed the smallest range (1.04 to 1.21 g/cm^3) and site M showed the largest range (0.84 to 1.93 g/cm^3). The high value at site M (1.93 g/cm^3) may be an error in sample collection resulting in sediment compaction. Most of the samples show values between 0.8 and 1.2 g/cm^3 indicating a high organic content in the sediments. Bulk density trended I > J > M > X.

Particle density (Fig. 4 d) of the lake sediments span values ranging from 1.39 to 3.92 g/cm^3. Site I showed the smallest range (2.66 to 2.93 g/cm^3) and site J showed the largest range (1.75 to 3.92 g/cm^3). The average for each site showed a smaller range of values between sites, the averages for sites M and X were similar and sites I and J were similar. Each sample was tested twice for accuracy (excluding site X sample B as it was a small sample, there wasn't enough material to run a second test). Even if we exclude the outlier value from site J (3.92 g/cm^3), these values range from 1.35 to 2.93 g/cm^3; this large range demonstrates the heterogeneity at each site as well as between sites.

4.2 Peat

Bulk density values are shown across every field site at varying depths up to 250 cm and was calculated using Eq. 5 (Fig. 5). Bulk density of peat ranged from 0.019 to 0.134 g/cm^3. Each site showed a close range of values at each sampled depth. The largest range was at site X at 50 cm depth (0.021 to 0.06 g/cm^3), whereas the smallest range was at site A at 50 cm depth (0.019 to 0.027 g/cm^3). The data shows that in most cases (all by X) as the sample depth increases so does the peat bulk density across each location.

Hydraulic conductivity values are shown across each field site (excluding I) at varying depths up to 170 cm measured using the Hvorslev[19] method (Fig. 6). Hydraulic conductivity of the peat data spanned 5 orders of magnitude ranging from 7.0×10^{-3} to 1.02×10^{3} cm/s. Site J had the smallest range in data from 8.3×10^{-1} to 2.24×10^{1} cm/s whereas site X had the largest range from 7.0×10^{-3} to 1.02×10^{3} cm/s.

K generally decreased with depth at sites A, X and P, but remained fairly consistent (range within a 1.5 orders of magnitude) with depth for sites J, and M.

5 Discussion

Peatlands in the western boreal plains, due to their hydrogeomorphic setting, have the potential for groundwater upwelling in times of drought when surficial hydraulic head is lower than the regional hydraulic head. However, the physical properties of underlying lake sediment materials as well as bedrock, can limit the amount of groundwater discharge. It was hypothesized that areas with lower bulk density and higher porosity and hydraulic conductivity K, would be in the areas with the bog-like vegetation[13, 14]. Our findings indicate that areas with higher relative bulk density but similar porosity and will be most bog like among the sites.

The lake sediments that have been tested for hydraulic conductivity (K) in this study range from a very sandy soil at 0.1 cm/s to a typical clay or compacted soil substrate at 1×10^{-5} cm/s[23] (Fig. 4 a). The difference in K values across sites show the local heterogeneity at Moss Spur. High K values corresponds with bog like vegetation at site J and I along with low K values corresponds with poor fen-like vegetation at site X[13, 14] (Table 1). Unexplained is site M having no real surficial vegetation, but similar K values to site I.

Related to the hydraulic conductivity, porosity values can indicate available pore space for water flow. According to Brady & Weil[23], ideal medium textured soil will have a porosity value of roughly 50% and may range between 25% and 60%. Soils of near 25% porosity are considered compacted soils (very little pore space) whereas those with a value of 60% (sufficient pore space) are well agitated and/or high in organic matter. It is important to note that clay typically has a very high porosity, despite a low K which is due to clay having many very small pores. Locations X and M cover the widest range of values while I and J (Fig. 4 b) are more consistent by comparison and have higher average values which are consistent with higher clay content or compacted soils[23]. This range in values illustrates the importance of understanding heterogeneity of the soil throughout the sub locations, especially for sites M and X. As shown in Table 1 , high porosity values corresponding with higher relative bulk densities are found at the more bog like sites J and I[13, 14]. These results are shown to be different than site X with relatively lower porosity and bulk density outlined as a poor fen[13, 14].

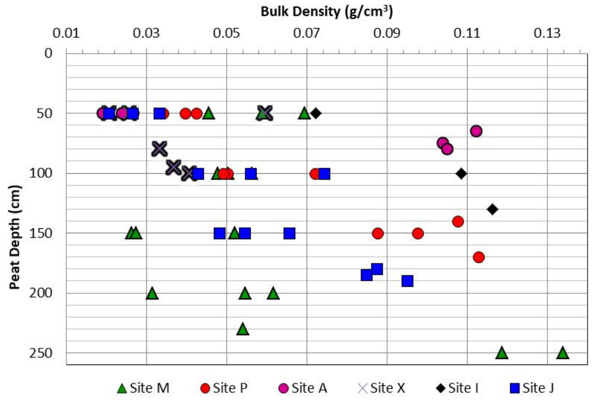

Figure 5: *Bulk density of peat samples (one point per sample) taken at each sub-location of each site.*

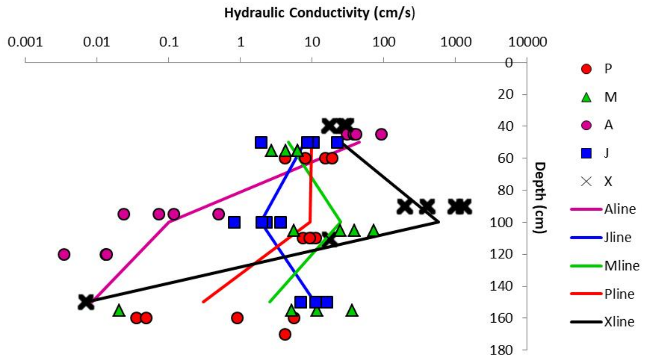

Figure 6: *Hydraulic conductivity values from roving nests at each sub-location and the main nest.*

Where bulk densities are lower and porosities are higher, and the hydraulic gradients are that of groundwater discharge, one might expect greater amounts of groundwater upwelling due to increased flow. Based on bulk density values from Skopp[24], soils ranging from 1.3 to 1.9g/cm^3 will be considered more sandy, silty or clay-like. Organic matter and compactive history influence these values[24]. Sediment samples below 1 g/cm^3 have higher organic compounds[23]. Values in this study were typically low, indicating higher clay or organic content amounts. If the gradients are such that discharge is possible, one might expect more water, or less obstruction to flow.

The particle density value for quartz (the dominant component of sand) is 2.65 g/cm^3 because most soils are made up of the colloidal silicate minerals[23]. Values below 2.6 g/cm^3 are consistent with higher organic content which have particle densities as low as 0.9 g/cm^3. Values higher than 3 g/cm^3 are consistent with higher density minerals. All but one of the particle densities reported here (Fig. 4 d) fall below 3.0 g/cm^3 with the majority below 2.6 g/cm^3. This makes sense as natural bogs are groundwater recharge areas (i.e., water moves from the bog down). Organic carbon would be carried with that water, which would increase the organic content in the lake sediments beneath the peat, decreasing the particle density. The particle density values for sites I, J and M (omitting the obvious outlier for J), show some variation, typically about 0.5 g/cm^3 between the most and least dense. Site X showed the greatest range where the most dense was more than double that of the least dense sample. Porosity calculated from particle density [Eq. 3] had a much higher range (0.24 to 0.69 g/cm^3) compared to direct porosity measurements [Eq. 2] (0.21 to 0.47g/cm^3) respectively (Fig. 4 b), suggesting that direct volumetric measurements of porosity are perhaps more reliable.

5.1 Peat

A lower bulk density (Fig. 5) typically equates to higher overall porosity [Eq. 3] which would restrict flow less and result in higher hydraulic conductivity (Fig. 6). Based on the results found for this study site, peat bulk density and hydraulic conductivity correlate fairly well, as depth increases so does the bulk density. According to Boelter[25], bulk density values for peat range between 0.01 g/cm^3 and 0.25 g/cm^3 and the values from this study fall between those ranges. The range in bulk density values between the subsites also underlines the importance of increasing sample sizes, as site M showed little variation with depth until the 250 cm layer, but a lot of variability at each depth.

Hydraulic conductivity decreased with depth at some sites (A. X, and P), but at at sites J and M remained fairly consistent with depth. At sites A and X, K decreased 4–5 orders of magnitude over the ~100 cm vertical distance. The range in K values at any one depth was usually varied by about an order of magnitude, but at the deeper depths at M and P ranged ~4 orders of magnitude. However, site P at 100 cm, varied less than 10% between the nests. This again highlights the importance of capturing the spatial heterogeneity of K in the profile, because even within a site (e.g., site P) K can be consistent at one depth (100 cm) and range considerably only 50 cm deeper.

Each site (excluding A and P, see Methods) was ranked from low to high for each parameter measured in the study (Table 1). From this list and ranked data we can determine the flow potential rank for each site and correlate the results against the classification[13, 14]. Based on these results it appears that strictly based on sediment samples for these sites, the highest flow results in a marsh like setting with standing water. Those with medium or high flow potential were most bog like in nature (sites I and J) and with low flow potential where found with a poor fen (Table 1). Based on this table, the ideal parameters for bog vegetation to accumulate are higher relative bulk density as well as high relative porosity and hydraulic conductivity. This would mean that decreased flow potential with respect to site M and an increase in flow potential with respect to site X is ideal. The literature that was reviewed stated that higher hydraulic conductivity and porosity values would equate to less restricted flow and more upwelling. Based on the reviewed literature combined with the results found, there is a so called 'goldilocks' situation where too much flow does not resemble bog-like vegetation, nor does too little flow [13, 14].

The other important finding of this work highlights the need for increasing sample size. Often the number of piezometer nests in a study is limited due to cost as well as the increased time required for installation and measurement. The system we proposed here, where a roving nest was used, reduced the cost but increased the installation time. That said, the range in values underscores the importance of recognizing potential errors in studies with only 1 nest in a single location. When K varies by over an order of magnitude within a ~30m lateral distance (Fig. 6), caution should be exercised when considering the veracity of the results reported.

6 CONCLUSION

The study attempted to link the underlying lake sediments and the properties of the peat to the vegetation patterns at the surface. While the results are not definitive, studies in natural environments are generally on going and added to. The "goldilock" zone of not being too wet, or too dry shows promise that a more rigorous assessment of these properties is warranted, in particular, going much deeper into the lake sediment profile, and potentially into the bedrock. This was beyond the scope and budget of this project. An additional finding to the project was that while the spatial heterogeneity within a site was not 0, sites did tend to clump together such that their hydraulic properties appeared different than the other sites. So, while caution must still be exercised in interpreting results from studies with little to no replication, the overall results of such studies are likely correct.

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