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Ecohydrological interactions in a boreal fen-swamp complex, Alberta, Canada

Matthew C. Elmes[1*], Scott J. Davidson[1,2], and Jonathan S. Price[1]

[1] Department of Geography and Environmental Management, University of Waterloo, 200 University Ave W, Waterloo, Canada, N2L 3G1

[2] School of Geography, Earth and Environmental Sciences, University of Plymouth, Drake Circus, Plymouth, PL4 8AA

* Corresponding author: matthew.elmes@uwaterloo.ca

Matthew C. Elmes ORCID 0000-0003-0301-3475
Scott J. Davidson ORCID 0000-0001-8327-2121
Jonathan S. Price ORCID 0000-0003-3210-6363

Abstract

The Western Boreal Plain (WBP) comprises a diverse array of wetland types; however, swamps are understudied in the WBP relative to other wetlands, despite their ubiquity. We apply an ecohydrological and GIS-based research approach at a fen-swamp complex in the WBP to characterize the ecohydrological properties of the varying wetland types and relate these interactions to the hydrologic function of the watershed. In this study, we evaluate three years of hydrological monitoring data, with additional hydrochemical, vegetation, and remote sensing data. In our analyses, we identified five land types: fen, flat peat swamp and peat margin swamp (peatlands), mineral swamp, and upland. Flat peat swamp was distinguished from fen using Ducks Unlimited criteria, stating fens cannot have trees >10 m in height. Little difference in water table variability, groundwater connectivity, vegetation composition, and water chemistry were found between flat peat swamp and fen, suggesting that for all practical purposes, they can be considered a single unit, and tree height alone cannot be used to differentiate these peatland types. In contrast, peat margin swamps exhibited lower and more variable water tables, consistent downward hydraulic gradients, and comprised a mixture of peatland and upland vegetation. Peat margin swamps, however, exhibited similar porewater pH, electrical conductivity, and base cation concentrations as upland, flat peat swamp and fen, suggesting that they are well connected hydrologically. Peat margin swamps were also found to modulate sub-surface water movement between fen and upland (via reduced transmissivity from lower water tables), and therefore act as distinct ecohydrological units.

1 Introduction

In the sub–humid Western Boreal Plain (WBP), wetlands are a dominant feature on the landscape, occurring primarily as peatlands (Vitt et al., 1996). Peatlands in the WBP overlie a generally deep and heterogeneous surficial geology (Andriashek, 2003; Devito et al., 2012), resulting in variable groundwater interactions with surrounding mixedwood uplands and underlying aquifers (Bachu et al., 1993; Devito et al., 2005; Devito et al., 2012). This variability establishes a wide range of peatland types, ranging from ombrotrophic bogs (no groundwater input) to minerotrophic and/or saline fens and forested swamps (Vitt et al., 1995; Devito et al. 1996; Wells et al., 2015).

Swamps are largely understudied components of Canadian wetlands in comparison to bogs and fens (Warner & Asada, 2006), and yet, could potentially be the second most abundant wetland class in Canada (Amani et al. 2019). Swamps are often mis-classified and overlooked in current wetland classifications as they can be hard to define (Warner & Asada, 2006). Swamps can be either mineral or organic wetlands, often classified based on the presence of hydric (permanently or seasonally saturated by water) soils as well as their tree cover (NWWG, 1997; Ducks Unlimited, 2015; Alberta Environment and Sustainable Resource Development, 2015). However, this can lead to confusion with regards to spatial classification of swamps in comparison to other wetland types, and often results in swamps being mis-categorized as other wetland types or even upland regions (Locky et al. 2005). Further, the hydrological dynamics of these wetlands (e.g., seasonal water table fluctuations; Zoltai & Vitt 1995; Devito & Mendoza 2007) can also lead to misclassification as fens if categorization is performed under wet conditions.

Swamps can exist on local topographic lows, or at the margin between peatland and upland. For example, bog margins (laggs), develop on a break in slope that initiates a convergence of runoff and groundwater from both bog and upland (Langlois et al., 2015). Although laggs typically do not contribute a groundwater flux to adjacent and topographically higher domed bogs (Ingram, 1983; Howie and van Meerveld, 2011; Langlois et al., 2015), they have been shown to exhibit an important hydrological function and control over the growth of bogs, primarily in helping retain higher water tables in the upper, more elevated sections of the peatland (Belyea and Baird, 2006; Langlois et al., 2015). Contrary to bogs, fens do not have elevated domes and the topographic gradient is downward from upland to peat margin to fen, and hydraulic gradients therefore typically follow the topography (Ferlatte et al., 2015, Elmes and Price, 2019). Prior studies have typically not focused on peat margins in fen-dominated peatlands; however, they have been shown to provide a direct source of lateral groundwater flow to lower–lying peatland areas. Reversals in the hydraulic gradient, from fen to peat margin to upland, have also been detected in the WBP (Ferone and Devito, 2004; Elmes and Price, 2019). Lukenbach et al. (2015) measured a greater degree of soil moisture variability at peat margins compared to lower–lying peatland areas. This left peat margins at a greater susceptibility to drying due to their relatively high bulk density coupled with lower soil moisture, and thus higher vulnerability to combustion and deep smoldering from wildfire (c.f. Elmes et al., 2018).

Given that swamps are understudied in Canada, little is known of their ecohydrological characteristics, and how they interact with adjacent uplands and wetlands. In this study, we apply an ecohydrological and GIS-based research approach at a fen-swamp complex within a watershed in the Athabasca Oil Sands Region (AOSR). The objectives of this study were to: 1) Use a combination of GIS and field-based methods to map the various wetland types; 2) characterize their ecological, physical, hydrological, and hydrochemical properties; 3) identify the key ecohydrological interactions between these units; and 4) relate these interactions to the function of the watershed.

2 Materials and Methods

2.1 Study site

This study is conducted in the AOSR in the Boreal Plains Ecozone (Ecoregions Working Group, 1989), where the average annual air temperature (1981–2010) is 1°C and average annual precipitation is 419 mm, with ~75 % falling as rain (Environment Canada, 2017). The climate in the AOSR is defined as sub–humid, where potential evapotranspiration (PET) often exceeds annual precipitation (Marshall et al., 1999).

Poplar Fen (56°56′ N, 111°32′ W; Fig. 1) is a ~2.4 km^2 treed moderate–rich fen-dominated watershed, located 25 km north of Fort McMurray, Alberta (Fig. 1). The watershed is situated within a ~10 km long meltwater channel belt characterized by outwash sand and gravel (McPherson and Kathol, 1977). Lithological logs reported by Elmes and Price (2019) show that the watershed is underlain by two relatively thick aquitards which constrain groundwater connectivity between local and regional aquifers. The watershed is characterized by low relief (~12 m) with peatland to upland slopes that range from 0.4–1.8%. Peatland area expands up-gradient, where peat depth reduces to 0.4 m in the margins between low-lying peatland and upland (Fig. 1). More information on the hydrogeologic setting of Poplar Fen can be found in Elmes and Price (2019).

2.2 GIS and remote sensing analyses

Peatland boundaries were mapped out in the field using a handheld GPS device and a piece of rebar was used to measure the depth of the organic layer. Areas with continuous organic soil deposits ≥0.4 m were assumed to be peatland (NWWG, 1997). Non-peatland (mineral) swamps - where hydric soils less than 0.4 m thick were present – occurred sporadically within upland boundaries and were mapped manually on site. These mineral swamp areas; however, were not mapped directly up-gradient of peatland/mineral land boundaries, as wetland vegetation indicator species were not detected consistently in these transition zones, and instead were classified as upland. Moreover, there was not sufficient information on hydric soil indicators in these areas; however, despite this uncertainty, these transitional areas represent a relatively miniscule proportional area. A decision-tree (Fig. 2), outlines the criteria for categorizing land-types discussed in this study. Peat margin swamp boundaries (NWWG, 1997) were mapped in QGIS (QGIS.org, 2020. Open-Source Geospatial Foundation Project) using an airborne LiDAR (Light Detection And Ranging) digital elevation model (DEM) with 2 m grid resolution (Airborne Imaging Inc. licensed to the Government of Alberta). Peat margin swamp areas were assumed to start at the boundary between upland and peatland mapped in the field, and end at the toe slope when the topographical gradient flattens substantially toward the peatland center. Following this, a LiDAR canopy height model (CHM; Figure S1) was used to distinguish fen from swamp areas within the low-lying peatland area, down-gradient of the margin and toe slope. In this study, we refer to these swamp areas as flat peat swamp, consistent with the Canadian Wetland Classification System (NWWG, 1997). The accuracy of the CHM was confirmed with the tree height data obtained in the field. Our criteria stated that fen areas should not have trees exceeding 10 m, which is consistent with the Ducks Unlimited boreal wetland classification system (Ducks Unlimited, 2015). Thus, five natural land types were mapped out at Poplar Fen: fen, flat peat swamp, peat margin swamp, mineral swamp, and upland. It is important to note that when mapping out fen boundaries, isolated or small clusters (<8m^2) of pixels with canopy heights 10 m or greater fell adjacent to fen boundaries. However, given that these were isolated and infrequent, we did not map them as flat peat swamp areas and instead categorized them as fen. Disturbed areas were delineated using Google satellite imagery. We compared our delineated wetland cover types with aerial estimates of wetland cover from the Alberta Merged Wetland Inventory (AMWI), a data layer produced using a combination of 32 inventories including the Ducks Unlimited Canada Boreal Enhanced Wetland Classification system, Landsat 5 and 7 ETM+ and Landsat 8 OLI imagery and other classification products. Wetland types in the AMWI are divided into bog, fen, swamp, marsh, and shallow open water (AMWI, 2018).

2.3 Hydrology and meteorology

A groundwater monitoring network comprising three transects (T1–T3; Fig. 1) were originally installed in the northwest portion of Poplar Fen between 2011-2013, extending south to north with well and piezometer nests installed into upland, peat margin swamp, flat peat swamp, fen, and disturbed areas. In 2015, additional nests were installed elsewhere throughout the watershed in west to east transects. Two transects (T4 and T5) comprised a denser network of nests, extending through the upland to peatland ecotone (Fig. 1). Screened wells and piezometers (0.2 m screened intake) were constructed from PVC (0.025 m I.D.) pipe and installed into the different substrates in grouped nests. Nests typically comprised a fully–slotted well, with piezometers installed in mid–peat and underlying mineral substrate. Nests were measured manually on a weekly basis during the spring and summer from 2011–2015. Pipe top and corresponding ground elevations were measured using a dual–frequency survey–grade differential global positioning system with a ± 0.005 m vertical accuracy (DGPS; Leica Viva GS14, 2014).

To explore differences in water table position between fen (n=12), flat peat swamp (n=7), and peat margin swamp (n=8) areas (refer to Fig. 1, hollow circles), daily averages were computed for each peatland type. However, due to occasional missing values at specific wells, and the fact that some wells were not installed until the spring of 2015, data were gap-filled so that values for each well were available for each measurement day (n=45) from 2013-2015. Gap filling was performed using highly correlated values (R^2 >0.9) of manual measurements for each peatland type. Gap filled data were used only for comparing differences in water table and were not used for calculating hydraulic gradients (see below).

Vertical hydraulic gradients ($\delta h/\delta l$) between the water table and underlying mineral layer were calculated each measurement day for all available nests. Horizontal hydraulic gradients ($\delta h/\delta l$) over the upland–fen ecotone were calculated weekly between all adjacent wells from water table elevation differences between the various undisturbed land types, using all wells shown in Figure 1.

2.4 Peat coring and analysis

To explore differences in hydrophysical properties, peat cores were obtained from peat margin swamp (n =2), flat peat swamp (n=1), and fen (n=1) locations, with depths ranging from 0.5–1.0 m. Note that cores were not obtained from mineral swamp areas, nor upland areas. For additional information on the hydrophysical properties of upland areas at Poplar Fen, refer to Elmes and Price (2019) and Elmes et al. (2019). Cores were extracted using a Wardenaar coring device, subdivided into 0.1–m stratigraphic intervals, and were then frozen and shipped for processing at the Wetlands Hydrology lab at the University of Waterloo. Samples were thawed, saturated, encased in wax, weighed, then tested for horizontal saturated hydraulic conductivity (in the x-direction: hereafter referred to as K_{sat}) using a constant head method (e.g., Freeze and Cherry, 1979). Following these tests, saturated samples were covered on top (to prevent evaporation) and left to drain under gravity for approximately 24 hr to determine drainable porosity, then dried in a furnace at 110°C to determine dry bulk density and porosity.

2.5 Ground-layer vegetation and tree surveys

During the summer of 2015, tree and vegetation surveys were conducted on 20m x 20m plots along the upland–fen ecotone at T4 (n=5) and T5 (n=4) (see Fig. 4 for locations). Locations of plots were chosen strategically based on observed differences in elevation and community composition. Within each plot, three 1 m^2 non-treed (saplings only) quadrats were chosen randomly for vegetation surveys. Percent cover of each species was determined visually (using Johnson et al. (1995) as reference) within each quadrant and was then averaged for the entire plot. All individuals were reported with species nomenclature following the USDA online plants database (USDA, 2020). Species were then grouped by type (brown moss, *Sphagnum* moss, feathermoss, herb, graminoid, horsetail, and shrub). Due to the three–dimensional vegetation cover, percent cover often exceeded 100%. As a result, percent cover of each species was converted to a relative proportion. Following vegetation surveys, all trees within the 20x20m plots were counted and grouped into size classes (≤1 m, ≤2 m, ≤4 m, >4 m). For ground-truthing purposes (see section 2.4), heights of all tall trees (>4 m) were measured using an inclinometer. Average tree height was calculated, where individuals <4 m in height were assumed a midpoint height for their respective class (e.g., ≤2 m = 1.5 m height).

2.6 Hydrochemistry

In August 2014, water samples were obtained from a subset of selected wells at T1–T3. In July of 2015, another round of water sampling was conducted on select wells and piezometers from the newly installed nests, with high resolution sampling at T4 and T5. All wells and piezometers were purged roughly 24 h prior to sampling. Samples were obtained using a rinsed peristaltic pump, which routed 50-100 mL of water from the pipe into a clean reservoir to measure electrical conductivity (EC) and pH using a multiparameter probe (Thermo Scientific™ Orion™ Star A329 pH/Conductivity Portable Multiparameter meter), which were calibrated prior to use. All water samples taken from Poplar Fen were filtered within 24 h using 0.45 µm nitrocellulose membrane filters. Samples were stored in 60 mL high–density polyethylene bottles and kept frozen prior to analyses. SHydrochemical analyses were completed at the Biotron Experimental Climate Change Research Centre at Western University. Major ions were measured with ion chromatography. Major cations were analyzed by the Dionex ICS-1600 Method EPA 300.0 with AS-DV auto-sampler for Na^+, K^+, Ca^{2+}, Mg^{2+}, and NH_4^+, with analytical precision to ± 1.0, 1.0, 0.1, 0.01, and 0.1 mg L^{-1}, respectively. Major anions were analyzed by a Dionex IC Method A-102 for Cl^-, F^-, NO_2^- , NO_3^- , and SO_4^{2-}, with analytical precision to ± 0.05, 0.05, 0.1, 0.1, and 0.05 mg L^{-1}, respectively. Field blanks (bottles filled with de-ionized water) and sample duplicates were also taken periodically throughout both sampling events for quality assurance/quality control measures.

2.7 Statistical Analyses

All statistical analysis was undertaken in R version 1.3.959. To explore differences in ion concentrations between peatland types (fen, flat peat swamp, and peat margin swamp) and upland, Kruskal Wallace tests were conducted, followed by a Dunn post-hoc test. A p-value less than 0.05 was considered to indicate a significant difference.

3 Results

3.1 Mapping of land types

Based on the field analyses, uplands were found to be the dominant land type, covering ~62% of the watershed (based on pre-disturbance estimates) (Table 1), with wetlands occupying the remaining 38%. For the 0.8 km^2 of peatland (based on current estimates), flat peat swamp had the highest cover (17%), followed by fen (11%), peat margin swamp (4%), and mineral swamp (1%).

Frequency histograms of canopy height returns for the CHM for the five land types were created using 1 m height bins (Fig. 3). Fen areas (pixel n = 68155) had the lowest CHM returns, averaging 3.8 ± 2.4 (SD) m, with 2.4% of returns in bins 10 m or taller. This was followed by mineral swamp (pixel n = 8784), which averaged 6 m and had 20% of CHM returns in bins 10 m or taller. Flat peat swamp (pixel n = 97709) and peat margin swamp (pixel n = 25549) had the third and fourth tallest CHM returns, averaging 6.5 ± 3.0 m and 7.6 ± 3.1 m, with 12 and 20% of returns in bins 10 m or taller, respectively. Upland areas (pixel n = 302576) had the tallest and most variable CHM returns, averaging 9.8 ± 4.5 m, with 59% of CHM returns in bins 10 m or taller. It was estimated that 15% of the watershed had some degree of disturbance (Table 1).

3.2 Vegetation Composition

A complete list of vegetation composition for all plots measured at T4 and T5 are located in supplementary tables S1 and S2, with results generalized into 7 groups in Table 2. Tree height and density information is located in Table S3. Both upland plots at T4 and T5 were at the highest topographic position relative to other plots and had the lowest organic layer thickness (~0.2 m; (Fig. 4). Upland quadrats were composed primarily of feathermosses and shrubs/saplings, with a small proportion of horsetail (*Equisetum spp.*) (Table 2). *Picea mariana* comprised 100% the overstory at both upland plots, with trees reaching up to 15 m in height. Across both transects, surface elevation decreased (Fig. 4) and community composition gradually transitioned with species richness increasing (Tables S1 and S2). Peat margin swamps were dominated by feathermosses and dwarf shrubs. Fen and flat peat swamp areas had similar vegetation, with subtle differences. For example, fens had a higher brown moss (primarily *Tomenthypnum nitens*) cover and lower *Sphagnum* moss cover relative to flat peat swamp areas (Table 2). At T4, the fen plot had double the proportion of graminoid species relative to the flat peat swamp plot (Table 2). At both T4 and T5, flat peat swamp locations had a higher tree density relative to adjacent fen locations (Table S3).

3.3 Topography and peat hydrophysical properties

At transects T4 and T5, total relief was 1.1 m and 10.2 m, length of upland along to the transect was 70 and 1000 m, and average upland slope was 0.8 and 1.8%, respectively (Fig. 4). Each transect had varying sequences of land types, and had nearby seismic line disturbances (Fig. 4)(refer to Fig. 1). Peat was thinnest at peat margin swamp locations, averaging 0.75 m, followed by flat peat swamp (0.96 m) and fen (1.30 m).

Little difference in bulk density was observed between fen, flat peat swamp, and peat margin swamp cores in the upper 0.3 m (Fig. 5). Values ranged from 0.06-0.08 g cm^{-3} in the top 0.1 m, 0.14-0.15 g cm^{-3} from 0.1-0.2 m, and from 0.13-0.17 g cm^{-3} at 0.2-0.3 cm b.g.s. From 0.3-0.5 m b.g.s., bulk density was consistently higher in peat margin swamp samples (mean = 0.27 g cm^{-3}) relative to fen (mean = 0.15 g cm^{-3}) and flat peat swamp (mean = 0.18 g cm^{-3}) samples. Little difference was found in drainable porosity between fen, flat peat swamp, and peat margin swamp cores, with differences ranging from 2-4% for a given depth. For lab measured K_{sat}, all cores had virtually indistinguishable values with depth. Differences were only visible for the peat margin swamp core at T5, which had the highest K_{sat}, typically by an order of magnitude, at all depths relative to the other three cores (Fig. 5).

3.4 Hydrological comparison of fen, flat peat swamp, and peat margin swamp areas

3.4.1 Water table position

A detailed overview of peat margin swamp and low-lying peatland water table trends can be found in Elmes and Price (2019). Note that in that study, flat peat swamp and fen areas were not distinguished separately at the time, and all peatland areas down-gradient of the margin and toe slope were simply characterized as fen. In this study, areas classified as fen exhibited the shallowest water tables relative to ground surface (Fig. S2) (mean = 0.05 ± 0.06 (SD) m b.g.s.), with average water table shallower than 0.10 m b.g.s. 85% of the time (Fig. 6). This was followed by flat peat swamp (Fig. S2) (mean = 0.11 ± 0.07 (SD) m b.g.s.), which exhibited similar water table variability; however, water tables were 0.06 m lower on average, and were above 0.10 m b.g.s. only 40% of the time (Fig. 6). Peat margin swamp (0.22 ± 12 (SD) m b.g.s.) and mineral swamp (0.21 ± 0.09 m b.g.s.) had lower water tables relative to flat peat swamp and fen areas (Fig. S2). Peat margin swamp areas had the highest variability of all wetland types, with spatially averaged water tables reaching as low as 0.62 m b.g.s. (Fig. 6). Uplands experienced lower and more variable water tables relative to all wetland types (Figs. 6, S2), averaging 0.51 ± 21 (SD) m b.g.s.

3.4.2 Water table connectivity between land types

At transects T1-T3, hydraulic gradients were strongest between upland and peat margin swamp, reaching up to 0.005 during 2013, and also had the most negative (flow reversed from peat margin swamp to upland) values (reaching -0.002), and averaging 0.002. Daily average hydraulic gradients between peat margin swamp and flat peat swamp or fen ranged between -0.001 and 0.003, averaging 0.001.

Across T4 and T5, which were installed in 2015, water tables were only measured on 10 occasions over the 2015 growing season, which was a dry year relative to 2012-2014 (Elmes et al., 2018). Hydraulic gradients at T4 were directed from peat margin swamp to upland (against topography) for 6 of the 10 days measured, with values ranging from 0.007 (upland to peat margin swamp) to -0.003 (peat margin swamp to upland). Hydraulic gradients between peat margin swamp and low-lying peatland (both flat peat swamp and fen) were virtually flat over this time, ranging from 0.001 to -0.001. Between the flat peat swamp and fen center locations, gradients were directed towards the flat peat swamp; however, gradients were also relatively small, ranging from -0.001 to -0.003. In contrast, water table gradients across the T5 ecotone were stronger. For example, water table gradients were directed from upland to peat margin swamp for the entire 2015 season, ranging from 0.007 to 0.01 and averaging 0.009. Across the low-lying peatland area (flat peat swamp and fen), hydraulic gradients were stable, averaging -0.002, and flow direction persisted west, through the swamp area (against topography) on the west end of the transect (refer to Fig. 4).

3.4.3 Vertical groundwater connectivity

Vertical flow direction between low-lying peatland areas (flat peat swamp and fen) and the underlying outwash aquifer was transient during 2011–2015, with flow reversals occurring in 2012, 2014, and 2015. A detailed description of these patterns can be found in Elmes and Price (2019). Vertical hydraulic gradients were an order of magnitude stronger than horizontal hydraulic gradients between wells from 2011-2015, with daily averages across the low-lying (flat peat swamp and fen) peatland ranging from -0.07 (downward from peat to the underlying outwash aquifer) to 0.03 (upward from the underlying outwash aquifer to the peat) and averaging 0.002. Vertical gradients were positive throughout the majority of the five–year period with flow reversals only occurring over extended dry periods (Elmes and Price, 2019). On further inspection, we found little difference in the strength or direction of vertical hydraulic gradients between flat peat swamp (n = 3) and fen (n = 3). In contrast, vertical hydraulic gradients in peat margin swamp areas were negative throughout the entire five–year record, averaging –0.02 (Table 1). Contrary to fen and flat peat swamp areas, where gradients were highest (positive) during the wet years (2013–2014), the lowest (most negative) vertical hydraulic gradients in peat margin swamp areas were measured during this time. Vertical hydraulic gradients were always negative at the mineral swamp nest throughout 2014-2015, averaging -0.04.

Large differences were found in the vertical groundwater connectivity of peat margin swamp areas of varying topographic positions. For example, peat margin swamp nests located closer to the upland/peatland boundary typically had the strongest gradients in 2015, which were always negative (mean = –0.04), directed towards the underlying outwash aquifer. Conversely, both peat margin swamp nests located closer to toe slopes still had negative vertical hydraulic gradients throughout the entire year; however, gradients in these nests were weaker (mean = –0.02). The greatest differences were measured at peat margin swamp nests located directly at toe slopes, where vertical hydraulic gradients were typically positive (mean = +0.001).

3.5 Hydrochemistry

For water samples obtained from 1-1.5 m deep wells at Poplar Fen in 2015, little difference in pH, EC, and ion concentrations were found between fen, flat peat swamp, and peat margin swamp areas (Table 3). Significant differences ($p<0.05$) were only detected between fen and peat margin swamp for Cl^- and SO_4^{2-}, and between flat peat swamp and peat margin swamp for SO_4^{2-}. No significant differences were measured between fen and flat peat swamp for any of the chemical variables. In contrast, upland water samples exhibited the lowest Na^+ and highest SO_4^{2-} concentrations (Table 3), which were significantly different from fen and flat peat swamp, and not peat margin swamp.

4 Discussion

4.1 Mapped land cover types within Poplar Fen Watershed

We found that a combination of LiDAR-based geospatial analyses and field-based ground-truthing can provide an efficient means of mapping fen and swamp boundaries at peatland-dominated watersheds with mixed peatland types. Such is the case at Poplar Fen, a channel peatland with undulating slopes and gradual transitions along the ecotone from upland to peat margin swamp to flat peat swamp to fen. We found flat peat swamp peatlands to be the most abundant wetland type within the watershed. Flat peat, mineral, and peat margin swamps totaled 0.58 km^2, 66% of the peatland area. Large discrepancies were detected between our estimates and those reported in the AMWI. For example, swamp and fen area reported by AMWI totaled 1.5 km^2, and our estimate totaled 0.86 km^2, highlighting an overestimation by the AMWI by 76%. Our results suggest that these discrepancies were caused by poor discrimination between land types. For example, 0.65 km^2 of upland area was improperly classified as wetland by the AMWI, with 82% of this area classified as swamp. Furthermore, the fen to swamp ratio determined by the AMWI was 2.8, whereas our analysis found it to be 0.47, suggesting that the AMWI had overestimated fen area, predominantly at peatland margins. One plausible explanation for such discrepancies may be due to the similarities in canopy characteristics between flat peat swamp, peat margin swamp and upland (Fig. 3). This presents limitations of relying solely on aerial imagery as a means of defining wetland boundaries (Gallant, 2015). The results generated in this study suggest that peatland extent, thus, peat carbon stocks, may be inaccurate in the AMWI, and that certain peatland types may be poorly classified. However, we do acknowledge that our results are bound to a single first order watershed, and additional studies should be conducted to compare peatland boundary estimates based on remote sensing versus those that incorporate field observations, specifically organic layer thickness.

4.2 Ecohydrological differences in land types

4.2.1 Vegetation

We identified a transition in vegetation community composition along the upland–peatland ecotone at transects T4 and T5 (Tables S1-S2). Uplands were composed primarily of feathermosses characteristic of boreal forests overlying mineral soils (Bauer et al., 2009). Across the ecotones, down-gradient, there was an increase in species richness, as well as the appearance of several peatland indicator species (cf. Vitt and Chee, 1990). Although peat margin swamps were dominated by feathermosses (Table 2), the emergence of peatland indicator species (Tables S1-S2) suggests that they are positioned within a transition zone characterized by more saturated conditions that support the presence of peatland vegetation (e.g., *T. nitens*, *Carex spp.*; Chee and Vitt, 1989; Vitt and Chee, 1990). Furthermore, the appearance of *T. nitens* (Tables S1-S2), a moderate–rich fen indicator species (Chee and Vitt, 1989) at peat margin swamp locations suggests that peatland margin non-vascular vegetation can access circumneutral, ion–rich water characteristic of low-lying peatland areas (see Table 3).

We found little difference in the vegetation composition between fen and flat peat swamp areas, as both were dominated by *T. nitens* (Tables S1-S2). Consistent between both transects were a higher proportional cover of *Sphagnum* moss species at flat peat swamp relative to fen locations (Table 2). This may be due to differences in canopy characteristics, as flat peat swamp locations have a larger tree height and density (Table S3). Flat peat swamp areas may therefore provide more shading, and thus, more optimal growing conditions for *Sphagnum* mosses (Laing et al. 2014).

4.2.2 Hydrology

Fen and flat peat swamp areas exhibited similar water table variability over the 2013-2015 record, despite flat peat swamp water tables being 0.07 m lower on average (Fig. 6). Furthermore, we did not find noticeable differences in the vertical groundwater connectivity between these two areas, as both were generally groundwater discharge zones during periods of high-water availability, and subject to flow reversals during dry periods. Higher tree density at flat peat swamp compared to fen locations (Table S3) can lead to greater interception loss and evapotranspiration, enhancing water table drawdown (Koivusalo et al., 2008; Verry, 1981; Jutras and Plamondon, 2005; Jutras et al., 2007). However, given the similarities in their hydrologic regime, it is likely that the contrasting canopy characteristics alone were not sufficient to cause significant hydrological differences between land types. It is likely that differing canopy characteristics are a consequence of relative position along the ecotone, as flat peat swamp areas, in general, are slightly higher in topographic position relative to fen, and closer to peat margin swamp areas (Fig. 1). In contrast, peat margin swamps exhibited much lower and more variable water tables, consistent with other studies in the WBP (Ferone and Devito, 2004; Lukenbach et al., 2015). Such differences are likely attributed to contrasting topographic positions between peat margin swamp and adjacent fen and flat peat swamp areas. Peat margin swamps at Poplar Fen are located on steeper slopes in groundwater recharge areas (Fig. 4), characterized by consistently downward hydraulic gradients, and thus, lower water tables and greater water table variability (Fig. 6).

The peat margin swamp located at T4 had higher bulk density (from 0.3-0.5 m b.g.s. only) and K_{sat}, and lower drainable porosity at depth compared to peat from flat peat swamp, T5 peat margin swamp and fen (Fig. 5). Differences in the hydrophysical properties would be expected, as lower water tables at peat margin swamp locations (Fig. 6), and thus oxidized conditions deeper in the profile, would enhance peat decomposition (Roulet et al., 2007) and lead to increased bulk density and decreased drainable porosity (Ise et al., 2008; Waddington et al., 2015). Differences at T4 peat margin swamp may simply be a consequence of the low resolution of our sampling, as it is acknowledged that K_{sat} is highly heterogeneous within a peatland (Hoag and Price, 1995; Fraser et al., 2001; Liu and Lennartz, 2019). The sampling resolution in this study was therefore not extensive enough to effectively capture this variability and effectively assess the differences in K_{sat} between peatland types. Unfortunately, all peat margin areas were impacted by the 2016 Horse River Wildfire (Elmes et al., 2018) and additional undisturbed peat samples cannot be obtained. However, future studies should aim to properly characterize differences in hydrophysical properties between peat margin swamps and lower lying peatland areas throughout the WBP.

Peat margin swamps may exhibit an important control on the lateral groundwater connectivity over the upland–fen ecotone. Elmes and Price (2019) described the importance of a transmissivity feedback mechanism (Waddington et al., 2015) at Poplar Fen, whereby horizontal groundwater is discharged at relatively higher volumes from upland to fen during wet periods, due to two primary processes: (1) the hydraulic gradient between upland and fen becomes higher following a rainfall event; and (2) the higher water table exploits higher K_{sat} layers, increasing the transmissivity of the upland-to-fen flow path. The results of this study help refine our understanding of the transmissivity feedback mechanism in boreal fens in the WBP. High vertical recharge (via downward hydraulic gradient) promotes lower peat margin swamp water tables, thus, reducing the transmissivity of the flowpath from upland to fen as the water table less-frequently exploits the upper, more transmissive peat layers. This may provide a negative feedback during dry periods, as lower transmissivity will reduce water flow from lower-lying peatland areas (fen and flat peat swamp) to upland during flow reversals.

Complete horizontal flow reversals from fen to peat margin swamp, and from peat margin swamp to upland, were detected, but only intermittently during the summer and fall of 2015, a particularly dry year. During certain dry periods in 2011 and 2012, convergent flow conditions occurred in the peat margin swamps, where lateral groundwater flow from the upland to the peat margin swamp converges with flow from the fen to the peat margin swamp. Similar convergent flow conditions were witnessed in laggs between upland and peatland in the Bécancour region of Quebec (Ferlatte et al., 2015). Despite these reversals, groundwater followed topography for the majority of the three-year period, specifically during wet periods when the transmissivity feedback mechanism was enhanced (Elmes and Price, 2019). Such findings are contrary to other conceptual models in the WBP (Hokanson et al., 2020), which state that water tables rarely follow topography in wetland-upland complexes the region. It is more likely that upland-peatland connectivity is site specific, with conditions similar to our findings in watersheds with hydrogeologic settings characterized by gentle slopes (common in the AOSR) and coarser grain sizes (higher K_{sat}). Whereas conditions similar to those described by Hokanson et al., 2020 are likely more representative of watersheds comminated by clay plains and steeper moraines with lower K_{sat} (Ferone and Devito, 2004).

Only one nest was installed into the mineral swamp area in 2014, limiting its comparability with other, more instrumented wetland types in the watershed. Water table position was similar, albeit less variable, to that which was measured in peat margin swamp areas, and both areas were characterized by downward hydraulic gradients. Lower water table variability may be attributed to a low K_{sat} (4.0 x 10^{-10} m s^{-1}) clay deposit under the mineral swamp at ~1.5 m b.g.s. (Elmes and Price, 2019), which would limit recharge to the underlying outwash aquifer. We postulate that the mineral swamp is a direct consequence of the clay lens, and would not exist in an upland characterized by high K_{sat} (3.0×10^{-4} m s^{-1}; Elmes and Price, 2019) and infiltrability (1.3 x 10^{-4} m s^{-1}; Elmes et al., 2019), given the absence of this confining lens. Discerning these systems from uplands with aerial imagery may prove difficult without the aid of LiDAR and ground-based observations, and may therefore not be properly accounted for in current wetland inventories.

4.2.3 Hydrochemistry

The similarities in hydrochemical composition between land types at Poplar Fen (Table 3) highlight a hydrologically well-connected upland-peatland ecotone. Fen, flat peat swamp, and peat margin swamp areas all had circumneutral pH and similarly high EC and base cation concentrations. Lower sodium concentrations in peat margin swamp peat porewaters relative to fen and flat peat swamp may be due to a lack of influence from underlying aquifers and aquitards. Fen and flat peat swamp areas are located in groundwater discharge zones. This is evidenced by stronger upward hydraulic gradients in these locations, highlighting a stronger groundwater influence, including diffusion from lower silt-dominated till, below the Pleistocene sand and gravel that comprises upland areas and directly under the peat (Elmes and Price, 2019). Furthermore, significantly higher sulphate concentrations in peat margin swamp areas are consistent with lower water tables (Fig. 7), thus more oxic conditions and higher redox potential (Devito and Hill, 1996).

4.3 Suggested land cover definitions of Poplar Fen Watershed

Based on the ecohydrological similarities outlined in the above section, we present a conceptual model (Fig. 7) of the ecohydrology of the distinct land types at Poplar Fen Watershed: treed moderate-rich fen (flat peat swamp and fen); peat margin swamp; mineral swamp; and upland.

Surprisingly, few ecohydrological differences were found between fen and flat peat swamp areas. The combined similarities in vegetation composition (Tables 2, S1, S2), water table patterns (Figs. 6, S2, groundwater connectivity, and hydrochemistry (Table 3) suggest that fen and flat peat swamp areas serve similar ecohydrological functions, and for practical purposes, may be considered a single peatland type with the same hydrological functions (i.e., moderate-rich fen; Elmes and Price, 2019) (Fig. 7). We cannot specify the exact reason for differences in canopy characteristics (e.g., tree height), the only real discernable difference. Instead, we propose that slight differences in topographic position may cause differences in water table position sufficient enough to influence tree growth. The lowest topographic positions are typically at fen center areas, and elevation increases towards flat swamp, peat margin swamp and upland (Fig. 7). More elevated topographic position favours lower water tables, thus providing more aerated conditions for tree growth.

In contrast, we found considerable difference between moderate-rich fen and peat margin and mineral swamp areas. Mineral swamps were the smallest land type in the watershed (1%). Despite their size, mineral swamps within upland environments may be an important permanent source of groundwater recharge (Fig. 7). Given the heterogeneous surficial geology found in the region (Andriashek, 2003), mineral swamp systems may be prevalent in uplands of the WBP. Future studies should focus on better detecting these systems and understanding their hydrologic role at the watershed scale.

Peat margin swamp areas at Poplar Fen, despite representing a relatively low proportion of the total watershed area (4%), appear to have an important ecohydrological function for the watershed. High transmissivity from upland to fen during wet periods and mitigation of fen drainage to adjacent upland areas during dry periods (Fig. 7) is an important characteristic for fen watersheds in the WBP that experience persistent water deficits. Here, we argue that the ecohydrological importance of peat margin swamps at Poplar Fen is greater than its relative proportion on the landscape. As such, peat margin swamps may be overlooked in hydrological studies. However, the results presented in this study apply to only one hydrogeological setting (i.e., meltwater channel belt) in one ecozone of Canada (i.e., Boreal Plains). Additional studies on peat margin swamps adjacent to varying fen types is necessary to identify how their ecohydrological functions change with differing hydrogeological and climatological settings. Overall, given the potential for swamps to make up a greater proportion of wetland landscapes than previously thought, this study provides a key understanding of their ecohydrological function and variability at the watershed scale.

5 Conclusions

Our results indicate that tree height (≥10 m) may not serve as a standalone metric for discriminating fens from peat-forming swamps in the Western Boreal Plain. Despite water tables being ~0.07 m lower in flat peat swamp areas, we found negligible differences in water table variation, groundwater connectivity, porewater chemistry, and vegetation composition between fen and flat peat swamp areas. Our results suggest that these hydrologically connected areas function as a single peatland type. In contrast, we found considerable differences between peat margin swamps and flat peat swamp and fen areas. Peat margin swamps had taller trees and a denser canopy, a more variable water table, and were recharge areas for the entire 2013-2015 monitoring period. Similarities in porewater chemistry suggest that peat margin swamps are well-connected to the landscape, hydrologically. However, lower water tables, thus intersection of the water table with deeper and lower K_{sat} peat highlights an important water preservation mechanism, whereby peat margin swamps regulate discharge from upland to low-lying peatland areas during typical non-water limited periods, and limit water loss from low-lying peatland areas during extended dry periods when flow can reverse to the upland. Peat margin swamps therefore have an important hydrologic function; however, given their similarities to uplands with respect to canopy characteristics, mapping peat margin swamp boundaries can be challenging. Such challenges may be minimized through the use of high-resolution LiDAR-based canopy height and digital elevation models to discriminate between subtle differences in tree height distribution and topographic position. Given the ubiquity of forested peatlands in the WBP, and therefore the potential for mineral and peat margin swamps to represent a greater proportion of wetland landscapes than previously thought, future studies should aim at better understanding how the ecohydrology of these systems vary in watersheds of varying hydrogeological settings.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interest statement

The authors declare that they have no conflict of interest.

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References

Alberta Environment and Sustainable Resource Development. Alberta Wetland Classification System;Water Policy Branch, Policy and Planning Division: Edmonton, AB, Canada, 2015.

Amani, M., Mahdavi, S., Afshar, M., Brisco, B., Huang, W., Mirzadeh, M.J., White, L., Banks, S., Montgomery, J., & Hopkinson, C. 2019. Canadian wetland inventory using Google Earth Engine: The first map and preliminary results. *Remote Sens.*, 11(7): 842, doi: 10.3390/rs11070842.

Andriashek L.D. 2003. *Quaternary geological setting of the Athabasca oil sands (in situ) area, northeast Alberta*. EUB/AGS Geo-Note 2002-03, Alberta Energy and Utilities Board, Edmonton, Alberta, 295 pp.Bachu, S., Underschultz, B.H., Hitchon, B, & Cotterill, D. 1993. *Regional-Scale Subsurface Hydrogeology in Northeastern Alberta*. Alberta Geological Survey, Edmonton, AB, 49 pp., available at: https://ags.aer.ca/document/BUL/BUL_061.pdf (last access: 28 Aug. 2018).

Bauer, I.E., Bhatti, J.S., Swanston, C., Wieder, R.K., & Preston, C.M. 2009. Organic Matter Accumulation and Community Change at the Peatland– Upland Interface: Inferences from ^{14}C and ^{210}Pb Dated Profiles. *Ecosystems*, 12: 636–653, doi: 10.1007/s10021-009-9248-2.

Beylea, L.R., & Baird, A.J. 2006. Beyond "The limits to peat bog growth": cross-scale feedback in peatland development. *Ecol. Monogr.*, 76(3): 299–322, 2006, doi: 10.1890/0012-9615(2006)076[0299:BTLTPB]2.0.CO;2

Chee, W.L., & Vitt, D.H. 1989. The vegetation, surface water chemistry and peat chemistry of moderate-rich fens in central Alberta, Canada. *Wetlands*, 9(2): 227-261, doi: 10.1007/BF03160747.

Devito, K.J., & Mendoza, C. 2007. Maintenance and Dynamics of Natural Wetlands in Western Boreal Forests: Synthesis of Current Understanding from the Utikuma Research Study Area. In: Guideline for wetland establishment on reclaimed oil sands lease[s] (2nd edition). Harris ML (ed.) Prepared by Lorax Environmental for the Wetlands and Aquatics Subgroup of the Reclamation Working Group of the Cumulative Environmental Management Association, Fort McMurray, AB. Appendix C-1.

Devito, K., Creed, I., Gan, T., Mendoza, C., Petrone, R., Silins, U., & Smerdon, B. 2005. A framework for broad-scale classification of hydrologic response units on the Boreal Plain: is topography the last thing to consider? *Hydrol. Process*., 19: 1705–1714, doi: 10.1002/hyp.5881.

Devito, K.J., Hill, A.R., & Roulet, N. 1996. Groundwater-surface water interactions in headwater forested wetlands of the Canadian Shield. *J. Hydrol.*, 181(1-4): 127-147. doi: 10.1016/0022-1694(95)02912-5.

Devito, K.J., & Hill, A.R. 1999. Sulphate mobilization and pore water chemistry in relation to groundwater hydrology and summer drought in two conifer swamps on the Canadian shield. *Water Air Soil Pollut.*, 113: 97–114. doi: 10.1023/A:1005081505086

Devito K, Mendoza C, Qualizza C. 2012. *Conceptualizing water movement in the Boreal Plains, Implications for watershed reconstruction*. Synthesis report prepared for the Canadian Oil Sands Network for Research and Development, Environmental and Reclamation Research

Group, 164 pp., doi: 10.7939/R32J4H.

Ducks Unlimited Canada. 2015. Field guide: Boreal wetland classes in the boreal plains ecozone of Canada. 92pp.

Ecoregions Working Group. 1989. *Ecoclimatic Regions of Canada*. Ecological Land Classification Series No. 23.

Elmes, M. C., Thompson, D.K., & Price, J. S. 2019. Changes to the hydrophysical properties of upland and riparian soils in a burned fen watershed in the Athabasca Oil Sands Region, northern Alberta, Canada. *Catena*, 181: 157-170. doi: 10.1016/j.catena.2015.104077.

Elmes, M. C., & Price, J. S. 2019. Hydrologic function of a moderate-rich fen watershed in the Athabasca Oil Sands Region of the Western Boreal Plain, northern Alberta. *J. Hydrol*., 570: 692–704, doi: 10.1016/j.jhydrol.2018.12.043.

Elmes, M.C., Thompson, D.K., Sherwood, J.H., Price, J.S., 2018. Hydrometeorological conditions preceding wildfire, and the subsequent burning of a fen watershed in Fort McMurray, Alberta, Canada. *Nat. Hazard. Earth Sys*. 18: 157–170, doi: 10.5194/nhess-18-157-2018.

Environment Canada. 2017. *Canadian Climate Normals 1981–2010 Station Data*. Government of Canada, Ottawa, Available at http://climate.weather.gc.ca/climate_normals/ (last access: 28 Aug. 2018).

Ferlatte M, Quillet A, Larocque M, Cloutier V, Pellerin S, Paniconi C. 2015. Aquifer–peatland connectivity in southern Quebec (Canada). *Hydrol. Process*., 29: 2600–2612, doi: 10.1002/hyp.10390.

Ferone JM, Devito KJ. 2004. Shallow groundwater-surface water interactions in pond-peatland complexes along a Boreal Plain topographic gradient. *J. Hydrol*., 292: 75–95, doi: 10.1016/j.jhydrol.2003.12.032.

Fraser CJD, Roulet NT, Moore TR. 2001. Hydrology and dissolved organic carbon biogeochemistry in an ombrotrophic bog. *Hydrol. Process.*, 15: 3151–3166, doi: 10.1002/hyp.322.

Gallant, A. 2015. The Challenges of remote monitoring of wetlands. *Remote Sens.*, 7: 10938–10950, doi: 10.3390/rs70810938.

Hoag RS, Price JS. 1995. A field-scale, natural gradient solute transport experiment in peat at a Newfoundland blanket bog. *J. Hydrol.*, 172: 171–184, doi: 10.1016/0022-1694(95)02696-M.

Hokanson, K.J., Peterson, E.S., Devito, K.J., and Mendoza, C.A. 2020. Forestland-peatland hydrologic connectivity in water-limited environments: hydraulic gradients often oppose topography. *Environ. Res. Lett*., 15(3): 034021, doi: 10.1088/1748-9326/ab699a.

Howie SA, Meerveld IT-v. 2011. The essential role of the lagg in raised bog function and restoration: a review. *Wetlands*, 31: 613–622, doi: 10.1007/s13157-011-0168-5.

Ingram HAP. 1983. Hydrology, in: Ecosystems of the World 4A. Mires: Swamp, bog, fen and moor, edited by: Gore AJP, Elsevier, Amsterdam, 67–224.

Ise T, Dunn AL, Wofsy SC, Moorcroft PR. 2008. High sensitivity of peat decomposition to climate change through water-table feedback. *Nat. Geosc.*, 1: 763–766, doi: 10.1038/ngeo331.

Johnson, D., L. Kershaw, A. MacKinnon, and J. Pojar. 1995. Plants of the western boreal forest and aspen parkland. Lone Pine Publishing. Edmonton, AB. Pp. 36.

Jutras, S., and Plamondon, A.P. 2005. Water-table rise after harvesting in a treed fen previously drained for forestry. *Suo*, 56: 95–100.

Jutras, S., Begin, J., Plamondon, A., and Hökkä, H. 2007. Draining an unproductive black spruce peatland stand: 18-year post-treatment tree growth and stand productivity. *For. Chron*. 83(5): 723–732, doi: 10.5558/tfc83723-5.

Koivusalo, H., Ahti, E., Laure´n, A., Kokkonen, T., Karvonen, T., Nevalainen, R., and Fine´r, L. 2008. Impacts of ditch cleaning on hydrological processes in a drained peatland forest. *Hydrol. Earth Syst. Sci*., 12: 1211–1227, doi: 10.5194/hess-12-1211-2008.

Laing, C.G., Granath, G., Belyea, L.R., Allton, K.E. & Rydin, H. 2014. Tradeoffs and scaling of functional traits in Sphagnum as drivers of carbon cycling in peatlands. *Oikos*, 123: 817–828, doi: 10.1111/oik.01061.

Langlois MN, Price JS, Rochefort L. 2015. Landscape analysis of nutrient-enriched margins (lagg) in ombrotrophic peatlands, *Sci. Total Environ.*, 505: 573-586, doi: 10.1016/j.scitotenv.2014.10.007.

Liu, H., Lennartz, B., 2019. Hydraulic properties of peat soils along a bulk density gradient—a meta study. *Hydrol. Process*., 33(1): 101–114, doi: 10.1002/ hyp.v33.110.1002/hyp.13314.

Locky, D.A., Bayley, S.E. & Vitt, D.H. The vegetational ecology of black spruce swamps, fens, and bogs in southern boreal Manitoba, Canada. *Wetlands*, 25: 564–582 (2005). doi: 10.1672/0277-5212(2005)025[0564:TVEOBS]2.0.CO;2

Lukenbach MC, Hokanson KJ, Moore PA, Devito KJ, Kettridge N, Thompson DK, Wotton BM, Petrone RM, Waddington JM. 2015. Hydrological controls on deep burning in a northern forested peatland, *Hydrol. Process.*, 29: 4114–4124, doi: 10.1002/hyp.10440.

Marshall IB, Schut P, Ballard M. 1999. A National Ecological Framework for Canada: Attribute Data. Environmental Quality Branch, Ecosystems Science Directorate, Environment Canada and Research Branch, Agriculture and Agri-Food Canada, Ottawa/Hull, available at http://sis.agr.gc.ca/cansis/nsdb/ecostrat/1999report/index.html (last access: 5 May, 2018).

McPherson RA, Kathol CP. 1977. Surficial geology of potential mining areas in the Athabasca Oil Sands region; unpublished report prepared for Alberta Research Council by Quaternary Geosciences Ltd., 177 p.National Wetlands Working Group (NWWG). The Canadian Wetland Classification System, 2nd ed.; Warner, B.G., Rubec, C.D.A., Eds.; National Wetlands Working Group, Wetlands Research Branch, University of Waterloo: Waterloo, ON, Canada, 1997.

Roulet NT, Lafleur PM, Richard PJH, Moore TR, Humphreys ER, Bubier JL. 2007. Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland, *Global Change Biol.*, 13: 397–411, doi: 10.1111/j.1365-2486.2006.01292.x

United States Department o.f Agriculture (USDA). 2020. Plants Database. Available at https://plants.sc.egov.usda.gov/java/ (last access: 05 Apr. 2021).

Verry, E.S. 1981. Water table and stream flow changes after strip cutting and clear cutting an undisturbed black spruce bog. In Proceedings of the 6th International Peat Congress, Duluth, Minnesota, August 1980. International Peat Society.

Vitt DH, Chee W-L. 1990. The relationships of vegetation to surface water chemistry and peat chemistry in fens of Alberta, Canada. *Vegetatio*, 89(2): 87–106, doi: 10.1007/BF00032163

Vitt, D. H, Bayley, S. E., and Jin, T-L. 1995. Seasonal variation in water chemistry over a bog-rich fen gradient in Continental Western Canada. *Can. J. Fish. Aquat. Sci.*, 52: 587–606, doi: 10.1139/f95-059.

Vitt D, Halsey L, Thormann M, Martin T. 1996. Peatland Inventory of Alberta. Phase 1: Overview of Peatland Resources in the Natural Regions and Subregions of the Province. University of Alberta, Edmonton.

Waddington JM, Morris PJ, Kettridge N, Granath G, Thompson DK, Moore PA. 2015. Hydrological feedbacks in northern peatlands, *Ecohydrology*, 8(1): 113–127, doi: 10.1002/eco.1493

Warner, B. G. and T. Asada, 2006. Biological diversity of peatlands in Canada. *Aquat. Sci*., 69 (3): 240–253, doi: 10.1007/s00027-006-0853-2.

Wells CM, Price JS. 2015. A hydrologic assessment of a saline spring fen in the Athabasca oil sands region, Alberta, Canada – a potential analogue for oil sands reclamation, *Hydrol. Process.*, 29: 4533–4548, doi: 10.1002/hyp.10518.

Zoltai, S. C., and D. H. Vitt (1995), Canadian wetlands: Environmental gradients and classification, *Plant. Ecol.*, 118(1–2): 131–137, doi: 10.1007/BF00045195.

Table 1. Estimated area of Poplar Fen watershed, along with the various land types, expressed as a total area, and a proportional cover. Note: Wetland and Upland (pre-disturbance) are estimated prior to any disturbance (disturbances go back to the 1970s).

	Pre-disturbance		**Current**	
	Area (km^2)	Proportional cover (%)	Area (km^2)	Proportional cover (%)
Watershed Total	**2.4**	**100**	**2.4**	**100**
Upland	1.5	64	1.3	52
Wetland	0.9	36	0.8	33
Flat peat swamp			*0.4*	*17*
Peat margin swamp			*0.1*	*4*
Mineral swamp			*0.04*	*1*
Fen			*0.3*	*11*
Disturbance			0.4	15

Table 2. Average vegetation proportion for triplicate locations at T4 and T5 (refer to Fig. 3), summarized into groups.

T4

	Upland	Peat margin swamp	Flat peat swamp	Fen
Feathermoss	80	36	0	0
Brown moss	4	1	40	46
Sphagnum moss	0	10	14	1
Herb	5	1	6	4
Graminoid	0	5	11	22
Shrub	6	27	23	23
Horsetail	0	7	0	0
Tree	5	12	6	4
Lichen	0	1	0	0
Plot tree density trees m^{-2}	0.20	0.16	0.13	0.09

T5

	Upland	Peat margin swamp	Flat peat swamp	Fen
Feathermoss	61	46	1	6
Brown moss	1	2	35	23
Sphagnum moss	0	0	1	14
Herb	9	4	17	12
Graminoid	0	1	9	7
Shrub	25	31	6	3
Horsetail	2	3	0	1
Tree	2	13	32	33
Plot tree density trees m^{-2}	0.11	0.11	0.24	0.17

Table 3. Average pH, electrical conductivity (EC), and ion concentrations for fen, flat peat swamp, peat margin swamp, mineral swamp. and upland locations. Note that values for mineral swamp are based on one water sample. Included are all significant differences detected between land types. Note that for individual ion species, concentrations are only significantly different from one another if they do not share a similar letter. Significance letters should only be read within and not across columns.

		pH	EC	Na^+	NH_4^+	K^+	Mg^{2+}	Ca^{2+}	F^-	Cl^-	SO_4^{2-}	TON
Upland		**7.0**	**411**	**4.5**	**0.5**	**1.7**	**14.4**	**58.8**	**0.1**	**2.3**	**16.8**	**0.4**
	SD	0.3	123	3.9	0.9	1.0	5.5	20.0	0.1	1.2	7.0	0.3
Peat margin swamp		**6.9**	**405**	**6.3**	**0.6**	**1.3**	**13.5**	**59.5**	**0.1**	**2.3**^{b}	**10.9**^{d}	**0.1**
	SD	0.3	81	2.3	0.5	0.8	3.1	14.4	0.0	1.4	6.9	0.1
Flat peat swamp		**6.8**	**429**	**8.3**	**0.4**	**1.1**	**13.3**	**57.0**	**0.1**	**1.3**	**3.3**^{c}	**0.1**
	SD	0.3	101	2.6	0.3	0.5	4.4	13.0	0.0	0.9	3.7	0.5
Fen		**6.8**	**478**	**10.6**	**0.4**	**1.4**	**13.4**	**67.0**	**0.1**	**1.5**^{a}	**3.2**^{c}	**0.1**
	SD	0.2	123	8.0	0.3	2.3	3.0	19.0	0.0	2.0	3.5	0.2
Mineral swamp		**5.6**	**165**	**3.4**	**0.2**	**0.5**	**2.6**	**8.2**	**0.0**	**2.3**	**15.1**	**0.0**

Figure Captions

Figure 1. Map of Poplar watershed, including fen, flat peat swamp, peat margin swamp, mineral swamp, and upland areas delineated using geospatial analyses. Note that hollow circles represent the only wells that were used for water table analyses, and all circles (black and white) were used for calculating hydraulic gradients between land types.

Figure 2. Decision tree outlining the criteria for classification of land types (thick black rectangles) at Poplar fen, including upland, mineral swamp, peat margin swamp, flat peat swamp, and fen.

Figure 3. Distribution histogram of canopy height model (CHM) returns for upland, mineral swamp, peat margin swamp, flat peat swamp, and fen land types at Poplar Fen

Figure 4. Cross–sections of transects T4 and T5 with peat (brown) thickness and well locations (all circles). Locations of vegetation and tree survey plots are indicated with white circles. From left to right, T4 and T5 are oriented West to East. For additional cross-section information on upland and mineral swamp sections of the Poplar Fen watershed, refer to Elmes and Price (2019).

Figure 5. Physical properties of peat cores obtained at T4 and T5 (see Fig. 1 and 2), including (**a**) bulk density, (**b**) drainable porosity, and K_{sat} for fen, flat peat swamp, and peat margin swamp peat cores.

Figure 6. Exceedance probability plots of average daily water table position for fen, flat peat swamp, peat margin swamp, and upland between 2013 and 2015 (n=44), and for mineral swamp between 2014 and 2015 (n=31). Note that 2011 and 2012 were excluded due to their small well sample size.

Figure 7. Conceptual model outlining the ecohydrological characteristics of the distinct land cover types at Poplar Fen, including a schematic of how transmissivity between upland and fen is influenced by water table position in the peat margin swamp area.