

2021-10

Ecohydrological interactions in a boreal fenswamp complex, Alberta, Canada

Elmes, MC

<http://hdl.handle.net/10026.1/18350>

10.1002/eco.2335

Ecohydrology

John Wiley and Sons

All content in PEARL is protected by copyright law. Author manuscripts are made available in accordance with publisher policies. Please cite only the published version using the details provided on the item record or document. In the absence of an open licence (e.g. Creative Commons), permissions for further reuse of content should be sought from the publisher or author.

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

2 Matthew C. Elmes^{1*}, Scott J. Davidson^{1,2}, and Jonathan S. Price¹

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

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

7 * Corresponding author: matthew.elmes@uwaterloo.ca

8 Matthew C. Elmes ORCID 0000-0003-0301-3475

9 Scott J. Davidson ORCID 0000-0001-8327-2121

10 Jonathan S. Price ORCID 0000-0003-3210-6363

11

12

13 **Abstract**

14

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

34

35 **1 Introduction**

36

37 In the sub-humid Western Boreal Plain (WBP), wetlands are a dominant feature on the
38 landscape, occurring primarily as peatlands (Vitt et al., 1996). Peatlands in the WBP overlie a
39 generally deep and heterogeneous surficial geology (Andriashek, 2003; Devito et al., 2012),
40 resulting in variable groundwater interactions with surrounding mixedwood uplands and
41 underlying aquifers (Bachu et al., 1993; Devito et al., 2005; Devito et al., 2012). This variability

42 establishes a wide range of peatland types, ranging from ombrotrophic bogs (no groundwater
43 input) to minerotrophic and/or saline fens and forested swamps (Vitt et al., 1995; Devito et al.
44 1996; Wells et al., 2015).

45 Swamps are largely understudied components of Canadian wetlands in comparison to bogs
46 and fens (Warner & Asada, 2006), and yet, could potentially be the second most abundant wetland
47 class in Canada (Amani et al. 2019). Swamps are often mis-classified and overlooked in current
48 wetland classifications as they can be hard to define (Warner & Asada, 2006). Swamps can be
49 either mineral or organic wetlands, often classified based on the presence of hydric (permanently
50 or seasonally saturated by water) soils as well as their tree cover (NWWG, 1997; Ducks Unlimited,
51 2015; Alberta Environment and Sustainable Resource Development, 2015). However, this can lead
52 to confusion with regards to spatial classification of swamps in comparison to other wetland types,
53 and often results in swamps being mis-categorized as other wetland types or even upland regions
54 (Locky et al. 2005). Further, the hydrological dynamics of these wetlands (e.g., seasonal water
55 table fluctuations; Zoltai & Vitt 1995; Devito & Mendoza 2007) can also lead to misclassification
56 as fens if categorization is performed under wet conditions.

57 Swamps can exist on local topographic lows, or at the margin between peatland and upland.
58 For example, bog margins (laggs), develop on a break in slope that initiates a convergence of
59 runoff and groundwater from both bog and upland (Langlois et al., 2015). Although laggs typically
60 do not contribute a groundwater flux to adjacent and topographically higher domed bogs (Ingram,
61 1983; Howie and van Meerveld, 2011; Langlois et al., 2015), they have been shown to exhibit an
62 important hydrological function and control over the growth of bogs, primarily in helping retain
63 higher water tables in the upper, more elevated sections of the peatland (Belyea and Baird, 2006;
64 Langlois et al., 2015). Contrary to bogs, fens do not have elevated domes and the topographic
65 gradient is downward from upland to peat margin to fen, and hydraulic gradients therefore
66 typically follow the topography (Ferlatte et al., 2015, Elmes and Price, 2019). Prior studies have
67 typically not focused on peat margins in fen-dominated peatlands; however, they have been shown
68 to provide a direct source of lateral groundwater flow to lower-lying peatland areas. Reversals in
69 the hydraulic gradient, from fen to peat margin to upland, have also been detected in the WBP
70 (Ferone and Devito, 2004; Elmes and Price, 2019). Lukenbach et al. (2015) measured a greater
71 degree of soil moisture variability at peat margins compared to lower-lying peatland areas. This
72 left peat margins at a greater susceptibility to drying due to their relatively high bulk density
73 coupled with lower soil moisture, and thus higher vulnerability to combustion and deep smoldering
74 from wildfire (c.f. Elmes et al., 2018).

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

83

84 2 Materials and Methods

85 2.1 Study site

86 This study is conducted in the AOSR in the Boreal Plains Ecozone (Ecoregions Working Group,
87 1989), where the average annual air temperature (1981–2010) is 1°C and average annual
88 precipitation is 419 mm, with ~75 % falling as rain (Environment Canada, 2017). The climate in
89 the AOSR is defined as sub-humid, where potential evapotranspiration (PET) often exceeds
90 annual precipitation (Marshall et al., 1999).

91 Poplar Fen (56°56' N, 111°32' W; Fig. 1) is a ~2.4 km² treed moderate-rich fen-dominated
92 watershed, located 25 km north of Fort McMurray, Alberta (Fig. 1). The watershed is situated
93 within a ~10 km long meltwater channel belt characterized by outwash sand and gravel
94 (McPherson and Kathol, 1977). Lithological logs reported by Elmes and Price (2019) show that
95 the watershed is underlain by two relatively thick aquitards which constrain groundwater
96 connectivity between local and regional aquifers. The watershed is characterized by low relief (~12
97 m) with peatland to upland slopes that range from 0.4–1.8%. Peatland area expands up-gradient,
98 where peat depth reduces to 0.4 m in the margins between low-lying peatland and upland (Fig. 1).
99 More information on the hydrogeologic setting of Poplar Fen can be found in Elmes and Price
100 (2019).

101 2.2 GIS and remote sensing analyses

102 Peatland boundaries were mapped out in the field using a handheld GPS device and a piece
103 of rebar was used to measure the depth of the organic layer. Areas with continuous organic soil
104 deposits ≥0.4 m were assumed to be peatland (NWWG, 1997). Non-peatland (mineral) swamps -
105 where hydric soils less than 0.4 m thick were present – occurred sporadically within upland
106 boundaries and were mapped manually on site. These mineral swamp areas; however, were not
107 mapped directly up-gradient of peatland/mineral land boundaries, as wetland vegetation indicator
108 species were not detected consistently in these transition zones, and instead were classified as
109 upland. Moreover, there was not sufficient information on hydric soil indicators in these areas;
110 however, despite this uncertainty, these transitional areas represent a relatively miniscule
111 proportional area. A decision-tree (Fig. 2), outlines the criteria for categorizing land-types
112 discussed in this study. Peat margin swamp boundaries (NWWG, 1997) were mapped in QGIS
113 (QGIS.org, 2020. Open-Source Geospatial Foundation Project) using an airborne LiDAR (Light
114 Detection And Ranging) digital elevation model (DEM) with 2 m grid resolution (Airborne
115 Imaging Inc. licensed to the Government of Alberta). Peat margin swamp areas were assumed to
116 start at the boundary between upland and peatland mapped in the field, and end at the toe slope
117 when the topographical gradient flattens substantially toward the peatland center. Following this,
118 a LiDAR canopy height model (CHM; Figure S1) was used to distinguish fen from swamp areas
119 within the low-lying peatland area, down-gradient of the margin and toe slope. In this study, we
120 refer to these swamp areas as flat peat swamp, consistent with the Canadian Wetland Classification
121 System (NWWG, 1997). The accuracy of the CHM was confirmed with the tree height data
122 obtained in the field. Our criteria stated that fen areas should not have trees exceeding 10 m, which
123 is consistent with the Ducks Unlimited boreal wetland classification system (Ducks Unlimited,
124 2015). Thus, five natural land types were mapped out at Poplar Fen: fen, flat peat swamp, peat
125 margin swamp, mineral swamp, and upland. It is important to note that when mapping out fen

126 boundaries, isolated or small clusters ($<8\text{m}^2$) of pixels with canopy heights 10 m or greater fell
127 adjacent to fen boundaries. However, given that these were isolated and infrequent, we did not
128 map them as flat peat swamp areas and instead categorized them as fen. Disturbed areas were
129 delineated using Google satellite imagery. We compared our delineated wetland cover types with
130 aerial estimates of wetland cover from the Alberta Merged Wetland Inventory (AMWI), a data
131 layer produced using a combination of 32 inventories including the Ducks Unlimited Canada
132 Boreal Enhanced Wetland Classification system, Landsat 5 and 7 ETM+ and Landsat 8 OLI
133 imagery and other classification products. Wetland types in the AMWI are divided into bog, fen,
134 swamp, marsh, and shallow open water (AMWI, 2018).

135 2.3 Hydrology and meteorology

136 A groundwater monitoring network comprising three transects (T1–T3; Fig. 1) were originally
137 installed in the northwest portion of Poplar Fen between 2011–2013, extending south to north with
138 well and piezometer nests installed into upland, peat margin swamp, flat peat swamp, fen, and
139 disturbed areas. In 2015, additional nests were installed elsewhere throughout the watershed in
140 west to east transects. Two transects (T4 and T5) comprised a denser network of nests, extending
141 through the upland to peatland ecotone (Fig. 1). Screened wells and piezometers (0.2 m screened
142 intake) were constructed from PVC (0.025 m I.D.) pipe and installed into the different substrates
143 in grouped nests. Nests typically comprised a fully-slotted well, with piezometers installed in mid-
144 peat and underlying mineral substrate. Nests were measured manually on a weekly basis during
145 the spring and summer from 2011–2015. Pipe top and corresponding ground elevations were
146 measured using a dual-frequency survey-grade differential global positioning system with a \pm
147 0.005 m vertical accuracy (DGPS; Leica Viva GS14, 2014).

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

156 Vertical hydraulic gradients ($\delta h/\delta l$) between the water table and underlying mineral layer were
157 calculated each measurement day for all available nests. Horizontal hydraulic gradients ($\delta h/\delta l$)
158 over the upland–fen ecotone were calculated weekly between all adjacent wells from water table
159 elevation differences between the various undisturbed land types, using all wells shown in Figure
160 1.

161 2.4 Peat coring and analysis

162 To explore differences in hydrophysical properties, peat cores were obtained from peat margin
163 swamp ($n=2$), flat peat swamp ($n=1$), and fen ($n=1$) locations, with depths ranging from 0.5–1.0
164 m. Note that cores were not obtained from mineral swamp areas, nor upland areas. For additional
165 information on the hydrophysical properties of upland areas at Poplar Fen, refer to Elmes and Price
166 (2019) and Elmes et al. (2019). Cores were extracted using a Wardenaar coring device, subdivided

167 into 0.1-m stratigraphic intervals, and were then frozen and shipped for processing at the Wetlands
168 Hydrology lab at the University of Waterloo. Samples were thawed, saturated, encased in wax,
169 weighed, then tested for horizontal saturated hydraulic conductivity (in the x-direction: hereafter
170 referred to as K_{sat}) using a constant head method (e.g., Freeze and Cherry, 1979). Following these
171 tests, saturated samples were covered on top (to prevent evaporation) and left to drain under gravity
172 for approximately 24 hr to determine drainable porosity, then dried in a furnace at 110°C to
173 determine dry bulk density and porosity.

174 2.5 Ground-layer vegetation and tree surveys

175 During the summer of 2015, tree and vegetation surveys were conducted on 20m x 20m
176 plots along the upland-fen ecotone at T4 (n=5) and T5 (n=4) (see Fig. 4 for locations). Locations
177 of plots were chosen strategically based on observed differences in elevation and community
178 composition. Within each plot, three 1 m² non-treed (saplings only) quadrats were chosen
179 randomly for vegetation surveys. Percent cover of each species was determined visually (using
180 Johnson et al. (1995) as reference) within each quadrant and was then averaged for the entire plot.
181 All individuals were reported with species nomenclature following the USDA online plants
182 database (USDA, 2020). Species were then grouped by type (brown moss, *Sphagnum* moss,
183 feathermoss, herb, graminoid, horsetail, and shrub). Due to the three-dimensional vegetation
184 cover, percent cover often exceeded 100%. As a result, percent cover of each species was
185 converted to a relative proportion. Following vegetation surveys, all trees within the 20x20m plots
186 were counted and grouped into size classes (≤ 1 m, ≤ 2 m, ≤ 4 m, >4 m). For ground-truthing
187 purposes (see section 2.4), heights of all tall trees (>4 m) were measured using an inclinometer.
188 Average tree height was calculated, where individuals <4 m in height were assumed a midpoint
189 height for their respective class (e.g., ≤ 2 m = 1.5 m height).

190 2.6 Hydrochemistry

191 In August 2014, water samples were obtained from a subset of selected wells at T1–T3. In
192 July of 2015, another round of water sampling was conducted on select wells and piezometers
193 from the newly installed nests, with high resolution sampling at T4 and T5. All wells and
194 piezometers were purged roughly 24 h prior to sampling. Samples were obtained using a rinsed
195 peristaltic pump, which routed 50-100 mL of water from the pipe into a clean reservoir to measure
196 electrical conductivity (EC) and pH using a multiparameter probe (Thermo Scientific™ Orion™
197 Star A329 pH/Conductivity Portable Multiparameter meter), which were calibrated prior to use.
198 All water samples taken from Poplar Fen were filtered within 24 h using 0.45 μ m nitrocellulose
199 membrane filters. Samples were stored in 60 mL high-density polyethylene bottles and kept frozen
200 prior to analyses. Hydrochemical analyses were completed at the Biotron Experimental Climate
201 Change Research Centre at Western University. Major ions were measured with ion
202 chromatography. Major cations were analyzed by the Dionex ICS-1600 Method EPA 300.0 with
203 AS-DV auto-sampler for Na⁺, K⁺, Ca²⁺, Mg²⁺, and NH₄⁺, with analytical precision to ± 1.0 , 1.0,
204 0.1, 0.01, and 0.1 mg L⁻¹, respectively. Major anions were analyzed by a Dionex IC Method A-
205 102 for Cl⁻, F⁻, NO₂⁻, NO₃⁻, and SO₄²⁻, with analytical precision to ± 0.05 , 0.05, 0.1, 0.1, and 0.05
206 mg L⁻¹, respectively. Field blanks (bottles filled with de-ionized water) and sample duplicates were
207 also taken periodically throughout both sampling events for quality assurance/quality control
208 measures.

209 2.7 Statistical Analyses

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

214 3 Results

215 3.1 Mapping of land types

216 Based on the field analyses, uplands were found to be the dominant land type, covering ~62% of
217 the watershed (based on pre-disturbance estimates) (Table 1), with wetlands occupying the
218 remaining 38%. For the 0.8 km² of peatland (based on current estimates), flat peat swamp had the
219 highest cover (17%), followed by fen (11%), peat margin swamp (4%), and mineral swamp (1%).

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

229 3.2 Vegetation Composition

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

245 246 3.3 Topography and peat hydrophysical properties

247 At transects T4 and T5, total relief was 1.1 m and 10.2 m, length of upland along to the transect
248 was 70 and 1000 m, and average upland slope was 0.8 and 1.8%, respectively (Fig. 4). Each

249 transect had varying sequences of land types, and had nearby seismic line disturbances (Fig.
250 4)(refer to Fig. 1). Peat was thinnest at peat margin swamp locations, averaging 0.75 m, followed
251 by flat peat swamp (0.96 m) and fen (1.30 m).

252 Little difference in bulk density was observed between fen, flat peat swamp, and peat
253 margin swamp cores in the upper 0.3 m (Fig. 5). Values ranged from 0.06-0.08 g cm⁻³ in the top
254 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-
255 0.5 m b.g.s., bulk density was consistently higher in peat margin swamp samples (mean = 0.27 g
256 cm⁻³) relative to fen (mean = 0.15 g cm⁻³) and flat peat swamp (mean = 0.18 g cm⁻³) samples. Little
257 difference was found in drainable porosity between fen, flat peat swamp, and peat margin swamp
258 cores, with differences ranging from 2-4% for a given depth. For lab measured K_{sat}, all cores had
259 virtually indistinguishable values with depth. Differences were only visible for the peat margin
260 swamp core at T5, which had the highest K_{sat}, typically by an order of magnitude, at all depths
261 relative to the other three cores (Fig. 5).

262 3.4 Hydrological comparison of fen, flat peat swamp, and peat margin swamp areas

263 3.4.1 Water table position

264 A detailed overview of peat margin swamp and low-lying peatland water table trends can be found
265 in Elmes and Price (2019). Note that in that study, flat peat swamp and fen areas were not
266 distinguished separately at the time, and all peatland areas down-gradient of the margin and toe
267 slope were simply characterized as fen. In this study, areas classified as fen exhibited the
268 shallowest water tables relative to ground surface (Fig. S2) (mean = 0.05 ± 0.06 (SD) m b.g.s.),
269 with average water table shallower than 0.10 m b.g.s. 85% of the time (Fig. 6). This was followed
270 by flat peat swamp (Fig. S2) (mean = 0.11 ± 0.07 (SD) m b.g.s.), which exhibited similar water
271 table variability; however, water tables were 0.06 m lower on average, and were above 0.10 m
272 b.g.s. only 40% of the time (Fig. 6). Peat margin swamp (0.22 ± 0.12 (SD) m b.g.s.) and mineral
273 swamp (0.21 ± 0.09 m b.g.s.) had lower water tables relative to flat peat swamp and fen areas (Fig.
274 S2). Peat margin swamp areas had the highest variability of all wetland types, with spatially
275 averaged water tables reaching as low as 0.62 m b.g.s. (Fig. 6). Uplands experienced lower and
276 more variable water tables relative to all wetland types (Figs. 6, S2), averaging 0.51 ± 0.21 (SD) m
277 b.g.s.

278 3.4.2 Water table connectivity between land types

279 At transects T1-T3, hydraulic gradients were strongest between upland and peat margin swamp,
280 reaching up to 0.005 during 2013, and also had the most negative (flow reversed from peat margin
281 swamp to upland) values (reaching -0.002), and averaging 0.002. Daily average hydraulic
282 gradients between peat margin swamp and flat peat swamp or fen ranged between -0.001 and
283 0.003, averaging 0.001.

284 Across T4 and T5, which were installed in 2015, water tables were only measured on 10
285 occasions over the 2015 growing season, which was a dry year relative to 2012-2014 (Elmes et
286 al., 2018). Hydraulic gradients at T4 were directed from peat margin swamp to upland (against
287 topography) for 6 of the 10 days measured, with values ranging from 0.007 (upland to peat margin
288 swamp) to -0.003 (peat margin swamp to upland). Hydraulic gradients between peat margin
289 swamp and low-lying peatland (both flat peat swamp and fen) were virtually flat over this time,

290 ranging from 0.001 to -0.001. Between the flat peat swamp and fen center locations, gradients
291 were directed towards the flat peat swamp; however, gradients were also relatively small, ranging
292 from -0.001 to -0.003. In contrast, water table gradients across the T5 ecotone were stronger. For
293 example, water table gradients were directed from upland to peat margin swamp for the entire
294 2015 season, ranging from 0.007 to 0.01 and averaging 0.009. Across the low-lying peatland area
295 (flat peat swamp and fen), hydraulic gradients were stable, averaging -0.002, and flow direction
296 persisted west, through the swamp area (against topography) on the west end of the transect (refer
297 to Fig. 4).

298 3.4.3 Vertical groundwater connectivity

299 Vertical flow direction between low-lying peatland areas (flat peat swamp and fen) and the
300 underlying outwash aquifer was transient during 2011–2015, with flow reversals occurring in
301 2012, 2014, and 2015. A detailed description of these patterns can be found in Elmes and Price
302 (2019). Vertical hydraulic gradients were an order of magnitude stronger than horizontal hydraulic
303 gradients between wells from 2011-2015, with daily averages across the low-lying (flat peat
304 swamp and fen) peatland ranging from -0.07 (downward from peat to the underlying outwash
305 aquifer) to 0.03 (upward from the underlying outwash aquifer to the peat) and averaging 0.002.
306 Vertical gradients were positive throughout the majority of the five-year period with flow reversals
307 only occurring over extended dry periods (Elmes and Price, 2019). On further inspection, we found
308 little difference in the strength or direction of vertical hydraulic gradients between flat peat swamp
309 ($n = 3$) and fen ($n = 3$). In contrast, vertical hydraulic gradients in peat margin swamp areas were
310 negative throughout the entire five-year record, averaging -0.02 (Table 1). Contrary to fen and
311 flat peat swamp areas, where gradients were highest (positive) during the wet years (2013–2014),
312 the lowest (most negative) vertical hydraulic gradients in peat margin swamp areas were measured
313 during this time. Vertical hydraulic gradients were always negative at the mineral swamp nest
314 throughout 2014-2015, averaging -0.04 .

315 Large differences were found in the vertical groundwater connectivity of peat margin
316 swamp areas of varying topographic positions. For example, peat margin swamp nests located
317 closer to the upland/peatland boundary typically had the strongest gradients in 2015, which were
318 always negative (mean = -0.04), directed towards the underlying outwash aquifer. Conversely,
319 both peat margin swamp nests located closer to toe slopes still had negative vertical hydraulic
320 gradients throughout the entire year; however, gradients in these nests were weaker (mean = $-$
321 0.02). The greatest differences were measured at peat margin swamp nests located directly at toe
322 slopes, where vertical hydraulic gradients were typically positive (mean = $+0.001$).

323 3.5 Hydrochemistry

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

332

333 4 Discussion

334 4.1 Mapped land cover types within Poplar Fen Watershed

335 We found that a combination of LiDAR-based geospatial analyses and field-based ground-truthing
336 can provide an efficient means of mapping fen and swamp boundaries at peatland-dominated
337 watersheds with mixed peatland types. Such is the case at Poplar Fen, a channel peatland with
338 undulating slopes and gradual transitions along the ecotone from upland to peat margin swamp to
339 flat peat swamp to fen. We found flat peat swamp peatlands to be the most abundant wetland type
340 within the watershed. Flat peat, mineral, and peat margin swamps totaled 0.58 km², 66% of the
341 peatland area. Large discrepancies were detected between our estimates and those reported in the
342 AMWI. For example, swamp and fen area reported by AMWI totaled 1.5 km², and our estimate
343 totaled 0.86 km², highlighting an overestimation by the AMWI by 76%. Our results suggest that
344 these discrepancies were caused by poor discrimination between land types. For example, 0.65
345 km² of upland area was improperly classified as wetland by the AMWI, with 82% of this area
346 classified as swamp. Furthermore, the fen to swamp ratio determined by the AMWI was 2.8,
347 whereas our analysis found it to be 0.47, suggesting that the AMWI had overestimated fen area,
348 predominantly at peatland margins. One plausible explanation for such discrepancies may be due
349 to the similarities in canopy characteristics between flat peat swamp, peat margin swamp and
350 upland (Fig. 3). This presents limitations of relying solely on aerial imagery as a means of defining
351 wetland boundaries (Gallant, 2015). The results generated in this study suggest that peatland
352 extent, thus, peat carbon stocks, may be inaccurate in the AMWI, and that certain peatland types
353 may be poorly classified. However, we do acknowledge that our results are bound to a single first
354 order watershed, and additional studies should be conducted to compare peatland boundary
355 estimates based on remote sensing versus those that incorporate field observations, specifically
356 organic layer thickness.

357 4.2 Ecohydrological differences in land types

358 4.2.1 Vegetation

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

371 We found little difference in the vegetation composition between fen and flat peat swamp
372 areas, as both were dominated by *T. nitens* (Tables S1-S2). Consistent between both transects were

373 a higher proportional cover of *Sphagnum* moss species at flat peat swamp relative to fen locations
374 (Table 2). This may be due to differences in canopy characteristics, as flat peat swamp locations
375 have a larger tree height and density (Table S3). Flat peat swamp areas may therefore provide more
376 shading, and thus, more optimal growing conditions for *Sphagnum* mosses (Laing et al. 2014).

377 4.2.2 Hydrology

378 Fen and flat peat swamp areas exhibited similar water table variability over the 2013-2015
379 record, despite flat peat swamp water tables being 0.07 m lower on average (Fig. 6). Furthermore,
380 we did not find noticeable differences in the vertical groundwater connectivity between these two
381 areas, as both were generally groundwater discharge zones during periods of high-water
382 availability, and subject to flow reversals during dry periods. Higher tree density at flat peat swamp
383 compared to fen locations (Table S3) can lead to greater interception loss and evapotranspiration,
384 enhancing water table drawdown (Koivusalo et al., 2008; Verry, 1981; Jutras and Plamondon,
385 2005; Jutras et al., 2007). However, given the similarities in their hydrologic regime, it is likely
386 that the contrasting canopy characteristics alone were not sufficient to cause significant
387 hydrological differences between land types. It is likely that differing canopy characteristics are a
388 consequence of relative position along the ecotone, as flat peat swamp areas, in general, are slightly
389 higher in topographic position relative to fen, and closer to peat margin swamp areas (Fig. 1). In
390 contrast, peat margin swamps exhibited much lower and more variable water tables, consistent
391 with other studies in the WBP (Ferone and Devito, 2004; Lukenbach et al., 2015). Such differences
392 are likely attributed to contrasting topographic positions between peat margin swamp and adjacent
393 fen and flat peat swamp areas. Peat margin swamps at Poplar Fen are located on steeper slopes in
394 groundwater recharge areas (Fig. 4), characterized by consistently downward hydraulic gradients,
395 and thus, lower water tables and greater water table variability (Fig. 6).

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

410 Peat margin swamps may exhibit an important control on the lateral groundwater
411 connectivity over the upland–fen ecotone. Elmes and Price (2019) described the importance of a
412 transmissivity feedback mechanism (Waddington et al., 2015) at Poplar Fen, whereby horizontal
413 groundwater is discharged at relatively higher volumes from upland to fen during wet periods, due
414 to two primary processes: (1) the hydraulic gradient between upland and fen becomes higher
415 following a rainfall event; and (2) the higher water table exploits higher K_{sat} layers, increasing the

416 transmissivity of the upland-to-fen flow path. The results of this study help refine our
417 understanding of the transmissivity feedback mechanism in boreal fens in the WBP. High vertical
418 recharge (via downward hydraulic gradient) promotes lower peat margin swamp water tables, thus,
419 reducing the transmissivity of the flowpath from upland to fen as the water table less-frequently
420 exploits the upper, more transmissive peat layers. This may provide a negative feedback during
421 dry periods, as lower transmissivity will reduce water flow from lower-lying peatland areas (fen
422 and flat peat swamp) to upland during flow reversals.

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

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

450 4.2.3 Hydrochemistry

451 The similarities in hydrochemical composition between land types at Poplar Fen (Table 3)
452 highlight a hydrologically well-connected upland-peatland ecotone. Fen, flat peat swamp, and peat
453 margin swamp areas all had circumneutral pH and similarly high EC and base cation
454 concentrations. Lower sodium concentrations in peat margin swamp peat porewaters relative to
455 fen and flat peat swamp may be due to a lack of influence from underlying aquifers and aquitards.
456 Fen and flat peat swamp areas are located in groundwater discharge zones. This is evidenced by
457 stronger upward hydraulic gradients in these locations, highlighting a stronger groundwater
458 influence, including diffusion from lower silt-dominated till, below the Pleistocene sand and gravel

459 that comprises upland areas and directly under the peat (Elmes and Price, 2019). Furthermore,
460 significantly higher sulphate concentrations in peat margin swamp areas are consistent with lower
461 water tables (Fig. 7), thus more oxic conditions and higher redox potential (Devito and Hill, 1996).

462 4.3 Suggested land cover definitions of Poplar Fen Watershed

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

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

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

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

499

500 **5 Conclusions**

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

523 **Data availability statement**

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

526 **Conflict of interest statement**

527 The authors declare that they have no conflict of interest.

528

529 **Acknowledgements**

530 The authors would like to acknowledge that this research takes place within the boundaries of
531 Treaty 8, traditional lands of the Dene and Cree, as well as the traditional lands of the Métis of
532 northeastern Alberta. The University of Waterloo is located on the traditional territory of the
533 Neutral, Anishnaabeg, and Haudenosaunee Peoples. The University of Waterloo is situated on the
534 Haldimand Tract, land promised to Six Nations, which includes six miles on each side of the Grand
535 River.

536 The authors wish to thank C. Wells, D. Price, E. Kessel, A. Green, and J. Asten for their
537 assistance in the field. We gratefully acknowledge funding from a grant to Jonathan S. Price from
538 the National Science and Engineering Research Council (NSERC) of the Canada Collaborative
539 Research and Development Program, co-funded by Suncor Energy Inc., Imperial Oil Resources
540 Limited, and Teck Resources Limited.

541

542 **References**

- 543 Alberta Environment and Sustainable Resource Development. Alberta Wetland Classification
544 System; Water Policy Branch, Policy and Planning Division: Edmonton, AB, Canada, 2015.
- 545 Amani, M., Mahdavi, S., Afshar, M., Brisco, B., Huang, W., Mirzadeh, M.J., White, L., Banks,
546 S., Montgomery, J., & Hopkinson, C. 2019. Canadian wetland inventory using Google Earth
547 Engine: The first map and preliminary results. *Remote Sens.*, 11(7): 842, doi:
548 10.3390/rs11070842.
- 549 Andriashek L.D. 2003. *Quaternary geological setting of the Athabasca oil sands (in situ) area,*
550 *northeast Alberta.* EUB/AGS Geo-Note 2002-03, Alberta Energy and Utilities Board,
551 Edmonton, Alberta, 295 pp. Bachu, S., Unterschultz, B.H., Hitchon, B., & Cotterill, D. 1993.
552 *Regional-Scale Subsurface Hydrogeology in Northeastern Alberta.* Alberta Geological
553 Survey, Edmonton, AB, 49 pp., available at: https://ags.aer.ca/document/BUL/BUL_061.pdf
554 (last access: 28 Aug. 2018).
- 555 Bauer, I.E., Bhatti, J.S., Swanston, C., Wieder, R.K., & Preston, C.M. 2009. Organic Matter
556 Accumulation and Community Change at the Peatland– Upland Interface: Inferences from ¹⁴C
557 and ²¹⁰Pb Dated Profiles. *Ecosystems*, 12: 636–653, doi: 10.1007/s10021-009-9248-2.
- 558 Beylea, L.R., & Baird, A.J. 2006. Beyond “The limits to peat bog growth”: cross-scale feedback
559 in peatland development. *Ecol. Monogr.*, 76(3): 299–322, 2006, doi: 10.1890/0012-
560 9615(2006)076[0299:BTLTPB]2.0.CO;2
- 561 Chee, W.L., & Vitt, D.H. 1989. The vegetation, surface water chemistry and peat chemistry of
562 moderate-rich fens in central Alberta, Canada. *Wetlands*, 9(2): 227-261, doi:
563 10.1007/BF03160747.
- 564 Devito, K.J., & Mendoza, C. 2007. Maintenance and Dynamics of Natural Wetlands in Western
565 Boreal Forests: Synthesis of Current Understanding from the Utikuma Research Study Area.
566 In: *Guideline for wetland establishment on reclaimed oil sands lease^s (2nd edition).* Harris ML
567 (ed.) Prepared by Lorax Environmental for the Wetlands and Aquatics Subgroup of the
568 Reclamation Working Group of the Cumulative Environmental Management Association,
569 Fort McMurray, AB. Appendix C-1.
- 570 Devito, K., Creed, I., Gan, T., Mendoza, C., Petrone, R., Silins, U., & Smerdon, B. 2005. A
571 framework for broad-scale classification of hydrologic response units on the Boreal Plain: is
572 topography the last thing to consider? *Hydrol. Process.*, 19: 1705–1714, doi:
573 10.1002/hyp.5881.
- 574 Devito, K.J., Hill, A.R., & Roulet, N. 1996. Groundwater-surface water interactions in headwater
575 forested wetlands of the Canadian Shield. *J. Hydrol.*, 181(1-4): 127-147. doi: 10.1016/0022-
576 1694(95)02912-5.
- 577 Devito, K.J., & Hill, A.R. 1999. Sulphate mobilization and pore water chemistry in relation to
578 groundwater hydrology and summer drought in two conifer swamps on the Canadian shield.
579 *Water Air Soil Pollut.*, 113: 97–114. doi: 10.1023/A:1005081505086
- 580 Devito K, Mendoza C, Qualizza C. 2012. *Conceptualizing water movement in the Boreal Plains,*
581 *Implications for watershed reconstruction.* Synthesis report prepared for the Canadian Oil
582 Sands Network for Research and Development, Environmental and Reclamation Research

- 583 Group, 164 pp., doi: 10.7939/R32J4H.
- 584 Ducks Unlimited Canada. 2015. Field guide: Boreal wetland classes in the boreal plains ecozone
585 of Canada. 92pp.
- 586 Ecoregions Working Group. 1989. *Ecoclimatic Regions of Canada*. Ecological Land
587 Classification Series No. 23.
- 588 Elmes, M. C., Thompson, D.K., & Price, J. S. 2019. Changes to the hydrophysical properties of
589 upland and riparian soils in a burned fen watershed in the Athabasca Oil Sands Region,
590 northern Alberta, Canada. *Catena*, 181: 157-170. doi: 10.1016/j.catena.2015.104077.
- 591 Elmes, M. C., & Price, J. S. 2019. Hydrologic function of a moderate-rich fen watershed in the
592 Athabasca Oil Sands Region of the Western Boreal Plain, northern Alberta. *J. Hydrol.*, 570:
593 692–704, doi: 10.1016/j.jhydrol.2018.12.043.
- 594 Elmes, M.C., Thompson, D.K., Sherwood, J.H., Price, J.S., 2018. Hydrometeorological
595 conditions preceding wildfire, and the subsequent burning of a fen watershed in Fort
596 McMurray, Alberta, Canada. *Nat. Hazard. Earth Sys.* 18: 157–170, doi: 10.5194/nhess-18-
597 157-2018.
- 598 Environment Canada. 2017. *Canadian Climate Normals 1981–2010 Station Data*. Government
599 of Canada, Ottawa, Available at http://climate.weather.gc.ca/climate_normals/ (last access: 28
600 Aug. 2018).
- 601 Ferlatte M, Quillet A, Larocque M, Cloutier V, Pellerin S, Paniconi C. 2015. Aquifer–peatland
602 connectivity in southern Quebec (Canada). *Hydrol. Process.*, 29: 2600–2612, doi:
603 10.1002/hyp.10390.
- 604 Ferone JM, Devito KJ. 2004. Shallow groundwater-surface water interactions in pond-peatland
605 complexes along a Boreal Plain topographic gradient. *J. Hydrol.*, 292: 75–95, doi:
606 10.1016/j.jhydrol.2003.12.032.
- 607 Fraser CJD, Roulet NT, Moore TR. 2001. Hydrology and dissolved organic carbon
608 biogeochemistry in an ombrotrophic bog. *Hydrol. Process.*, 15: 3151–3166, doi:
609 10.1002/hyp.322.
- 610 Gallant, A. 2015. The Challenges of remote monitoring of wetlands. *Remote Sens.*, 7: 10938–
611 10950, doi: 10.3390/rs70810938.
- 612 Hoag RS, Price JS. 1995. A field-scale, natural gradient solute transport experiment in peat at a
613 Newfoundland blanket bog. *J. Hydrol.*, 172: 171–184, doi: 10.1016/0022-1694(95)02696-M.
- 614 Hokanson, K.J., Peterson, E.S., Devito, K.J., and Mendoza, C.A. 2020. Forestland-peatland
615 hydrologic connectivity in water-limited environments: hydraulic gradients often oppose
616 topography. *Environ. Res. Lett.*, 15(3): 034021, doi: 10.1088/1748-9326/ab699a.
- 617 Howie SA, Meerveld IT-v. 2011. The essential role of the lagg in raised bog function and
618 restoration: a review. *Wetlands*, 31: 613–622, doi: 10.1007/s13157-011-0168-5.
- 619 Ingram HAP. 1983. Hydrology, in: *Ecosystems of the World 4A. Mires: Swamp, bog, fen and*
620 *moor*, edited by: Gore AJP, Elsevier, Amsterdam, 67–224.

- 621 Ise T, Dunn AL, Wofsy SC, Moorcroft PR. 2008. High sensitivity of peat decomposition to
622 climate change through water-table feedback. *Nat. Geosc.*, 1: 763–766, doi: 10.1038/ngeo331.
- 623 Johnson, D., L. Kershaw, A. MacKinnon, and J. Pojar. 1995. Plants of the western boreal forest
624 and aspen parkland. Lone Pine Publishing. Edmonton, AB. Pp. 36.
- 625 Jutras, S., and Plamondon, A.P. 2005. Water-table rise after harvesting in a treed fen previously
626 drained for forestry. *Suo*, 56: 95–100.
- 627 Jutras, S., Begin, J., Plamondon, A., and Hökkä, H. 2007. Draining an unproductive black spruce
628 peatland stand: 18-year post-treatment tree growth and stand productivity. *For. Chron.* 83(5):
629 723–732, doi: 10.5558/tfc83723-5.
- 630 Koivusalo, H., Ahti, E., Laure´n, A., Kokkonen, T., Karvonen, T., Nevalainen, R., and Fine´r, L.
631 2008. Impacts of ditch cleaning on hydrological processes in a drained peatland forest.
632 *Hydrol. Earth Syst. Sci.*, 12: 1211–1227, doi: 10.5194/hess-12-1211-2008.
- 633 Laing, C.G., Granath, G., Belyea, L.R., Allton, K.E. & Rydin, H. 2014. Tradeoffs and scaling of
634 functional traits in Sphagnum as drivers of carbon cycling in peatlands. *Oikos*, 123: 817–828,
635 doi: 10.1111/oik.01061.
- 636 Langlois MN, Price JS, Rochefort L. 2015. Landscape analysis of nutrient-enriched margins
637 (lagg) in ombrotrophic peatlands, *Sci. Total Environ.*, 505: 573-586, doi:
638 10.1016/j.scitotenv.2014.10.007.
- 639 Liu, H., Lennartz, B., 2019. Hydraulic properties of peat soils along a bulk density gradient—a
640 meta study. *Hydrol. Process.*, 33(1): 101–114, doi: 10.1002/hyp.v33.110.1002/hyp.13314.
- 641 Locky, D.A., Bayley, S.E. & Vitt, D.H. The vegetational ecology of black spruce swamps, fens,
642 and bogs in southern boreal Manitoba, Canada. *Wetlands*, 25: 564–582 (2005). doi:
643 10.1672/0277-5212(2005)025[0564:TVEOBS]2.0.CO;2
- 644 Lukenbach MC, Hokanson KJ, Moore PA, Devito KJ, Kettridge N, Thompson DK, Wotton BM,
645 Petrone RM, Waddington JM. 2015. Hydrological controls on deep burning in a northern
646 forested peatland, *Hydrol. Process.*, 29: 4114–4124, doi: 10.1002/hyp.10440.
- 647 Marshall IB, Schut P, Ballard M. 1999. A National Ecological Framework for Canada: Attribute
648 Data. Environmental Quality Branch, Ecosystems Science Directorate, Environment Canada
649 and Research Branch, Agriculture and Agri-Food Canada, Ottawa/Hull, available at
650 <http://sis.agr.gc.ca/cansis/nsdb/ecostrat/1999report/index.html> (last access: 5 May, 2018).
- 651 McPherson RA, Kathol CP. 1977. Surficial geology of potential mining areas in the Athabasca
652 Oil Sands region; unpublished report prepared for Alberta Research Council by Quaternary
653 Geosciences Ltd., 177 p. National Wetlands Working Group (NWWG). The Canadian
654 Wetland Classification System, 2nd ed.; Warner, B.G., Rubec, C.D.A., Eds.; National
655 Wetlands Working Group, Wetlands Research Branch, University of Waterloo: Waterloo,
656 ON, Canada, 1997.
- 657 Roulet NT, Lafleur PM, Richard PJH, Moore TR, Humphreys ER, Bubier JL. 2007.
658 Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland,
659 *Global Change Biol.*, 13: 397–411, doi: 10.1111/j.1365-2486.2006.01292.x
- 660 United States Department of Agriculture (USDA). 2020. Plants Database. Available at
661 <https://plants.sc.egov.usda.gov/java/> (last access: 05 Apr. 2021).

- 662 Verry, E.S. 1981. Water table and stream flow changes after strip cutting and clear cutting an
663 undisturbed black spruce bog. In Proceedings of the 6th International Peat Congress, Duluth,
664 Minnesota, August 1980. International Peat Society.
- 665 Vitt DH, Chee W-L. 1990. The relationships of vegetation to surface water chemistry and peat
666 chemistry in fens of Alberta, Canada. *Vegetatio*, 89(2): 87–106, doi: 10.1007/BF00032163
- 667 Vitt, D. H, Bayley, S. E., and Jin, T-L. 1995. Seasonal variation in water chemistry over a bog-
668 rich fen gradient in Continental Western Canada. *Can. J. Fish. Aquat. Sci.*, 52: 587–606, doi:
669 10.1139/f95-059.
- 670 Vitt D, Halsey L, Thormann M, Martin T. 1996. Peatland Inventory of Alberta. Phase 1:
671 Overview of Peatland Resources in the Natural Regions and Subregions of the Province.
672 University of Alberta, Edmonton.
- 673 Waddington JM, Morris PJ, Kettridge N, Granath G, Thompson DK, Moore PA. 2015.
674 Hydrological feedbacks in northern peatlands, *Ecohydrology*, 8(1): 113–127, doi:
675 10.1002/eco.1493
- 676 Warner, B. G. and T. Asada, 2006. Biological diversity of peatlands in Canada. *Aquat. Sci.*, 69
677 (3): 240–253, doi: 10.1007/s00027-006-0853-2.
- 678 Wells CM, Price JS. 2015. A hydrologic assessment of a saline spring fen in the Athabasca oil
679 sands region, Alberta, Canada – a potential analogue for oil sands reclamation, *Hydrol.*
680 *Process.*, 29: 4533–4548, doi: 10.1002/hyp.10518.
- 681 Zoltai, S. C., and D. H. Vitt (1995), Canadian wetlands: Environmental gradients and
682 classification, *Plant. Ecol.*, 118(1–2): 131–137, doi: 10.1007/BF00045195.
- 683

684 Table 1. Estimated area of Poplar Fen watershed, along with the various land types, expressed as
 685 a total area, and a proportional cover. Note: Wetland and Upland (pre-disturbance) are estimated
 686 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
<i>Flat peat swamp</i>			<i>0.4</i>	<i>17</i>
<i>Peat margin swamp</i>			<i>0.1</i>	<i>4</i>
<i>Mineral swamp</i>			<i>0.04</i>	<i>1</i>
<i>Fen</i>			<i>0.3</i>	<i>11</i>
Disturbance			0.4	15

687

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

T4

	Upland	Peat margin swamp	Flat peat swamp	Fen
Feathermoss	80	36	0	0
Brown moss	4	1	40	46
<i>Sphagnum</i> 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
<i>Sphagnum</i> 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

690
 691

692
 693
 694
 695
 696
 697
 698

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

699
 700

701 **Figure Captions**

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

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

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

710 Figure 4. Cross-sections of transects T4 and T5 with peat (brown) thickness and well locations
711 (all circles). Locations of vegetation and tree survey plots are indicated with white circles. From
712 left to right, T4 and T5 are oriented West to East. For additional cross-section information on
713 upland and mineral swamp sections of the Poplar Fen watershed, refer to Elmes and Price
714 (2019).

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

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

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

725