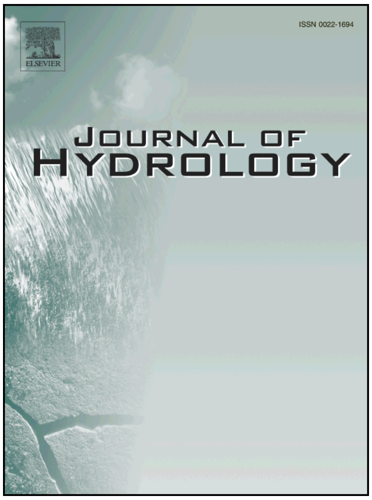

Research papers

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Hydrologic function of a moderate-rich fen watershed in the Athabasca Oil Sands Region of the Western Boreal Plain, northern Alberta

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Abstract

Peatlands are a dominant land feature in the Athabasca Oil Sands Region (AOSR) of the Western Boreal Plain (WBP), comprising >50% of the total land area, many of which are moderate–rich fens. The carbon stocks of moderate–rich fens in the WBP are susceptible to degradation through anthropogenic– and climate–related factors, yet, few studies have aimed to understand their hydrologic function. This study, located in a meltwater channel belt characterized by relatively thin outwash sand and gravel (~6 m) underlying the peat, provides the first hydrological assessment of a moderate–rich fen in the AOSR. The lithology, hydrological function and groundwater geochemistry all point to the dominance of a local flow system supplying groundwater to the fen areas, evidenced by a thick (~16 m) and shallow (~7 m below ground surface) aquitard underlying the outwash, restricting hydrological connectivity between the fen and underlying regional aquifers. Vertical hydraulic gradients between the peat and underlying outwash aquifer, and horizontal hydraulic gradients between the fen and upland varied in response to both short–term and seasonal precipitation trends. Groundwater discharge to the fen was enhanced during wet periods characterized by high rainfall. Conversely, flow reversals (groundwater recharge; fen to underlying aquifer and upland), and subsequently, enhanced fen water table drawdown persisted during extended dry periods. This local groundwater flow–

system influences recharge/discharge patterns at Poplar Fen, with hydraulic head in the underlying outwash aquifer highly susceptible to fluctuations in the presence and absence of precipitation–driven recharge from adjacent uplands. Moderate–rich fens similar to that studied here will likely become more susceptible to drying in the future due to a changing climate, leading to enhanced water table drawdown, peat oxidation and subsequent decomposition, vulnerability to wildfire, and seral succession to a more ombrogenous peatland system.

1 Introduction

Within the Western Boreal Plain (WBP), northern Alberta, Canada, peatlands are a ubiquitous feature on the landscape, representing a large proportion of the total land area (Vitt et al., 1996). The peatlands in this region comprise a relatively large pool of terrestrial carbon (Gorham, 1991), with stocks susceptible to enhanced drying and decomposition under anticipated climate change scenarios (Flannigan et al., 2016), as well as other disturbances, including oil sands mining (Rooney et al., 2012) and wildfire (Turetsky et al., 2004). This susceptibility is compounded by the sub–humid climate of the WBP, where annual precipitation is typically less than potential evapotranspiration (PET), with storage deficits replenished by infrequent wet periods occurring over 10 to 15–year cycles (Marshall et al., 1999). The combination of these stressors can induce changes to the water balance from subsequent alterations to the hydrophysical properties of peat (Waddington et al., 2014) as well as the hydrological connectivity of the peatland to the surrounding surficial geology (Devito et al., 2012).

Peatlands in the WBP range from ombrotrophic bogs to minerotrophic swamps and poor, moderate–rich, extreme–rich (Chee and Vitt, 1989), and saline fens (Wells and Price, 2015a), with peatland type ultimately controlled by the local and regional hydrogeologic setting (Winter et al., 2001, 2003; Devito et al., 2005; Wells and Price, 2015b). Bogs and poor–fens generally form over groundwater recharge areas, where fine–grained substrates minimize landscape connectivity and restrict recharge of peat subsurface water to underlying mineral aquifers (Ferone and Devito, 2004; Wells et al., 2017; Riddell, 2008). Conversely, base–rich fens receive solute–laden runoff and/or groundwater, and generally form over groundwater discharge areas

(Siegel and Glaser, 1987; Winter et al., 2003), where coarse–grained substrates can enhance groundwater connectivity (Reeve et al., 2000) and help sustain near–surface water tables. Groundwater discharge has been linked to several important ecological and biogeochemical functions within peatlands. For example, groundwater can influence peatland water chemistry (Siegel, 1983) and drive the geochemical and ecological gradients associated with specific peatland types (Sjörs, 1950; Siegel, 1983; Siegel and Glaser, 1987; Chee and Vitt, 1989). Gorham (1953) suggested that modest amounts of base–rich groundwater were sufficient enough to maintain fen surface water pH above 4.5. By buffering the organic (humic and fulvic) acids that are produced in–situ through peat decomposition, base–rich groundwater can therefore inhibit the dominance of *Sphagnum* mosses that succeed in peatlands with low–pH surface waters (Dasgupta et al., 2015).

Peat accumulation (carbon uptake) is highly influenced by hydrology, with lower water tables resulting in enhanced oxygen availability and concomitant peat decomposition (Ise et al., 2008; Waddington et al., 2014). Consequently, carbon accumulation and storage in peatlands is in part controlled by water table position (Clymo, 1984; Adkinson et al., 2011). Fens can be adaptive to water stress as groundwater discharge has been shown to partially offset water losses during years of low annual precipitation (Siegel and Glaser, 1987). The strength and scale of groundwater connection influences the hydraulic head distribution, and thus the patterns in discharge and flow direction (Tóth, 1999; Winter et al., 2001, 2003). Peatlands connected to intermediate/regional flow systems will receive discharge from groundwater associated with longer travel times and therefore are less susceptible to seasonal and annual hydrometeorological variability (Smerdon et al., 2005). Conversely, peatlands connected to shallower local flow systems receive groundwater that is more susceptible to short–term (e.g., seasonal and annual) trends in precipitation–driven recharge in adjacent topographic highs (Tóth, 1999). Thus, peatlands influenced primarily by local, rather than regional flow systems are likely to be more susceptible to vertical flow reversals in the absence of precipitation (Devito et al., 1997; Fraser et al., 2001), potentially becoming groundwater recharge areas during periods of low water availability.

Within the WBP, the hydrologic function of pond–peatland complexes have been explored in the Utikuma Region Study Area (URSA), located ~300 km north of Edmonton, AB.

There, peatlands overlying clay plains and till moraines act as diffuse recharge features, with little or no supplemented discharge from adjacent uplands and underlying mineral substrates (Ferone and Devito, 2004). The hydrogeology of bogs (Scarlett and Price, 2013) and poor fens (Wells et al., 2017) in the Athabasca Oil Sands Region (AOSR) have also been shown to exhibit limited groundwater connectivity. Conversely, pond–peatland complexes in the URSA situated within coarser–grained substrates have been shown to exhibit a greater connection to regional groundwater, receiving supplemented discharge during drier periods (Smerdon et al., 2005). Similar results were illustrated at a moderate–rich fen overlying a glaciofluvial outwash plain in central Saskatchewan, highlighting a dynamic lateral groundwater connection with adjacent upland areas, which was enhanced during wetter conditions (Barr et al., 2012). Saline fens in the AOSR receive diffuse discharge from a saline groundwater plume sourced by the Grand Rapids formation, a regional saline aquifer (Wells and Price, 2015a, 2015b).

Despite considerable efforts in characterizing their vegetation and water chemistry (Chee and Vitt, 1989; Vitt and Chee, 1990; Thormann and Bayley, 1997; Locky and Bayley, 2010), the hydrology of moderate–rich fen systems in northern Alberta requires further exploration (Elmes et al., 2018). The purpose of study was to examine the hydrologic setting of a moderate–rich fen watershed in the AOSR to better understand the natural variability in wetland function in the WBP. The primary objective is to identify the hydrogeologic connectivity of a moderate–rich fen to the local watershed and link this connection to the hydrologic function of the watershed. The results generated in this study can help to better understand how moderate–rich fen systems in the region may respond to climate change and other natural and anthropogenic stressors, and may help in expanding our understanding of the range of peatland function in a region characterized by a high degree of wetland and associated species diversity (Vitt et al., 1996). Here, field data are analyzed and presented from a moderate–rich fen watershed over a five–year period, between 2011 and 2015.

2 Site Description and regional hydrogeologic setting

The AOSR is located on the northeastern edge of the Alberta Basin, a sub–basin of the Western Canadian Sedimentary Basin (Grasby and Chen, 2005). The regional groundwater regime follows a south to north direction, primarily through Cambrian sandstones and Devonian through Mississippian carbonates. Cretaceous shales and silts associated with the Clearwater formation act as regional aquitards; however, interbedded sandstones often act as local and regional aquifers (Bachu, 1995). Drift thickness is variable in the region, ranging from <1 m to >200 m. The thickest drift deposits are located in topographic highs, including Muskeg Mountain (~600 m ASL) and the Birch Mountains (~800 m ASL), thinning to <20 m towards the Dover and Kearl Lake plain regions adjacent to the Athabasca River (at ~240 m ASL) (Andriashek and Atkinson, 2007). The topographic highs are underlain by cretaceous shales and sandstones, and act as regional recharge areas, creating confined regional aquifers that eventually discharge into the Athabasca River (Andriashek, 2003).

This study was conducted at ‘Poplar Fen’ (56°56′N; 111°32′W; ~320 m ASL), a 2.5 km^2 treed moderate–rich channel fen watershed (total relief: ~11 m) located 25 km north of Fort McMurray, within the Dover Plain region of the AOSR, northern Alberta (Fig. 1). The watershed is located within the Central Mixedwood Subregion of the Boreal Plains Ecozone (Natural Regions Committee, 2006). The climate in the region is defined as sub–humid (Bothe and Abraham, 1993; Marshall et al., 1999), with annual potential evapotranspiration (PET) typically exceeding annual precipitation (P) (Devito et al., 2012). 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). Drift is relatively thin (<20 m) in the Poplar Fen area and is dominated by fine to coarse sand with heterogeneous deposits of boulders, gravel, silt, and clay (Andriashek and Atkinson, 2007). The site is situated within a long ~10 km belt of meltwater channels extending northward to the southern portion of the Syncrude basemine (Fig. 1). Prior to glaciation, relict channels in this area were incised into the Cretaceous strata (McPherson and Kathol, 1977) during a period of erosion extending from the late Cretaceous into the late Pleistocene (Andriashek, 2003). It was hypothesized that these lows were later infilled with lacustrine sediment prior to, till during, and outwash following glaciation. Following the deposition of the outwash, meltwater eroded into the channels forming them into the existing post–glacial features. Since deglaciation, the original depositional surface has been modified by the accumulation of peat soil in topographic ‘lows’ and aeolian sand deposits in ‘highs’ (McPherson and Kathol, 1977).

Poplar Fen is composed primarily of brown moss–dominated (Goetz et al., 2014) moderate–rich channel fens (~0.7 km^2), with two additional *Sphagnum* and feather moss–dominated elongated depressional wetlands, located within upland areas and sitting at a higher elevation than the larger channel fen areas (Fig. 1). This includes a relatively small, (~0.5 ha) wetland (“West wetland”; 56̊56′4″N; 111̊32′30″W) along the western portion of the watershed, and a larger (~3 ha) wetland (“East wetland”; 56̊56′4″N; 111̊31′36″W) along the eastern portion of the watershed. The Poplar Fen watershed was delineated using an airborne LiDAR (Light Detection And Ranging) digital elevation model (Airborne Imaging Inc. licensed to the Government of Alberta). The area has been altered by linear disturbances associated with resource exploration and extraction, including the construction of several cut lines with areas cleared for drill logs, and a pipeline and corridor extending west to east along the north end of the watershed (Fig. 1).

Tamarack (*Larix laricina*) and black spruce (*Picea mariana*) are the dominant tree species within Poplar Fen, with saplings (<1 m height) dominant in the West wetland, saplings and mid–sized trees (<3 m height) dominant in channel fen areas, and taller trees (>3 m height) dominant in the East wetland. Surface cover in moderate–rich channel fen areas is characterized primarily by mosses *Tomenthypnum nitens*, *Aulacomnium palustre*, *Pleurozium schreberi*, and from the genus *Sphagnum* (*S. fuscum* and *S. capillifolium*). Surface cover in the East and West wetland areas is dominated primarily by *S. fuscum*, and feathermosses *Hylocomium splendens*, and *P. schreberi*. Upland areas are dominated by *P. mariana* and feather mosses in riparian zones, with jack pine (*Pinus banksiana*) and aspen (*Populus tremuloides*) mixedwood overstorey and lichen ground cover in topographically higher areas.

3 Methodology

Field lithology drill logs were obtained from Suncor Energy Inc. (personal communication), and used to construct geologic cross–sections of Poplar Fen. Logs included interpretations of specific geological sequences extending down to the Precambrian Shield, which were ultimately used to construct cross–sections. Two primary west–east transects (A–A’ and B–B’ in Fig. 1) were drawn for the watershed, extending through several land types. To aid with the interpolation of shallow substrate attributes between drill logs (e.g., surface elevation, peat thickness, and mineral grain size directly underlying the basal peat), information obtained during groundwater monitoring nest installation was also used in producing the cross–sections.

Hydrological investigations at Poplar Fen began in June of 2011, and instrumentation initially comprised three transects at the northwestern portion of the channel fen (NT1–NT3; Fig. 1), extending southward with nests installed along the fen–upland ecotone. In 2014 and early 2015, additional nests were installed elsewhere throughout the watershed to capture a greater representative area. Nests were installed at several fen and adjacent upland locations, comprising four transects along a narrow and gentle–sloping upland on the west side of the watershed (WT1–WT4; Fig. 1) to the adjacent fen, and four transects along a more expansive and steeper upland on the east side of the watershed (ET1–ET4; Fig. 1) to the adjacent fen. A nest was also installed in both the West and East wetlands (Fig. 1). Nests were also installed into margins at all transects, although water levels and hydraulic gradients are not reported in this study. Screened wells and piezometers (20 cm screened intake) were constructed from PVC (2.5 cm inner diameter) pipe and installed into the different substrates in grouped nests. Nests typically comprised a fully–slotted well, with piezometers installed in mid–peat (0.6–0.75 m depth) and underlying mineral sediment (1.25–1.5 m depth). The depth to water table and piezometer head at nests were measured manually on a weekly basis during the spring and summer from 2011–2015 and once in October for all years with the exception of 2014. A continuous record of channel fen water table was obtained at a nest in NT1 using a logging pressure transducer (from 2011–12; Schlumberger Mini–Diver) or a capacitance water level recorder (from 2013–15; Odyssey Dataflow Systems Ltd.). Average manual water table was then extrapolated into a continuous record, based on highly correlated values between average manual water table and logged water table. Saturated hydraulic conductivities (K_{sat}) of peat, mineral sediment underlying the peat, and upland sediment were determined by bail tests on all piezometers (and wells in uplands) installed at Poplar Fen between 2011–15 using the hydrostatic time–lag method (Hvorslev, 1951). Triplicate K_{sat} measurements were performed for all pipes measured in which the arithmetic average was taken. For the upper 60 cm of peat, K_{sat} was determined in the lab using peat cores extracted from channel fen (n= 2), Margin (n= 2), and West wetland (n= 1) areas. Cores were extracted using a Wardenaar coring device and samples were frozen and shipped for processing at the lab. Cores were subdivided into 10–cm stratigraphic intervals, and horizontal and vertical K_{sat} were determined using a constant head method (e.g. Freeze and

Cherry, 1979). Lab and field K_{sat} values were grouped and arranged by depth to estimate average K_{sat} versus depth, which were later used in groundwater flux calculations.

Darcy's Law (Freeze and Cherry, 1979) was used to estimate groundwater fluxes in and out of the channel fen (NT1–NT3) and West wetland areas:

$$q = -K_{sat}\ \frac{dh}{dl} \tag{1}$$

where q is the specific discharge (m s^{-1}), K_{sat} is the saturated hydraulic conductivity (m s^{-1}), and dh/dl is the hydraulic gradient (dimensionless).

Vertical fluxes were calculated using vertical hydraulic gradients between the mid–peat and underlying mineral layer for each channel fen nest and for the West and East wetlands. Vertical area–weighted groundwater flux rates (mm d^{-1}) were estimated at each nest (with the exception of the East wetland) by multiplying the vertical hydraulic gradient by a weighted harmonic mean K_{sat} between the piezometers measured, using all available K_{sat} data at Poplar Fen (including Ksat data obtained outside of NT1–NT3). The harmonic mean is typically used for calculating vertical flux rates through horizontally layered strata (Freeze and Cherry, 1979). Given negligible differences between laboratory–measured vertical and horizontal K_{sat} (not shown), an anisotropy of 1 was used for field–measured K_{sat} values.

Horizontal groundwater fluxes, laterally into the channel fen, were calculated using the differences in channel fen and upland water table elevations. To prevent overestimation of K_{sat}, depth–weighted arithmetic means were calculated individually for fen and margin areas, using K_{sat} data that were grouped and averaged by depth using a geometric mean. The weighted arithmetic mean is typically used for calculating flux rates for horizontal flow through horizontally layered strata (Freeze and Cherry, 1979). Depth–weighted arithmetic means were calculated for fen and margin at each transect depending on their average water table positions. For example, if the average fen water table position was 15 cm below ground surface at NT1, K_{sat} values measured at 0–10 cm depth were not used in the calculation, and 5 cm weighting was given to the K_{sat} values measured at 10–20 cm depth. Once mean K_{sat} values were calculated, a harmonic mean was taken between the weighted arithmetic mean fen and margin K_{sat} values, and the geometric mean upland K_{sat}. Final K_{sat} values were then multiplied by the horizontal hydraulic gradient to calculate the specific discharge fluxes (mm d^{-1}) at each transect. Average fluxes were applied across a flow face (thickness and length of NT1–NT3 peat flow face) to obtain a volumetric flux (m^3). Then, the volumetric flux was divided by the estimated fen surface area of NT1–NT3 (~47,000 m^2) to which this flow face was assumed to contribute to.

Precipitation was measured in an open area of the site with a logging Onset RG3–M tipping bucket rain gauge. Missing daily totals (fall to early spring) were supplemented with rainfall data for the Poplar Fen area (township: T092R10W4), which were estimated using an inverse-distance weighting interpolation procedure (closest climate station located ~12 km north of Poplar Fen) (Alberta Agriculture and Forestry, 2017). The same interpolated data were obtained from Oct. 1995 to Sept. 2015 to produce a 30–year record of precipitation of the area. Mean precipitation was calculated for each hydrologic year (Oct. 01 – Sept. 30).

In August 2014, June 2015, and July 2015, porewater samples were taken from specific nests within the channel fen, West and East wetland, and upland water table wells, as well as specific underlying mineral piezometers at channel fen nests and the West wetland. All water samples were sent for laboratory analysis of major cations and anions, as well as oxygen ($\delta^{18}O$) and hydrogen (δD) isotopes. All water samples were filtered within 24 hours using 0.45 μm nitrocellulose membrane filters. Samples for ion analyses were stored in 60 mL high–density polyethylene bottles and kept frozen prior to analyses. Isotope samples were stored in tightly sealed 20 mL scintillation vials with no head space, at 4°C, for isotope analyses. Major ions were measured with a Dionex ICS–1600 Method EPA 300.0 with AS–DV auto–sampler, with analytical precision to ±1.0 mg L^{-1} or less. Isotopes were measured with a Picarro L2120–i Cavity Ring–Down Spectroscopy analyzer. This technique yields an analytical precision of ±0.4‰ for δD and ±0.2‰ for $\delta^{18}O$.

4 Results

4.1 Lithology

Within the watershed boundaries – along cross–sections A–A' and B–B' – there was a combined average drift and recent sediment thickness of 12.3 m (range: 5–23 m) overlying the Cretaceous Clearwater formation (Fig. 2). Although not reported in the lithology drill logs, a thin

(~0.1 m) silty sand layer is dominant at most channel fen nest locations, detected during well and piezometer installations. A similar underlying silty sand layer is located at the West wetland at ~1 m depth below ground surface (b.g.s.); however, between this and the peat layer is a ~0.5 m thick sand and gravel layer. Underlying the peat at the East wetland is a ~1 m sand layer, which is underlain by a clay layer (≥0.5 m). The uppermost mineral sediment is composed of coarse outwash sand and gravel, which averages 6.2 m in thickness, ranging from 0.5–13.4 m (Fig. 2). Outwash depth is thicker, more elevated, and more consistent along the more elevated eastern side of the watershed. Underlying the outwash is a fine–grained silt–dominated till unit, which averages 5.3 m in thickness, ranging from 0–9.5 m. This unit becomes shallower and more elevated along the west side of the watershed. Underlying the silty–till is the Clearwater formation, a known regional aquitard, which varies in thickness and texture ranging from sandy silt to pure clay, with an average combined thickness of 10.9 m (range: 0.5–19 m). Underlying the Clearwater formation is the bitumen–bearing McMurray formation, which has an average depth below ground surface of 22.7 m.

4.2 Hydraulic Conductivity

Peat thickness measured in this study ranged from 1.3–1.5 m in channel fen areas, commonly thinning to 0.3–0.7 m in margins between fen and upland; however, drill logs obtained for the area report peat thickness can reach up to 3 m. Peat depth averaged ~0.5 m in the West wetland and ~0.3 m in the East wetland. K_{sat} of the channel fen peat declined with depth by orders of magnitude, ranging from 4.7 x 10^{-3} m s^{-1} in the upper 10 cm to as low as 1.2 x 10^{-8} m s^{-1} at the basal layer (Fig. 3). The peat at the base of the channel fen (1.0–1.1 m depth) had a geometric mean K_{sat} of 4.5 x 10^{-7} m s^{-1}, ranging from 3.1 x 10^{-5} m s^{-1} to 1.2 x 10^{-8} m s^{-1} (n=11), spanning three orders of magnitude (Fig. 3). Directly underlying the channel fen peat (below 1.2–1.5 m) is a ~0.3 m thick, heterogeneous mineral layer above the outwash layer, ranging from fine–medium sand to silty sand. K_{sat} in this layer and the outwash layer ranged by four orders of magnitude, and had a geometric mean of 5.6 × 10^{-6} m s^{-1} (n=33). K_{sat} measured at the West wetland ranged by two orders of magnitude, from 3.5 × 10^{-3} m s^{-1} at the surface, to 2.7 × 10^{-5} m s^{-1} at the basal layer (0.5–0.6 m depth). Directly underlying the West wetland is a ~0.4 m thick sand layer (K_{sat} not measured at this depth). Below the sand layer (at 1 m depth b.g.s.) is a silt–dominated layer with a K_{sat} of 3.4 × 10^{-8} m s^{-1}. K_{sat} was not measured for the peat layer at the

East wetland; however, the sand–dominated mineral layer directly underlying the peat (0.3–1.4 m) had a measured K_{sat} of 1.0 × 10^{-5} m s^{-1}. Underlying the sand layer is a clay–dominated layer which had a K_{sat} of 3.9 × 10^{-10} m s^{-1} (not shown). In upland areas, composed primarily of sand and gravel, K_{sat} was relatively high with a geometric mean of ~3.0 x 10^{-4} m s^{-1} (n = 8) (not shown in Fig. 3).

4.3 Hydrology

4.3.1 Precipitation

Total rainfall interpolated for the Poplar Fen area averaged 412 mm between hydrologic years 1985–86 and 2014–15. The first twelve years of the 30–year record were characterized by relatively wetter conditions, with nine of these years having above average rainfall. Conversely, the latter half (1999–00 to 2014–15) of the record was characterized by several years that did not depart far from the mean (eight years ranging from –26 to +25 mm from the mean). In addition, six years were characterized by precipitation more than 35 mm lower than the mean, with only two years that were particularly wet. With respect to the five–year period during which this study was conducted, it began towards the end of a drying period. The 2010–11 year was the driest on record (–191 mm from mean); 2011–12 (+25 mm) and 2012–13 (+80 mm) were above average (wetting period), and 2013–14 (–36 mm) and 2014–15 (–85 mm) were below average (drying period).

4.3.2 Water table

Average channel fen water table position at NT1–NT3 ranged by ~0.77 m (+0.1 m to –0.66 m) between Jun. 08, 2011 and Oct. 04, 2015 (Fig. 4a). The general five–year water table trend was relatively low water tables (dry conditions) at the beginning (2011 to mid–2012), increased water table in the middle years (late 2012 to mid–2014), and lower water tables in a drying period towards the end (mid–2014 to late 2015) of the 5–year record (Fig. 4a). Over this time, horizontal hydraulic gradients were relatively stable down the channel fen towards the culvert (location shown in Fig. 1), averaging 0.0026 ± 0.0005 (SE) (data not shown on Fig. 4). Horizontal groundwater flow was typically low during the drier periods (2011 to summer 2012 and 2015), ranging from 0.004–0.254 mm d^{-1} (average = 0.05 ± 0.01 (SE) mm d^{-1}). During wet periods (fall 2012 to summer 2014), horizontal flow was higher, ranging from 0.07–0.30 mm d^{-1} (average = 0.26 ± 0.01 (SE) mm d^{-1}).

4.3.3 Vertical groundwater connection between channel fen and underlying outwash

Between 2011 and 2015, hydraulic head in the underlying outwash aquifer (Fig. 4b) and vertical hydraulic gradients between the peat and underlying mineral substrate at the channel fen (Fig. 4c) varied in correspondence with diurnal and seasonal precipitation trends. Vertical flow direction at NT1–NT3 fen nests (location shown in Fig. 1) was downward (indicating groundwater recharge) throughout most of 2011 (95% of the field season), corresponding to a period of low water tables and below average rainfall (Fig. 4a). Over this period vertical discharge averaged –0.13 mm d^{-1} (Table. 1). In 2012, several large rain events had occurred (Fig. 4a), with several vertical flow reversals occurring during these events (Fig. 4c). For the majority of this period (87% of the field season), vertical flow was directed primarily upwards (indicating groundwater discharge), with average vertical discharge equaling +0.04 mm d^{-1}. Discharge conditions persisted throughout 2013 until Aug. 2014, during an extended period of above average rainfall and high fen water tables, reaching upward gradients as high as +0.016 (Fig. 4c). Throughout this period, average vertical discharge equaled +0.13 mm d^{-1} (Fig. 4c). In July 2014, fen water tables began declining steadily into the fall (Fig. 4a), and another vertical flow reversal was initiated, back to groundwater recharge. Recharge conditions persisted for roughly half of the 2014 study period, and vertical discharge averaged –0.04 mm d^{-1} over this time (Fig. 4c). Spring 2015 exhibited high (near–surface) fen water tables (Fig. 4a), and at this time, Poplar Fen was a groundwater discharge area. However, throughout the growing season, several more flow reversals were initiated, including recharge during a period of low rainfall in June, discharge in mid–July during a period of increased rainfall, and recharge from early August until the late fall (Fig. 4c). Over this period, recharge conditions persisted for 65% of the time, and vertical discharge averaged –0.09 mm d^{-1} (Table. 1). The annual net groundwater fluxes measured over each respective field season were –13.9 mm in 2011 (111 days), +8.1 mm in 2012 (170 days), +17.8 mm in 2013 (147 days), +5.2 mm in 2014 (84 days), and –11.0 mm in 2015 (125 days).

Average vertical hydraulic gradients measured at NT1–NT3 (–0.008) were lower in 2015 than those calculated from new nests (WT1–WT4; ET1–ET4; Fig. 1) that were installed in 2014 and 2015 (–0.001) (Fig. 4c). The newer nests exhibited flow reversals throughout 2015 in response to precipitation; however, vertical hydraulic gradients did not reach values as low as those measured at NT1–NT3 and therefore did not experience the same variation (Fig. 4c). This resulted in smaller loss (–0.02 mm d^{-1}) of water to the underlying outwash aquifer compared to NT1–NT3 (–0.11 mm d^{-1}).

4.3.4 Lateral upland–channel fen groundwater connection

The fen to upland slope along NT1–NT3 transects (Fig. 1) averaged 0.5% and had a relief of ~1.1 m. Horizontal hydraulic gradients between fen and upland at these transects were positive throughout most of the five–year record (Fig. 4d), indicating that the lateral flow was directed primarily towards the fen (average: +0.001). On average, horizontal gradients were weaker by an order of magnitude than vertical gradients (see Fig. 4c). Flow reversals occurred only in late June, mid–August, and early October 2015, corresponding to periods of low rainfall. Average horizontal discharge ranged from –0.01 to +1.15 mm d^{-1} (Fig. 4d). During drier periods characterized by lower rainfall and water tables (Aug. 2011–Aug. 2012, 2015; Fig. 4a), horizontal discharge averaged +0.01 mm d^{-1}. During wetter periods characterized by higher rainfall and water tables (Fall 2012–July. 2014; Fig. 4a), horizontal discharge averaged +0.50 mm d^{-1}. The annual net groundwater fluxes measured over each respective field season were +2.8 mm in 2011 (111 days), +10.7 mm in 2012 (170 days), +79.2 mm in 2013 (147 days), +44.5 in 2014 (84 days), and +1.2 mm in 2015 (125 days).

In the more expansive East upland (transects ET1–ET4; average upland to channel fen slope = 1.5%; total relief = ~7.0 m), horizontal hydraulic gradients in 2015 were stronger by an order of magnitude along this flow face than those measured at NT1–NT3 (Fig. 4d). Although weakening in the absence of precipitation, horizontal hydraulic gradients at ET1–ET4 remained positive in 2015 and no flow reversals were detected over this relatively dry (–86 mm from 30–year mean) summer. This resulted in horizontal discharge ranging from +0.09 to 1.08 mm d^{-1} (not shown on Fig. 4d). Conversely, average horizontal gradients at the narrower and more gently–sloping West upland (transects WT1–WT4; average upland to channel fen slope = 0.5%; total relief = ~1.0 m) were generally lower and more variable than at NT1–NT3 (Fig. 4d). This resulted in horizontal discharge ranging from –0.08 to +0.19 mm d^{-1} (not shown on Fig. 4d).

4.3.5 Hydrology of West and East wetlands

Water tables in the East and West wetlands were below ground surface for the entire instrumental period (Fig. 5a). Water table position was nearly identical between the East and West wetlands in 2014. Conversely, water tables differed more in 2015, as the West wetland was consistently lower (Fig. 5a); it had fallen below the base of the peat layer and into the underlying sand layer (not shown) by October, 2015.

Vertical hydraulic gradients differed notably between wetlands (Fig. 5b). Vertical gradients were negative in the East wetland throughout all of 2014–15, indicating that the peat was recharging the underlying mineral layers throughout this whole period. In contrast, vertical flow reversals were detected in the West wetland during both years. Unlike in channel fen areas, where gradients became positive in response to rainfall, vertical flow direction showed opposite patterns in the West wetland, as it became a recharge zone during wetter periods and a discharge zone following extended periods of water table drawdown (Fig. 5b). Due to the relatively high saturated hydraulic conductivity of the basal peat layer (Fig. 3), vertical flux rates in the West wetland were typically higher compared to the channel fen, ranging from –0.9 mm d^{-1} during wet periods to +0.7 mm d^{-1} during dry periods. Due to insufficient information on the hydraulic properties of the 30 cm deep peat in the East wetland, fluxes were not calculated.

Horizontal gradients also differed greatly between wetlands in 2015 (Fig. 5c). Horizontal gradients between the West wetland and adjacent uplands were negative throughout the entire sampling period, indicating that the wetland received no supplemented lateral discharge, and instead, recharged the adjacent uplands. Contrary to the West wetland, a strong and consistent positive gradient was measured between the East wetland and the upland to the east throughout 2015 (Fig. 5c).

4.4 Water chemistry

Porewater samples obtained from channel fen, underlying outwash, and upland pipes all had similar pH (6.8–7.0), electrical conductivity (EC; 411–532 µS cm^{-1}), and concentrations of calcium (Ca^{2+}; 59–79 mg l^{-1}) and magnesium (Mg^{2+}; 13.9–17.1 mg l^{-1}) (Fig. 6). Comparatively, the West and East wetland wells, as well as the sandy silt layer underlying the West wetland, had lower pH (4.5–5.6), EC (109–165 µS cm^{-1}), Ca^{2+} (8.2–14.2 mg l^{-1}), and Mg^{2+} (1.2–2.6 mg l^{-1}). All locations had similar chloride (Cl^{-}) concentrations, ranging from 1.3–3.5 mg l^{-1} (Fig. 6).

All water samples obtained from these three locations appeared to be of similar recent meteorological origin, plotting close to the local meteoric water line (LMWL), and showing little or no evidence of isotopic enrichment or depletion. The West wetland water table well sample plotted close to the corresponding underlying mineral piezometer, both in the middle of the LMWL. The East wetland water table in June 2015 was virtually similar in isotopic composition to upland water table samples obtained during that period. However, by July, 2015, the East wetland water table and corresponding underlying sand piezometer sample had isotopic composition characteristic of late summer precipitation (Fig. 7).

5 Discussion

5.1 Conceptualizing Water Movement at Poplar Fen Watershed

Based on what was observed at Poplar Fen, the following conceptual model is proposed (Fig. 8), which highlights the hydrogeologic setting and hydrologic function of fens and uplands that are thought to be typical of moderate–rich fen watersheds in the AOSR. Given that this study included two seasons with less than typical rainfall, the conceptual model may be a useful guide for understanding the likely response of moderate–rich fens in the AOSR under a future climate, where increases in precipitation are not expected to effectively offset increases in evapotranspiration due to warming (Collins et al., 2013).

5.2 Geologic Setting

Field lithology drill logs identified a veneer–type layering of coarse– over fine–grained glacial deposits over the Cretaceous Clearwater formation at Poplar Fen. This establishes a relatively thick (~16 m) and shallow aquitard throughout the watershed (Fig. 2). The combined low K_{sat} units restrict the connectivity between the watershed and underlying regional flow systems. Overlying the aquitard, outwash sand and gravel are the dominant sediment textures in adjacent uplands and outwash underlying the channel fen. These higher K_{sat} units allow for a local unconfined flow–system to develop, which focusses discharge to low–lying channel fen areas. The silty sand layer underlying the channel fen, although thin and heterogeneous, limits the strength of this connection, lowering specific discharge during wet periods, while also reducing water loss (via downward flow through the basal peat) during drier periods. In addition, the West and East wetlands have a relatively shallow, low K_{sat} unit underlying the organic soil, which helps confine the downward flow of subsurface water and promotes more saturated peat–forming conditions.

5.3 Hydrogeologic Setting and its Influence on the Hydrologic Regime of Poplar Fen

Vertical recharge–discharge patterns between the peat and underlying outwash aquifer were variable both spatially and temporally over the five–year instrumental period at channel fen nests (Fig. 4c). Vertical flow reversals occurred several times (Fig. 4c), with discharge conditions (upward flow from underlying outwash to peat) initiating and persisting over relatively wet periods, and recharge conditions (downward flow from peat to underlying outwash) over extended dry periods (summarized in Fig. 8). These flow patterns are different from those reported on pond–peatland complexes overlying outwash sediments at the URSA (Smerdon et al., 2005), a spring fen (Siegel and Glaser, 1987) and raised–bog (Glaser et al., 1997) in northwestern Minnesota, and fens overlying esker aquifers in northern Finland (Kløve et al., 2012). These locations comprise relatively thick coarse-grained sediments that extend deeper than those underlying Poplar Fen, and subsequently, water table drawdown is moderated by more consistent sources of groundwater discharge, which the authors all attribute to deep regional flow. The variability in hydraulic head in the relatively thin coarse–grained outwash sediment underlying Poplar Fen, in correspondence with short-term precipitation trends, indicates a local groundwater flow–system characterized by short travel times (Tóth, 1999; Kløve et al., 2012). Although localized, this hydrogeologic setting is different from bog and poor fen watersheds connected to local flow systems at URSA (Ferone and Devito, 2004), where low K_{sat} clay or till underlying the peat confined the hydrological connectivity between peatlands and underlying groundwater. Thus, flow direction and magnitude at Poplar Fen are more responsive to precipitation–driven recharge from adjacent uplands leading to subsequent discharge from underneath the channel fen (Fig. 8a). However, without a regional groundwater connection to supplement discharge during extended dry periods, recharge conditions will likely become more dominant in moderate–rich fens with a climatic and hydrogeologic setting similar to Poplar Fen

(Fig. 8b), rendering them susceptible to enhanced water table decline during dry periods.

Horizontal recharge–discharge patterns between upland and channel fen were also highly variable between 2011–2015 (Fig. 4d); however, the flow direction was typically from upland to fen with flow reversals only occurring during in the fall of 2011 and in the summer and fall of 2015, two relatively dry years (Environment and Climate Change Canada, 2018). During these dry periods (2011 and 2015), discharge from upland to fen averaged +0.05 and +0.02 mm d^{-1}, roughly equaling lateral discharge (0.04 and 0.02 mm d^{-1}) measured down the fen towards the culvert during those years, respectively. Conversely, during wetter periods (2013–2014), specific discharge fluxes along the NT1–NT3 flow face became higher by up to several orders of magnitude (Fig. 4d). This resulted in average area–weighted fluxes of +0.54 mm d^{-1} in 2013, and +0.53 mm d^{-1} in 2014, roughly two times higher than the lateral discharge measured down the fen during those years. The results presented in this study differed from poor–fen and bog systems studied at the URSA, where fine–grained sediment dominant in the uplands limited connectivity, resulting in negligible groundwater fluxes (Ferone and Devito, 2004). Results were more similar to those reported on a minerotrophic fen overlying a coarse-grained glaciofluvial outwash plain in central Saskatchewan (Barr et al., 2012), where bidirectional flow was measured between fen and adjacent black spruce– and jack pine–dominated upland areas, with higher groundwater fluxes directed towards the fen during wet periods.

The difference in lateral flux rates to channel fen areas between dry and wet years at Poplar Fen is explained largely by the hydraulic conductivity of the upper peat, which increases by several orders of magnitude from base to surface (Fig. 3), and is regarded as a common physical characteristic of peat (Price and Maloney, 1994; Hoag and Price, 1995; Ferone and Devito, 2004; Whittington and Price, 2006; Wells et al., 2017). The presence of the water table within shallower and relatively high K_{sat} layers had greatly increased the transmissivity of the fen peat layer (McCarter and Price, 2017). In addition, the hydraulic gradient between upland and fen becomes much higher during wet periods as the fen water table reaches the surface and specific yield approaches 1, causing it to rise at a slower rate than the upland water table. These two primary attributes, when combined, produce a transmissivity feedback mechanism (Bishop, 1991; Waddington et al., 2014), which conveys relatively higher groundwater fluxes from upland to fen (summarized in Fig. 8). Despite these high fluxes, margin water table position exhibited a relatively important control on the overall transmissivity of the fen–upland flow path, due to its lower water tables and therefore lower arithmetic K_{sat}. This suggests that margins operate as distinct hydrological units and should be understood better in future studies. Conversely, lower horizontal gradients during dry periods (Fig. 4d), along with the water table (Fig. 4a) positioned in deeper, lower K_{sat} peat (Fig. 3), results in fluxes that are much lower (Table 1). This weak connection during flow reversals; however, results in negligible flux rates from fen to upland. This negative feedback is regarded as an important feature for water conservation in peatlands (Waddington et al., 2014); however, it does not account for potential water losses via transpiration by aspen trees (deep clonal roots) via hydraulic lift from deeper substrates and adjacent wetlands (Depante et al., 2016). Therefore, uplands may still act as water sinks despite this limited hydrological connection between fen and upland. It is important to outline the degree of uncertainty regarding our calculated fluxes, primarily due to the heterogeneity of K_{sat} that is characteristic of peat (Beckwith et al., 2003). However, despite this potential for error, we are confident with the differences in magnitude observed between wet and dry years (Table 1), at least sufficiently to support our conceptual model (Fig. 8).

Transects NT1–NT3 provided replicates of a similar upland–fen setting that is common in the watershed, but not ubiquitous. Additional insight is gained from installations and 2015 data from WT1–WT4 and ET1–ET4, which illustrate contrasting patterns of landscape connection. The upland area west of WT1–WT4 has a relatively small contributing area (~0.05 km^2) and low relief (~1 m), and consequently, its horizontal hydraulic gradients were more variable than NT1–NT3, and susceptible to flow reversals. In contrast, the upland east of ET1–ET4 has a larger contributing area (~0.68 km^2) and steeper (relief ~7 m) than the West upland (see Fig. 8). This yielded stronger and consistently positive flow towards the fen in 2015 (cf. Hokanson et al., 2016). It also helps explain~~s~~ why the local vertical hydraulic gradients in the channel fen remained stronger than those measured at NT1–NT3. This upland apparently plays a pivotal role in providing water to the channel fen areas in Poplar Fen watershed. In addition, a shallower depth to confining layer on the west side of the watershed (Fig. 2) may also promote enhanced and extended discharge conditions within this area, which could help in explaining why WT1–WT4 had stronger vertical hydraulic gradients in 2015 than ET1–ET4, a fen system located farther east and at a higher topographic position (Elmes et al., 2018).

The West wetland had a net loss of groundwater to adjacent uplands throughout 2014 and 2015, as evidenced by consistent negative horizontal hydraulic gradients. However, vertical hydraulic gradients were susceptible to flow reversals during both years (Fig. 5b), and in contrast to channel fen areas, the West wetland became a groundwater recharge area during periods of high precipitation. The elevation and position relative to the adjacent upland can explain why the West wetland became a recharge zone during wet periods (Fig. 8), as uplands and topographic highs typically recharge topographic lows (Tóth, 1999; Winter, 1999). Conversely, flow reversals in the West wetland occurred in between rainfall events in the summer. It is postulated that although the wetland is a predominant recharge feature, the relatively low specific yield (~0.08) of humified peat causes water table drawdown at a faster rate than the decrease in hydraulic head in the underlying outwash aquifer. Large fluctuations in the vertical hydraulic gradient resulted, and when multiplied by the relatively high harmonic mean hydraulic conductivity of the West wetland peat, resulted in vertical groundwater fluxes that were up to twenty times higher than those measured in channel fen areas. This dynamic groundwater connection can help explain why the water table declined below the base of the peat in the West wetland twice in 2015, highlighting its heavy reliance on rainfall for a stable source of water storage.

The East wetland was characterized by negative vertical hydraulic gradients throughout 2014 and 2015 (Fig. 5b), suggesting that it is a prominent recharge feature. This is likely due to the relative position of the wetland, located within an expansive upland system and at an elevation ~2.5 m higher than the channel fen area directly to the west. The East wetland, with an organic layer thickness of only ~30 cm, does not classify as a peatland, and has characteristics more like a basin swamp (NWWG, 1997). It hosts peat–forming mosses (*S. fuscum* and *P. schreberi*), as the underlying low K_{sat} clay layer (4.0×10^{-10} m s^{-1}) helps to sustain high, yet strongly variable, water tables. In addition, the strong positive horizontal hydraulic gradients measured from the upland to the wetland (Fig. 5c) highlight the importance of throughflow as a means of maintaining high water tables in the East wetland.

Geochemical results supported the lithological and hydrological evidence of a localized flow system influencing recharge–discharge patterns at Poplar Fen. Virtually indistinguishable pH and similar EC and Ca^{2+} and Mg^{2+} concentrations between channel fen, underlying outwash aquifer, and upland suggests that waters in these locations are of similar origin. Furthermore, Cl^- concentrations 4.7 times lower than SO_4^{2-} concentrations (not shown in Fig. 6) in the underlying outwash aquifer points to local groundwater with virtually no contact with regional groundwater, as Cl^- is typically the dominant anion in deep regional groundwater due to a longer time and distance of travel (Domenico, 1972). Lower pH, EC, Ca^{2+}, and Mg^{2+} in the West and East wetlands points to a reliance on precipitation–driven recharge rather than groundwater, suggesting that these wetlands act predominantly as recharge rather than discharge features within the watershed. The δ^2H and $\delta^{18}O$ signatures also confirmed the dominance of a local–flow system at the Poplar Fen watershed (Fig. 7). Channel fen and West and East wetland water table well samples and corresponding underlying mineral substrates and adjacent upland samples were nearly indistinguishable in isotopic composition between 2014 and 2015. Samples from the majority of these locations plotted in the middle of the LMWL, suggesting that they receive recently precipitated meteoric water in the form of both snowfall and rainfall. Groundwater sourced by a regional (older) groundwater would plot elsewhere on the $\delta^{18}O/\delta D$ plot, along a water line (e.g., CFWL & HFFWL; Figure 8) with a different slope and δD–excess (y–intercept) more reflective of the hydrometeorological conditions (e.g., relative humidity and temperature) during the time of recharge (Kendall and Caldwell, 2006). The heavy reliance on precipitation, combined with relatively low pH and base cation concentrations, suggests that the West wetland functions as a poor or intermediate fen (Chee and Vitt, 1989; Vitt et al., 1995).

5.4 Implications of Climate Change on the Hydrologic Function of Poplar Fen

The results from this study suggest that peatlands in the region that are fed by localized flow systems are particularly susceptible to drainage and drying under a climate characterized by warmer and drier conditions (Flannigan et al., 2016), especially during extended drought periods that are becoming more frequent (IPCC, 2013). Unlike fen systems connected to regional groundwater sources (Winter et al., 2003; Smerdon et al., 2005; Kløve et al., 2012), those with only a local hydrogeological connectivity similar to Poplar Fen may receive substantially less groundwater discharge from coarse–grained uplands and underlying mineral aquifers during periods of water table drawdown. Consequently, these fen systems may be subjected to enhanced peat decomposition and carbon release (Roulet et al., 2007), as well as seral succession to more ombrogenous peatlands characterized by shifts in vegetation community composition to more drought–tolerant species (e.g., *Hylocomium splendens*; Vitt, 1990).

Caution is required in generalizing the results of this study of one moderate–rich fen system to all such systems in the AOSR, although it does include a variety of transects and wetland configurations. The plain regions of the AOSR are typically dominated by outwash sand and gravel; however, are not all situated within meltwater channel features (McPherson and Kathol, 1977). Slight modifications in grain size, watershed area, and topographic relief may result in large differences in the connection to, and scale of, groundwater flow systems (Reeve et al., 2000; Tóth, 1999; Winter, 2001). The results presented in this study are consistent with conceptual models developed for the Utikuma Region Study Area (Devito et al., 2005; 2012), which stress the need for careful consideration of the local physiography when predicting the hydrologic function of peatlands on this heterogeneous and low–relief post–glacial landscape. It is recommended that additional hydrological studies be conducted on base–rich fen systems overlying coarse–grained glacial deposits in the AOSR outside of the Poplar Fen vicinity. This will help refine our understanding of the potential variability in hydrogeological connectivity of peatlands in the WBP and how they will respond to future climate– and potential human–related disturbances.

6 Conclusions

The purpose of study was to examine the hydrogeologic setting and hydrologic regime of a moderate–rich fen watershed in the AOSR to better understand the natural variability in wetland function in the WBP. Groundwater flow direction between moderate–rich fen areas and the surrounding mineral landscape was transient during the 2011–2015 sampling period at Poplar Fen, changing between recharge and discharge during dry and wet periods, respectively. The variability in vertical and horizontal hydraulic gradients in response to precipitation patterns, along with supporting lithological and geochemical evidence, points to the dominance of a local flow–system generated by precipitation–driven recharge in the upland areas of Poplar Fen. During years of above average precipitation, hydrological connection is strong, with discharge higher than dry years by orders of magnitude. These results are contrary to results from previous studies of peatlands connected to deep regional flow systems (Siegel and Glaser, 1987; Glaser et al., 1997; Winter et al., 2003; Smerdon et al., 2005; Kløve et al., 2012), where peatland water levels are moderated by more consistent sources of groundwater discharge characterized by longer travel times (Tóth, 1999). This local groundwater connection; however, may render Poplar Fen, and peatlands watersheds with a similar hydrogeologic connectivity more susceptible to dramatic changes in the face of climate change, including drainage, enhanced peat decomposition, seral succession and wildfire.

Considerable time, effort, and resources have been invested in oil sands wetland reclamation in recent years. Regulatory requirements require mined lands to be returned to the crown in a state of 'equivalent capability' (OSWWG, 2000), and reclamation has therefore focused on testing the feasibility of engineering fen peatlands (i.e. Nikanotee Fen watershed: Price et al., 2010; Ketcheson et al., 2016; 2017). Reclaimed watersheds must be engineered as 'closed' local systems to minimize hydrological connectivity with the regional water table (Price et al., 2010), at least during the period of mine operation. The results presented in this thesis suggest that the hydrologic function of natural fen systems (i.e. moderate–rich fens) in the AOSR can be replicated. The physiography of Poplar Fen, including coarse–grained drift, low relief, veer–type (coarse over fine) layering, and shallow depth to confining layer, are all conducive for generating local flow–systems in the sub–humid WBP. However, considering the susceptibility of fen watersheds with local flow systems, to drying over WBP climate cycles, fen reclamation should focus on engineering landscapes to minimize vertical flow reversals, water loss, and susceptibility to carbon degradation from enhanced decomposition and/or wildfire.

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Competing interests

The authors declare that they have no conflict of interest.

Contributions

M. Elmes completed the data analysis, generated the original ideas of the conceptual model, and wrote the first draft of the manuscript. J. Price contributed to the study design and provided feedback on the analysis and writing of the manuscript.

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Figure 1. (a) Map showing the regional setting of the study area, and (b) map of Poplar Fen study site, including transect locations and instrumentation. The channel fen extends south of the watershed boundary, but has a hydraulic gradient towards the south.

Figure 2. Field lithology drill logs of transects A─A’ and B─B’ (vertical exaggeration = 4.6) at Poplar Fen watershed (see Figure 1 for locations).

Figure 3. Laboratory (0–0.6 m) and field estimates (0.6–1.5 m) of saturated horizontal hydraulic conductivities for channel fen and West wetland peat and underlying mineral sediments.

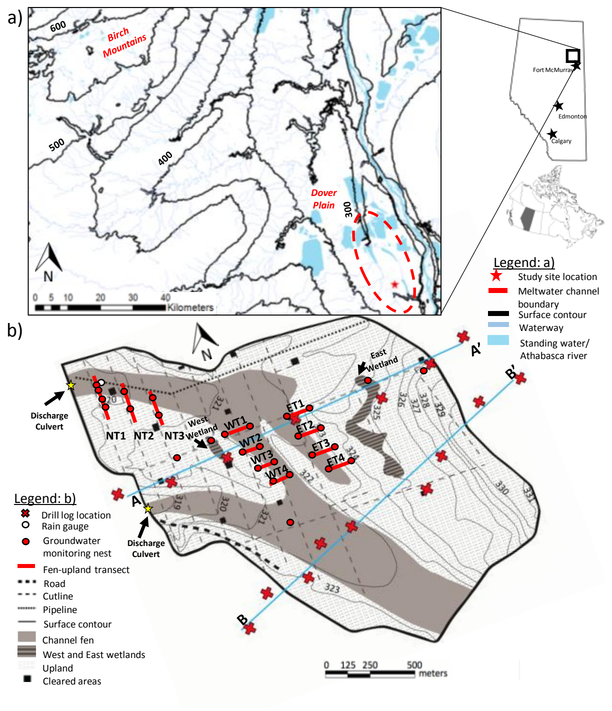
Figure 4. Average hydrological results for NT1–NT3 (see Fig. 1) from 2011–2015, including (a) channel fen water table with daily regional precipitation illustrated, (b) change in hydraulic head since last measurement in outwash piezometers underlying channel fen areas, (c) average vertical hydraulic gradients between channel fen peat and underlying mineral substrate (open and black circles) and corresponding average vertical groundwater fluxes (grey circles), and (d) average horizontal hydraulic gradients between upland and channel fen (open and black circles) and corresponding average horizontal groundwater fluxes (grey circles). Also included are vertical (c) and horizontal (d) hydraulic gradients for newly installed 2015 nests (black circles). Positive gradients and fluxes represent flow towards the fen. Note that calculated discharge in (c) and (d) in 2015 correspond only to gradients measured at NT1–NT3 and not the newly installed nests.

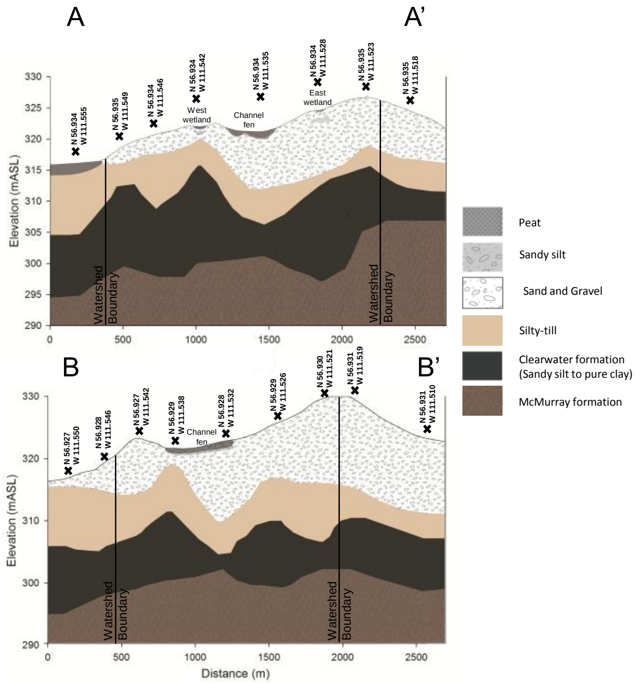
Figure 5. (a) Comparison of water table position, (b) vertical hydraulic gradients between wetland water table and underlying mineral, and (c) horizontal gradients between wetland water table and upland to the west (hashed lines) and east (solid lines) of the West and East wetland areas (see Fig. 1).

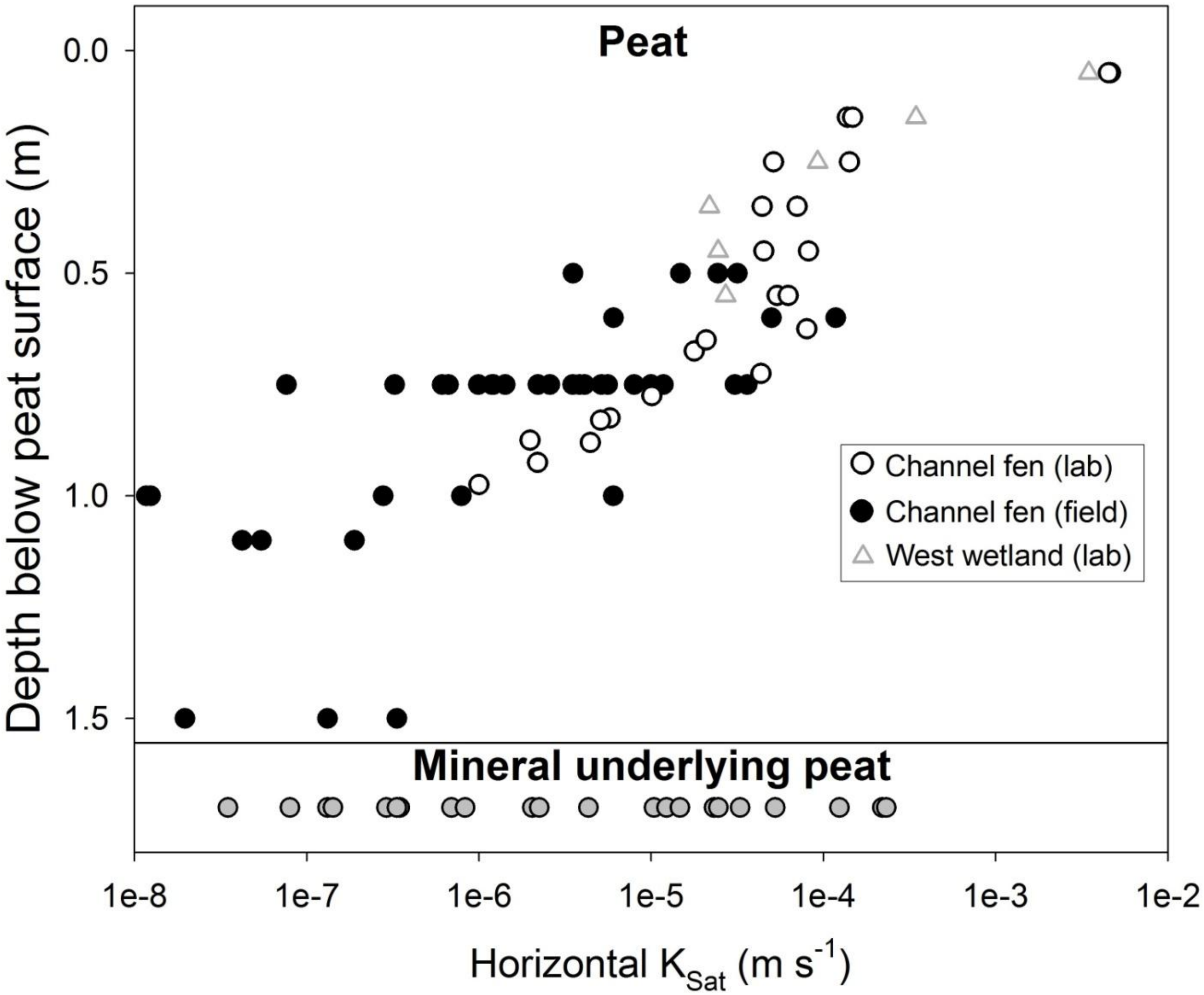
Figure 6. Average pH, electrical conductivity (EC), and concentrations of major cations (Na^+, Ca^{2+}, and Mg^{2+}) and Cl^- for samples obtained from channel fen, upland, and West and East wetland wells, as well as underlying mineral piezometers from channel fen and West wetland nests obtained throughout 2015.

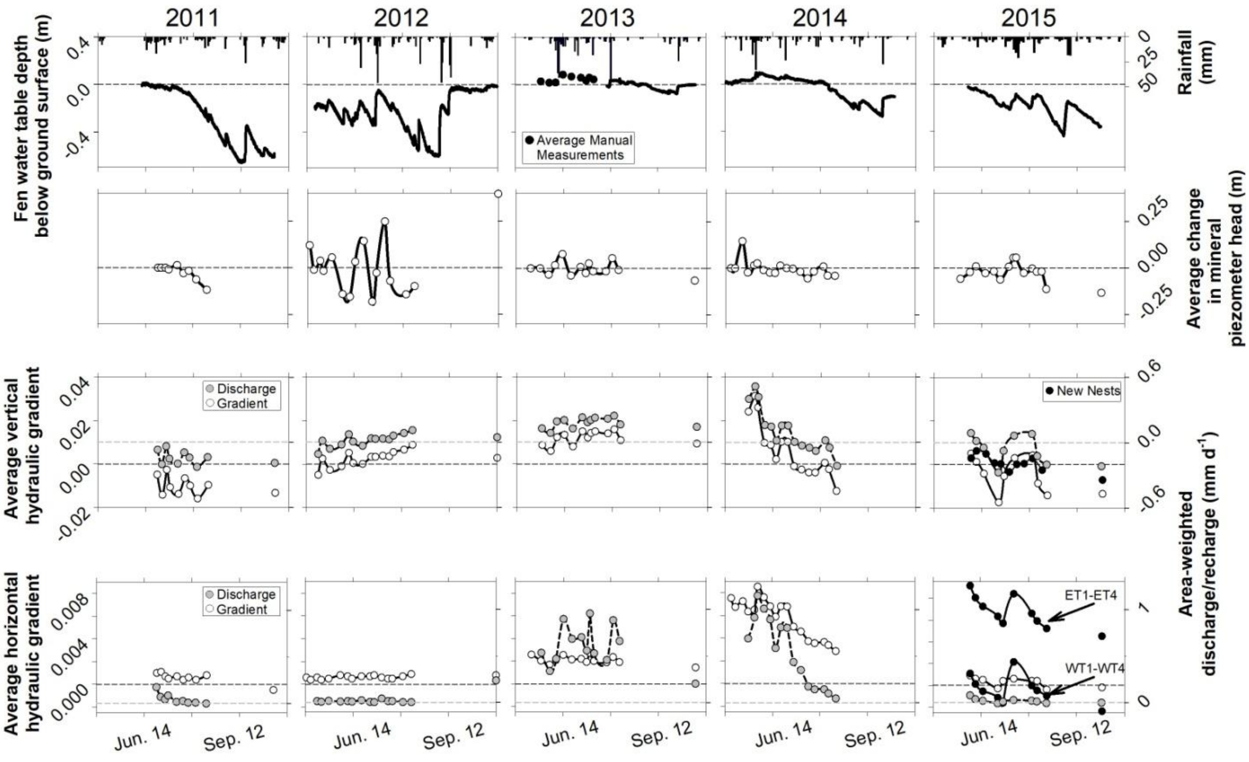
Figure 7. Isotopic signatures $\delta^{18}O$ and δD for precipitation obtained ~5 km from Poplar Fen (used to produce LMWL), and for water samples obtained at channel fen, West and East wetlands, and upland water table wells and underlying outwash piezometers (see legend for colour scheme), at Poplar Fen in August, 2014 (circles), June, 2015 (squares), and July, 2015 (triangles). Additional water lines were plotted, including the GMWL, as well as water lines of regional Alberta Basin formation water samples reported in Connolly et al., 1990 (CFWL) and Hitchon and Friedman, 1969 (HFFWL), adapted from Lemay, 2002.

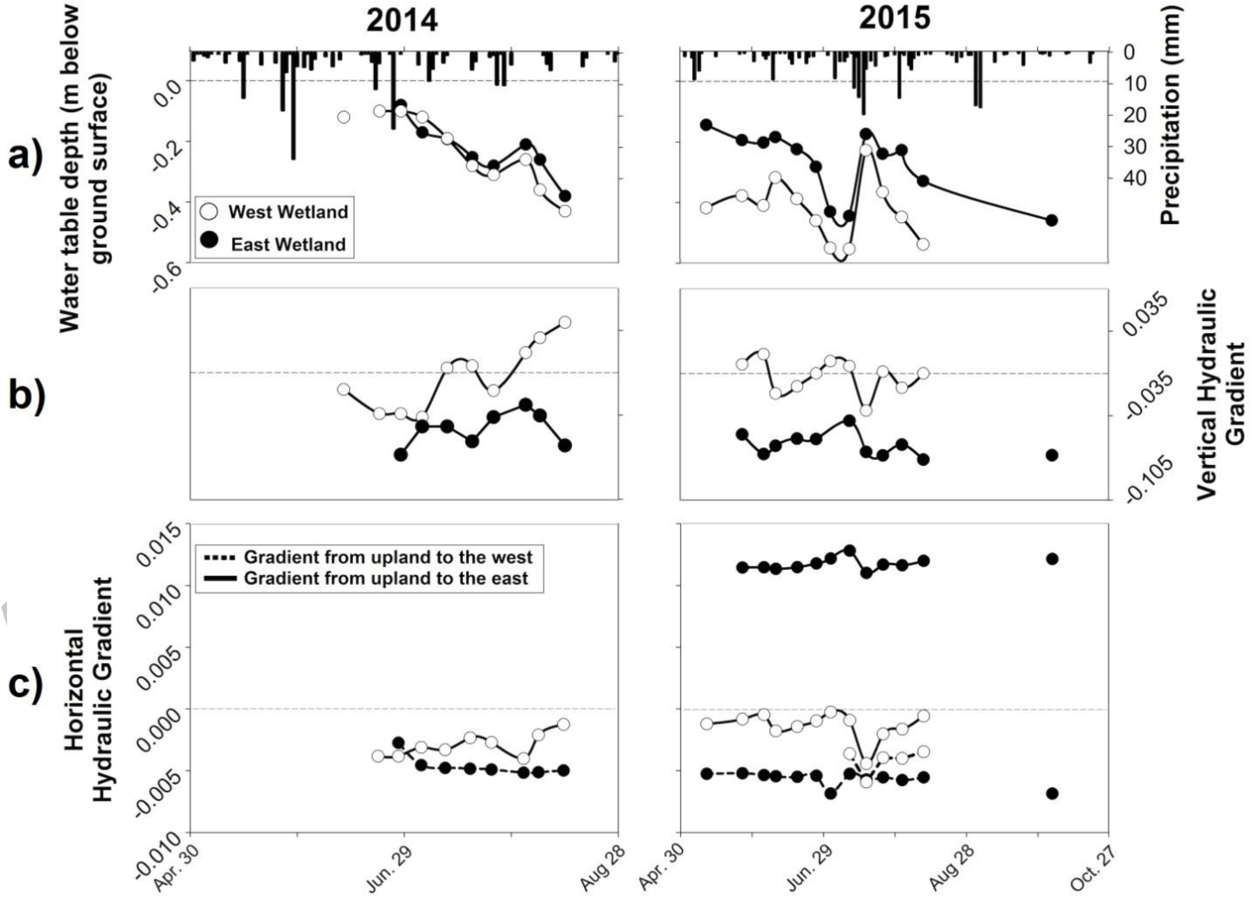
Figure 8. Conceptual model of fen landscape connectivity at Poplar Fen for moderate–rich channel fen, poor–fen, and spruce swamp systems, comprising lithological information from cross–section A–A’ (Fig. 2) during typical wet and dry conditions observed between 2011–15 (vertical exaggeration = 4.6). Due to insufficient hydrological information below 2.0 m, equipotential and flow lines are idealized.

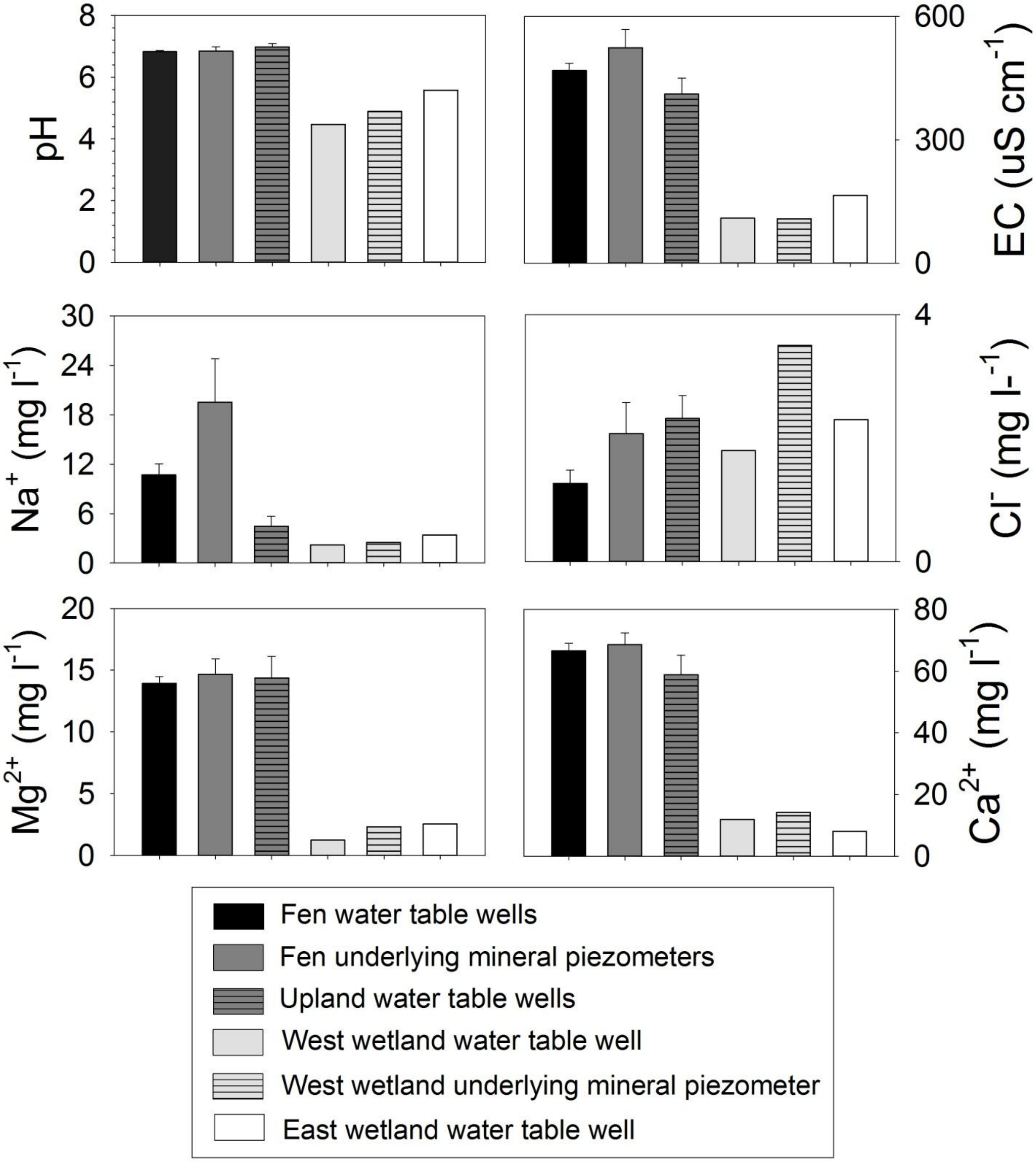

a)
600
500
400
300
Birch Mountains
Dover Plain
N
0 5 10 20 30 40 Kilometers
Fort McMurray
Edmonton
Calgary
Legend: a)
★ Study site location
Meltwater channel boundary
Surface contour
Waterway
Standing water/ Athabasca river
b)
N
A
A'
B
B'
Discharge Culvert
Discharge Culvert
East Wetland
West wetland
NT1
NT2
NT3
WT1
WT2
WT3
WT4
ET1
ET2
ET3
ET4
320
321
323
325
326
327
328
329
330
331
Legend: b)
Drill log location
Rain gauge
Groundwater monitoring nest
Fen-upland transect
Road
Cutline
Pipeline
Surface contour
Channel fen
West and East wetlands
Upland
Cleared areas
0 125 250 500 meters

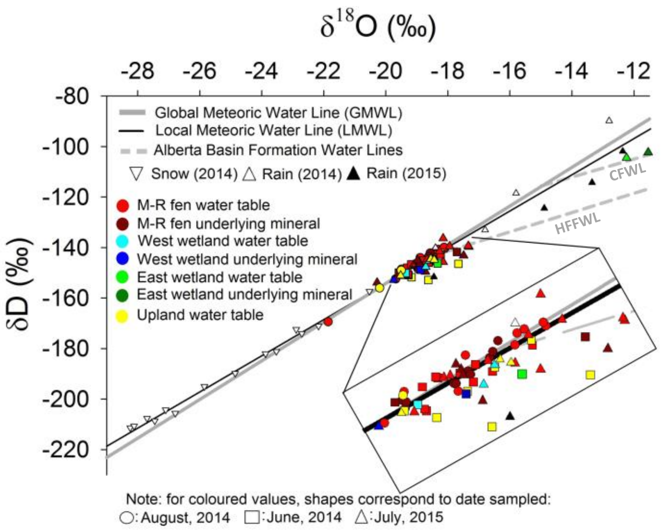

A
A'
N 56.934 W 111.555
N 56.935 W 111.549
N 56.934 W 111.546
N 56.934 W 111.542
N 56.934 W 111.535
N 56.934 W 111.528
N 56.935 W 111.523
N 56.935 W 111.518
West wetland
Channel fen
East wetland
Watershed Boundary
Watershed Boundary
Elevation (mASL)
330
325
320
315
310
305
300
295
290
0
500
1000
1500
2000
2500
B
B'
N 56.927 W 111.550
N 56.928 W 111.546
N 56.927 W 111.542
N 56.929 W 111.538
N 56.928 W 111.532
N 56.929 W 111.526
N 56.930 W 111.521
N 56.931 W 111.519
N 56.931 W 111.510
Channel fen
Watershed Boundary
Watershed Boundary
Elevation (mASL)
330
320
310
300
290
0
500
1000
1500
2000
2500
Distance (m)
Peat
Sandy silt
Sand and Gravel
Silty-till
Clearwater formation (Sandy silt to pure clay)
McMurray formation


Peat
Mineral underlying peat
Depth below peat surface (m)
0.0
0.5
1.0
1.5
Horizontal K_{Sat} (m s^{-1})
1e-8
1e-7
1e-6
1e-5
1e-4
1e-3
1e-2
○ Channel fen (lab)
● Channel fen (field)
△ West wetland (lab)


2011
2012
2013
2014
2015
Fen water table depth below ground surface (m)
0.4
0.0
-0.4
Rainfall (mm)
0
25
50
● Average Manual Measurements
Average change in mineral piezometer head (m)
0.25
0.00
-0.25
Average vertical hydraulic gradient
0.04
0.02
0.00
-0.02
Discharge
Gradient
● New Nests
Area-weighted discharge/recharge (mm d-1)
0.6
0.0
-0.6
Average horizontal hydraulic gradient
0.008
0.004
0.000
1
0
ET1-ET4
WT1-WT4
Jun. 14
Sep. 12


2014
2015
a)
b)
c)
Water table depth (m below ground surface)
0.0
-0.2
-0.4
-0.6
Precipitation (mm)
0
10
20
30
40
West Wetland
East Wetland
Vertical Hydraulic Gradient
0.035
-0.035
-0.105
Horizontal Hydraulic Gradient
0.015
0.010
0.005
0.000
-0.005
-0.010
Gradient from upland to the west
Gradient from upland to the east
Apr. 30
Jun. 29
Aug 28
Aug 28
Oct. 27


pH
0
2
4
6
8
EC (uS cm^{-1})
0
300
600
Na$^+$ (mg l^{-1})
0
6
12
18
24
30
Cl$^-$ (mg l-$^{-1}$)
0
4
Mg^{2+} (mg l^{-1})
0
5
10
15
20
Ca^{2+} (mg l^{-1})
0
20
40
60
80
Fen water table wells
Fen underlying mineral piezometers
Upland water table wells
West wetland water table well
West wetland underlying mineral piezometer
East wetland water table well



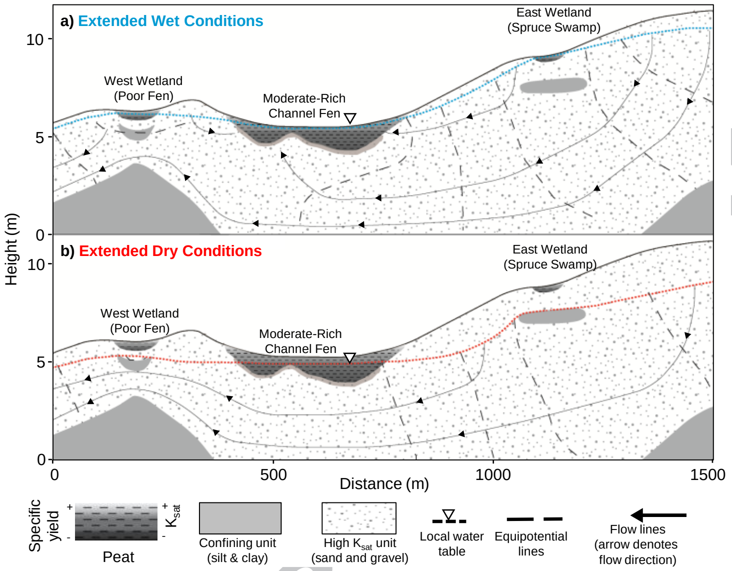


Table 1. Summary of estimated vertical and horizontal groundwater fluxes averaged (weighted) annually for 2011–2015 field seasons, along with average daily precipitation over the same time period. Note: a negative gradient and flux represents a loss of water from the fen.

Year	**2011**	**2012**	**2013**	**2014**	**2015**
Number of days in study period	111	170	147	84	125

Total Rainfall during study period (mm)	Jun. 26 – Oct. 14	May 10 – Oct. 26	May 24 – Oct. 17	May 22 – Aug. 13	Jun. 04 – Oct 06
Vertical discharge to fen					
Average vertical hydraulic gradient between fen and underlying outwash	–0.011	+0.004	+0.011	+0.006	–0.008
Net groundwater exchange over study period (mm)	–17.9	+7.7	+24.6	+7.4	–13.6
Horizontal discharge to fen					
Average horizontal hydraulic gradient between fen and upland	+0.0004	+0.0007	+0.0019	+0.0017	+0.0001
Net groundwater exchange over study period (mm)	+2.8	+10.7	+77.7	+44.9	+1.1

Highlights

- Groundwater connectivity at Poplar Fen is restricted to shallow local flow systems.
- During wetter periods lateral groundwater discharge from the upland was the major source of groundwater to fens.
- During extended dry periods fen areas experienced vertical flow reversals (downward to outwash aquifer).
- Local groundwater connectivity makes moderate-rich fen systems like Poplar Fen more susceptible to drying in the future due to climate change.