Ecological Engineering 139 (2019) 105575

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

The influences of vegetation and peat properties on the hydrodynamic variability of a constructed fen, Fort McMurray, Alberta

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ARTICLE INFO

Keywords:
Constructed peatland
Oil sands
Western Boreal Plain
Reclamation
Revegetation
Ecohydrology
Soil water
Hydraulic conductivity
Water retention

ABSTRACT

In Alberta's Western Boreal Plain, oil sands mining strips overburden materials including vegetation and soils, leaving unnatural, undulating landforms where wetlands previously covered > 50% of the landscape. Due to their complexity, the re-establishment of peatland ecosystems had not been tested prior to two fen reclamation projects on oil sands leases north of Fort McMurray. One of which, the Nikanotee Fen, was constructed using peat stripped as part of the mining process and placed in an engineered watershed designed to provide the requisite groundwater supply to support fen hydrological functions and vegetation. The unknown effects of disturbed, placed peat and vegetation treatments on the constructed fen's soil water dynamics were studied from 2013 to 2015, the first three growing seasons post-construction. Water table, soil moisture (θ), pore water pressure (ψ), evapotranspiration (*ET*) and surface elevation were monitored in thirty-one study plots designed to test revegetation strategies, including control (bare peat), moss, seedling, mulched moss and mulched seedling treatments. Fifty-four peat samples were tested for a suite of hydrophysical parameters, including saturated and unsaturated hydraulic conductivity and soil-water retention. Plot water table positions fluctuated 36 cm below ground surface (bgs) despite a relatively small range in surface elevation between plots (~24 cm), where plots located at higher elevations had consistently lower and more variable water tables. Although average plot water tables all ranged within 5–7 cm bgs, θ, ψ and *ET* differed significantly between certain plot types ($p < 0.05$). The observed hydrology is partially affected by the heterogeneous peat properties across the fen, created by the salvage and placement methods of the peat, which significantly differed with location ($p < 0.05$). The variability in the hydrophysical properties and surface elevations, thus water table position, appear to mask the effects of vegetation and treatment type on plot hydrology, at least at this early stage of development. While significant increases in plot ψ and θ were observed from 2013 to 2015, further studies are required to track the effects of greater vegetation establishment and peat formation and elucidate the effects of different vegetation treatments.

1. Introduction

In the Athabasca Oil Sands Region (AOSR) of Alberta, a region of the Western Boreal Plain (WBP) where wetlands cover > 50% of the landscape (Vitt et al, 1996), overburden materials including vegetation and soils are stripped to access the underlying oil sand bearing formations. This leaves a disturbed, undulating landscape that promotes the establishment of ecosystems non-native to the region (Rooney et al., 2012). Due to their complexity, the re-establishment of peatland ecosystems had not been tested prior to two pilot fen creation projects in the AOSR. One of which, the Nikanotee Fen, was designed based on the conceptual and numerical model proposed by Price et al. (2010), where peat stripped to access the bitumen, was placed in a constructed watershed designed to provide the requisite groundwater supply to support the establishment of a fen peatland. The design aimed to engineer a self-sustaining, carbon-accumulating ecosystem, capable of supporting representative fen species and resilient to normal stresses, such as prolonged periods of atmospheric water deficits (Daly et al., 2012).

As reclaiming landscapes to peatland is a new concept, the hydrology of constructed fens is not well understood. While recent studies have looked at the watershed-scale hydrology (Ketcheson et al., 2017; Ketcheson and Price, 2016a,b; Nicholls et al., 2016) and hydrometeorology (Scarlett et al., 2017) of constructed peatlands in the WPB, the effects of disturbed, placed peat and vegetation treatments on the soil water dynamics is unknown. Peatland hydrology is highly

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https://doi.org/10.1016/j.ecoleng.2019.08.005
Received 27 March 2019; Received in revised form 8 July 2019; Accepted 6 August 2019
Available online 26 August 2019

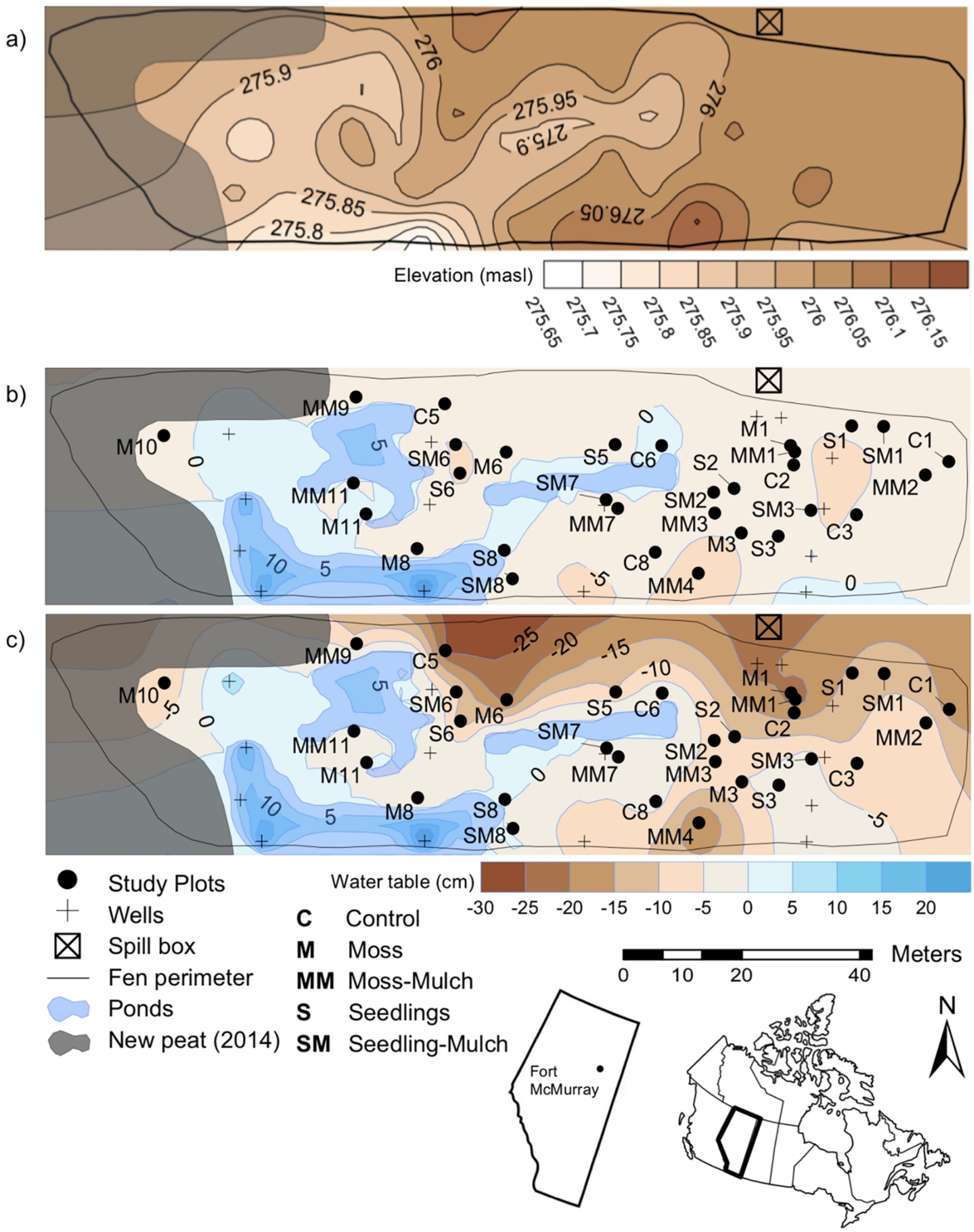

Fig. 1. Map of the 2.9 ha Nikanotee Fen, the northernmost portion of the larger 32 ha constructed watershed (not shown). Flow direction is generally south to north, from the constructed upland to towards the spill box to the northeast, with groundwater upwelling under the fen (Ketcheson et al., 2017). Ponds shown were not part of the original design but had permanent standing water during the study period. a) Illustrates surface elevation of the fen. b) and c) show water table contours in centimeters relative to ground surface. Negative contours (brown) are below ground surface and positive contours (blue) above ground surface. Water table position is shown during b) wetter (July 30th, DOY 211) and c) drier (June 18th, DOY169) periods, which were chosen based on maximum and minimum site average water table elevations. Kriging was used for data interpolation. Numbers following plot abbreviations indicate the experimental block number. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

dependent on peat properties (Boelter and Verry, 1978; Price, 2003), vegetation water requirements (Kim and Verma, 1996) and meteorological controls (Petrone et al., 2004). Nwaishi et al. (2015) compares the physical properties and saturated hydraulic conductivity of the Nikanotee Fen peat to those of the dewatered donor site, where the peat material was collected, and a local undisturbed fen. The study found that placement had greatly altered the hydrophysical peat properties of the constructed fen. Nwaishi et al. (2015) discuss the potential ecohydrological impacts of the placed peat properties, however, the spatial variability of these properties and the influence of different revegetation treatments on the fen's hydrology were not considered. Furthermore, the unsaturated zone hydrology of placed peat has not yet been reported.

There have been numerous comprehensive hydrological studies on peatland restoration following peat harvesting for energy or horticultural use (e.g. Price, 1997; Schlotzhauer and Price, 1999; Petrone et al., 2004; Ketcheson and Price, 2011; McCarter and Price, 2013), which creates a landscape similar in some respects to that of a constructed peatland. Cutover harvested peatlands have had their vegetation and upper peat profiles removed, exposing deeper, more decomposed layers (Price et al., 2003), similar to the peat placed in the constructed fen. However, although compacted, the natural structure of the unused deeper peat profiles remain intact in harvested sites, unlike the placed peat of the constructed fen, which has been highly disturbed through the salvage and placement process. Moreover, the broader hydrogeomorphic conditions that contributed to the initial establishment of a harvested peatland are generally still present, unlike the constructed systems that rely on informed design. Yet, despite differences in peat structure and peatland setting, restoration of harvested peatlands provides a partial analogue for landscape reclamation to peatland. Both practices are left with dewatered, highly decomposed peat, which can result in smaller pore sizes, decreased hydraulic conductivity and higher soil water retention capacity compared to undisturbed natural systems (McCarter and Price, 2015), complicating the reestablishment of the desired vegetation, particularly non-vascular mosses sensitive to hydrologic conditions (Price et al., 2003).

Rochefort et al. (2003) outline restoration practices for North American peatlands, however, these practices are focused on *Sphagnum* dominated bogs. Although these methods (i.e., moss-transfer, mulching) have been previously tested at restored harvest sites (e.g. Bugnon et al., 1997; Price et al., 1998; McCarter and Price, 2013; Malloy and Price, 2014), they have not been applied in a post-mined oil sands landscape where, in the dry sub-humid climate of the WBP, potential evapotranspiration typically exceeds precipitation (Devito et al., 2005). In the AOSR, fens are the dominant wetland class (~90%) (Vitt et al, 1996), and although *Sphagnum* mosses are present, many of these fens are dominated by brown mosses with dense vascular cover (Chee and Vitt, 1989). While standard bog restoration practices, such as mulching, aim to keep moisture at the peat surface for moss establishment (Price et al., 1998; Petrone et al., 2004), these practices may not have the same effect on fens, where there is the potential for increased drying at the near-surface and lowering of the water table through vascular transpiration (Takagi et al., 1999; Farrick and Price, 2009; Rezanezhad et al., 2012).

To date, there are no studies evaluating the influences of disturbed, placed peat and revegetation treatments on hydrophysical properties and soil water dynamics of a constructed fen. It is hypothesized that vegetation and mulch treatments will significantly influence soil water dynamics due to differences in water conducting mechanisms (i.e. vascular vs. non-vascular tissue) and the sheltering effects of mulch. It is expected that plots with vascular plants will experience lower soil moisture and water table positions, due to greater evapotranspiration rates, whereas lower evaporative losses will mitigate drying in moss and mulched plots. However, variability in peat properties, surface elevation and thus water table position will further affect plot-scale soil water dynamics, which could mute the effects of individual plot types. Therefore, this study aims to evaluate the effects of peat placement and specific vegetation treatments (Borkenhagen and Cooper, 2019) on the hydrology of the constructed Nikanotee Fen. The specific objectives of this study are to 1) characterize plot-scale soil water dynamics with respect to vegetation type, mulch and surface elevation, 2) quantify the hydrophysical properties of the placed peat and their spatial variability, and 3) determine the impact of the placed peat on unsaturated zone hydrologic processes.

2. Study site

The study was conducted on the Nikanotee Fen (56.932° N, 111.417° W; Fig. 1), a 2.9 ha constructed peatland located on an oil sands lease within the AOSR, north of Fort McMurray, Alberta. The region has normal (1981–2010) average temperatures ranging from −17.4 °C (January) to 17.1 °C (July) and receives an average of 419 mm precipitation annually, of which ~ 76% is rainfall (measured at the Fort McMurray Airport, 33 km south of the study; Environment Canada, 2015).

The fen was constructed in 2013 using donor peat salvaged from a natural fen in an oil sands lease area scheduled for extraction. The peat was placed to a depth of 2 m on the constructed site. The donor peat was well-decomposed and highly disturbed during the salvage process, losing its natural structure, and in places incorporating minor quantities of the mineral sediments underlying the donor fen. Consequently, and perhaps due to deposition of mineral sediments in surface runoff from unvegetated upland areas, Nwaishi et al. (2015) found the average bulk density of the top 0–60 cm of the placed peat (0.19 g/cm^3) was greater than that of the donor peat (0.16 g/cm^3). Construction of the fen, and surrounding watershed (32 ha), was completed in January 2013. Ketcheson et al. (2017) provide an assessment of watershed function and hydrological connection to the fen, while Kessel et al. (2018) couple watershed hydrology to fen water chemistry. Ketcheson et al. (2017) found May to August groundwater inflow to the fen in 2014 was substantial, 177 mm, compared to 201 mm of rainfall. The layering design of the fen (Price et al., 2010) resulted in primarily upward flow through the fen peat to the surface. These flows flushed solutes from the constructed upland to beneath the fen, and upwards towards the rooting zone, although their presence was not observed in the rooting zone during the present study (Kessel et al., 2018).

The fen was revegetated in June 2013, using an experimental factorial design by Borkenhagen and Cooper (2019) (not shown). The 2.9 ha fen was divided into twelve blocks of replicate vegetation treatments, which were sub-divided into five vegetation types, control (bare peat), moss, seedlings, seedling-moss and seeds. Plots measured 17 m × 18 m for moss, seedlings and seedling-moss plots. Control and seed plots were smaller, 8 m × 18 m, to reduce the unplanted areas of the fen. Each plot was sub-divided into unmulched and mulched treatments using WoodStraw© ECM mulch. Moss was mechanically harvested (upper 10 cm) from previously disturbed but well-revegetated cut lines from a local donor fen not on the oil sands lease. The site was chosen for the dominance of rich-fen moss species (i.e. *Tomenthypnum nitens, Aulacomnium palustre, Sphagnum warnstorfii).* The moss was hand-spread on the constructed site to an average thickness of ~1 cm at a ratio of 1:10 (collected:spread), in accordance with the moss-layer transfer technique (Qunity and Rochefort, 2003). Seedlings were hand planted on the fen after germination in a greenhouse (Coast to Coast Reforestation, Smokey Lake Nursery, Alberta). Seedlings were sub-divided into salt-tolerant (*Juncus balticus, Triglochin maritima, Calamagrostis inexpansa*) and freshwater (*Carex aquatilis, Betula pumila*) plots. In 2014, additional peat was placed on the west side of the fen to infill ponds that developed due to peat settlement. This area was not included in the original planting design or this study. Note – here we do not report on the success of the vegetation treatments, only the effect of the treatments on the hydrology of the site.

3. Methods

3.1. Field data collection

Thirty-one study plots were selected within the experimental plot design (Fig. 1, experimental design not shown). For the study reported herein, the plot types examined included bare control (n = 6), moss (n = 6), moss-mulch (n = 7), salt-tolerant seedlings (n = 6) and salt-tolerant seedling-mulch (n = 6). All plots were in weeded treatments for consistency between plot types and to reduce the influence of non-peatland species. Plots were chosen randomly across a hydrological gradient but permanently flooded sections were avoided (Fig. 1b and c). In 2014, new peat was placed on flooded sections of the west side of the fen; this area was not part of the original fen design and therefore was not included in this study. Freshwater seedling, seeds and seedling-moss plots were not monitored for this particular study, due to time and equipment constraints. Elevations of the fen surface presented in this study were measured in 2014 using a Leica DGPS unit. Surface elevations were taken at all study plots, as well as all water table monitoring wells across the fen.

Plot-scale hydrology was monitored 3–4 times weekly from June 1 to August 15 in 2014, during the second season of plant establishment. Manual water table measurements (depth below ground surface) were taken at wells or small pits where the water table was shallow enough (< 15 cm). An average of three volumetric soil moisture (θ; Delta-T Devices WET-Sensor) measurements, representing the 0–5 cm bgs, were taken at each plot. Field θ measurements were corrected with a gravimetrically-determined calibration curve developed for the constructed fen peat using θ readings taken from a sample with a known volume that was progressively dried and weighed (Scarlett, 2015). Manual tensiometers were used to measure pore water pressure at 5 cm bgs (ψ_{-5}) in each plot. θ and ψ_{-5} were also measured in 2013 (July 10–August 23) and 2015 (June 2–July 28) growing seasons at the same 31 study plots. It should be noted that the frequency of measurement was less for these years.

Weighing lysimeters (10 L) were installed in each plot at the time of revegetation, filled with the placed peat and covered with the representative plot treatment. Seedlings were transplanted into lysimeters during their installation. Lysimeters were used in conjunction with data from a meteorological station installed in the fen to estimate evapotranspiration using the equilibrium evapotranspiration (ET_{eq}) approach (Priestley and Taylor, 1972), where evapotranspiration (ET) was calculated as,

$$ET = \alpha\left(\frac{\Delta}{\Delta + \gamma}\right)\left(\frac{Q^* - Q_G}{\lambda\rho}\right) \tag{1}$$

where Δ is the slope of the saturation vapour-pressure curve (kPa/°C), γ is the psychrometric constant (0.00662 kPa/°C at 20 °C), λ is the latent heat of vaporization (MJ/kg) and ρ is the density of water (kg/m^3). The coefficient of evaporability, α, has a value of 1 for ET_{eq} (Priestley and Taylor, 1972), and otherwise is the slope of the regression relating actual evapotranspiration (ET_a) obtained from the lysimeters to the calculated ET_{eq}. Individual α-values were derived for each plot type (Scarlett et al., 2017) to calculate representative plot-scale α-adjusted ET_{eq}, herein referred to as ET. Aerially weighted site average ET was calculated based on the known areas of plots, ponds and unplanted fen. Unplanted areas were considered to have comparable ET rates to control plots (Scarlett et al., 2017).

Precipitation was measured using a graduated manual rain gauge (3–4 times weekly) and logged with a tipping bucket rain gauge (Texas Electronics tipping bucket; located ~100 m south of the fen). The effects of mulch and seedlings on precipitation interception were quantified using throughfall troughs (100 cm × 9 cm) installed under seedlings (n = 2) and under mulch “baskets” with representative mulch percent cover (n = 2). Troughs drained into buckets, which were weighed following rain events to quantify throughfall.

Nine 0–5 cm bgs peat samples were taken using 5 cm dia. PVC rings at 6 locations across the fen (n = 54) to quantify spatial variability in hydrophysical peat properties. All sampling locations were undisturbed, bare peat (outside of study plots), since the objective was to characterize the variability caused by placement, not treatment. Additional peat profiles from 0 to 20 cm were sampled using the method as described above at 3 locations across the fen (east, central, west).

3.2. Laboratory analysis

Vertical saturated hydraulic conductivity (K_{sat}), bulk density, porosity, specific yield and mineral content were determined in the laboratory for the surface (0–5 cm bgs) peat samples from the six sampling locations (n = 54). K_{sat} was measured using a Darcy permeameter following the constant-head method outlined in Hoag and Price (1987). K_{sat} was calculated using Darcy’s Law,

$$Ksat = \frac{Q}{A(\Delta h/\Delta l)} \tag{2}$$

where Q is the discharge rate (mL/s), A is the flow face area (cm^2) and $\Delta h/\Delta l$ is the hydraulic gradient. Specific yield was calculated from the weight change after 24 h of gravity drainage of a saturated sample. Samples were oven-dried at 80 °C until they reach a stable weight (~48 h) to determine bulk density (ρ_b). Eighteen sub-samples (n = 3 at each location) were analyzed for their percent mineral content using loss-on-ignition (LOI), where samples were finely ground and heated to 500 °C for 4 h following the methods described by Pansu and Gautheyrou (2006). A weighted average particle density (ρ_p) was then determined for each sample using a known particle density of the fen peat (1.7; McCarter, unpublished data) and a standard mineral particle density of 2.65 (Freeze and Cherry, 1979). Porosity (ϕ) was calculated as,

$$\phi = 1 - (\rho_b/\rho_p) \tag{3}$$

Unsaturated hydraulic conductivity (K_{unsat}) and θ retention were measured at ψ-steps of -5, -10, -15, -20, -25 cm of water on 5 cm long segments of the peat profile cores (0–20 cm; n = 12), therefore each depth (0–5, 5–10, 10–15 and 15–20) had triplicate measurements. It should be noted that the 15–20 cm segment of the west profile was discarded due to an unrepresentatively large mineral content. The $\psi - \theta$ and $K_{unsat} - \psi$ curves were determined using the method outlined in McCarter et al. (2017). Briefly, each sample was placed on a tension plate covered in 25 µm mesh that was connected to an outflow flask. The flask had a constant head and was adjusted relative to the midpoint of the sample to control the ψ (−5, −10, −15, −20, −30 cm). Samples and flasks were covered to minimize evaporative losses and allowed to equilibrate for ~7 days (< 1 g/day change), after which they were weighed to determine the θ at each tested ψ. At this time K_{unsat} was measured by placing a second 25 µm mesh tension plate on top of the sample, attached to a reservoir with a constant head equal to the equilibrated ψ from the top of the sample. The outflow flask was then lowered by half the sample height to achieve a uniform ψ across the sample, creating a hydraulic gradient of 1. The flask drained into a graduated cylinder to measure Q. Samples were run for ~1 h to equilibrate before K_{unsat} was calculated from Q using Darcy’s Law (Eq. (2)).

3.3. Statistical analysis

R statistical software (R Core Team, 2013) was used for all statistical data analyses. Data sets were tested for normality using the Shapiro-Wilk test. For normally distributed datasets, an ANOVA was used to determine differences among group means, whereas the non-parametric Kruskal-Wallis one-way analysis of variance was used when a normal distribution could not be assumed. If significant effects were found, a post-hoc pairwise *t*-test (parametric) or Wilcoxon rank sum test (non-parametric) with a Bonferroni adjustment was used to isolate significant differences between groups. A 95% confidence level ($\alpha = 0.05$) was the significance threshold for all tests.

An ordination was done in R, using the “Vegan” package, to illustrate the relationship between environmental variables and plot types (Oksanen et al., 2013; R Core Team, 2013). A nonmetric multidimensional scaling (NMDS) test was chosen, as normalcy could not be assumed, which is often the case with ecological data sets. The ordination results were plotted on an NMDS biplot. Environmental variables were plotted as vectors, where the length and direction of the vectors indicate their correlation with the plot types.

A repeated measures general linear mixed-effects model (GLM) was performed by Scarlett (2015) on the peat samples collected in this study to quantify the relationships between measured peat properties and their influence on K_{sat}. Detailed methods and results of the GLM are presented in Scarlett (2015).

4. Results

4.1. Climate and micrometeorology

From June 1 to August 15, 2014, precipitation (P) at the study site totaled 132 mm, with the largest event (14.2 mm) occurring on July 29 (DOY 210; Fig. 2). This total was 79 mm less than the 30-year regional average (211 mm; Environment Canada (1981–2010), 2015). Site averaged evapotranspiration (ET) totaled 260 mm over this period, averaging 3.4 mm/day with maximum rates in early July (5.8 mm, DOY 185; Fig. 2). Cumulative ET consistently exceeded cumulative P after June 12 (DOY 163; Scarlett et al., 2017). Average daily air temperature was 19 °C, ranging from 7.9 °C on June 5 (DOY 156) to 26.8 °C on July 14 (DOY 195; not shown).

The 2013 and 2015 growing seasons were, on average, atmospherically cooler and wetter than the 2014 season (Environment Canada, 2019). Over the same period as 2014 (June 1–August 15), 2013 received 255 mm of rain with an average temperature of 16.8 °C, and 2015 received 140 mm with an average temperature of 17.2 °C.

Mulch and seedling P interception each averaged ~1 mm per event

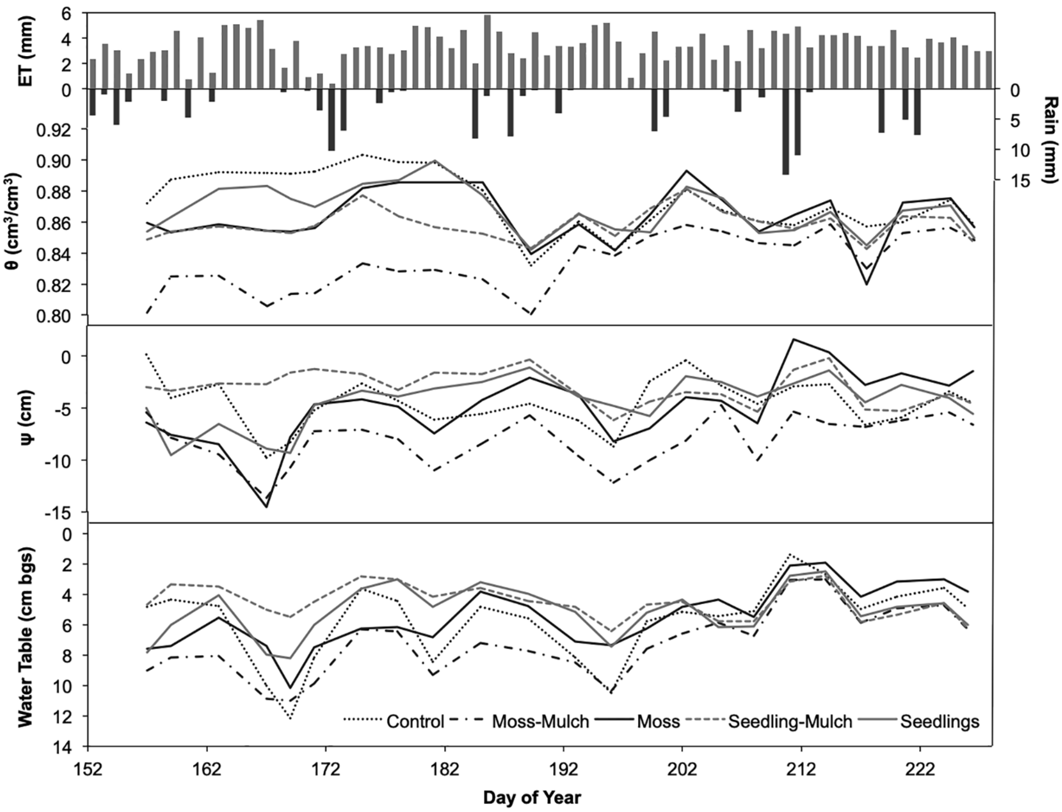

Fig. 2. Time series of average soil water dynamics for each plot type (2014). Evapotranspiration (*ET*) is an aerially weighted average site value. Water table is presented as cm below ground surface (bgs). Note pressure (ψ) was measured in mbar, where 1 mbar ≈ 1 cm.

Table 1
Summary of plot hydrology and *ET* for each plot type. Average pore water pressure (ψ_5) and soil moisture (θ) are shown for 2013, 2014 and 2015 study seasons. Average water table (*WT*), elevation (Elev), *ET* and *P-ET* are from 2014. *P-ET* represents average plot total *ET* subtracted from total precipitation (accounting for interception in mulched and seedling plots). Plot averages with different letters indicates a significant difference ($p < 0.05$). No significant differences were found between average plot ψ in 2013 and 2015. One standard deviation is shown in parentheses.

Plot type	*ET* (mm/day)	*P–ET* (mm)	*WT* (cm bgs)	Elev (masl)	2013		2014		2015	
					Ψ (mbar)	θ (cm^3/cm^3)	Ψ (mbar)	θ (cm^3/cm^3)	Ψ (mbar)	θ (cm^3/cm^3)
Control	3.2^{ab} (± 1.2)	−114	6^{ab} (± 5)	276.008	−6.8 (± 11.4)	0.85^{a} (± 0.04)	0.5^{ab} (± 7.1)	0.87^{a} (± 0.02)	0.9 (± 8.2)	0.90^{a} (± 0.01)
Moss	2.8^{ac} (± 1.0)	−80	5^{ab} (± 5)	275.996	−5.9 (± 11.6)	0.83^{b} (± 0.04)	0.2^{ac} (± 6.2)	0.86^{ab} (± 0.04)	1.2 (± 7.0)	0.88^{a} (± 0.01)
Moss-Mulch	2.4^{c} (± 0.9)	−90	7^{a} (± 6)	276.024	−8.5 (± 12.6)	0.80^{bc} (± 0.07)	−3.1^{b} (± 6.2)	0.83^{c} (± 0.04)	2.1 (± 5.4)	0.83^{b} (± 0.01)
Seedlings	3.9^{bd} (± 1.3)	−201	5^{ab} (± 4)	276.023	−4.4 (± 6.3)	0.87^{a} (± 0.03)	0.6^{c} (± 4.7)	0.87^{a} (± 0.02)	1.6 (± 6.2)	0.88^{a} (± 0.01)
Seedlings-Mulch	3.6^{bd} (± 1.3)	−205	5^{a} (± 3)	276.023	−4.7 (± 5.6)	0.81^{c} (± 0.04)	1.9^{c} (± 3.9)	0.86^{b} (± 0.02)	3.1 (± 7.0)	0.84^{b} (± 0.01)

over the study season. Storm magnitude did not have a notable effect on mulch interception, with negligible differences in interception between small and large events. However, the relative importance of seedling interception appeared to increase during larger events. While mulch and seedling interception was small for individual rain events, it accounted for 32 and 29% of total seasonal *P*, respectively. Table 1 shows that the largest seasonal water deficit (*P* – *ET*) was in seedling plots, while mulched plots showed a marginally greater deficit than respective unmulched plots.

4.2. Site-scale hydrology and microtopography

The elevation of the peat surface varied 40 cm across the fen (Fig. 1a), with the lowest elevations in ponds and highest points to the southeast. Water table elevation and thus groundwater flow directions under wet and dry conditions are presented in Fig. 1b and c. Under dry conditions the east side of the fen drained toward the outflow while the water table remained at or above the surface under all conditions on the west side of the fen, showing poor connectivity to the outflow, at least at the surface. As a result, plot water tables on the west side of the fen were significantly shallower than the east (Wilcoxon test, $p < 0.01$). On average individual plot water tables varied 7 cm between wet and dry periods (Fig. 1b and c). However, changes in water table position > 20 cm were observed at the higher elevation points and near the outflow (Fig. 1), whereas lower elevation areas experienced small (< 5 cm) or no water table fluctuations between the two periods. Plot elevations were not significantly different (Wilcoxon test, $p > 0.1$; Table 1) and only varied 24 cm between the highest (MM4; 276.161 masl) and lowest (C6; 276.923 masl) plots (Fig. 1a). However, plot water table position was significantly related to plot elevation ($p < 0.01$; Fig. 3) under wet and dry hydrological conditions; the strongest relationships were observed under wet conditions ($R^2 = 0.73$). While the outlier observed in Fig. 3 shows the natural variability of the site, it did not skew the significance of the relationship

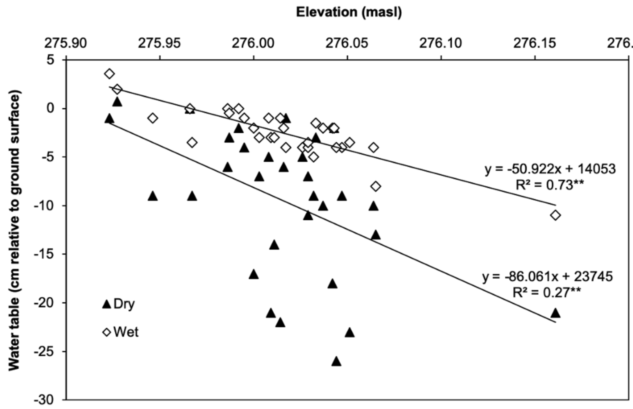

Fig. 3. Plot water table positions (2014) related to plot elevations under wetter (July 30th, DOY 211) and drier (June 18th, DOY 169), chosen based on maximum and minimum site average water table elevations. ** = significant slope at $p < 0.01$.

as both relationships remained significant ($p < 0.01$) with this data point removed.

4.3. Plot-scale soil water dynamics

Over the 2014 study season, plot water tables generally increased and became less variable (Fig. 2). Plot ψ_{-5} trends closely followed water table (Fig. 4), while θ was not consistently related to water table position, notably in control, unmulched moss and unmulched seedling plots (Fig. 5). These plots experienced high θ despite lower relative water tables positions during the first half of the season. Moss-mulch and seedling-mulch θ generally followed respective water table positions over the study season. Following peak *ET* rates on DOY 185, θ was less variable, decreasing in all plot types and more closely mirroring water table position. Water table position and ψ_{-5} were generally less affected by consistent and higher *ET* rates later in the season (i.e. post DOY 185; Fig. 2).

Relationships between ψ_{-5} and water table in 2014 were significant in all plot types ($p < 0.01$; Fig. 4) and exhibited similar responses to changes in water table. ψ_{-5} – water table relationships for control, moss and moss-mulch plots showed greater ranges in ψ_{-5}, reflecting their greater range of water table positions. Consistently shallower water tables in seedling and seedling-mulch plots (< 14 cm bgs) gave weaker ψ_{-5} – water table relationships ($R^2 = 0.61$ and 0.28, respectively). In contrast, θ – water table responses varied more between plot types (Fig. 5). However, all relationships were significant ($p < 0.05$), except in control plots ($p > 0.1$), where changes in water table were very weakly related to changes in θ. Thus control plots were found to have a small range in near-surface θ despite displaying large variability in ψ_{-5} under the same water table conditions. Moreover, mulched plots appear to have a notably stronger θ response to water table than respective unmulched plots (Fig. 5).

Although average plot water tables only ranged 5–7 cm bgs in 2014, water table depths were significantly different between the moss-mulch (average 7 cm bgs) and seedling-mulch plots (average 5 cm bgs; Kruskal-Wallis, $p < 0.05$; shown in Table 1). θ and ψ_{-5} also differed significantly between plot types despite a limited range in plot averages (Kruskal-Wallis, $p < 0.05$; shown in Table 1). *ET* rates are reported in Scarlet *et al.* (2017), which shows they differed significantly between plot types (ANOVA, $p < 0.001$; Table 1), with the greatest rates measured in seedling plots (3.9 mm/day), followed by control (3.2 mm/day) and moss plots (2.8 mm/day). Daily *ET* rates of mulched plot were on average 0.4 mm/day lower than respective unmulched vegetation, although this difference was not significant (ANOVA, $p > 0.05$, shown in Table 1). θ responses to peak seasonal *ET* rates on DOY 185 (5.8 mm/day) were less dramatic in mulched plots compared to unmulched plots (Fig. 2). While no significant relationships between θ and *ET* ($p > 0.05$) were found, seedling plots (mulched and unmulched) showed weak yet significant relationship between water table and *ET* ($p < 0.05$). To minimize the effects of variable water table positions on the observed differences in the plot hydrology, individual plots where water table did not differ significantly (~5 cm bgs; Kruskal-Wallis, $p > 0.05$) were compared. No significant differences were found between plot θ (Kruskal-Wallis, $p > 0.05$), and ψ_{-5} differences were only

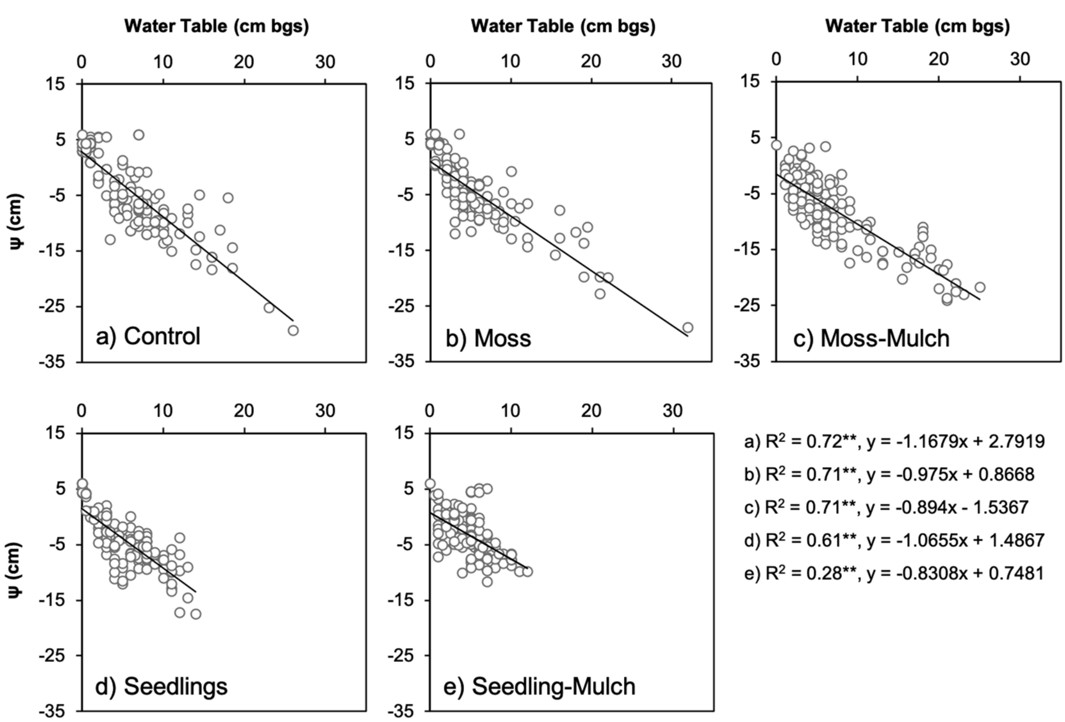

Fig. 4. Pressure (ψ_{-5}) and water table relationships for each plot type (2014). ** = significant slope at $p < 0.01$.

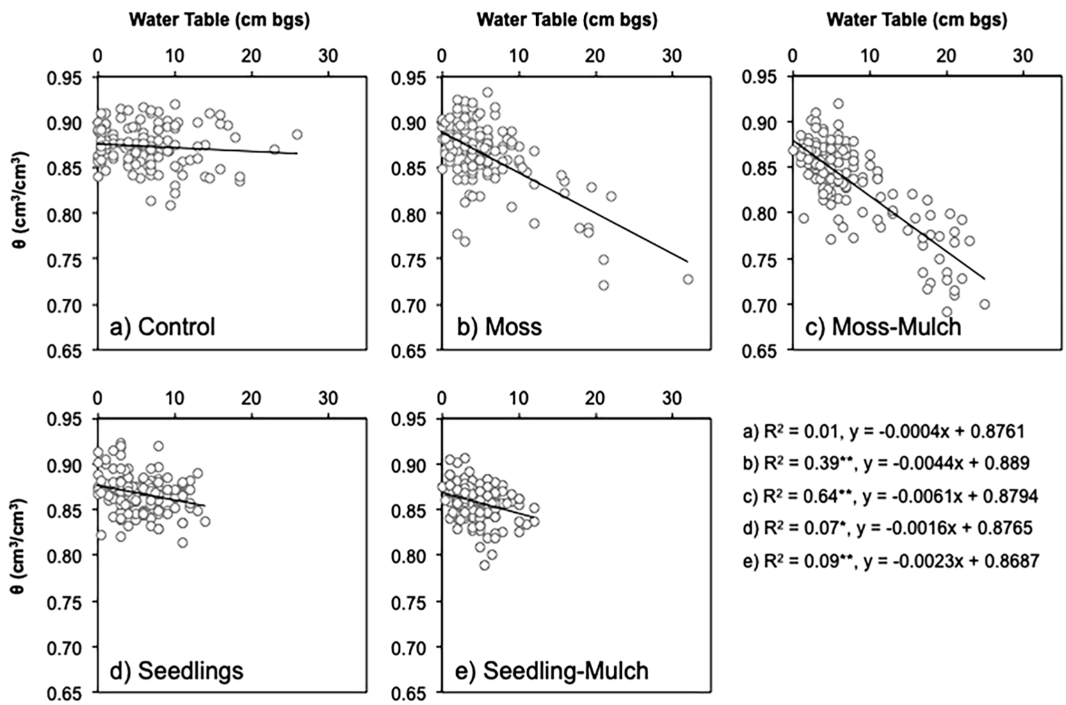

Fig. 5. Soil moisture (θ) and water table relationships for each plot type (2014). * = significant slope at $p < 0.05$; ** = significant slope at $p < 0.01$.

significant between control and moss-mulch plots (Kruskal-Wallis, $p < 0.05$), where moss-mulch ψ_{-5} was significantly higher than that of the control plot.

An NMDS ordination was used to test the relationship between plot types and measured environmental variables. Plots are presented on an NMDS biplot, clustered by treatment, in relation to water table, elevation, ψ_{-5}, θ and *ET* (Fig. 6). The biplot illustrates plot treatment placement along environmental gradients. Moss and mulch treatments (moss-mulch, seedling-mulch) were primarily located in drier areas of the fen, as they exhibited positive correlations with elevation and water table depth and were negatively related to θ and ψ_{-5}. In contrast, seedling and bare peat plots had a negative correlation with elevation and water table depth and were thus related to high θ and positive ψ_{-5}. However, the only significant environmental variable was *ET* ($p < 0.05$), which was positively correlated to seedling and bare peat plots.

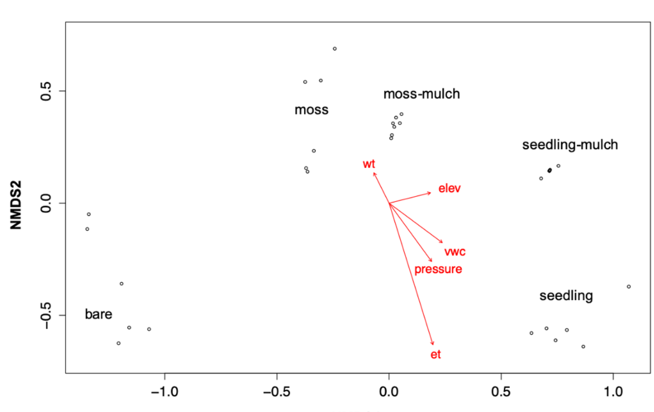

Fig. 6. NMDS plot of the 31 study plots (points) in relation to measured environmental variables (vectors). Plot labels indicate the mean position of the treatment type. wt = water table (cm below ground surface), elev = elevation (masl), vwc = volumetric moisture content (θ), pressure = pore water pressure (ψ_{-5}) and et = evapotranspiration (mm/day). The only significant vector was evapotranspiration ($p < 0.05$).

Plot hydrology changed between the three study years. The average fen water table was 15 cm and 9 cm lower in 2013 and 2015, respectively, compared to 2014 (2 cm above ground surface on average). While the fen experienced a decrease in average water table position from 2014 to 2015, annual average plot ψ_{-5} and θ significantly increased year to year, from -6.1 mbar and 0.83 cm^3/cm^3 in 2013 to 1.8 mbar and 0.87 cm^3/cm^3 in 2015, respectively (Kruskal-Wallis, $p < 0.05$; Table 1). However, moisture trends between plot types remained similar during the different hydrologic regimes of the three years.

4.4. Hydrophysical peat properties

The placed peat was highly variable across the site, where most measured properties (except specific yield) varied significantly with sampling location (bare peat, p-values shown in Table 2). Saturated hydraulic conductivity (K_{sat}) ranged two orders of magnitude (10^{-2}–10^{-4} cm/s), yet the GLM showed no significant relationships between K_{sat} (response variable) and the measured physical properties, bulk density, porosity and specific yield (predictor variables; $p > 0.05$; Scarlett, 2015). Furthermore, the GLM showed that neither bulk density nor porosity were significantly related to specific yield (Scarlett, 2015). The significant relationship between bulk density and porosity was likely an artifact of the use of bulk density and particle density in the calculation of porosity. Although a higher percent mineral content and average bulk density were observed in the 0–5 cm bgs samples (Table 2), the significance of relationships between percent mineral content and the other properties could not be tested due to limited sample size. Apart from the surface values, bulk density generally increased with depth, averaging 0.19 g/cm^3 in the upper peat profile (5–50 cm) and 0.22 g/cm^3 in the lower profile (50–200 cm).

The $\psi-\theta$ relationships for the upper 20 cm of the placed peat profile is presented in Fig. 7a. Water retention was substantially lower in the surface (0–5 cm) layer at all ψ-steps, despite all layers having comparable saturated θ contents ($\psi = 0$). Water retention was similar between 5 and 10, 10–15 and 15–20 cm layers at all ψ-steps. Hysteresis was present in all layers, where lower θ were observed at each ψ-step when the sample was re-wet; this was most evident in the 0–5 cm layer. K_{unsat}

Table 2
Summary of hydrophysical peat properties from six bare peat sampling locations across the fen. All samples are from the peat surface (0–5 cm), unless otherwise indicated. P-values indicate if the measured parameter varied significantly between sampling locations (NS = not significant at the 0.05 level). Test statistics represent the F-statistic for parametric ANOVA tests (i.e. specific yield, K_{sat}) and the chi-squared value for non-parametric Kruskal-Wallis tests (i.e. bulk density, porosity). Percent mineral content could not be tested for significance due to limited sample numbers at each location.

		Mean	± SD	Max	Min	n	p-value	Test statistic
Bulk density (g/cm^3)		0.27	0.05	0.43	0.20	54	< 0.05	18.75
Porosity		0.88	0.02	0.91	0.81	53	< 0.05	19.40
Specific yield		0.05	0.02	0.10	0.03	54	NS	1.10
% Mineral	0–5 cm	47.8	6.9	64.7	40.4	18	–	–
	5–20 cm	32.3	9.3	48.2	19.4	8	–	–
K_{sat} (cm/s)		3.3×10^{-3}	3.9×10^{-3}	2.6×10^{-2}	3.9×10^{-4}	53	< 0.05	7.84

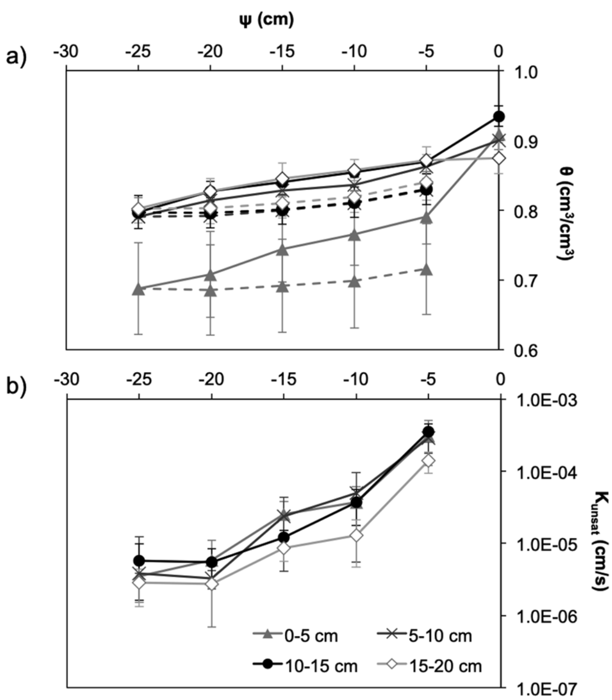

Fig. 7. a) $\psi - \theta$ retention and b) $K_{unsat} - \psi$ curves for the upper 20 cm of the peat profile (n = 3 for all layers). θ at $\psi = 0$ determined from sample porosity. Solid and dashed lines in a) show drying and wetting curves, respectively. Error bars indicate 1 standard deviation.

$- \psi$ relationships were similar for all aforementioned layers (Fig. 7b). K_{unsat} dropped 2 orders of magnitude (10^{-4}–10^{-6} cm/s) in all layers from $\psi = -5$ and $\psi = -25$. While K_{unsat} of the 15–20 cm layer was lower at all ψ-steps, values only varied within ~1 order of magnitude between layers at any given ψ.

5. Discussion

5.1. Plot-scale hydrological conditions

While studies such as Price et al. (1998) and Petrone et al. (2004) illustrate the importance of vegetation reestablishment and mulching during the initial years post-restoration on peatland hydrology, treatment type in this study did not show a significant control on soil water dynamics during the initial years following construction of the fen. Fig. 2 shows that there was little difference in water table position once plants had become more established in July and August of 2014, and for plots selected because of water table similarity, ψ_{-5} and θ were generally not statistically different. Additionally, the NMDS (Fig. 6) shows water table, ψ_{-5} and θ had a weaker relationship with plot type (shorter vectors). When comparing between study years, higher water tables in 2014 and 2015 compared to 2013, despite less P in both years, can be explained by higher and more stable water levels in the constructed upland and thus, a greater groundwater supply to the fen (Ketcheson et al., 2017). A site-wide increase in average plot ψ_{-5} and θ from year to year with no significant difference in ψ_{-5} between plot types in 2015, may suggest weakened differences in vegetation controls on plot hydrology as the site matures and plot types become less distinguishable (Borkenhagen and Cooper, 2019).

As shown in Scarlett et al. (2017), Fig. 6 illustrates that ET was the only measured environmental variable significantly related to plot type ($p < 0.05$). Differences in plot elevations appear to exert a notable influence on water table position and thus soil water dynamics, as plots located at higher elevations had consistently lower water tables under all hydrological conditions (Fig. 3). Weaker θ – water table relationships may be explained by high average water table positions in all plot types (5–7 cm bgs; Table 1) which kept the near-surface saturated, through the capillary fringe, despite water table variations (Fig. 5). This is emphasized in plots with higher average water tables (i.e. seedling, seedling-mulch). Stronger θ – water table relationships were typically observed in plot types with greater water table range (Fig. 5). While θ was significantly lower in mulched plots compared to unmulched plots of the same vegetation cover during 2013, 2014 and 2015 (except between moss plots in 2013; Table 1), the differences were < 5%. Generally high average θ in all plot types (> 80%) made the specific effects of mulch and seedling interception difficult to elucidate. However, in addition to lower ET rates in mulched plots, ET from these plots includes water that had been intercepted, in part mitigating any potential negative effects of interception on θ (Price et al., 1998).

5.2. Impacts of peat transplanting on hydrophyscial properties

The highly heterogeneous hydrophysical properties of the fen peat (Table 2), caused by the peat salvage and placement methods, contrasts strongly with the layered heterogeneity of undisturbed peatlands (Beckwith et al., 2003; Verry et al., 2011). Moreover, the porosity and specific yield were lower and bulk density was substantially higher than measured values from a local reference fen (Goetz and Price, 2015a; Nwaishi et al., 2015), which generally reported > 0.88 porosity, > 0.1 specific yield and < 0.17 g/cm^3 bulk density. However, these parameters were comparable to the range of values reported by Nwaishi et al. (2015) for the Nikanotee Fen. Bulk density was also comparable to that documented at an unrestored harvested peatland (> 0.13 g/cm^3; McCarter and Price, 2015), despite differences in botanical composition. The salvaged peat for the constructed fen and that from drained and harvested peatlands were both dewatered prior to peat extraction. The increased aeration results in increased decomposition and alters physical properties stemming from the collapse of the pore-structure (Rezanezhad et al., 2016). Furthermore, a general increase in bulk density with depth (not shown) is likely due to repeated compaction from the placement of peat layers during construction. The exception to this trend is the high bulk densities occurring at the surface (0–5 cm bgs), a result of greater mineral content (Table 2). This is caused by a thin layer of mineral sediment found over much of the fen, derived from erosion of the constructed upland during high rainfall events and snowmelt, especially during the spring and summer following construction (2013; Ketcheson and Price, 2016a). Mineral contents within the upper 20 cm of the placed peat are also comparable to values reported by Nwaishi et al. (2015). High bulk densities of degraded or decomposed peat (compared to moss-covered sites), thus high capillarity, could explain the relatively high *ET* from bare peat (control sites; Price, 1996).

Water retention of the placed peat (Fig. 7a) is substantially greater than measured values from a nearby reference fen (Goetz and Price, 2015a), at comparable sample depths and ψ-steps. Increased water retention capacity of the constructed fen peat is a result of the relatively small pore-size distribution associated with peat of greater bulk density (Goetz and Price, 2015a, McCarter and Price, 2015). Despite high retention capacity, the lack of natural structure in the disturbed peat resulted in low K_{unsat} for given ψ-steps over all depths, and values that were approximately an order of magnitude lower than the deeper, anaerobic peat layer from a reference fen (Goetz and Price, 2015a) and from cutover bog peat from harvested sites (McCarter and Price, 2015; Taylor and Price, 2015). However, the role of botanical composition of the peat was not determined. K_{sat} of the near-surface peat was comparable to vertical K_{sat} measured by Nwaishi et al. (2015), but averaged an order of magnitude lower than surface K_{sat} at harvested sites (cutover peat; McCarter and Price, 2015; Taylor and Price, 2015). Other studies have found relationships between K_{sat} and physical properties such as bulk density or porosity (Boelter, 1968; Branham and Strack, 2014; Taylor and Price, 2015), yet based on the GLM these relationships were not found to be significant in this study ($p > 0.05$). The independence of K_{sat} from other measured properties, and significant dependence on location, illustrates the heterogeneity of the Nikanotee Fen peat.

During the initial years following revegetation, influences of the different plot types could be masked by the high variability of the peat itself (Table 2), which influences water retention and thus θ. The lack of evident trends found between plot type hydrology may largely depend on plot location and local elevation effects on water table rather than vegetation type and/or presence of mulch. This is supported when plots with statistically similar water tables showed comparable soil water dynamics. Significant difference between control and moss-mulch ψ_{-5} could be attributed to higher *ET* rates over bare peat (Table 2; Price, 1996; Petrone et al., 2004), while it could also be an artifact of only having one sampling location to compare. Although plot surface elevation only differed 24 cm across the fen, this resulted in plot water table fluctuations of 36 cm over the 2014 study period, predominantly in higher elevation areas (Table 1), which could be explained by the low specific yield of the placed peat (0.03–0.1) compared to that of a natural fen (0.1–0.8; Goetz and Price, 2015b). The exaggerated water table response in wetter and dryer periods illustrates the important role of differences in elevation, which can affect solute redistribution in the vadose zone (Simhayov et al.,2018) and vegetation diversity (Borkenhagen and Cooper, 2019). However, despite elevation and water table variability, there were relatively wet conditions (average $\theta > 0.80$) throughout this study, which likely muted the effects of vegetation or mulch on soil water dynamics, as most plots showed no significant differences in θ or ψ_{-5} under comparable water table positions. The hydrologic conditions of the fen may have been further influenced by the engineered drainage points and resultant flow patterns, which also governed local water table positions.

6. Conclusions and recommendations

During the initial years post-construction of the Nikanotee Fen, plot location appears to govern soil water dynamics, as opposed to the plot types themselves. Despite successful vegetation establishment during the first growing seasons post-construction (Borkenhagen and Cooper, 2019), differences in soil water dynamics between vegetation treatments seem to be masked by variable and relatively high water tables. While significant increases in plot ψ and θ were observed from 2013 to 2015, further studies are required to determine the influence of vegetation and treatment controls on the hydrology.

Despite lower *ET* rates and stronger θ – water table relations in mulched plots, when plots with similar water tables were compared, mulch treatments did not appear to notably affect soil water dynamics and the observed hydrology in mulched plots may instead be an artifact of water table variability. While mulched plots had slightly lower near-surface θ contents than respective unmulched plots, likely due to *P* interception caused by the mulch layer, the effects of mulch on the fen's hydrology could not be clearly elucidated in this study. While mulch reduced *ET* and created a favorable microclimate (higher humidity and lower temperatures) for moss establishment (Scarlett et al., 2017; Price et al., 1998), Borkenhagen and Cooper (2019) found that the use of mulch had negative or no effect on moss cover over a 4-year study.

Significant spatial variability of the placed peat hydrophysical properties further contributed to the lack of evident trends in plot-scale hydrology. As noted by Nwaishi et al. (2015), findings from this study highlight the importance of maintaining the quality of the peat used in reclamation projects. The high water retention capacity of the decomposed placed peat may affect the ecohydrological function by limiting hydrological connectivity to the moss layer as it establishes and becomes thicker. Depending on the desired vegetation composition, it is recommended that measures be taken from the time of dewatering (i.e. reduced aeration time) to post-construction (i.e. silt fencing between uplands and peatland) to limit decomposition and mineral soil deposition.

While this study found significant differences in the measured variables between plot types, there was generally limited hydrological variability across the fen during the three study years, which made it challenging to identify and deduce trends between plot types. It was found that differences in elevation and peat properties masked the effects of vegetation and mulch treatments. Price et al. (1998) found that the creation of microtopography did not significantly alter moisture conditions or improve moss establishment in a restored post-harvested bog peatland and was thus unnecessary. However, variability in surface topography and thus water table position could result in greater species diversity and ultimately the successful establishment of a peatland ecosystem (Vitt et al., 2016). Future constructed fens could intentionally create subtle but systematic topographic differences and select the appropriate planting to take advantage of drier or wetter local conditions. As the Nikanotee Fen develops, litter deposition and moss accumulation will likely further drive the development of microtopography through new peat formation. It is therefore important that ongoing studies be conducted in the coming years to track the effects of greater vegetation establishment and peat formation, as well as capture drier conditions that may reveal the effects of different vegetation treatments on soil water dynamics. Consequently, this research site and study presents considerations for the engineering of future peatland systems, specifically those in a post-mined WBP landscape.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We gratefully acknowledge funding from the Natural Sciences and Engineering Research Council of Canada (NSERC; #418,557-2011) under the Collaborative Research and Development Grant (CRD) co-sponsored by Suncor Energy Inc., Shell Canada Ltd., and Imperial Oil Resources Ltd., as well as from the Northern Scientific Training

Program (NSTP). We are also grateful for field assistance from Eric Kessel, Dylan Price, Emma Bocking, Adam Green and Scott Ketcheson, logistical and data management support from James Sherwood, and statistical analysis assistance from Emma Bocking.

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