Journal of Hydrology: Regional Studies 40 (2022) 101031

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

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

Changes to the hydrology of a boreal fen following the placement of an access road and below ground pipeline

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A R T I C L E I N F O

Keywords:
Athabasca oil sands area
Wetlands
Fen
Hydrological alteration
Linear disturbances

A B S T R A C T

Study region: A channel fen in the Athabasca Oil Sands Area, Alberta, Canada
Study focus: We assessed the hydrological changes to the hydrology of a moderate-rich fen after the construction of a road (perpendicular to flow) in 2003 and a pipeline (obliquely to flow) in 2011.
New hydrological insights for the region: Flow obstruction was most prominent where the fen intersected the road. Changes to hydrophysical properties from pipeline construction were most pronounced in the top 10 cm of peat, which demonstrated significantly higher bulk density (by 170% and 112%) and lower hydraulic conductivity (by 94% and 91%) above the buried pipeline and in adjacent cleared locations, respectively, relative to areas not cleared or directly disturbed during pipeline development. Changes to water table levels from the pipeline were more pronounced farther down-gradient as the pipeline cut through the fen obliquely to direction of flow, and water tables became more variable on the side where the flow face had decreased in length. If built through peatlands, pipelines should be oriented parallel to flow direction and located along the central axis of the fen. Additional culverts should be considered in the event of building a pipeline through an already existing road to facilitate flow on either side.

1. Introduction

In the Athabasca Oil Sands Area (AOSA) of the sub-humid Western Boreal Plain (WBP), northern Alberta, peatlands are important sources of water to streams and rivers during periods of high water availability. Peatlands in the AOSA are a dominant land cover type (~50% of the landscape; Vitt et al., 1996), and represent key drainage routes within the Athabasca River watershed (Hwang et al., 2018), contributing up to 81% of annual streamflow to its tributaries (Gibson et al., 2016).

In peatland-dominated boreal regions including the WBP, peatland processes and associated water table feedbacks have a strong control on the sub-surface flow regime and therefore runoff generation (i.e., transmissivity feedback mechanism (Waddington et al., 2014; Elmes and Price, 2019). During periods of low water table levels, peatlands mitigate water movement by limiting flow to deeper peat, that is relatively dense and decomposed with a low saturated hydraulic conductivity (K_{sat}) (Bishop, 1991; Price, 2003; McCarter and Price, 2017; Elmes and Price, 2019). In contrast, flow is enhanced during wet periods when shallow water tables intersect

Abbreviations: AOSA, Athabasca Oil Sands Area; WBP, Western Boreal Plain; K_{sat}, saturated hydraulic conductivity; K_H, horizontal saturated hydraulic conductivity; n_d, drainable porosity; ϕ, total porosity; ρb, bulk density; RWI, ring-width index; DEM, digital elevation model; b.g.s., below ground surface; SD, standard deviation.

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https://doi.org/10.1016/j.ejrh.2022.101031
Received 4 August 2021; Received in revised form 19 November 2021; Accepted 7 February 2022
Available online 10 February 2022
2214-5818/

near-surface peat comprising living or poorly decomposed organic matter, which commonly has a lower bulk density and higher K_{sat} relative to deeper peat (Price and Maloney, 1994; Quinton and Roulet, 1998; Balliston et al., 2018; McCarter and Price, 2017; Elmes and Price, 2019). Such self-regulating water retention/conveyance mechanisms help maintain optimal soil moisture conditions in

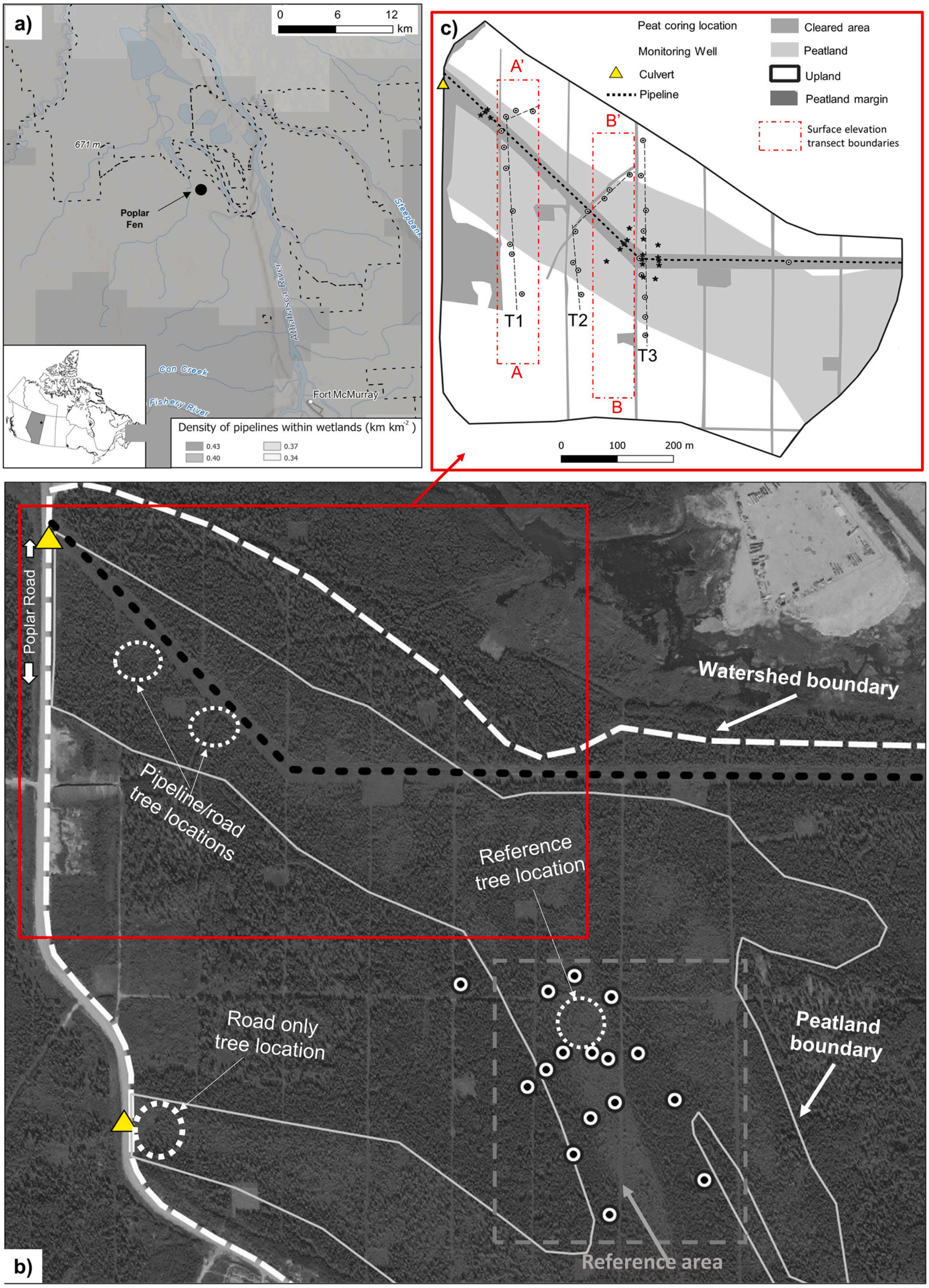

Fig. 1. Study site map of a) the AOSA, as well as Poplar Fen, including b) temporal satellite imagery, c) watershed map, and d) an inset map of the disturbed study area (T1-T3).

peatlands, which influences vegetation productivity and carbon sink efficiency (water-use efficiency; Petrone et al., 2014). However, peatlands and the autogenic processes described above are quite sensitive to ground disturbance, for example from linear disturbances, which can impact the hydrophysical properties of the peat and the overall hydrologic regime of the peatland (Volik et al., 2020; Elmes et al., 2021a).

Linear disturbances, including roads and pipelines (for oil and gas transport), are common across the AOSA, totaling 15,400 km and 19,900 km, respectively (based on the Alberta Biodiversity Monitoring Institute's Human Footprint Inventory (ABMI, 2019). Road development over peatlands involves placement of mineral material over peat, causing compression that increases the bulk density of the underlying peat (Trombulak and Frissell, 2000; Strack et al., 2018; Elmes et al., 2021a) and can cause barriers to sub-surface flow, altering water table fluctuations, vegetation characteristics (community composition, and afforestation or deforestation), and geochemical regime (Elmes et al., 2021a). Pipeline installation in the AOSA uses heavy machinery that typically removes at least 40 cm of the upper peat layer; this disturbed peat is then replaced over the excavated area after installation (Enbridge Pipelines Inc, 2012). This influences the hydrophysical properties of the near-surface peat (Soon et al., 2000; Olsen and Doherty, 2012), and thus, the transmissivity feedback mechanism described above.

Effects of linear disturbances on AOSA peatlands has gained increasing attention over the past decade, with most hydrological studies focusing on seismic lines (Petrone et al., 2008; Davidson et al., 2020) and roads (Bocking et al., 2017; Strack et al., 2018; Saraswati et al., 2020; Elmes et al., 2021a), with little or no information on pipelines. Furthermore, no studies have addressed the influence of multiple disturbance types and the potential for cumulative effects. In this study, we explore the hydrophysical impacts of a road and pipeline on a channel fen watershed (Poplar Fen) in the AOSA using a combination of hydrological and dendrochronological analyses. Specific objectives are to:

1. Evaluate differences in hydrophysical properties (total porosity, bulk density, drainable porosity, and saturated hydraulic conductivity) of peat replaced above the pipeline, adjacent to the pipeline in cleared areas, and in uncleared areas adjacent to cleared areas; and
2. Use contemporary hydrological as well as dendrochronological analyses to evaluate water table and subsurface flow regimes of the peatland area around the pipeline and road and determine whether it differs from less disturbed areas of the fen.

2. Methods

2.1. Study site

This study was conducted within the WBP, where the climate is defined as sub-humid (Bothe and Abraham, 1993; Devito et al., 2012), where the annual potential evapotranspiration typically exceeds precipitation, and dry conditions are interrupted by infrequent wet periods occurring over a roughly 10-year cycle (Marshall et al., 1999).

Analyses were conducted at a sub-watershed (2.5 km^2) of the Poplar Creek watershed, (hereafter referred to as Poplar Fen; 56°56′N; 111°32′W; Fig. 1b) located ~25 km north of Fort McMurray (refer to Fig. 1a). The watershed is located within a meltwater channel belt, characterized by treed moderate-rich channel fen (Chee and Vitt, 1989) at the center (1.5–1.7 m deep), which transitions to peat margin swamp towards the gentle sloping uplands (slope: 0.4–1.8%) (Elmes et al., 2021b). For more detail on the hydrogeologic setting and hydrological regime of the watershed, refer to Elmes and Price (2019) and Elmes et al. (2021b).

Anthropogenic disturbances had started in the area in the late 1960's when industrial oil sands development began. However, human impact was low at that time and the main disturbances included 3 seismic lines and a winter road in the northern and central parts of Poplar Fen. By the 1980 s, the current grid of cutlines outlined in Fig. S1 (2012) was established. Within this time, the upland area on the east side of the watershed had a permanent gravel road (Aostra Road) constructed through it, along a local drainage divide. An additional road was constructed in 2003 on the west side of Poplar Fen extending north to south, to provide access to gravel mining operations and a work camp (both located on the west side of the watershed in Fig. S1), establishing the final watershed boundary depicted in Fig S1. Culverts were installed at two different locations where peatland systems met the road to reduce potential flow restriction (refer to Fig. 1c).

In the spring of 2011, a below-ground pipeline was constructed along the northwest section of the site, extending southeast through a peatland system, and then east toward Aostra road (refer to Fig. 1b and c). Although details on the construction of the pipeline are unavailable, standard practices in the region involve the initial removal of a minimum of 40 cm of peat during installation; which is then replaced over the excavated area after installation (Enbridge Pipelines Inc, 2012). A ~40 m wide corridor was also disturbed alongside the pipeline, which included the removal of trees by heavy machinery. In the summer of 2011, a 0.3–0.5 m protuberance in topography over the pipeline was present due to the exposed overburden; however, in some areas, specifically near T3, this protuberance was not visible.

2.2. Methodology

2.2.1. Hydrological monitoring

Hydrological instrumentation of Poplar Fen began in 2011, comprising three north-south transects extending through peatland and upland areas (T1-T3) (Fig. 1c) to observe and monitor general sub-surface flow patterns. However, cleared areas near the pipeline were not monitored until 2012 (T2) and 2014 (T1 and T3). The final network comprised 13 wells in uncleared peatland areas, 4 in cleared areas near the pipeline (three of which were installed in the spring of 2014), 10 in upland areas, and one in a disturbed peatland area east of the road near the culvert (Fig. 1c). In 2014 and 2015, additional wells were installed at a reference location ≥300 m up-gradient from the pipeline (Fig. 1b). A total of 8 peatland and 4 upland wells were installed in this reference location. Across all field seasons and for all wells at Poplar Fen, absolute top of pipe elevations (meters above sea level; mASL) were measured using a DGPS (Leica Geosystems Viva GS14 GNSS RTK GPS system). The wells were constructed of perforated, screened 1.5-inch inner diameter PVC piping driven 0.8–1.5 m into the ground. Water table measurements were made ~weekly throughout the 2012–2015 monitoring period (May-Aug). In addition, a continuous measurement of fen water table level was recorded at T1 using a capacitance water level recorder (Odyssey Dataflow Systems Ltd.) set to collect depth to water table at 30-minute intervals throughout 2012–2015. Water levels on the east side of Poplar Road, adjacent to the culvert, were also recorded half-hourly in 2014 using the same capacitance water level recorder.

2.2.2. Soil sampling and analysis

To examine potential changes to peat hydrophysical properties due to pipeline development, 0.5–1.1 m-long peat cores were obtained in the summer of 2019 from pipeline (n = 5), cleared (n = 8) and uncleared (n = 6) locations (refer to Fig. 1c) using a 10-cm diameter PVC tube fitted with a hacksaw blade on the bottom. Once retrieved, samples were then sectioned into 10-cm stratigraphic intervals, frozen, and shipped to the Wetlands Hydrology Research Laboratory at the University of Waterloo. Once ready for analysis, peat samples were thawed, laid horizontally, and trimmed to fit into a 7-cm diameter stainless steel core and saturated with water for several days. Saturated samples were weighed for future analyses, and were then analyzed for horizontal saturated hydraulic conductivity (K_H) using a KSAT device (METER Group Inc., USA). A subset of samples was also measured for K_H manually using a constant-head method (Freeze and Cherry, 1979) to validate the accuracy of the KSAT device. Some samples from undisturbed sites (typically the near-surface samples) were only measured manually because they were too permeable (10^{-3} m s^{-1}) for the KSAT device to measure accurately. Following K_H tests, saturated samples were immediately measured for total volume using the area of the stainless-steel core and a sample height averaged from 10 measurements along random locations. Samples were then left to drain (and covered to prevent evaporation) for 24 h, and were then dried in an oven at 80 °C to remove all moisture (O'Kelly and Sivakumar, 2014). Saturated weight and volume, along with drained and dried mass, were used to calculate drainable porosity (n_d), total porosity (ϕ), and dry bulk density (ρb) using standard methods (Klute, 1986).

2.2.3. Dendrochronological analysis

To explore historical changes to the peatland due to road and pipeline construction, black spruce (*Picea mariana*) tree stem discs were obtained from three separate peatland locations, comprising a reference (undisturbed) location (n = 16), a road- and pipeline-disturbed location (n = 20) near within T1 and T2, as well as a road-only location (n = 13) adjacent to a different culvert farther south and away from the pipeline (refer to Fig. 1b). In this study, we were unable to sample a "pipeline-only" location, as no such peatland locations existed at a far enough distance from the road. As Poplar Fen was impacted by the Horse River Wildfire in 2016 (Elmes et al., 2018), some trees were burned, with the last ring corresponding to 2015. Only trees with slightest burning to the trunk were chosen to ensure that the tree and ring record had endured minimal damage. Tree stem discs were sanded using incremental grit sizes (with 600 grit being the finest) and rings were counted using a Velmex sliding stage micrometre (precision 0.001 mm). Duplicate measurements were made for each core, taken at a roughly 45° angle from the first measurement.

Chronologies for the three tree sampling locations were established using the R dplR package (Bunn, 2008). First, to detect user-error, all individual series were correlated against their master chronology using a negative exponential regression. Series with low R^2 (<0.35) and/or high p-values (>0.05) were reanalyzed until these conditions were satisfied. Cores that could not provide satisfactory correlations after several reanalyses were discarded from the final chronologies. The index series within each location (reference, road-only, and road/pipeline) were then combined using a negative exponential model, yielding three separate standardized ring-width index (RWI) chronologies each dating from 1970 to 2015, whereby an RWI > 1 denotes above average growth for a given year, and an RWI < 1 denotes below average growth.

2.2.4. Geospatial analyses

To analyze ground surface changes from road and pipeline development, elevation cross-sections were created in QGIS using an airborne LiDAR (Light Detection And Ranging) digital elevation model (DEM) with 2-m grid resolution (Airborne Imaging Inc. licensed to the Government of Alberta). Due to the hummock-hollow topography characteristic of peatlands, multiple parallel cross-sections (20 per transect) were made and averaged to smooth the surface to detect changes from disturbance. DEM elevations were ground-truthed using ground elevations obtained during DGPS pipe top surveys.

2.2.5. Statistical analysis

Since water table depth and peat hydrophysical property data were characterized by non-normal distributions (assessed by kurtosis and skewness coefficients, and the Shapiro–Wilk test), the Kruskal-Wallis test ($\alpha = 0.05$) was used to identify: 1) differences in hydrophysical properties among peat samples; and 2) differences in water table levels among all well locations across T1 and T2. Dunn's post-hoc tests were conducted with a Bonferroni correction following the Kruskal-Wallis tests to reveal differences in hydrophysical peat properties between sampling locations and between well locations. All statistical analyses were conducted using the Performance Analytics package (Peterson et al., 2020) in R (R Core Team, 2017).

3. Results

3.1. Surface elevation

For averaged cross-sections A-A' and B-B' (refer to Fig. 1c for locations), elevation changes from upland to fen were not smooth (Fig. 2), as is common in peatland and riparian systems with hummock/hollow microform topography. At cross-section A-A', the pipeline (oblique to the flow direction of the channel fen) was positioned at the peat margin swamp, north of the channel fen (refer to Fig. 1c). On the south side of the cleared area, near the vicinity of the pipeline is a sharp increase in surface elevation and a slope of 1% relative to the average slope of the remaining cross-section (0.25%). No such change in slope was observed on the north side of the pipeline (Fig. 2). For cross-section B-B', the pipeline was positioned in a local topographic low, near the center of the fen. The slope along the disturbed area at cross-section B-B' averaged 0.07%. This was similarly low relative to the slope in the low-lying peatland area to the southwest, which averaged 0.02%. Mounding from the replaced overburden over the pipeline could not be discerned visually in the B-B' cross-section (Fig. 2) nor could it be by field observations in 2019.

3.2. Peat hydrophysical properties

Peat cores obtained from the top 0–10 cm below ground surface (b.g.s.) from cleared areas north and south of the pipeline demonstrated significantly higher ρb (112%) and lower n_d (59%), ϕ (10%), and lower K_H (91%) relative to cores from uncleared areas (Fig. 3; refer to Table S.1. for standard deviations). Below 0–10 cm b.g.s., no significant differences were detected between disturbed and uncleared areas in any of the hydrophysical parameters (Fig. 3). For the replaced overburden directly over the pipeline, samples exhibited the highest ρb and lowest ϕ at all depths, with significant differences detected for most depths when compared with cores from both cleared and uncleared locations. At 0–10 cm b.g.s., replaced overburden directly over the pipeline demonstrated significantly higher ρb (170%) and lower n_d (65%), ϕ (17%), and lower K_H (94%) relative to cores from uncleared areas. Higher ρb and lower ϕ is consistent with mineral fragments (sand and gravel) that were found in the replaced overburden during core retrieval, compared to uncleared locations that did not comprise these fragments. For the remaining hydrophysical properties, significant differences were detected between pipeline and uncleared samples for K_H at 0–10 cm b.g.s., n_d at 0–10 and 10–20 cm b.g.s., and between pipeline and cleared for n_d at 30–40 cm b.g.s. (Fig. 3).

3.3. Water table

Fig. 4 illustrates spatial water table (kriged) patterns for above (June 2014) and below (August 2015) average water levels in road/pipeline and reference conditions. Throughout the measurement period, the general flow regime from T3 to the culvert south of the

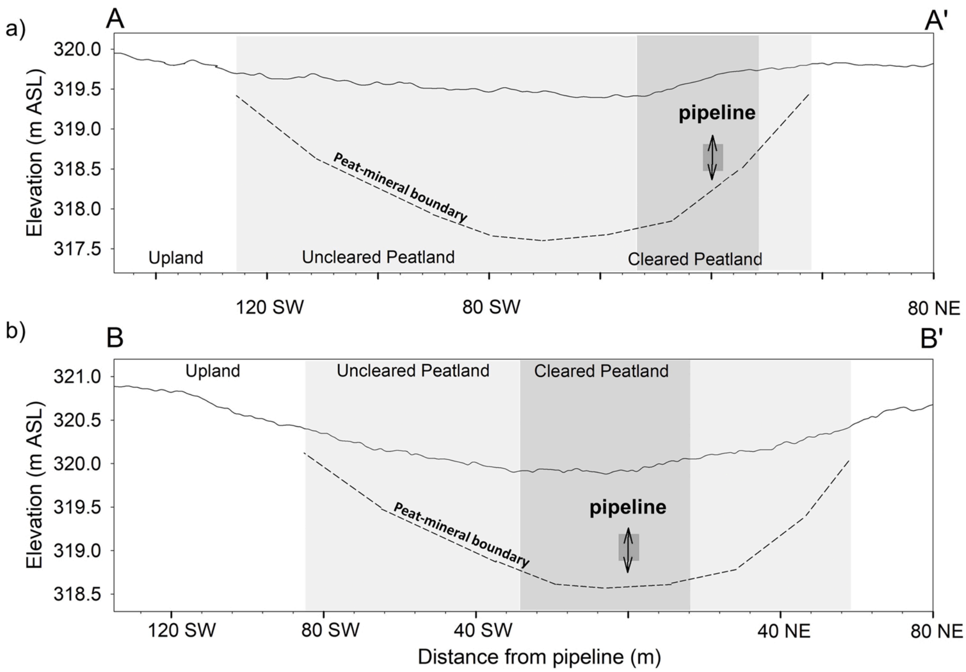

Fig. 2. Averaged surface elevation (solid line) cross-sections for transects A-A" and B-B" (see Fig. 1) highlighting cleared, uncleared, and above pipeline areas. Hash lines represent the peat/mineral boundary, interpolated from field observations. Pipeline upper and lower boundaries are estimated, highlighting uncertainty of the exact placement.

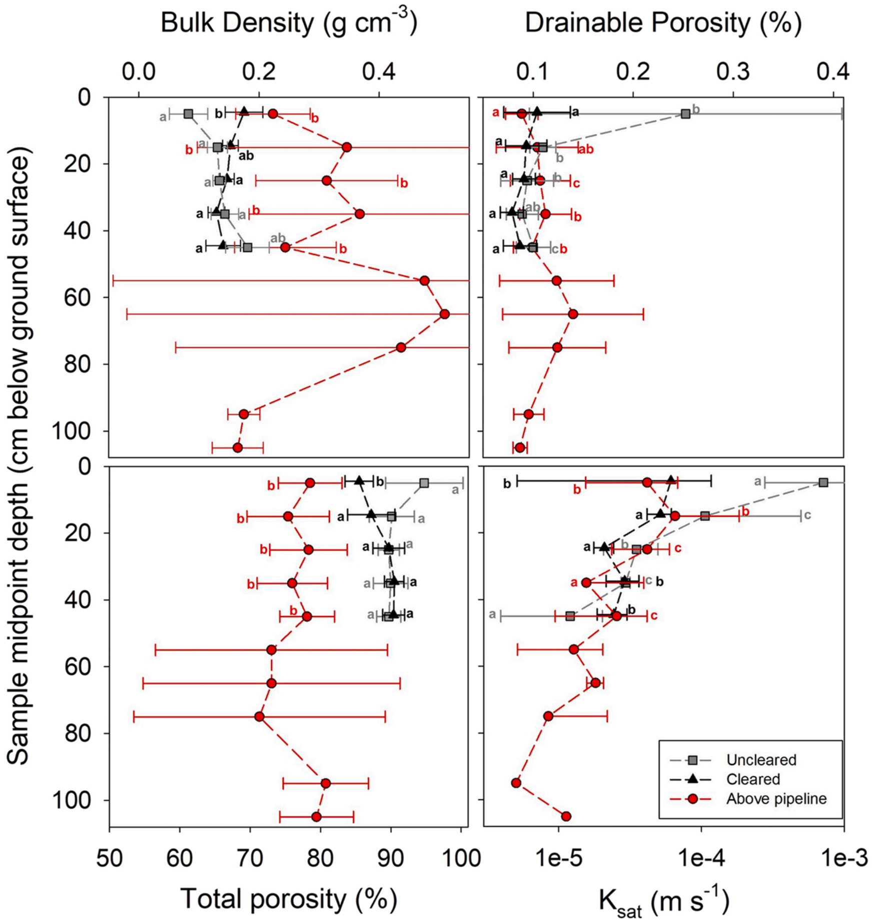

Fig. 3. Average values (with standard deviation bars) for hydrophysical properties with depth below ground surface for uncleared, cleared, and above pipeline locations sampled in 2019 (see Fig. 1). Statistical results are reported for each depth. Letter colour corresponds to location type, and locations that share a common letter are not significantly different from one another.

pipeline (interpreted as being orthogonal to the isopotential lines representing water table) was directed northwest down the peatland, roughly parallel to the direction of the pipeline. However, during the characteristically "wet" period (Fig. 4a), flow north of the pipeline was in a southwestern direction, toward the pipeline. Similar down-fen flow patterns were observed (Fig. 4c) in the reference location (refer to Fig. 1c); however, during extended dry conditions, the water table was directed west into the upland (Fig. 4d). Hydraulic gradients down the fen from T1 to T2 to T3, in 2015 (mean = 0.0025) were similar to those measured in the reference location (0.0021) over the same period.

The complete table of p-values between water table levels of wells at T1 and T2 is reported in Table S.2. Water table levels and variability were similar between cleared and uncleared peatland areas at T2 (Fig. 5). Here, no significant differences were detected between peat margin swamp locations north and south of the pipeline, and between fen locations north and south of the pipeline, including in the cleared area (Table S.2). Despite this, peat margin swamp and fen wells on the north side of the pipeline exhibited less variability (margin SD = 0.13 m; Fen SD = 0.12 m) relative to those measured south of the pipeline (margin SD = 0.19 m; fen SD = 0.15 m; cleared fen SD = 0.14 m) (Fig. 5). Further, both cleared and uncleared fen locations at T2 illustrated shallower water tables relative to peat margin swamp and upland locations (Fig. 5).

At T1, there was no fen water table level north of the pipeline due to its placement on the north peat margin swamp area of the channel fen (refer to Fig. 1c). Peat margin swamp water tables north of the pipeline (mean = 0.46 ± 0.27 m b.g.s (where ± denotes the standard deviation) were shallower on average, yet more variable relative to peat margin swamp water tables south of the pipeline (mean = 0.53 ± 0.20 m b.g.s); however, they were not significantly different from one another (Table S.2). South of the pipeline at T1, water table measurements in cleared (mean = 0.10 ± 0.22 m b.g.s) and uncleared (mean = 0.09 ± 0.16 m b.g.s) locations were not significantly different from one another (Table S.2).

Between transects, significant differences in water table level were not detected south of the pipeline between fen locations at T1 and T2; however, they were detected between peat margin swamp locations (Table S.2). Despite this, peat margin swamp locations exhibited similar standard deviations (T1 = 0.20 m; T2 = 0.19 m). Differences were more pronounced north of the pipeline in peat margin swamp locations. The peat margin swamp location at T1 had significantly lower (Table S.2) and more variable (SD = 0.27 m)

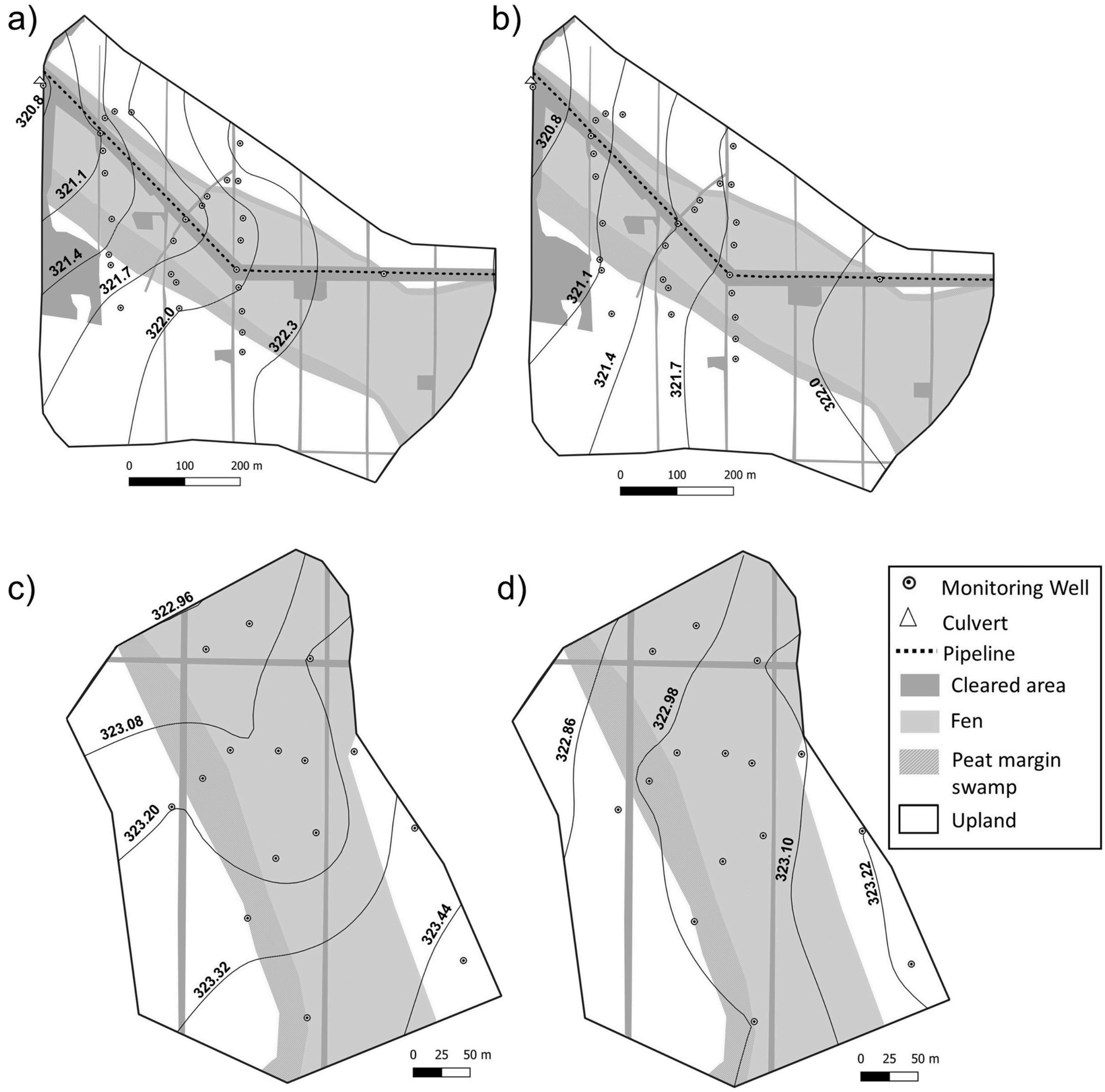

Fig. 4. Spatial water table level (kriged) for characteristically wet and dry conditions at the road/pipeline location in a) June 2014 and b) August 2015, respectively, and at the reference location in c) June 2015 and d) August 2015, respectively.

water table levels relative to T2 (SD = 0.13 m) (Fig. 5).

To investigate whether the road and pipeline were restricting flow out of the watershed, manually measured water table levels from 2012 to 2015 were plotted against one another for select well locations (Fig. 6). As was the case between all uncleared fen locations south of the pipeline, including reference fen water tables (refer to Fig. 1b), water table levels generally followed a strong linear relationship, as is illustrated in Fig. 6a. Comparisons of uncleared fen water tables south of the pipeline at T1 (180 m up-gradient from the road), and water tables adjacent to the culvert displayed a non-linear relationship (Fig. 6b). A similar curve is observed when comparing two uncleared peat margin swamp wells at T1, one located north and one located south of the pipeline (Fig. 6c). This non-linear relationship was not evident between fen water tables north and south of the pipeline at T3, and instead was linear (Fig. 6d).

3.4. Dendrochronology

Interseries correlations of ring width (negative exponential regression) for road/pipeline, road-only, and reference locations were 0.66, 0.63, and 0.54, respectively. RWI followed a similar pattern from 1970 to 2015 in pipeline/road, road only, and reference

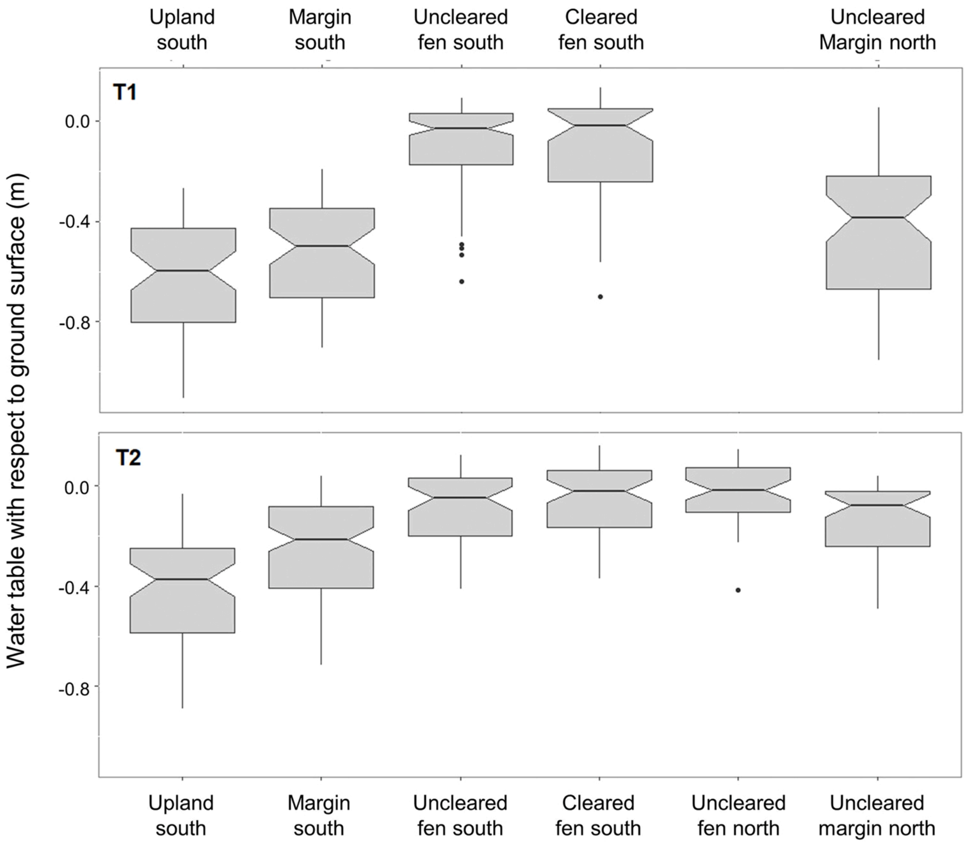

Fig. 5. Notched boxplots of water table level for all manual water table measurement days at T1 and T2 from 2012 to 2015 (days = 59). Note that dots represent outliers, and the notches in the boxplots display the confidence interval around the median. If box notches do not overlap, there is a 95% confidence that the medians differ.

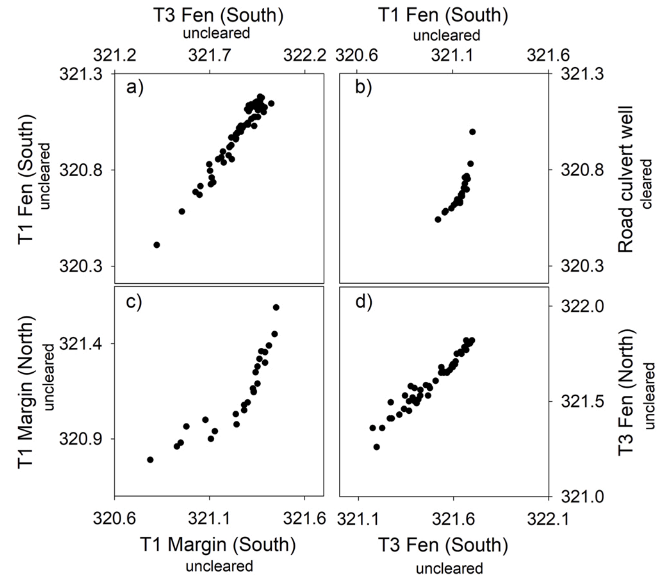

Fig. 6. Scatter plots displaying relationships between select wells, including a) T1 and T3 fen locations south of the pipeline, b) T1 fen location south of the pipeline and the road culvert well, c) T1 peat margin swamp wells north and south of the pipeline, and d) T3 fen wells north and south of the pipeline.

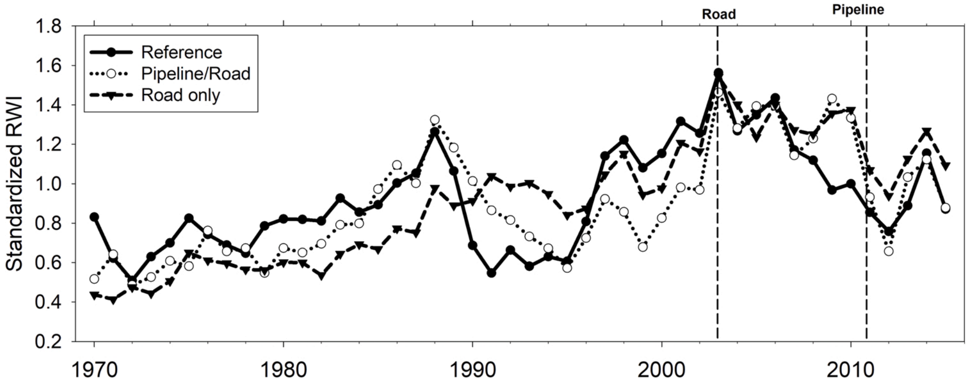

Fig. 7. Plotted RWI chronologies for reference, pipeline/road, and road only locations (see Fig. 1) from 1970 to 2015 at Poplar Fen.

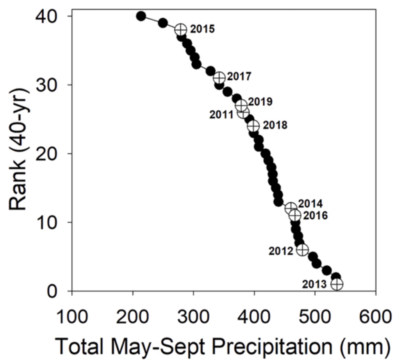

Fig. 8. Rankings of total growing season (May-Sept) precipitation for 1980–2019, with years since development of the pipeline (2011) highlighted.

locations (Fig. 7). In general, chronologies included a period of above average growth in the late 1980's, followed by a period of below average growth in the early 1990's, and another period of above-average growth in the mid-2000's. The trends in the late 1980's to mid-1990's; however, were not as apparent in the road-only location. In the second half of the chronology (1995–2015), all three locations showed strong agreement, and similar trends following road construction in 2003, and pipeline construction in 2011. The only detectable deviations between disturbed and reference chronologies in the second half of the record were in 2009 and 2010 (pre-pipeline) where pipeline/road and road-only locations both demonstrated above average growth relative to the reference location, which was close to average (RWI ~1) (Fig. 7). RWI at all three locations displayed weak and mostly statistically insignificant relationships with monthly air temperature and precipitation (Table S3).

4. Discussion

4.1. Changes to peat hydrophysical properties from pipeline construction

The peat sampling campaign above the pipeline and around its perimeter highlighted significant changes to peat hydrophysical properties at Poplar Fen, 8 years after construction. Differences were most pronounced directly over the pipeline, which exhibited a general absence of trends in properties with depth, relative to other sampled areas of Poplar Fen. Such differences can be explained by ground disturbance during the installation of the pipeline. For example, excavation from heavy machinery would lead to compression of the peat column (Gauthier et al., 2018), and excavation and replacement of the peat would have altered the natural layering of peat and its various stages of decomposition and associated hydrophysical properties. Furthermore, the presence of mineral soil grains within the replaced peat matrix (observed during laboratory analysis), which typically have a lower porosity and higher bulk density relative to peat, suggests that the pipeline was constructed into the mineral layer (>1.7 m depth), thus influencing the properties of the entire peat layer. Reductions in K_H and increases in bulk density, especially at the shallow, and normally most permeable peat layers, are synonymous with a reduction in flow (Elmes et al., 2021a).

Between cleared and uncleared fen locations, the greatest differences in peat hydrophysical properties were observed in the top 10 cm (Fig. 3). The heavy machinery used over the cleared area appeared to have significantly reduced the hydraulic conductivity and drainable porosity of the upper peat layer, which can even occur during winter when the ground is frozen (c.f. Gauthier, 2019). Such changes can influence water table dynamics and associated autogenic processes unique to peatlands (Waddington et al., 2014), which may result in a reduction in subsurface flow and thus runoff generation to downstream water bodies, due to a reduction in peat transmissivity. Such changes could further influence soil moisture dynamics (Chow et al., 1992; Silins and Rothwell, 1998; Price and Schlotzhauer, 1999), moss productivity and water-use efficiency (Kettridge et al., 2016), thus altering the peatland water balance. While some compression caused by ground disturbance is reversible, loads associated with heavy machinery well exceed pre-consolidation pressures associated with natural processes (Gauthier et al., 2018). Steps should also be taken to minimize disturbance around the pipeline, including minimizing the area cleared, and constructing during winter months when the peat substrate is frozen and more stable (Gauthier et al., 2018).

As peat sampling was conducted 8 years after pipeline construction, any potential rebound should be complete, as a wide range of hydrometeorological conditions have occurred over this time (Fig. 8). It is worth noting that over the 8 years since construction of the pipeline, the peat substrate may have experienced additional damage. For example, linear disturbances are often key travel routes for wildlife (James and Stuart-Smith, 2000) and heavy all-terrain vehicles (ATVs), both of which were observed in cleared areas south of the pipeline. These activities, specifically ATV use in the summer when the peat substrate is thawed can significantly compress and damage the natural peat structure (Ahlstrand and Racine, 1993). This may also explain why changes in surface elevation were more prominent on the south side of the pipeline near T1 (Fig. 2), as this wider and therefore more accessible side may have been more vulnerable to further degradation from recreational use.

4.2. Changes to the hydrology of Poplar Fen from pipeline and road construction

Despite changes to peat hydrophysical properties in disturbed areas (Fig. 2) no significant differences in water table levels were observed between uncleared and adjacent cleared locations south of the pipeline (Fig. 5). Although the pipeline was oriented obliquely to the flow direction, it was oriented toward the north side of the channel fen, and therefore did not obstruct flow down the fen on the south side of the pipeline. Furthermore, peat compression and associated changes to surface elevation and peat hydrophysical properties can lead to surface ponding during wet periods, and enhanced water table decline (via reductions to peat drainable porosity) during drier periods (Whittington and Price, 2006), which were not detected between 2012 and 2015. However, groundwater movement at Poplar Fen is influenced primarily by a local flow system generated in the adjacent uplands (Elmes and Price, 2019). It is likely that disturbed and uncleared locations are both influenced by vertical recharge/discharge patterns generated by this local groundwater flow system. Such hydrogeological controls seem to strongly moderate the water table in cleared and uncleared areas to minimize any changes that may result from the pipeline.

The influence of disturbance was more apparent north of the pipeline at T1. Higher water table variability (Fig. 5) and a faster water table rise and recession (Fig. 6c) at T1 peat margin swamp north of the pipeline can be explained by the orientation of the pipeline, as it cut into the peat margin swamp in this area of the channel fen (Fig. 1c). We argue that this caused flow obstruction (Fig. 4) and greater water table variability that was otherwise not witnessed at T2 (Fig. 5), where the pipeline was positioned closer to the center of the fen (Fig. 1c). As discharge zones in local flow systems typically develop at local elevational lows (Winter, 1999; Winter et al., 2003), the pipeline and denser replaced material likely acted as a barrier, establishing uncharacteristic discharge conditions in the peat margin swamp area north of the pipeline (Elmes et al., 2021b). This was not witnessed at the peat margin swamp area south of the pipeline at T1, where there was a wider flow face and no evidence of flow impediment towards the fen center (Fig. 4). Furthermore, the changes in water table levels north of the pipeline at T1 were likely exacerbated by being in close proximity to the road (~180 m), as an additional road culvert was not installed on the north side of the pipeline following construction.

The results presented in this study suggest that in the event of building a pipeline along a peatland, ideally, it should be built parallel (rather than obliquely) to the direction of flow, and at the fen center (local topographic low) to minimize obstruction to local recharge/discharge patterns. This is not to suggest that pipelines cannot be built perpendicular to flow, just that this orientation may have a greater impact on the hydrology of the peatland. Where the ideal orientation is impractical, pipelines would require permeable drains (E.g., French drains) across the obstruction to facilitate flow down-gradient. Where pipelines and roads intersect in a peatland, additional culverts under the road should be considered to minimize flow obstruction.

The relationship between water levels adjacent to the road and 180 m up-gradient of the road (south of the pipeline) (Fig. 6b) highlights the influence of flow obstruction, more severe than that which was observed north of the pipeline (Fig. 6c). This specific culvert was found to stop conveying water out of the watershed when the water table level fell below 320.58 mASL. It is close to this elevation (320.65 mASL) where water around the culvert recedes at a slower rate than up-gradient (Fig. 6c). Over the 5-year monitoring period, water levels fell below this minimum ~35% of the time. However, during this time, additional autogenic water table feedbacks would be restricting flow down the fen (Elmes and Price, 2019), corresponding to periods of typically low runoff generation (Devito et al., 2005). Here we suggest that during these periods when the water table falls below the culvert, the Athabasca River and tributaries are receiving limited runoff from peatlands regardless of whether or not they are disturbed. In contrast, the non-linear rise and recession in water table level near the road (Fig. 6b) relative to up-gradient fen locations during wetter periods (water level near road > 320.58 m) (Fig. 6a) illustrates how the culvert cannot convey water out of the watershed sufficiently once water table elevations rise beyond this threshold. We argue that the relationship observed in Fig. 6b is explained by flow obstruction, as standing water near the culvert (with a drainable porosity of 1) should rise due to precipitation at a slower pace relative to up-gradient locations where the water table is typically below ground surface, and drainable porosity is significantly lower (Fig. 2).

In spite of the hydrological changes described above, similar flow patterns were illustrated in the disturbed and reference locations during characteristically wet conditions (Fig. 4). In both cases, water table levels in the fen were lower relative to adjacent upland, suggesting that the fen transmits sub-surface water more efficiently out of the system relative to the upland. Thus, the primary hydrologic function of Poplar Fen appears to remain intact in spite of these disturbances.

Although the culvert was found to impede flow, it is assumed that ponded water will leave the watershed during wet periods, albeit at a slower pace relative to natural conditions. Road development will therefore cause a lagged stream response and lower peak flow. Standing water conditions can, however, lead to increased evaporation, which may reduce discharge from the system (Wells et al., 2017). Flow obstruction could be reduced at the Poplar Fen watershed by using larger diameter culverts that can handle higher discharge volumes during wet periods, or multiple culverts positioned at different elevations, which could continue to convey water out of the watershed during the dry periods. In addition, geosynthetics, including fabrics and underdrains) can aid in maintaining natural flow volumes under the road and reinforcing road-stream crossings (Keller, 2016). Given the age of the road in this study (est. 2003), it is unlikely that such technologies were used.

4.3. The use of dendrochronology to infer changes in hydrology from disturbance

We detected no large deviations (with the exception of 2009) in radial growth of black spruce between the three locations post-2003 (year of road construction). Results presented here suggest that black spruce are not particularly sensitive to any of the hydrological changes that may have occurred over this time. Our results contrast with those reported by Bocking et al. (2017), who detected tree die-off in a poor fen in the AOSA, ~10 years after the development of a permanent gravel road built perpendicular to flow. The lagged die-off that was observed by Bocking et al. (2017) was attributed to damming of the culvert from beavers, suggesting that the culvert was working sufficiently prior to damming. In contrast, the general agreement of our disturbed and reference RWI plots suggest that the culverts at Poplar Fen have either not been clogged, or have undergone regular maintenance and upkeep. It is important to note that no trees could be sampled north of the pipeline, as the 2016 Horse River Wildfire was more destructive to this particular area. We suggest that flow obstruction north of the pipeline at the peat margin swamp area of T1 (Fig. 6c) may have been sufficient to influence black spruce growth in this area; however, this can only be speculated.

5. Conclusions

This research provides insight into the impacts of road and below-ground pipeline development on peat hydrophysical properties and fen hydrology. Directly above the pipeline and in adjacent cleared areas, disturbance sufficiently altered the top 10 cm of peat, a highly transmissive layer that is important for conveying water down-gradient during wet periods. Given that the cores were obtained eight years after pipeline construction, any peat rebound would have already occurred. However, despite these changes, water table levels were roughly similar in disturbed and uncleared locations, and flow patterns were as expected along the peatland south of the pipeline. The largest impacts were observed north of the pipeline, as it was not built in the center of the fen, but rather closer to the north end of the fen and not entirely parallel to the flow direction. As a result, water table levels on the north side showed evidence of flow obstruction. Such changes were exacerbated by the road, which obstructed flow out of the watershed during wet periods. Despite construction of the pipeline and road, hydraulic gradients were approximately similar between areas near the disturbances and a reference location ~300 m and ~1 km up-gradient of the pipeline and road, respectively.

The above hydrological findings, combined with the inability to detect changes in radial growth of black spruce during the period of disturbance (2003–2015), suggests that these disturbances did not notably influence the hydrologic function of the majority of the watershed. However, precautionary steps should be taken during design and construction to minimize these impacts. For example, when building linear infrastructure within channel fens (e.g., roads pipelines), they should be constructed exactly parallel to the dominant flow direction, and in the center of the fen, to minimize flow obstruction on either side. When constructing linear disturbances through fens, perpendicular to the dominant flow direction (e.g., roads), efficient cross-drainage networks should be implemented. Furthermore, in the event of multiple disturbances (e.g., parallel following perpendicular), culverts should be located at the disturbance perpendicular to flow, on each side of the parallel disturbance. Minimizing the impact of a fen to these developments will depend on an efficient culvert network that is capable of conveying water over a wide range of hydrological conditions reflective of the Athabasca Oil Sands Area, as well as any geosynthetic underdrains beneath the road that can help in maintaining flow at greater depths.

CRediT authorship contribution statement

Matthew C. Elmes: Conceptualization, Formal analysis, Writing – original draft. **Richard M. Petrone:** Writing – review & editing, Conceptualization. **Olena Volik:** Project administration, Writing – review & editing, Conceptualization. **Jonathan S. Price:** Writing – review & editing, Conceptualization.

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.

Data availability statement

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

Acknowledgements

The authors wish to thank E. Davis, C. Raine, K. Tyler, J. Hu, G. Dube, G. King, A. Green, and J. Sherwood for their assistance in the field and/or laboratory, and to Andrew Trant for access to the Ecological Legacies Lab at the University of Waterloo to support dendrochronological analysis. We gratefully acknowledge funding from a grant to Richard Petrone from Suncor Energy Inc. This work was partly funded under the Oil Sands Monitoring Program and is a contribution to the Program but does not necessarily reflect the position of the Program.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101031.

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