Hydrochemical Transport of Wastewater Solutes from a Continuous Point Source in a Northern Ribbed Fen

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Abstract

To minimize the discharge of wastewater contaminants from remote northern communities and mining operations, fen peatlands in sub-arctic regions are used for tertiary wastewater treatment to detain, transform, and remove these contaminants. However, there is a limited understanding of contaminant transport in fen peatlands, particularly in sub-arctic Canada. To better characterize contaminant transport in these systems, approximately 43 m^3 day^{-1} of simulated wastewater (concentrated custom-blend fertilizer and Cl^- diluted with water) was pumped into a small 0.5 ha sub-arctic northern ribbed fen continuously for 47 days (July 15th – August 31st 2014). Specific conductance (SC) of 3 similar undisturbed northern ribbed fens varied between 15 (min) and 88 (max) $\mu S\ cm^{-1}$ over the study period (May – September 2014). Water table increased quickly (~0.16 m in 6 days) nearest the point source (8 m down-gradient), resulting in rapid solute transport, as measured by SC (20 to 140 $\mu S\ cm^{-1}$ in 11 days). This rapid transport was due to the large increase of hydraulic conductivity (~2 to 82 m day^{-1}) as the water table rose. More gradual increases in water table (0.18 m in 13 days) and SC (140 $\mu S\ cm^{-1}$ in 15 days) were observed farther (~50 m) from the point source; this delay was likely due to increased total storage capacity rather than differences in transmissivity. After 38 days, the water table had risen on average 0.16 m across the site but SC (113 $\mu S\ cm^{-1}$ in 25 days) was limited to a final distance of 117 m. Northern ribbed fens have a large capacity to detain wastewater (retardation factors between 1.1 – 2.2) from as illustrated by the solute plume only travelling 49 % of the total site length (notwithstanding the large increase in transmissivity as the water table rose) and have the potential to significantly decrease wastewater contamination in northern aquatic environments.

Introduction

Peatlands have been successfully used to treat primary (Yates *et al.*, 2012) and tertiary (Kadlec, 2009) wastewater that minimizes the discharge of contaminants from remote northern communities and mining camps into surrounding aquatic ecosystems. The effectiveness to treat wastewater depends on the biogeochemical controls (biological uptake, availability and quality of organic material, and solute constituents and concentrations) (Maina *et al.*, 2012) and the hydrological residence time, which typically has the most influence on the efficiency of these systems as it controls the time the solute is in contact with the substrate (Holcová *et al.*, 2013). Residence time is controlled by the transmissivity (T) of the aquifer and the hydraulic gradient but can also be increased through diffusion of solute into inactive and dead-end pores (herein referred to as inactive pores) (Hoag and Price, 1997). Furthermore, residence time is greatly affected by the presence of preferential flow paths (PFP) (Holcová *et al.*, 2013), which can be abundant in northern ribbed fen peatlands, generally occurring as rivulets or diffuse flow through vegetation (Price and Maloney, 1994; Quinton and Roulet, 1998).

Northern ribbed fen peatlands consist of a rib-pond topography where the connectivity pond-to-pond is inversely related to the size and directly related to the transmissivity of the peat rib (Price and Maloney, 1994). The ribs are oriented perpendicular to the main flow direction, but may have a low-lying PFPs that increases connectivity with adjacent ponds during periods of high water table (Quinton and Roulet, 1998). Ridges typically detain water due to more decomposed peat imposing lower hydraulic conductivity (K) at the same water table elevation than PFPs. There is a general understanding of the role and influence of the pond-rib morphology (Price and Maloney, 1994; Roulet, 1991); however, there are relatively few studies (Baird and Gaffney, 2000; Hoag and Price, 1995) examining the hydrochemical transport of conservative or reactive of solutes in peatlands.

Retardation into inactive pores decreases solute advection rates compared to the average linear groundwater velocity (υ) of conservative and reactive solutes (Baird and Gaffney, 2000; Hoag and Price, 1995). In lightly to moderately decomposed fen peat, Baird and Gaffney (2000) observed transport rates between 0.55 – 13.9 m day^{-1} and average K in the top 1 m of peat of 0.05 – 0.54 m day^{-1}, resulting in transport rates higher than the observed υ. Average K can be several orders of magnitude lower than the K of the upper few centimeters of the peat aquifer; thus, partly explaining the observed discrepancy between υ and transport rates. Conversely, at a blanket bog, Hoag and Price (1995) found K of 1382 m day^{-1} in the upper 0.1 m of the peat and the solute plume was retarded by a factor of 2.2 (retardation factor, RF) than the υ. Both studies noted the influence of inactive pores through measurements of solute retardation, deceases in the effective porosity, or solute diffusing out of inactive pores, as noted by prolonged tracer concentrations at the end of the experiments. However, both studies used single pulse injection and conservative solutes; whereas, wastewater is often a continuous point source contaminant and contains both reactive and conservative solutes (Kadlec, 2009). Furthermore, there is little information on the transport of solutes in northern ribbed fens peatlands, especially of reactive solutes.

With the planned development in the James Bay Lowland (JBL) and Ring of Fire the potential to use northern ribbed fen peatlands for wastewater treatment will increase, thus understanding the processes controlling the efficiency of these peatlands for wastewater treatment will help devise management strategies to minimize detrimental environmental effects. Therefore, the primary objective of this study is to understand the processes controlling the hydrochemical transport mechanisms within a northern ribbed fen.

Study Site

The study site (herein refereed as EXP Fen) was located in a small northern ribbed fen peatland in the JBL ~90 km west of Attawapiskat (Figure 1). The site consists of a pond-rib-pond topography, where the ribs consisted of two distinct microtopographic units, ridges and PFP. The ridges were topographically higher and dominated by hummock-forming *Sphagnum* moss (chiefly *Sphagnum fuscum*), ericaceous shrubs and *Picea mariana*, while the low-lying PFPs were dominated by *Sphagnum rubellum* and graminoid species. The site was laterally bound by bogs on either side and drained into a small tributary of the Attawapiskat River. The site topography sloped south east, resulting in flow perpendicular across the ridges.

Methods

Water (~43 m^3 day^{-1}) was pumped continuously (July-Aug) from a small bog complex adjacent to the EXP Fen and released into the uppermost pond (Figure 1). A concentrated fertilizer solute solution was pumped for 2

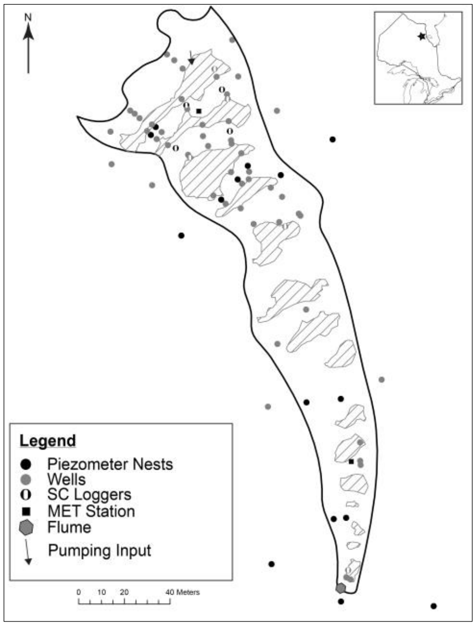

Figure 1 Map of the study site; EXP Fen.

minutes every 2 hours into the water line to achieve target solute concentrations of: NO_3^- = 9 mg L^{-1}, NH_4^+ = 9 mg L^{-1}, PO_4^{3-} = 7 mg L^{-1}, SO_4^{2-} = 35 mg L^{-1}, and Cl^- = 50 mg L^{-1}. Wells (1.25 m, 0.0254 m diameter) and piezometers (25 cm SI centred at 0.125, 0.375, 0.625, and 1.125 m) (Figure 1) were measured every 2 days for hydraulic head and specific conductance (SC) (SC in wells only). SC of the piezometers were taken 3 times during the field season (once prior to pumping, after 29 days of pumping, and after 14 days post-pumping) to determine the vertical distribution of the solute. Water table and SC were recorded every 20 minutes in the different microforms on pressure transducers and electrical conductivity loggers, respectively. The Hvorslev (1951) time-lag solution was used to determine the *K* of the piezometers, while Hvorslev (1951) variable head solution was used in conjunction with single-packer tests on fully penetrating (~2.5 m) wells to determine the *K* in the upper 0.5 m of the peat aquifer in 0.1 m increments. Effective porosity was determined for the upper 0.25 cm of the water table in both microforms using the soil water retention method at -100 mb (Bear, 1972).

Results

The average water table increase due to pumping was ~0.16 m across the site from pre-pumping conditions and was maintained throughout the experiment. *K* decreased rapidly within the upper 0.5 m of the of the peat aquifer from ~80 m day^{-1} to ~0.08 m day^{-1} at 0.5 m and remained consistently low in the bottom 1.5 m of the peat (Figure 2). Although water tables between microforms were at the same elevation, their position relative to the surface was different where the water table in the PFPs was typically within a few centimeters of the surface, while 0.3 – 0.5 m in the ridges. Although *K* in the upper 0.5 m of the peat deposit between microforms was similar (10 m day^{-1} vs 5 m day^{-1}, in PFP and ridge, respectively), the upper 0.1 m was higher in the PFPs (82 m day^{-1} vs 18 m day^{-1}, in PFP and ridge, respectively). Additionally, the *T* of the peat in the upper 0.5 m was higher in PFPs (4.9 m^2 day^{-1}), due to a larger saturated zone, than ridges (2.7 m^2 day^{-1}). There was no systematic difference in effective porosity between microforms, which ranged from 0.14 – 0.46, and resulted in average linear groundwater velocities of 0.67 - 5.71 m day^{-1} and 0.4 - 2.26 m day^{-1} in the PFPs and ridges, respectively.

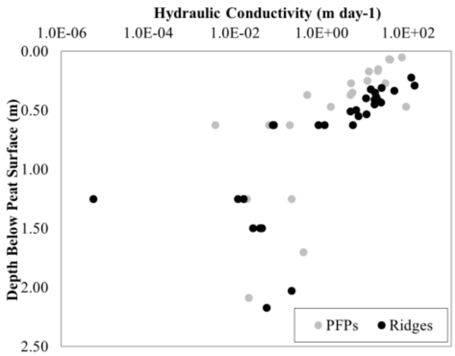

Figure 2 Hydraulic conductivity in PFPs and Ridges and peat depth. Note the several order of magnitude decrease with depth.

The majority of solute transport occurred in the upper 0.25 m of the water table as indicated by the 0-0.25 and 0.25-0.5 m piezometer measurements in the PFPs and ridges, respectively

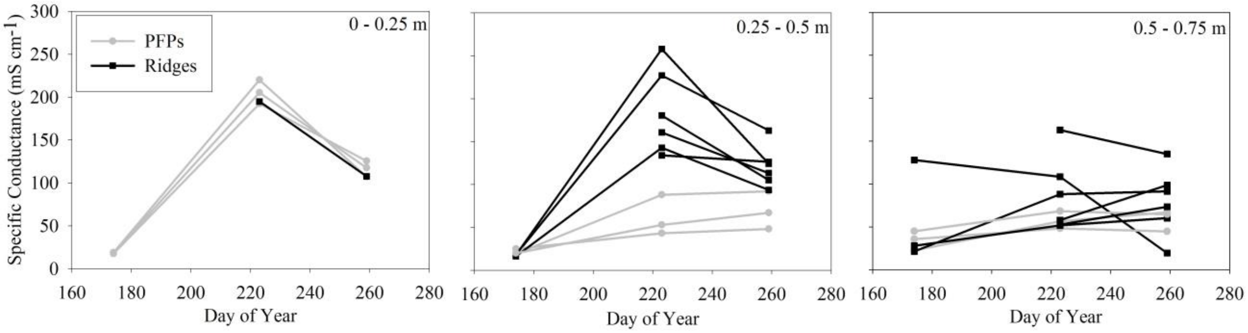

Figure 3 Specific conductance in the upper 0.75 m (separated into 0.25 m piezometers) of the aquifer over the study period. Only 1 ridge and the 3 PFPs are saturated in the upper 0.25 m of the peat profile. Few piezometers increased in SC above the background levels (92 µS cm^{-1}) in the 0.5 – 0.75 m peat layers.

(Figure 3). Although a sharp increase in solute (SC) was noted in the PFP's upper 0.25 m (25 µS cm^{-1} to 220 µS cm^{-1}), there was not a similar increase between 0.25 – 0.50 m indicating limited downward transport of solute; notwithstanding high downward hydraulic gradients (0.2). This trend was also observed in the ridges between the 0.25 – 0.50 m and 0.50 – 0.75 m piezometers (Figure 2). Solute breakthrough (50 % of the relative SC value) due to advection/dispersion occurred 38 days after pumping began, 44 m (peat only; total distance 117 m) down gradient (1.16 m day^{-1} in the peat) (Figure 4), while lateral advection near the point source (into the adjacent bogs) was 0.29 m day^{-1} (Figure 4) and an υ of 0.83 m day^{-1}. Near the terminal edge of the plume minimal longitudinal dispersion (0.8 m day^{-1}) was observed and was typically limited within the EXP Fen (Figure 4). Solute breakthrough rates determined from logged SC values (data not shown) within microforms (0.62 - 2.88 m day^{-1} and 0.35 - 1.02 m day^{-1} for PFPs and ridges, respectively) indicate a RF of 1.2 - 2.0 and 1.1 - 2.2 for PFPs and ridges, respectively. Excluding the ponds, the entire site had a RF of 1.4 based on the maximum solute breakthrough rate (1.16 m day^{-1}) and site υ in the upper 0.1 m (1.67 m day^{-1}). Mineral groundwater upwelling, and not the solute release, in the southern portion of the EXP Fen increased the SC above background levels (Figure 4, +14 Days).

Discussion

The degree of connectivity between ponds directly controls the ability of peatlands to treat wastewater (Holcová *et al.*, 2013; Kadlec, 2009) and this connectivity is controlled by the T of the rib microforms. However, the dual porosity structure of peat (Ours *et al.*, 1997) further inhibits solute transport through the diffusion of solute into inactive pores, resulting in the retardation of conservative solutes; typically expressed as the factor of the breakthrough rate over the υ (Hoag and Price, 1997; Hoag and Price, 1995). The input of wastewater not only contains elevated nutrients (Kadlec, 2009) but large volumes of water that raised the water table (~0.16 m) and thus, increased the T of the ribs as higher K peat layers become saturated (Figure 2) and increased the connectivity between ponds. This increase in T resulted in the majority of solutes to be transported within the upper 0.25 m of water table, representing the 0.25 and 0.50 m piezometers in the PFPs and ridges, respectively (Figure 3). The average K of the upper 0.2 m (40 m day^{-1}) resulted in average linear groundwater velocities (0.91 m day^{-1}) lower than the average solute advection rate (1.16 m day^{-1}); thus, it is highly probable that the majority of solute must be transported in the uppermost 0.1 m of the aquifer, resulting in higher υ (1.67 m day^{-1}) and a RF of 1.4. The range of RFs observed within microforms (1.2 - 2.0 and 1.1 - 2.2, PFP and ridges, respectively) and the EXP Fen average (1.4) agree with the value reported by Hoag and Price (1995) (2.2) and indicates, on average, a reduced influence of inactive pores throughout the EXP Fen compared to the observed maximums. Although the high SC values near the point source are due to both reactive and conservative solutes, Cl$^-$ (determined through titration) and SC agreed well towards the middle

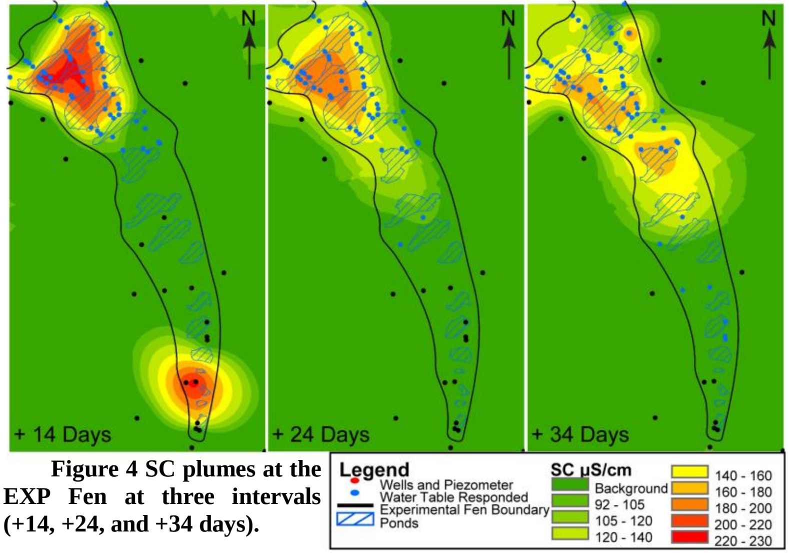

Figure 4 SC plumes at the EXP Fen at three intervals (+14, +24, and +34 days).

and toe of the plume (data not shown) indicating the site RF (1.4) is likely derived from the conservative solute; however, further geochemical investigation is required to confirm this value.

Near the point source, higher hydraulic gradients increased the lateral advection, resulting in solute transport into the surrounding bogs (Figure 4). However, similar to Hoag and Price (1995) longitudinal advection was higher than mechanical dispersion and transverse advection (Figure 4), which was typically limited to the EXP Fen boundaries as lateral hydraulic gradients were negligible. Within microforms, bypassing flow was not evident as double or treble SC peaks (Baird and Gaffney, 2000) typically correlated well with precipitation events or unexpected variations with pumping rates. However, the higher *T* in PFPs created bypassing flow through a rib. This bypassing flow increased the solute transport within the PFPs but not the ridges, resulting in an asymmetric solute plume. The highest SC values observed away from the point source (i.e. second rib) was along the western edge of the EXP Fen (Figure 4) where a greater density of PFPs were observed and typically associated with higher *T*. The bypassing flow due to higher *T* in the PFPs increased the connectivity of the EXP Fen and decreases the ability of the system to detain wastewater.

Conclusions

Solute transport in northern ribbed fen peatlands is highly dependent on the *T* of the peat aquifer and the proportion of PFPs with the peat ribs. The exponentially higher *K* of the upper 0.1 m of the peat aquifer resulted in rapid solute transport and minimal vertical advection. Although northern ribbed fen peatlands are able to passively retard solutes through diffusion into inactive pores, the transport was still quite rapid and may decrease the treatment efficiency of these systems. However, decreasing the total hydrological load would likely decrease the overall water table height, lowering the *T* and thus, reducing the solute transport rate. By imposing a lower water table, wastewater would remain in contact with the peat substrate longer and increase the treatment efficiency in northern ribbed fen peatlands.

References

Baird AJ, Gaffney SW. 2000. 'Solute movement in drained fen peat: a field tracer study in a Somerset (UK) wetland', Hydrol. Process. 1414, 2489-2503

Bear J. 1972. *Dynamics of Fluids in Porous Media*. Dover Publications, Inc. : New York.

Hoag RS, Price JS. 1995. 'A field-scale, natural gradient solute transport experiment in peat at a Newfoundland blanket bog', J. Hydrol. 172, 171-184

Hoag RS, Price JS. 1997. 'Effects of matrix diffusion on solute transport and retardation peat', J. Contam. Hydrol. 28, 193-205

Holcová V, Šíma J, Dušek J. 2013. 'A comparison of fluorescein and deuterated water as tracers for determination of constructed wetland retention time', Cent. Eur. J. Chem. 112, 200-204

Hvorslev MJ. 1951. *Time Lag and Soil Permeability in Ground-Water Observations*. US Army Corps of Engineers: Vicksburg, Mississippi.

Kadlec RH. 2009. 'Wastewater treatment at the Houghton Lake wetland: Hydrology and water quality', Ecol. Eng. 35, 1287–1311

Maina CW, Mutua BM, Oduor SO. 2012. 'Simulation of constructed wetland treatment in wastewater polishing using PREWet model', DESALIN WATER TREAT. 411-3, 356-363

Ours D, Siegel DI, Glaser PH. 1997. 'Chemical dilation and the dual porosity of humified bog peat', J. Hydrol. 196, 348-360

Price JS, Maloney DA. 1994. 'Hydrology of a Patterned Bog-Fen Complex in Southeastern Labrador , Canada', NORD HYDROL. 25, 313-330

Quinton WL, Roulet NT. 1998. 'Spring and Summer Runoff Hydrology of a Subarctic Patterned Wetland', Arct. Alp. Res. 303, 285-294

Roulet N. 1991. 'Surface Level and Water Table Fluctuations in a Subarctic Fen', Arct. Alp. Res. 233, 303-310

Yates CN, Wootton BC, Murphy SD. 2012. 'Performance assessment of arctic tundra municipal wastewater treatment wetlands through an arctic summer', Ecol. Eng. 440, 160-173